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.