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