

2025). Supplementary light of different wavelengths also improved soluble solids, glucose, fructose, and monoterpene accumulation, with blue light giving the best overall promotion of fruit quality under facility cultivation (Li et al., 2025). These results show that in low-radiation systems, canopy optimization includes light supplementation and not only shoot or leaf manipulation.

Under heat stress, stability depends more on avoiding excessive cluster and canopy temperatures than on maximizing exposure. In rain-shelter ‘Shine Muscat’, the upward-trained pendulous trellis maintained the lowest canopy temperatures, higher relative humidity, less sunburn, higher chlorophyll content, and better gas exchange and fluorescence performance than H-shaped trellising, and PCA identified it as the most heat-tolerant system (Luo et al., 2026). Shade-net studies reached a similar conclusion from another angle: shading cooled the canopy, improved the consistency of soluble solids and coloring, and increased berry uniformity, with green and blue nets performing best (Zha et al., 2022). Broader canopy-architecture work also found that shading through modulated shoot positioning altered berry water relations and stress responses, with effects becoming more pronounced in hotter, drier, or more climatically anomalous seasons (Zarrouk et al., 2024). At the reproductive level, canopy microclimate also matters for the next crop, because improved bud-zone light interception increases bud fruitfulness and inflorescence primordia development, supporting more stable bunch number in the following season (Collins et al., 2020).

6 Case Implications and Future Development Directions

The establishment of precision canopy management systems should be based on cultivar characteristics, as grape cultivars differ significantly in vigor, cluster compactness, fruitfulness, and responses to canopy regulation practices. Canopy management should not rely on fixed pruning or leaf-removal standards, but should consider canopy surface area, internal shading, cluster exposure, and the balance between fruit development and shoot growth. Optimizing canopy architecture according to cultivar characteristics affects not only current-season yield but also fruitfulness in the following growing season. Studies on fresh table grapes have shown that reducing canopy density combined with summer pruning improved yield, cluster weight, soluble solids content, and anthocyanin accumulation in ‘Crimson Seedless’ grapes, while T-trellis systems in muscat-flavored table grapes promoted moderate vigor, improved sugar-acid ratios, and enhanced polyphenol and monoterpene accumulation. Therefore, future research should establish cultivar-specific canopy management systems by integrating parameters such as trellis type, shoot density, leaf-area distribution, and cluster exposure thresholds to meet different production objectives.

Canopy regulation should be integrated with water-fertilizer management and crop-load control because canopy structure alone cannot fully determine grape yield and quality when water availability, nutrient status, and sink demand vary. Irrigation, canopy architecture, and production targets interact with each other. Studies have shown that reduced irrigation can decrease berry weight and yield but increase anthocyanins, tannins, and total phenolic compounds, whereas higher irrigation levels promote berry enlargement and yield formation. Fertilization management also influences canopy function and productivity; combined organic and inorganic fertilization can improve soil nutrient availability, enhance photosynthetic capacity, and increase grape yield and quality. Therefore, future fresh table grape production should develop an integrated management system based on the coordination of “canopy structure-water status-nutrient supply-fruit load”. Through comprehensive regulation, source-sink balance can be maintained, marketable yield stability can be improved, and vineyard adaptability to climate variability can be enhanced.

Digital technologies can improve the precision of grape canopy management by monitoring canopy spatial variation, physiological status, and yield changes. Currently, UAVs, proximal sensors, satellite remote sensing, and ground-based monitoring platforms have been applied to assess grapevine growth, canopy structure, leaf area index (LAI), water status, nutrient status, yield, and fruit quality. Low-cost RGB photogrammetry can estimate canopy structure, UAV-derived canopy thickness can effectively predict yield ($R^2 = 0.80$), and machine-learning models have achieved an average yield prediction accuracy of 85.95% across different years and vineyards. In the future, multimodal sensing technologies integrating hyperspectral imaging, thermal imaging, and canopy