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Effects of Canopy Management Practices on Fruit Development and Yield Stability of Fresh Table Grapes

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Abstract Canopy structure plays an important role in regulating plant growth, fruit development, and yield stability during fresh table grape production. Appropriate canopy management can improve fruit quality and production stability by regulating light distribution, microenvironmental conditions, source-sink relationships, and nutrient allocation. However, grape cultivars, cultivation systems, and ecological environments show different responses to canopy management practices, and the establishment of suitable precision management systems remains an important challenge in current production. This review used 'Shine Muscat' (*Vitis vinifera* 'Shine Muscat') as a representative case to synthesize the mechanisms by which canopy optimization management affects growth, fruit development, and yield formation in fresh table grapes. The effects of canopy structure regulation, light environment optimization, and microenvironment improvement on vegetative growth, photosynthetic efficiency, and fruit quality formation were summarized. Based on the production practice of 'Shine Muscat' grape, the effects of shoot control, trellis optimization, inflorescence thinning, cluster regulation, and light environment management on plant growth, berry enlargement, fruit maturation, and marketable fruit rate were analyzed. Furthermore, the regulatory roles of canopy management in source-sink balance, nutrient allocation, and yield stability under different environmental conditions were discussed. It is suggested that canopy management in fresh table grapes should shift from single-factor regulation toward an integrated management system based on cultivar characteristics, water-fertilizer supply, and crop load optimization. In addition, the integration of remote sensing, intelligent sensing, and artificial intelligence technologies will promote the development of precision canopy management. This review provides theoretical references and practical approaches for high-quality, efficient, and stable production of fresh table grapes.
Keywords Canopy management; Fresh table grapes; 'Shine Muscat'; Fruit development; Yield stability

1 Introduction

Fresh table grape production depends on achieving high marketable yield together with stable berry size, color, firmness, soluble solids, and cluster uniformity under increasingly variable seasonal conditions. Canopy management is central to this goal because it regulates canopy microclimate, light interception, air circulation, source-sink balance, and the spatial distribution of vegetative and reproductive organs, all of which affect fruit development and productivity (Collins et al., 2020; Du et al., 2023). In grapevine, the light environment within the canopy is especially important because shade reduces yield components, delays ripening, and lowers quality, whereas improved canopy microclimate can simultaneously enhance yield and fruit composition. This importance is becoming even greater under climate change, as longer growing seasons, faster ripening, overheating stress, sunburn, and more frequent extreme events are forcing renewed attention to training systems and in-season canopy manipulation as practical adaptation tools (Del Zozzo and Poni, 2024; Lan, 2025).

In fresh table grapes, canopy management has particular significance because commercial value depends not only on total yield, but on visible and textural traits that directly determine consumer acceptance. Seasonal fluctuations in environment can alter yield and berry composition, making the maintenance of high and consistent fruit quality a continuing challenge in table grape systems (Petoumenou and Patris, 2021). Studies across grape production systems show that canopy interventions such as shoot thinning, leaf removal, pruning intensity adjustment, shoot topping, cluster thinning, and training-system selection are used to optimize light distribution and vegetative growth, thereby influencing berry growth, ripening, disease risk, and harvest quality (Poni et al., 2023;

Galar-Martínez et al., 2024; Lan, 2025). Mechanistically, greater light interception in the canopy and bud zone improves photosynthetic performance, carbohydrate status, and reproductive development. Shoot thinning increased inflorescence primordia number and size through changes in bud microclimate, shoot growth capacity, and carbohydrate content, and bud light interception was positively correlated with bud fruitfulness, indicating that canopy management can influence not only the current crop but also the following season's yield potential (Collins et al., 2020). At the berry level, contrasting high- and low-light canopy positions altered phenolic compounds, sugar-related metabolism, and transcription of genes associated with photosynthesis, carbohydrate metabolism, and photoprotection, showing that canopy light environment directly shapes fruit developmental physiology and composition (Yang et al., 2024).

Research progress over the last two decades shows that canopy management can deliver substantial agronomic value, but responses are strongly practice-, cultivar-, and climate-dependent. Reviews of summer pruning note that shoot positioning, shoot thinning, trimming, leaf removal, and cluster thinning are no longer viewed only as corrective operations, but as flexible tools for directing ripening and adapting vineyards to warming conditions. Leaf removal and shoot thinning can improve cluster exposure and hasten maturity, yet excessive exposure in warm climates can reduce the expected benefit for some quality traits and increase economic cost; in Cabernet Sauvignon, shoot thinning raised soluble solids by about 2.5 °Brix but also halved yield and increased labor cost markedly (Torres et al., 2020). Likewise, modern warm-climate viticulture increasingly applies leaf removal and shoot thinning more cautiously because clusters often need protection from overheating and sunburn (Poni et al., 2023). Training-system effects are also prominent. In North Dakota, leaf removal had no significant effect on 'Frontenac' fruit quality, whereas the Geneva Double Curtain increased cluster number and yield without reducing soluble solids or acidity (Olson et al., 2021). In a rainy region of China, the single-curtain system improved cluster-zone light, photosynthetic capacity, assimilate allocation to fruit, and reduced vegetative growth (Du et al., 2023). Canopy division has also doubled yield relative to dense vertical systems in vigorous vineyards, while open canopies increased photon flux, photosynthetic rate, soluble solids, and phenols in berries (Hernández-Ordoñez et al., 2024). In table grape cultivars, preharvest canopy-related applications improved red coloration and consumer acceptability in 'Crimson Seedless' under warming conditions, while summer pruning in 'Alphonse Lavallée' increased cluster and berry size, soluble solids, maturity index, phenolics, antioxidant activity, and berry mechanical resistance important for transportability (Petoumenou and Patris, 2021; Doğan, 2025). Yet not all interventions are consistently beneficial: in 'Sugraone', lateral-shoot formation increased yield with limited effects on standard quality traits, whereas in 'MidSouth' grapes early pruning, leaf removal, and shoot thinning often reduced yield and did not sufficiently improve fruit quality, underscoring the need for locally calibrated management (Leão and Lima, 2018; Williams et al., 2023).

This review examines the effects of canopy management practices on fruit development and yield stability in table grapes. Existing studies indicate that canopy management plays an important role in regulating the grapevine growing environment, improving fruit quality, and enhancing production stability. However, substantial differences exist among grape cultivars, training systems, ecological conditions, and combinations of management practices, and the precise matching of cultivar characteristics with canopy regulation strategies still requires further investigation. Using 'Shine Muscat' grape (*Vitis vinifera* 'Shine Muscat') as a representative case, this review synthesizes evidence on how optimized canopy management influences vine growth, fruit development, and yield formation. Particular attention will be given to the effects of different canopy regulation practices on vine growth, canopy structure, photosynthetic characteristics, fruit quality, and yield stability, while also summarizing the application effects of shoot control, training-system optimization, inflorescence thinning, cluster regulation, and light-environment management. This review provides a theoretical basis for optimizing canopy architecture in table grapes, improving the stability of fruit quality and yield performance in commercial production, and providing a reference for the precise, efficient, and sustainable development of the grape industry under climate change.

2 Mechanisms of Canopy Management Affecting Growth and Development of Fresh Table Grapes

2.1 Regulation of canopy structure and balance of vegetative growth

Canopy structure determines whether grapevines allocate resources to productive fruit growth or to excessive vegetative expansion. Foundational reviews describe canopy management as the manipulation of shoot number, shoot spacing, leaf area, fruit-zone exposure, and vigor so that the canopy is neither overly dense nor overly sparse, with the goal of maintaining an appropriate balance between shoot growth and fruit load (Lan, 2025). Dense, vigorous canopies promote long shoots, active laterals, and shading, which divert photosynthates into superfluous leaf area and create imbalance, while excessively short or thinned canopies can leave insufficient leaf area to ripen fruit adequately. In vigorous vineyards, lateral shoots often worsen crowding, humidity, and disease pressure, but in moderate-vigor systems lateral leaves can support sugar accumulation during ripening and increase starch reserves, showing that the value of vegetative growth depends on canopy context rather than on leaf area alone.

Experimental evidence shows that structural interventions affect fruit set, bunch architecture, and yield components by changing sink competition and carbohydrate partitioning. Removing active vegetative sinks at bloom increased fruit set, berries per cluster, and cluster weight in Pinot noir, whereas promoting vegetative growth during that period reduced reproductive allocation. Early canopy practices also altered berry number, berry fresh weight, and bunch compactness determinants in cultivar-dependent ways, indicating that the position and timing of leaf or shoot removal matter physiologically (Mataffo et al., 2023). In pre-flowering leaf-removal trials, intensive removal of main leaves and lateral shoots reduced yield potential by 47% on average, while even partial removal lowered yield potential and shifted must composition, supporting cautious use of severe early defoliation (Verdenal et al., 2024). Multi-season work in Montepulciano further showed that shoot thinning alone reduced canopy density without reliably improving composition, whereas shoot thinning plus pre-flowering defoliation reduced yield, lowered *Botrytis* incidence, improved fruit composition, and produced a carry-over reduction in the following year’s yield (Silvestroni et al., 2019).

2.2 Optimization of canopy light environment and improvement of leaf photosynthetic efficiency

The most consistent mechanism linking canopy management to grapevine performance is the regulation of the internal light environment. Canopy architecture directly controls light quantity and quality in leaves, buds, and clusters, and light interception is repeatedly identified as the dominant microclimatic driver of canopy photosynthesis, fruitfulness, and ripening. Practices such as shoot thinning, positioning, leaf removal, and divided or alternative training systems improve light penetration and canopy porosity, but the target is balance rather than maximum openness because excessive gaps waste incident radiation and excessive exposure can cause photoinhibition or quality losses (Lan, 2025). In overhead table grape systems, modeling showed that the most productive leaf layers were those receiving intermittent shade plus sunflecks, whereas the topmost continuously exposed leaves showed some photoinhibition, indicating that moderate internal illumination can support whole-canopy carbon gain efficiently even at relatively high leaf area index.

Training-system and canopy-opening studies show how this mechanism translates into photosynthetic performance. In ‘Miguang’ grape, the single-curtain system increased photosynthetic photon flux density in the cluster zone, raised chlorophyll content, improved net photosynthetic capacity of basal-to-middle leaves during berry expansion and veraison, and increased assimilate allocation to fruit while reducing vegetative growth (Du et al., 2023). In a desert vineyard, open canopies increased photon flux density, daily light integral, photosynthetic rate, and leaf area during vegetative growth, while berries from open canopies had higher soluble solids and total phenols, although canopy opening also increased temperature (Hernández-Ordoñez et al., 2024). Canopy architecture also modified water-use behavior: a sprawl system in Syrah improved radiation interception efficiency and water-use efficiency relative to vertical shoot positioning under semiarid stress (De La Fuente et al., 2026). Under drought, variation in photosynthesis within canopies was mainly explained by differences in light interception, while severe stress progressively suppressed gas exchange across most canopy positions, showing that light optimization and water status interact rather than acting independently.

2.3 Regulation of canopy microenvironment and fruit quality formation

Canopy management also affects fruit development by altering the berry microenvironment, including temperature, humidity, airflow, evaporation, and solar exposure. Reviews emphasize that canopy manipulation changes not only sunlight but also temperature and humidity around clusters, thereby influencing disease incidence, berry thermal relations, and ripening conditions (Lan, 2025). This mechanism is especially important in humid or rainy regions, where vigorous shoot growth, high air humidity, and poor ventilation accelerate fungal spread and depress fruit quality (Du et al., 2023). It is also increasingly important in warm climates, where excessive cluster exposure and heat accumulation can impair color development and composition rather than improve them (Hunter et al., 2021; Petoumenou and Patris, 2021; Dou et al., 2024).

Berry-quality responses show that the effect of exposure is nonlinear. In warm-climate Cabernet Sauvignon, shoot thinning hastened maturity, increased soluble solids by about 2.5 °Brix, and reduced methoxypyrazines, but it did not improve anthocyanins at harvest and reduced yield substantially, indicating that more exposure does not necessarily improve all quality traits (Torres et al., 2020). Row-orientation work showed that morning-exposed berries with cooler afternoon profiles had slightly advanced sugar ripening and generally higher anthocyanins and phenols, whereas bunches reaching late-afternoon heat peaks had poorer composition (Hunter et al., 2021). Controlled-environment studies confirm the mechanism: high temperature and low light both impaired coloring, high temperature promoted sugar accumulation but caused softening, and high heat downregulated anthocyanin-pathway genes while reducing total anthocyanin accumulation in sensitive cultivars (Dou et al., 2024; Zha et al., 2024). At the molecular level, high-light berry microclimates increased expression of genes linked to photosynthesis, carbohydrate metabolism, photoprotection, and flavonol synthesis, supporting a direct connection between canopy-regulated microclimate and fruit metabolic composition. In table grapes specifically, improving canopy-associated preharvest conditions enhanced red color and consumer acceptability in ‘Crimson Seedless’, with Sunred® increasing anthocyanin accumulation and overall market acceptance (Petoumenou and Patris, 2021).

3 Case Background: Canopy Optimization Management Practice in ‘Shine Muscat’ Grapes

3.1 Cultivar characteristics and problems in production

A major practical problem in ‘Shine Muscat’ is that basic cultivation standards remain incompletely standardized despite fast acreage expansion. Korean studies note that growers lack cultivar-specific protocols for seedlessness induction and cluster thinning, and leaving inflorescences longer than 5 cm increases later berry-thinning labor and often produces clusters exceeding 1 000 g (Figure 1) (Shin et al., 2019). Related work showed that natural berries can be relatively small and clusters sparse, while rust spot near maturity can reduce appearance quality and commodity value.

Figure 1 Shape of ‘Shine Muscat’ clusters at harvest time following floral cluster thinning to 3 cm (A), 4 cm (B), and 5 cm (C) (Adopted from Shin et al., 2019)

Fruit-load and uniformity problems are central because heavier or less-regulated clusters tend to dilute quality. Floral cluster thinning is used to improve cluster uniformity and regulate fruit quality, and in ‘Shine Muscat’ larger cluster load is associated with poorer within-cluster consistency and lower sugar-acid balance (Shin et al., 2019; Choi et al., 2023). Low crop load increased single-berry weight, sugar-acid ratio, phenolics, antioxidant activity, terpene and C13-norisoprenoid contents, and sensory scores, showing that this cultivar is highly responsive to source-sink regulation (Li et al., 2023).

3.2 Design of canopy optimization management practices

Canopy optimization in ‘Shine Muscat’ should be designed as a combined system rather than a single operation, integrating training architecture, shoot-vigor control, crop-load regulation, and fruit-zone management. Broader trellis research shows that training-system choice changes canopy architecture, light exposure, photosynthetic activity, yield, and berry composition, and divided or high-canopy systems often improve radiation capture or yield stability relative to dense vertical systems (Del Zozzo and Poni, 2024; Domingues Neto et al., 2024). In table grapes under protected cultivation, trellis and thinning must be coordinated because the SAYM system produced larger leaf area index (LAI) but lower light transmission and photosynthetically active radiation (PAR) than pergola, while heavy berry thinning improved total soluble solids (TSS), TSS/titratable acidity (TA), pH, color density, and skin anthocyanins (Yin et al., 2022).

For ‘Shine Muscat’ specifically, the design of canopy optimization practices should include standardized cluster-length control, precise berry thinning, and carefully dosed growth regulators to synchronize vegetative control with berry development. Thinning clusters to 3~4 cm or about 4 cm improved fruit growth and maintained a more appropriate sugar-acid ratio than 5 cm treatments, which left more berries but smaller berry size and lower ratio (Shin et al., 2019; Choi et al., 2023). PGR programs also require restraint: GA_3+TDZ and GA_3+CPPU can achieve near-complete seedlessness and increase berry size, but excessive CPPU, GA_3, EBR, or high retardant doses can lower soluble solids, increase hollowness, thicken rachises, or restrict leaf and cluster development (Cheng et al., 2025; Yang et al., 2025).

3.3 Evaluation indicators for different canopy management systems

The evaluation of different canopy management systems in ‘Shine Muscat’ should cover three dimensions: canopy structure and physiology, yield stability, and market-oriented fruit quality. Classic canopy-assessment work recommends quick field diagnosis by point quadrat analysis and canopy scoring, together with multiple numeric descriptors of canopy surface, shade, spacing, and fruit-zone exposure. Consistent with this, recent trellis studies assessed budbreak, bearing-shoot proportion, LAI, transmission coefficient, PAR, mean leaf angle, transpiration, and photosynthetic rate as core indicators of canopy performance (Yin et al., 2022).

Yield and fruit-quality indicators should then be tracked together because training systems often shift productivity and quality in different directions. Useful production indices include cluster number, cluster weight, berry weight, total yield, and leaf area-to-fruit balance, while quality indices include SSC, TA, SSC/TA ratio, firmness, peel residual feel, color density, anthocyanins, phenolics, sugars, aroma, and postharvest disease incidence (Shin et al., 2019; Olson et al., 2021; Yin et al., 2022; Yu et al., 2022; Choi et al., 2023). For ‘Shine Muscat’, this expanded indicator set is especially justified because supplementary blue light improved TSS, sugars, berry hue, and monoterpene-driven floral and fruity aroma, rootstocks altered berry weight, TSS/TA, phenolics, and volatile profiles, and rain-shelter plus root restriction reduced disease incidence and postharvest risk (Chen et al., 2024; Ren et al., 2024; Li et al., 2025).

4 Effects of Canopy Optimization on Fruit Development of ‘Shine Muscat’ Grapes

4.1 Effects on plant growth and canopy structure

‘Shine Muscat’ shows a strong tendency toward excessive vegetative growth, and this vigor is a primary reason canopy optimization is necessary in commercial production (Cheng et al., 2026). Dense canopies reduce photosynthetic efficiency, worsen the canopy microclimate, delay maturation, and can also impair flower-bud differentiation and shoot maturation (Cheng et al., 2025). In response, chemical growth-control strategies have been effective at suppressing shoot elongation in ‘Shine Muscat’, with both mepiquat chloride and chlormequat chloride reducing shoot growth, and CCC showing stronger inhibition than MC. A later study similarly found that Pro-Ca alone had limited effect at low concentrations, whereas Pro-Ca 300 mg/L+MC 300 mg/L effectively inhibited shoot elongation and improved canopy branch density. These results indicate that canopy optimization in

'Shine Muscat' depends not only on reducing vigor, but on reshaping canopy architecture into a more open and better-distributed structure (Collins et al., 2020).

Training and canopy-positioning studies support the same conclusion from a structural perspective. In grapevines, canopy manipulation is used to optimize canopy structure, balance vegetative and reproductive growth, and ensure more effective fruit exposure to sunlight (Collins et al., 2020). In a related table-grape system, the single-curtain training system reduced vegetative growth, shortened internodes, and redistributed leaf area toward the middle canopy, producing a more functionally efficient canopy than pergola training (Du et al., 2023). Under heat stress in rain-shelter 'Shine Muscat', trellis-system effects were also integrated canopy effects, simultaneously altering vigor, water relations, and canopy microclimate, with the upward-trained pendulous system maintaining the lowest canopy heat load and the least sunburn damage (Luo et al., 2026). Structural optimization is therefore best understood as a coordinated adjustment of shoot growth, branch density, leaf distribution, and cluster exposure, rather than simple canopy reduction (Zarrouk et al., 2024).

4.2 Effects on photosynthetic characteristics and dry matter accumulation

The clearest physiological effect of canopy optimization in 'Shine Muscat' is the improvement of the canopy light environment, especially under rain-shelter or facility cultivation where incoming light is often limited (Yuan et al., 2024; Li et al., 2025). In protected 'Shine Muscat', reflective ground film increased net leaf photosynthetic rate by 24.9% on 3309C and 35.2% on 5BB rootstocks, showing that light-environment optimization can substantially raise leaf carbon assimilation even without major changes in vegetative growth indices. Supplemental lighting also improved production performance in the same cultivar, although the mechanism was more complex: night lighting at 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ produced the highest yield, sugar-acid ratio, and economic return, while differences in Pn, Pmax, and apparent photosynthetic efficiency among treatments were small. This suggests that canopy-light optimization can enhance whole-vine productivity not only by increasing instantaneous leaf photosynthesis, but also by extending effective light use and improving the fruit developmental environment (Yuan et al., 2025).

Evidence from related grape systems clarifies how these changes translate into dry matter accumulation. In 'Miguang', the single-curtain system increased cluster-zone photon flux density, chlorophyll content, net photosynthetic capacity of basal and middle leaves at berry expansion and veraison, and assimilate distribution to fruit, while also increasing shoot soluble sugar and starch content and reducing vegetative growth (Figure 2) (Du et al., 2023). In 'Shine Muscat', reduced light intensity had the opposite effect: shading decreased leaf photosynthetic activity, transpiration, and stomatal conductance, reduced organic matter accumulation, and then suppressed glucose, fructose, and soluble solids while increasing malic, tartaric, and citric acids in berries (Yang et al., 2024). Heat-tolerant trellis optimization also preserved stomatal aperture, chlorophyll content, chlorophyll fluorescence, and net photosynthetic rate under prolonged heat stress, especially in the U-PT system, indicating that canopy optimization protects dry matter production by maintaining photosynthetic apparatus stability under stress (Luo et al., 2026). Grafting adds a related resilience mechanism in 'Shine Muscat', because grafted plants under drought maintained better water status, photosynthesis, and antioxidant defense than self-rooted plants, helping sustain assimilate production under environmental stress (Jiao et al., 2023).

4.3 Effects on fruit enlargement, maturation, and quality formation

The most direct fruit response to canopy optimization in 'Shine Muscat' is improved berry enlargement and more favorable ripening, but the benefit depends strongly on treatment intensity and combination. Moderate shoot-control treatments such as MC 500 mg/L or CCC 100 mg/L improved berry size, soluble solids, and the sugar-acid ratio while maintaining effective shoot control, whereas high concentrations restricted leaf and cluster development (Cheng et al., 2025). The combined Pro-Ca 300 mg/L + MC 300 mg/L treatment also increased single-berry weight, berry diameter, and SSC, supporting the idea that regulating vigor can redirect growth toward fruit development (Cheng et al., 2026). Floral cluster thinning further improved fruit development in this cultivar: thinning to 4 cm promoted fruit growth and maintained an appropriate sugar-acid ratio, whereas 5 cm thinning left more berries but produced smaller berries and a lower sugar-acid ratio (Choi et al., 2023). More broadly, low crop load increased single-berry weight, sugar-acid ratio, phenolics, antioxidant activity, terpene and

C13-norisoprenoid contents, and sensory scores, showing that source-sink optimization is a major route by which canopy-related management improves 'Shine Muscat' quality (Li et al., 2023).

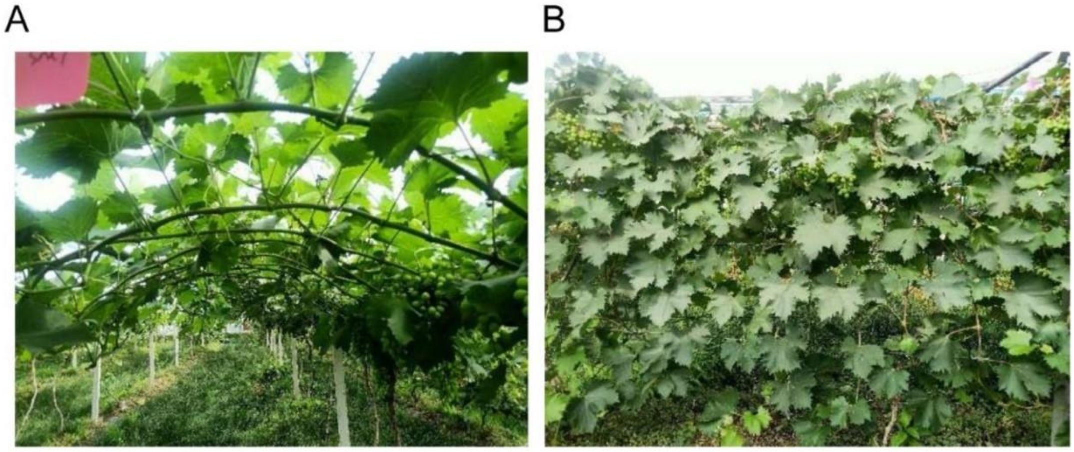

Figure 2 PER (pergola) (A) and SCT (single-curtain training system) (B) of 'Miguang' grape (Adopted from Du et al., 2023)

Berry-quality formation also responds to canopy-regulated light, temperature, and hormonal conditions. Supplementary light under facility cultivation reduced green hue, lowered organic acids, increased soluble solids, glucose, and fructose, and enhanced monoterpene accumulation and floral-fruity sensory quality, with blue light giving the best overall quality improvement (Li et al., 2025). Reflective ground film likewise improved sugar-acid ratio and aroma composition in protected 'Shine Muscat' (Yuan et al., 2024). PGR combinations produced strong but differentiated berry responses: GA_3+TDZ and GA_3+CPPU achieved nearly or fully 100% seedlessness, CPPU and TDZ increased berry weight and size through cortical expansion, GA_3 increased berry weight but also promoted rachis thickening and lowered TSS, and EBR at higher concentrations inhibited berry growth (Yang et al., 2025). At the cellular level, GA_3 promoted berry longitudinal elongation by enlarging cells and reducing cell density, whereas CPPU promoted transverse expansion by increasing both cell number and cell dimensions, explaining why different management combinations can improve berry size while also altering berry shape and commercial appearance (Chen et al., 2025).

5 Case Analysis: Effects of Canopy Optimization on Yield Stability of 'Shine Muscat' Grapes

5.1 Effects on yield components and marketable fruit rate

Canopy optimization changes yield stability first through its effects on the immediate components of yield, including fruit set, bunch number, bunch weight, berry number, and berry weight. In grapevine, fruit weight per node is determined by shoots per node, bunches per shoot, bunch weight, berries per bunch, and berry weight, so canopy practices can stabilize total output only if they improve several of these components together rather than enlarging one at the expense of another. In 'Shine Muscat', combined GA_3 and CPPU treatments significantly improved fruit set, cluster density, the percentage of seedless berries, and overall yield stability, while also increasing single-berry mass, cluster mass, soluble solids, and fruit hardness. Floral cluster thinning also changed the balance between cluster compactness and individual berry growth: a 4 cm thinning standard promoted fruit growth and maintained a better sugar-acid ratio, whereas 5 cm thinning produced more berries per cluster but smaller berries and a lower sugar-acid ratio (Figure 3) (Choi et al., 2023).

The marketable fruit rate in 'Shine Muscat' depends not only on total yield but also on maintaining berry size, appearance, firmness, sugar accumulation, and peel eating quality within commercial ranges. PGR treatments combining GA_3 with TDZ produced the largest cluster weight, berry weight, and berry diameter, while CPPU-based treatments better preserved fruit skin and flesh firmness and the positive residual feel of the edible peel, both of which are relevant to market acceptance (Choi et al., 2023). Yield control studies further showed that raising production to 24 000 kg/ha did not reduce fruit size, but it lowered soluble solids, worsened coloration, increased acidity and hardness, and retained more chlorophyll, whereas keeping yield at or below 21 000 kg/ha better balanced productivity and fruit quality (Kim et al., 2019). More generally, early canopy interventions can alter fruit set, berry number per bunch, and berry fresh weight in cultivar-dependent ways, so stable marketable yield requires moderate and cultivar-specific regulation rather than severe canopy reduction (Mataffo et al., 2023).

Figure 3 Effects of different floral cluster thinning intensities on the cluster shape of 'Shine Muscat' grapes at harvest (Adopted from Choi et al., 2023).
Image caption: Floral cluster thinning was performed to 3 cm, 4 cm, and 5 cm, respectively, seven days before full bloom (Adopted from Choi et al., 2023)

5.2 Effects on source-sink balance and nutrient allocation

The second mechanism is the regulation of source-sink balance, because canopy optimization determines how much assimilating leaf area is available per unit fruit mass and how dry matter is partitioned among shoots, berries, and reserve organs. Grapevines are managed around the ratio of leaf area to fruit mass, and imbalance can appear as delayed ripening, fruit abortion, or alternate bearing (Martínez-Lüscher and Kurtural, 2021). Modeling work supports the same framework by showing that weather and source-sink ratio at critical stages determine bunch number, berry number, and berry fresh weight, while carbohydrate allocation must account for both sink strength and sink priority, including reserve storage (Zhu et al., 2021). In practice, this means canopy optimization in 'Shine Muscat' should aim to preserve enough functional leaf area to support ripening while preventing excessive vegetative demand from competing with clusters.

Evidence across grape systems shows that nutrient and assimilate allocation shifts strongly with canopy structure and crop load. In source-sink manipulation studies, moderate to high leaf or cane density increased berry weight, bunch weight, bunch volume, and yield in some cultivars, while the lowest cane density combined with the highest leaf density improved assimilate accumulation efficiency per gram of berry. By contrast, severe defoliation had major negative effects on berry size, berries per cluster, soluble solids, root starch, root mass, and ripening date, and these effects carried over into the following season as reduced leaf area, clusters per vine, berries per cluster, and yield (Martínez-Lüscher and Kurtural, 2021). Related experiments showed that under shade, vegetative development was maintained at the expense of berries, whereas under water deficit and high crop load, berry growth became the priority sink, confirming that carbon and nutrient allocation are plastic and environment-dependent (Poupard et al., 2025). For 'Shine Muscat', this supports using moderate vigor control, cluster thinning, and light optimization to direct assimilates toward fruit without triggering carbon starvation of the vine (Cheng et al., 2025; Lan, 2025).

5.3 Effects on yield stability under different environmental conditions

Yield stability in 'Shine Muscat' also depends on whether canopy optimization can buffer environmental stress, especially low light in protected cultivation and high temperature during ripening. Supplemental LED lighting under rain-shelter conditions increased 'Shine Muscat' yield, and the 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ night treatment raised yield by 45.1% relative to the unsupplemented control while also giving the highest economic return (Yuan et al., 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 physiological parameters may further improve the prediction of yield and quality traits. However, large-scale adoption of digital technologies is still limited by equipment costs, data-processing capacity, and technical compatibility. Therefore, future development should focus on sensor integration, Internet of Things (IoT)-based monitoring, and intelligent decision-support platforms to promote precision pruning, irrigation, fertilization, and harvesting management.

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Conflict of Interest Disclosure
The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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