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,