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Influence of Planting Density on Citrus Yield and Tree Vigor

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Abstract This study analyzes the mechanisms by which different planting densities affect citrus yield and tree vigor, and compares low-, medium-, and high-density cultivation systems in terms of yield formation, tree structure, and resource use efficiency. Increasing planting density can significantly improve early yield per unit area and accelerate canopy closure and light interception efficiency. However, it also reduces yield per tree and intensifies competition for light, water, and nutrients, which may lead to excessive canopy shading, increased pests and diseases, and a decline in long-term productivity. In long-term production, medium-density systems often perform better in terms of yield stability and economic returns. Rootstock type and cultivar characteristics play a decisive role in adaptability to dense planting. Dwarfing or semi-dwarfing rootstocks can effectively control tree vigor and improve fruiting efficiency, serving as an important foundation for high-density cultivation. Proper pruning, water and fertilizer management, and mechanization support can help mitigate the negative effects of high-density planting. In the future, combining precision agriculture technologies with breeding innovations will enable dynamic optimization of planting density and sustainable orchard design.

Keywords Planting density; Citrus; Yield formation; Tree vigor regulation; High-density cultivation

1 Introduction

Citrus is one of the most economically important and widely grown fruit crops in the world. It includes sweet orange, mandarin, grapefruit, lemon, and lime. Citrus fruits are also an important part of the human diet, as they are rich in vitamin C, dietary fiber, and various phytochemicals.

Traditional citrus orchards usually use low planting density and wide spacing. This allows trees to develop large canopies and makes mechanized operations easier. However, it also leads to slow canopy closure and low land and resource use efficiency during the early fruiting stage (Wheaton et al., 1995). In contrast, high-density planting systems aim to speed up canopy development, improve light interception, and increase yield per unit area in the early growth and early bearing stages. At the same time, high density can increase competition for light, water, and nutrients, raise the risk of pests and diseases, and make management practices such as pruning, spraying, and harvesting more complex. It may even shorten orchard lifespan or reduce long-term economic returns (Vidalakis et al., 2011).

In low-density systems, the number of trees per hectare is small and spacing is large. This usually supports vigorous growth, larger canopy size, and easy machine movement, but it may delay canopy closure and the achievement of maximum yield. Medium-density systems try to balance faster canopy formation with higher early yield, while controlling tree vigor, reducing shading, and lowering management costs. High-density and super-high-density systems can reach or exceed 1 000~2 000 trees per hectare. In some citrus studies, these systems have shown clear advantages in improving early yield and land use efficiency, especially when combined with dwarfing or semi-dwarfing rootstocks (Haque and Sakimin, 2022). In citrus production, the development of semi-dwarfing and dwarfing rootstocks, dwarfing viroids, precision irrigation and fertilization, and improved pruning and training practices has further supported the use of high-density planting systems (Azevedo et al., 2020).

This study aims to systematically evaluate how different planting densities affect citrus yield and vegetative growth. It compares low-, medium-, and high-density systems in terms of canopy development, tree size, and vigor. It also quantifies yield per tree, yield per unit area, and their components under different density levels. In addition, the study explores the relationship between tree vigor and yield efficiency under different planting densities. The results are expected to provide a theoretical basis for selecting an optimal planting density that balances land use efficiency and tree performance, and to offer practical guidance for orchard design and management under different production conditions.

2 Theoretical Basis of Planting Density Effects

2.1 Light interception and canopy structure

Crop yield is closely related to the amount of light intercepted per unit land area. It also depends on how efficiently this light energy is converted into chemical energy and finally into harvestable yield. Canopy structure—defined by tree height, canopy width, leaf area index (LAI), and the spatial distribution of leaves—determines both the amount and vertical distribution of photosynthetically active radiation (PAR) within the canopy (Murchie and Burgess, 2022).

In recent years, studies in citrus orchards have used UAV-based LiDAR and radiation transfer models to analyze the relationship between canopy structure and light interception. By linking canopy geometry, tree spacing, and row orientation with PAR interception, researchers found that both canopy structure and planting density strongly affect the daily and seasonal patterns of light interception. These changes further influence water use and overall productivity (Guillén-Climent et al., 2012; Rojo et al., 2023).

Planting density interacts with these structural factors by altering tree size, canopy overlap, and LAI. High-density planting usually leads to faster canopy closure and higher LAI, which improves light interception at the population level. However, it also increases self-shading within the canopy (Singh et al., 2020; Oliveira et al., 2024).

When LAI becomes too high, further increases in leaf area contribute little to total light interception but significantly increase internal shading. Once light interception exceeds about 50%, the positive relationship between light interception and yield starts to weaken (Dian et al., 2023).

2.2 Resource competition mechanisms

Plants compete for resources mainly in two ways. First, individuals can capture resources before their neighbors (pre-emption of resource supply). Second, they can reduce the availability of resources in a shared environment.

As tree density increases, root systems overlap more, which strengthens belowground competition. Under strong resource limitation, this may lead to earlier self-thinning (Huang et al., 2021). In plantations, high density intensifies competition for light, water, and CO_2. It also increases shading and limits resource access for smaller individuals. When density exceeds the environmental carrying capacity, mortality risk rises and overall productivity declines.

In semi-arid regions or under irrigation systems, water competition is especially important in citrus production. Different rootstock genotypes vary in their ability to explore soil and tolerate low water potential. Water competition mainly works by reducing soil water availability. As a result, genotypes that can tolerate drought or maintain water uptake under low water conditions gain an advantage (Craine and Dybzinski, 2013).

Under high-density planting, overlapping root zones increase the consumption of soil water and nutrients within tree rows. If irrigation and fertilization are not adjusted to match higher demand, drought stress and nutrient deficiency may become more severe (De Oliveira Sousa et al., 2024; Pokhrel et al., 2025).

When water is limited, belowground competition becomes more important than aboveground competition. This shows that root competition is a major constraint in high-density systems under water stress (Foxx and Fort, 2019). In contrast, when water is sufficient, aboveground competition-mainly for light-becomes the main factor limiting growth.

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}).

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).

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 and flavonoids. Although substandard, semi-dwarf, and dwarf rootstocks reduce yield per tree, they improve yield efficiency (kg fruit m^{-3} canopy) and allow closer spacing. In ‘Lane Late’ sweet orange, FA13 and FA41 produce smaller trees, and under higher density they show strong yield potential per area. FA13 also improves nutrient use efficiency under low fertilizer input, making it suitable for intensive but sustainable systems (Hervalejo et al., 2021) (Figure 1).

In ‘Valencia’, several low-vigor trifoliate hybrids (such as IPEACS-239, IPEACS-256, and US-802) showed about 55% higher production efficiency than the vigorous ‘Rangpur’ lime, making them good candidates for high-density systems (Domingues et al., 2021). In high-density systems, dwarfing citrandarin rootstocks such as IAC 1600, 1697, and 1711 maintained high productivity while improving water use efficiency and reducing HLB susceptibility, performing better than standard Swingle (Devite et al., 2025).

Figure 1 Overview of the experimental plot (Adopted from Hervalejo et al., 2021)

5.3 Matching planting density with genetic traits

The optimal planting density in citrus depends on a proper balance among scion vigor, rootstock dwarfing ability, and production goals. For traditional vigorous rootstocks, densities above 1 000 trees ha^{-1} are usually not justified. Once orchards reach full production, yield per year is often no longer strongly affected by density, while excessive density increases competition and management difficulty. When both scion and rootstock are vigorous, a moderate density (about 300~700 trees ha^{-1}) is more appropriate. When vigorous scions are grafted onto dwarf or semi-dwarf rootstocks, higher or even super-high densities can be used because tree size is controlled and efficiency is improved. Long-term trials with ‘Valencia’ grafted onto dwarf TSKC × TRFD citrandarins showed that adjusting spacing based on smaller tree size can increase productivity to about 40 t ha^{-1} $year^{-1}$, nearly doubling yield (Costa et al., 2021).

In Spain, ‘Salustiana’ grafted onto the dwarf FA517 rootstock performed well under super-high-density planting with mechanical harvesting. Proper rootstock selection can support both high-density systems and mechanization (Hervalejo et al., 2022). For ‘Flying Dragon’, spacing of 1.5~2.5 m within rows and 4~5 m between rows is recommended to balance early yield and canopy management (Kumar, 2024). Compact or naturally small scions (such as some mandarins and ‘Murcott’) can be combined with moderately dwarfing rootstocks to create “walkable” orchards, allowing ground-based harvesting and reducing pesticide use.

In ‘Shamouti’, weaker trifoliate-related rootstocks (such as Swingle and C-13) support higher planting densities than vigorous citrus or Rangpur rootstocks, while still maintaining good fruit quality (Carvalho et al., 2022). On the other hand, under water-limited conditions or high HLB pressure, using high-density systems together with small, efficient rootstocks (such as dwarf citrandarins or some tetraploid rootstocks) can stabilize yield per area, improve water use efficiency, and reduce the risk caused by individual tree loss.

6 Agronomic Management Practices Supporting Optimal Planting Density

6.1 Pruning and canopy management

In a study on 35-year-old ‘Valencia’ sweet orange trees, four pruning treatments were applied every year in mid-February, removing 0%, 25%, 50%, and 75% of the main branches. As pruning intensity increased, overall canopy volume decreased, but vegetative growth was stimulated, with longer shoots and larger leaves. At the same time, light penetration inside the canopy improved (Al-Saif et al., 2023). Heavy pruning (75% branch removal) resulted in the highest fruit yield, increasing by nearly 20% compared with the unpruned control. It also significantly improved fruit size, juice content, total soluble solids (TSS), TSS/acid ratio, and vitamin C content. Even in older and larger trees, strong pruning can renew the canopy, restore internal light conditions, and improve both yield and fruit quality.

Mechanical pruning is widely used in high-density orchards to control canopy size and reduce labor costs. It is especially suitable for hedgerow systems combined with topping and side hedging. In ‘Finn 95’ lemon, a 4-year comparison of five pruning strategies showed that alternating full mechanical pruning (topping, skirting, and double-sided hedging) with manual pruning, or using only mechanical pruning, significantly reduced pruning time and increased net profit compared with continuous manual pruning. These approaches did not show clear long-term yield reduction (Martin-Gorriz et al., 2021). Similarly, in ‘Clemenules’ mandarin, a 4-year experiment comparing 12 pruning strategies showed that alternating mechanical pruning (topping plus one-sided hedging) with manual pruning maintained stable tree size and canopy vitality. Yield was comparable to fully manual pruning, while costs were lower (Fonte et al., 2022).

In China, new labor-saving cultivation systems further highlight the link between canopy structure and light use. In Hubei, a comparison among traditional planting, wide-row–narrow-spacing planting, and a “fence-type” system showed clear differences in vertical canopy structure measured by UAV LiDAR. The point cloud density above half tree height was 64.85% in the wide-row system and 71.94% in the fence-type system, compared with only 50.02% in the traditional system (Dian et al., 2023). The fence-type system forms a vertical hedgerow canopy using support structures and pruning. This improves light distribution and increases photosynthetic rates in all canopy layers. The average photosynthetic rate of lower canopy leaves in the fence system was 1.74 times that of the traditional system and 1.66 times that of the wide-row system.

6.2 Nutrient and water management

Under high planting density, competition for soil resources becomes stronger. Therefore, precise water and nutrient management is essential to maintain tree vigor, yield, and root health. In semi-arid orange orchards, a 5-year study on deficit irrigation showed that compared with full irrigation (100% ETc), sustained subsurface deficit irrigation (SSDI), regulated deficit irrigation (RDI), and partial root-zone drying (PRD) reduced water use by 25%, 33%, and 49%, respectively, without significant yield loss (Stagno et al., 2024). At the same time, water use efficiency increased and some fruit quality traits improved. Vitamin C content was higher under RDI (62.7 vs 58.5 mg 100 mL^{-1}). SSDI and PRD increased pulp color index to around 10, compared with 8.44 in the control. Leaf nutrient levels remained generally adequate, although potassium was slightly low, suggesting that K monitoring is important under deficit irrigation.

In high-density young ‘Valencia’ orchards (955 trees ha^{-1}) under Huanglongbing (HLB) conditions in Florida, drip or microsprinkler irrigation combined with fertigation was compared with standard-density orchards (358 trees ha^{-1}) using controlled-release fertilizers (Ferrarezi et al., 2020). Nitrogen application followed UF/IFAS recommendations: 0.11-0.34 kg N per tree annually for non-bearing trees, and 224 kg N ha^{-1} annually for bearing trees, adjusted based on leaf analysis. After seven years, leaf nutrient concentrations were generally within or above recommended levels. High-density fertigation treatments produced the highest yield per unit area and total soluble solids. In some years, yields were 86%~300% higher than standard density, even though individual tree canopy volume was smaller (4.3~5.9 m^3 vs 6.2~7.2 m^3).

In Florida sandy soils, irrigation levels of 50%, 78%, and 100% ETc were compared under different planting densities. The moderate irrigation level (about 78% ETc) improved fine root length density, root survival, and root lifespan compared with both deficit and full irrigation (Atta et al., 2024). At the highest density, trees experienced stronger water stress in spring, indicated by lower stem water potential, showing more intense competition. Moderate irrigation reduced stress and improved stomatal conductance in both low- and medium-density treatments. Compared with traditional irrigation, reducing water by about 20%~30% may improve soil moisture distribution and promote deeper, more resilient root systems. This is especially important in high-density orchards, where shallow roots are more vulnerable to drought and nutrient depletion.

In southern China, a 2-year field experiment combined drip irrigation at 70% field capacity with 2.5 g L^{-1} alginate oligosaccharide (AOS) applied 8–10 times (W70AOS2.5). Compared with no AOS, this treatment increased yield by 11.9%~13.3%, total soluble sugars by 15.2%~17.5%, and sucrose by 18.9%-20.8%. Potassium use efficiency and water use efficiency increased by 51.1%~62.2% and 12.0%~13.3%, respectively (Li et al., 2024). This treatment also increased net photosynthetic rate, total root length, root surface area, and root volume. It improved soil aggregate stability (>0.25 mm), increased available potassium and cation exchange capacity in the topsoil (0-20 cm), and reduced leaching of water and potassium to deeper soil layers.

Monitoring tools such as mobile lysimeters and leaf analysis can further improve fertilization accuracy. In a ‘Nules’ clementine orchard in Morocco, nutrient concentrations in soil solution and leaves showed high variability (about 55% in soil solution and 63% in leaf macronutrients), mainly driven by irrigation, fertilization, and soil conditions (Zayani et al., 2024). Regular monitoring of N, P, K, Mg, and Ca in soil and leaves allows better adjustment of fertilization timing and rates, helping meet crop needs while reducing nutrient loss and production costs.

6.3 Mechanization and labor efficiency

High-density planting, combined with controlled tree height and narrow canopy width, makes it easier for tractors to pass and supports mechanical pruning, precision spraying, and even mechanical harvesting in some systems.

Maintaining an appropriate canopy size and avoiding overcrowding not only improves light interception and yield, but also enhances spray coverage and machine efficiency. Large and unmanaged canopies reduce spray penetration inside the canopy and interfere with machine operation. When canopies are too dense and irregular, up to 28% of spray droplets may not reach the tree surface (Verbiest et al., 2020).

In pome fruit systems, semi-autonomous pruning systems have been developed for planar “upright fruiting offshoot” structures. A robotic pruning prototype achieved a cutting success rate of 58% on 10 trees in a planar sweet cherry orchard (You et al., 2023).

7 Future Perspectives

7.1 Integration with precision agriculture: remote sensing and density optimization

High-density citrus orchards are well suited for integration with precision agriculture. Many key limitations in these systems—such as resource competition, spatial variability, and complex canopy structure—are essentially spatial problems. Multi-scale remote sensing can now quantify canopy nitrogen content (CNC) and link it directly to yield. This makes it possible to manage nutrients under different planting densities. In commercial citrus orchards in Israel, a model combining UAV multispectral indices, Sentinel-2 indices, and UAV structural data derived from SfM achieved good accuracy in estimating CNC ($R^2 = 0.80$), which was better than using a single data source (UAV only: $R^2 = 0.68$; Sentinel-2 only: $R^2 = 0.48$) (Avioz et al., 2025). CNC expressed per tree was also strongly related to yield ($R^2 = 0.66$). This suggests that nitrogen status from remote sensing can be used as an indicator of productivity and may reflect stress levels related to planting density.

Although evergreen and dense canopies, as well as pigment saturation, can make measurements more difficult, remote sensing has shown the ability to estimate leaf area index, chlorophyll, water status, and biochemical traits at leaf, tree, and orchard scales (Ali and Imran, 2021). These traits affect light interception and photosynthesis, and therefore influence the performance of planting density. UAV and satellite-based trait maps can guide variable fertilization and irrigation, and help identify overcrowded areas. These areas may need canopy thinning or local spacing adjustments. More broadly, precision agriculture based on remote sensing—using high-resolution images, vegetation indices, yield mapping, and cloud platforms—has already been widely used in annual crops. It is now providing useful experience for orchard systems (Sishodia et al., 2020).

Small UAVs are increasingly used to measure tree geometry (such as height and canopy size), productivity, and resource use efficiency. In citrus, UAV phenotyping of 4,931 trees across 25 rootstocks achieved 99.9% accuracy in tree detection and counting. The estimated canopy size also showed a strong correlation with field measurements (R = 0.84) (Ampatzidis et al., 2019). The cloud-based AI platform Agroview further extended this approach. It analyzed 175 977 citrus trees across 39 blocks under both normal and high-density systems. The mean absolute percentage error was 2.3% for tree detection, 4.5%~12.9% for tree height, and 12.9%~34.6% for canopy area (Ampatzidis et al., 2020). In the future, combining canopy trait maps, soil sensor data, and decision algorithms will support dynamic density management. This means planting, pruning intensity, and input use can be adjusted over time based on spatial performance.

7.2 Breeding for varieties suitable for high-density systems

The long-term success of high-density systems depends on whether varieties and rootstocks are biologically suited to crowded conditions. Dwarfing and size-controlling rootstocks are key components of modern high-density orchards. They allow higher planting density and make pruning, harvesting, and spraying easier and more efficient. Rootstocks such as 'Flying Dragon', 'FA 517', 'HTR-051', 'US-897', and 'Red tangerine' have made it possible to test very high densities (up to 10,000 trees·hm^{-2}), such as in Japanese Wase satsuma systems. However, the best spacing still depends on the variety and location, and must be determined through long-term trials under modern production conditions (Hayat et al., 2022).

A study in Florida compared diploid and tetraploid rootstocks for 'Valencia' orange under Huanglongbing conditions. Tetraploid rootstocks reduced tree size by about 55% and increased yield efficiency by 27%. Although total yield per tree was lower, this shows their potential in compact high-density systems, where yield loss per tree can be offset by more trees per area (Kunwar et al., 2022).

New plant breeding techniques (NPBTs), especially gene editing and cisgenesis, provide new tools for developing ideal materials for high-density systems. Most current work focuses on disease resistance, such as editing CsLOB1 to improve resistance to citrus canker. However, once key genes are identified, these tools can also be used to improve tree architecture, growth vigor, and early bearing (Salonia et al., 2020). Major challenges in citrus breeding—such as long juvenile periods, apomixis, and high heterozygosity—are still limiting progress. Combining NPBTs with early flowering systems and marker-free selection could speed up the development of dwarf, early-bearing, and stress-tolerant genotypes. High-throughput phenotyping using UAV and imaging technologies has already been used to evaluate canopy size and health in rootstock populations. Controlled drought studies have identified genotypes such as X639 and RLC-4 with better water uptake, improved root systems, and stronger stress tolerance (Morade et al., 2025). In the medium term, combining genomic selection, NPBTs, and high-throughput phenotyping will support breeding programs designed specifically for high-density orchards under different climates and management levels.

7.3 Sustainable orchard design strategies

Future high-density citrus systems should not only focus on yield but also consider ecological sustainability, including soil quality, biodiversity, and long-term resilience. A framework for agroecological orchard design, based on studies in apple and citrus systems, highlights several key principles: (i) agronomic goals should be defined separately for non-bearing and bearing stages; (ii) variety selection and spatial arrangement of trees and ground cover are key management tools; (iii) perennial spatial design (such as row spacing, traffic lanes, and vegetation layers) must be planned in advance; (iv) long-term interactions (such as pest accumulation and soil fertility changes) require full life-cycle evaluation, not just short-term yield analysis (Simon et al., 2016). In tropical citrus systems, there is no clear dormant period, which leads to higher pest pressure. However, continuous vegetation can also support biological control through ground cover and hedgerows, as long as disruptive practices like broad-spectrum pesticides and intensive tillage are minimized.

Orchards managed under organic or biodynamic systems, including agroforestry systems, generally show better soil properties than conventional citrus orchards. These include improved chemical properties (higher pH, phosphorus, cation exchange capacity, and soil organic carbon), better physical structure (lower bulk density and improved porosity), and stronger biological activity (higher enzyme activity and soil fauna feeding) (Pilon et al., 2023). Agroforestry citrus systems can reach soil quality levels similar to forests aged 40-200 years. Rich herbaceous vegetation, especially species from the Fabaceae family, plays an important role by providing green manure and ecological services. In the future, high-density orchards can integrate agroforestry practices or diverse ground covers between rows to maintain soil structure, organic matter, and biodiversity.

Managing drip irrigation at about 70% of field capacity, combined with alginate oligosaccharide treatment, can improve yield, sugar content, sucrose levels, and the efficiency of potassium and water use (with potassium use efficiency increasing by up to 62%). It also improves root growth, soil aggregate stability, and increases available potassium and cation exchange capacity in the topsoil, while reducing deep leaching losses (Li et al., 2024). Low-input practices such as organic fertilization, field margin vegetation, and integrated pest management are practical and cost-effective ways to reduce environmental impact. However, better technical guidance and demonstration are still needed to promote their wider adoption.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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