vigor by distributing shoots horizontally, whereas single-curtain systems can increase cluster light, photosynthesis, and assimilate allocation to fruit (Du et al., 2023). Divided and non-positioned systems often show high LAD in the outer shell and lower LAD inside, supporting better fruit-zone exposure at comparable total leaf area (Mabrouk et al., 2015).

2.3 Evaluation indicators of canopy structure

Leaf area index (LAI) and related descriptors are core indicators linking canopy structure to function. LAI and plant area index (PAI) are used to estimate canopy growth, light interception, and water requirements, and can now be obtained indirectly from smartphone apps (e.g., VitiCanopy) and point-quadrat methods. UAV-derived 3D point clouds and Sentinel-2 LAI time series enable plot-scale and seasonal mapping of LAI, canopy thickness, and leaf density distribution along the canopy wall (Comba et al., 2019; Abubakar et al., 2023).

Light interception and microclimate metrics complement area-based indices. PPFD and red:far-red ratios measured in the fruit zone decrease sharply as leaf area per meter of canopy or LAD increases, defining thresholds for “low” and “high” density canopies (Gladstone and Dokoozlian, 2003). Indirect metrics such as leaf layer number, canopy porosity, percent sunlit area, and atmometer evaporation are closely correlated with fruit-zone PPFD and are now obtainable with on-the-go RGB imaging or simple gap analysis. Together, LAI/LAD and light-based indicators describe how canopy architecture governs photosynthesis and fruit exposure.

Grapevine canopy structure integrates canopy shape, foliage distribution, and shoot architecture, all of which regulate light interception and microclimate around leaves and clusters. VSP, pergola, and divided canopies differ markedly in density patterns and fruit-zone exposure, so training choice is a primary lever for managing photosynthesis and berry composition. Quantitative indicators such as LAI, LAD, leaf layer number, porosity, and PPFD provide practical tools to evaluate and optimize canopy structure for both productivity and fruit quality.

3 Regulatory Mechanisms of Canopy Structure on Light Environment

3.1 Characteristics of light distribution and spatial heterogeneity

Light within grapevine canopies is highly stratified, with strong vertical and horizontal gradients. Measurements along transects show photosynthetic photon flux density (PPFD) and red:far-red ratio decrease sharply from the canopy exterior toward the fruit zone and centre, then increase again closer to the ground. This pattern generates a narrow interior region where PPFD and sunflecks reach their lowest values, while upper and outer layers intercept most of the incoming radiation. Three-dimensional reconstructions similarly indicate that only a minority of leaves capture the majority of intercepted light, leaving extensive shaded leaf area deep in the canopy (Iandolino et al., 2013).

This uneven light field produces marked spatial heterogeneity in leaf function and microclimate. In dense canopies, as much as half of the leaf area can remain in constant shade, with a small proportion of outer leaves absorbing most direct radiation. Inner leaves often operate at very low radiation levels and contribute little to net carbon gain, while exposed leaves experience higher temperatures and transpiration (Escalona et al., 2020). Row orientation further modifies spatial patterns, with different sides and zones of the canopy receiving contrasting radiation regimes over the day and season (Hunter et al., 2020). Such heterogeneity underpins within-canopy differences in photosynthesis, water status, and ultimately berry composition.

3.2 Effects of canopy density on light interception and transmission

Canopy density, commonly quantified as leaf area density or leaf area per row length, is a primary determinant of fruit-zone and interior light. Field surveys show that when leaf area exceeds about 8 $m^2\ m^{-1}$ of canopy length, fruit-zone PPFD can fall to ≤1% of ambient and red:far-red ratio to about 10% of ambient; at ≤4 $m^2\ m^{-1}$, these values remain ≥5%-10% of ambient. Similar relationships were observed for fruit-zone PPFD and sunflecks, which decline sharply as leaf area density increases beyond moderate levels. In non-positioned systems, small increases in leaf area density between 2 and 4 $m^2\ m^{-3}$ cause steep reductions in fruit-zone PPFD before the decline levels off at higher densities (Gladstone and Dokoozlian, 2003).