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Influence of Canopy Structure on Photosynthesis and Fruit Quality in Grapevines

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Abstract Canopy structure plays a critical role in regulating light distribution, photosynthetic efficiency, and ultimately fruit quality in grapevines. This study systematically reviews the characteristics of different canopy architectures and their effects on the vineyard light environment. It further analyzes how variations in canopy density and spatial configuration influence leaf photosynthesis, including differences among canopy layers and the accumulation and transport of photosynthates. The relationship between canopy structure and key fruit quality parameters, such as sugar content, organic acids, and secondary metabolites, is also discussed. In addition, common canopy management practices, including pruning, leaf removal, and training systems, are evaluated for their effectiveness in optimizing canopy microclimate. Case studies comparing different training systems and management strategies highlight practical approaches to improving grape quality. The interactions between canopy structure and environmental factors, such as light, water, and nutrients, are also addressed. Overall, this study provides a theoretical basis and practical guidance for optimizing canopy structure to enhance grapevine productivity and fruit quality.

Keywords Canopy structure; Grapevine; Photosynthesis; Fruit quality; Canopy management

1 Introduction

Grapevine canopy structure governs how light, temperature, and air flow are distributed within the vine, thereby regulating photosynthesis, carbon balance, and berry development. Light interception and its spatial distribution strongly affect sugar accumulation, acidity, color, and aroma compounds that define grape and wine quality. In the context of climate change and increasingly warm, dry regions, refining canopy architecture has become a key strategy to maintain productivity and fruit quality while moderating excessive heat and radiation loads (Torres et al., 2020; Pallotti et al., 2025). Understanding how specific structural features of the canopy translate into physiological responses and fruit composition is therefore of both scientific and practical importance (Zhu et al., 2021).

Biomass production and yield potential are closely related to the amount of solar radiation intercepted by the foliage, while grape composition depends on the exposure of leaves and clusters to light within the canopy microclimate. Excessive shading reduces photosynthesis and is linked to poor grape and wine quality, whereas overly open canopies may induce overheating, sunburn, and degradation of acids and phenolics (Torres et al., 2020). Canopy management practices such as leaf removal, shoot thinning, and crop load adjustments are widely used to balance source–sink relationships, control microclimate, and optimize ripening. Recent work shows that canopy size and architecture largely determine whole-plant carbon gain, the speed of ripening, and the allocation of non-structural carbohydrates, often more strongly than crop level itself. Consequently, quantitative knowledge of how canopy structure shapes photosynthetic efficiency and berry composition is essential for designing training systems and management strategies adapted to diverse climates (Zhu et al., 2021; Del Zozzo et al., 2024).

Internationally, detailed studies have linked canopy geometry, light interception, and grape quality using field measurements, 3D digitizing, and radiation models. Structural indices and light microclimate variables explain variation in sugars, anthocyanins, and phenolics, and demonstrate that canopy division and shoot orientation are major determinants of bunch exposure. Whole-canopy gas exchange and training-system comparisons indicate

that canopy geometry affects net CO₂ exchange, transpiration, drought resilience, and final fruit maturity, with some systems showing higher photosynthetic efficiency under water deficit. Manipulations of canopy porosity and solar exposure via leaf removal and shoot thinning reveal complex, compound-specific responses of flavonoid groups and methoxy-pyrazines, and highlight economic trade-offs between improved maturity and higher labor costs. At the same time, microclimate studies within clusters and along row orientations show that the timing and intensity of radiation and berry temperature strongly modulate anthocyanin profiles, phenolic content, and volatile composition, with overexposure often detrimental in hot, high-radiation environments. More recently, source-sink adjustment experiments and carbon-limitation treatments have clarified how leaf area and canopy architecture regulate sugar and anthocyanin accumulation, as well as reserve carbohydrates and carry-over effects across seasons (Escalona et al., 2020; Wang et al., 2022). Despite these advances, there remains a need for integrative work directly linking measurable canopy structural traits to spatial patterns of photosynthesis within the canopy and to detailed berry quality parameters across contrasting environments.

Building on this body of work, the present study titled “Influence of Canopy Structure on Photosynthesis and Fruit Quality in Grapevines” aims to clarify the functional links between canopy architecture, leaf-level and canopy-scale photosynthesis, and grape quality attributes. The first objective is to quantify how different canopy structures—defined by parameters such as leaf area index, porosity, vertical and lateral distribution of foliage, and training configuration—affect light interception, within-canopy light gradients, and gas-exchange characteristics under field conditions. A second objective is to relate these structural and physiological variables to key fruit quality metrics, including sugars, acidity, phenolic composition (especially anthocyanins and flavonols), and selected aroma-relevant metabolites, across ripening. A third objective is to evaluate how canopy structural manipulation can be used as a practical tool to balance source–sink status and microclimate, with particular attention to warm or water-limited sites where excessive radiation and heat can compromise color and flavor. To achieve these aims, the study will combine quantitative characterization of canopy structure (e.g., geometric or imaging-based indices), measurements of light microclimate and whole-canopy or segment-level photosynthesis, and detailed berry composition analyses. By integrating structural, physiological, and compositional data, the study seeks to provide a mechanistic framework that can guide the design and management of grapevine canopies to optimize both photosynthetic performance and fruit quality under current and future growing conditions.

2 Basic Concepts and Types of Canopy Structure

2.1 Definition and components of canopy structure

Canopy structure encompasses the shape, volume, and spatial arrangement of foliage and woody organs, including shoot path, foliage envelope, and leaf orientation (Louarn et al., 2007). Grapevine canopies are discontinuous and heterogeneous, so parameters such as leaf area density (LAD), leaf inclination, and azimuth are used to characterize their 3D distribution (Mabrouk et al., 2015). This structure controls light gradients within the canopy, affecting stomatal behavior and photosynthetic activity from the outer sunlit leaves to the shaded interior.

Structural components are strongly influenced by training and trellis design, which determine shoot positioning, canopy height, and the division or concentration of foliage (Louarn et al., 2008). Canopy density in the fruiting zone, expressed as leaf layer number or LAD, governs light quantity and quality around clusters, with high densities driving photosynthetic photon flux density (PPFD) below 1%-5% of ambient. The balance between exposed and interior leaf area is therefore a central feature of canopy structure (Reynolds and Heuvel, 2009).

2.2 Common grapevine canopy types

Vertical shoot positioned (VSP) systems arrange shoots upright along catch wires, producing a relatively narrow, dense curtain with high average LAD, especially near the fruit zone (Gladstone and Dokoozlian, 2003). In Cabernet Sauvignon, two-wire VSP systems can exceed 8-10 m² leaf area per meter of canopy, sharply reducing fruit-zone PPFD and increasing leaf layer number. VSP canopies are widely adopted but often require leaf removal or shoot thinning to maintain suitable light in the cluster region (Louarn et al., 2008).

Pergola and other high-wire or divided systems (e.g., lyre, Geneva Double Curtain, single-curtain) spread foliage over a larger volume, frequently reducing local density and modifying microclimate. Pergola structures may limit

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 $8 \text{ m}^2 \text{ m}^{-1}$ of canopy length, fruit-zone PPFD can fall to $\leq 1\%$ of ambient and red:far-red ratio to about 10% of ambient; at $\leq 4 \text{ m}^2 \text{ m}^{-1}$, these values remain $\geq 5\%$ -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 $4 \text{ m}^2 \text{ m}^{-3}$ cause steep reductions in fruit-zone PPFD before the decline levels off at higher densities (Gladstone and Dokoozlian, 2003).

Different training and trellis systems express canopy density in distinct spatial patterns, altering light interception and transmission. Shoot-positioned systems tend to concentrate higher leaf area density near the fruit zone, yet can maintain relatively higher fruit-zone light at a given density by reducing leaf layer number and improving exposure geometry (Figure 1) (Gladstone and Dokoozlian, 2003). Divided canopies, such as lyre or Geneva double curtain, achieve more even light penetration by splitting the foliage wall, lowering leaf layer number and slowing the decline of PPFD with rising density. Indices such as leaf layer number, exposed leaf area, and porosity integrate these effects and correlate closely with interior PPFD, making them useful tools to assess functional canopy density (Shtirbu et al., 2022).

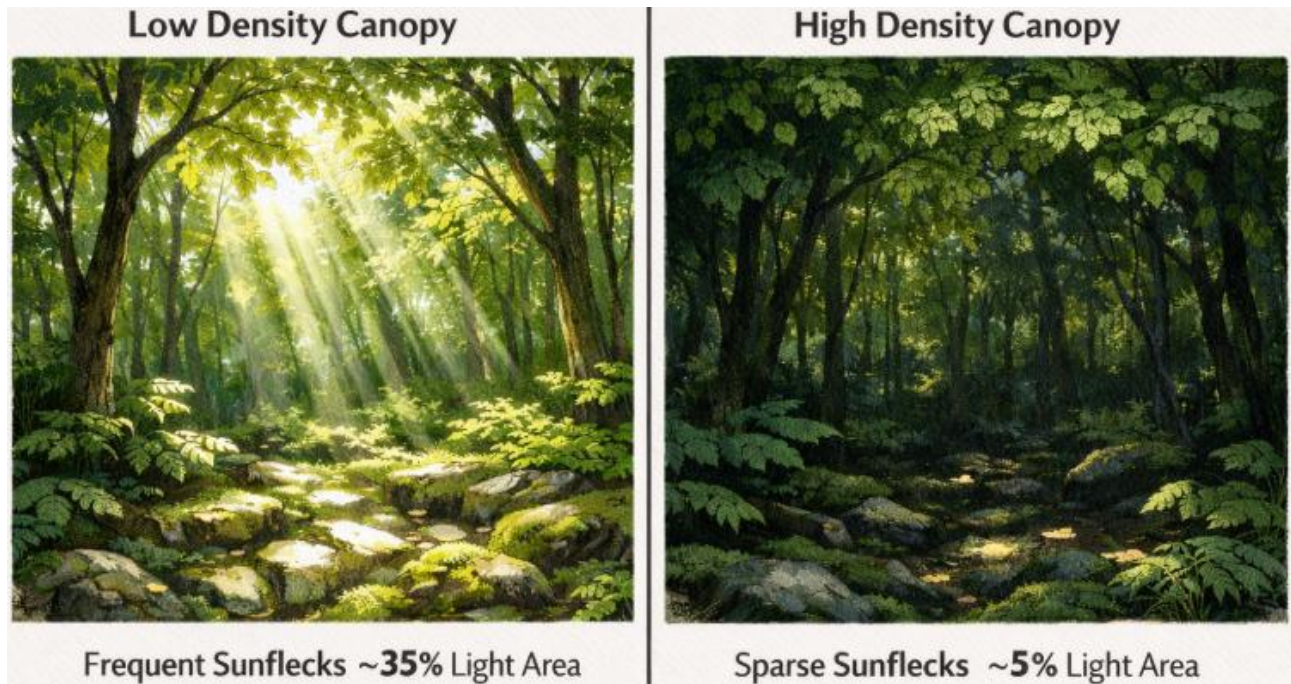


Figure 1 Comparison of sunfleck distribution under low and high canopy density, illustrating reduced light penetration with increased leaf area density (Adopted from Gladstone and Dokoozlian, 2003)

3.3 Improvement of light use efficiency through canopy optimization

Optimizing canopy architecture aims to balance total light interception with its distribution to maximize light use efficiency (LUE) at leaf and canopy scales. Three-dimensional and functional-structural models show that a relatively small proportion of leaves (20%-30%) can intercept roughly 80% of absorbed light, implying substantial scope to reduce unproductive shaded leaf area without sacrificing total interception (Iandolino et al., 2013; Prieto et al., 2019). Simulated and measured canopies with more favorable leaf area density and leaf orientation achieve similar or higher absorbed light with less total leaf area, thus improving radiation use efficiency and whole-canopy carbon gain.

Structural adjustments through training system choice, row orientation, and targeted canopy management can enhance LUE. Divided or high-wire systems, and single-curtain compared with pergola in humid climates, have been shown to increase light in the cluster zone, raise leaf photosynthetic rates in key canopy strata, and promote assimilate allocation to fruit. Opening dense canopies by shoot thinning or leaf removal increases porosity and fruit-zone light, often improving berry soluble solids and phenolic traits, although excessive exposure may risk flavonoid degradation in warm climates (Martínez-Lüscher et al., 2019; Torres et al., 2020). Functional-structural modeling further indicates that allowing non-uniform nitrogen and light distribution among leaves increases whole-canopy photosynthesis relative to uniform distributions, underscoring that canopy optimization should consider both geometry and physiological acclimation to heterogeneous light (Prieto et al., 2019).

Light distribution in grapevine canopies is highly heterogeneous, shaped by canopy density, geometry, and orientation. Dense canopies intercept large amounts of radiation but transmit little to the fruit zone and interior,

whereas optimized architectures maintain adequate total interception while improving light penetration and use efficiency. Through informed selection of training systems and targeted canopy management, growers can refine light interception, enhance photosynthetic efficiency, and better support desirable fruit composition.

4 Effects of Canopy Structure on Grapevine Photosynthesis

4.1 Changes in leaf photosynthetic characteristics

Canopy structure alters the light and thermal environment around leaves, driving changes in net photosynthetic rate (P_n), stomatal conductance (G_s) and transpiration (T_r). Opening dense Cabernet Sauvignon canopies increased photon flux density and daily light integral, leading to higher photosynthetic rate and transpiration during vegetative growth (Hernández-Ordoñez et al., 2024). Under field shading, reduced PAR lowered P_n , transpiration and stomatal conductance, while light compensation and saturation points shifted downward, indicating acclimation to low light but with reduced radiation-saturated P_n .

Stomatal regulation links these structural and microclimatic shifts to water use. At the canopy scale, bulk stomatal conductance varies diurnally with vapor pressure deficit and net radiation, and declines seasonally as soil water deficits develop (Gowdy et al., 2022). Grapevine canopies can reduce conductance exponentially with increasing vapor pressure deficit to stabilize transpiration, maintaining near-constant water loss despite large atmospheric demand changes. Progressive drought reduces P_n and T_r first in sun-exposed leaves, and later across the canopy, with stomatal conductance emerging as a key integrative indicator of photosynthetic down-regulation in C3 plants including grapevine (Medrano et al., 2002; Escalona et al., 2020).

4.2 Differences in photosynthesis among leaves at different canopy layers

Light gradients created by canopy structure cause strong vertical differences in leaf gas exchange. In overhead parronal systems, the highest canopy photosynthesis comes from mid-layers (about 20-40 cm above the trellis), where leaves experience mixed shade and sunflecks; leaves at the very top show some photoinhibition, while lower leaves remain productive rather than parasitic (Cortázar et al., 2005). In vertically trellised Shiraz, photosynthetic output declines from apical to basal canopy zones, with particularly low and erratic values in the light-limited interior, reflecting strong light constraints in the centre of dense canopies (Hunter et al., 2020).

Drought and row orientation further modulate these layer differences. Under progressive water deficit, photosynthesis and transpiration are first reduced in outer sunlit leaves, with shaded inner leaves affected later and some deeply shaded leaves remaining almost unresponsive but with negligible carbon gain (Escalona et al., 2020). Orientation-driven radiation patterns lead to higher average P_n on east and north-facing sides, while south-exposed layers show lower photosynthesis and more negative water status. Functional-structural modelling confirms that differences in leaf nitrogen distribution and light interception among layers translate into substantial variation in their contribution to whole-canopy carbon gain under different training systems (Prieto et al., 2019).

4.3 Accumulation and transport of photosynthates

Changes in P_n , G_s and T_r at leaf and canopy levels ultimately determine the supply of photosynthates available for growth and fruit ripening. Defoliation experiments show that reductions in leaf area (source) have a stronger effect on season-long carbon assimilation, sugar-induced growth and speed of ripening than changes in crop load, underscoring the dominance of canopy size and activity over sink level (Martínez-Lüscher and Kurtural, 2021). Under shading, reduced P_n is accompanied by lower leaf soluble carbohydrates and starch, as well as decreased vine yield and berry soluble solids, indicating limited carbohydrate production and altered allocation.

Photosynthate transport depends on both whole-plant carbon balance and phloem capacity. Long-term shading experiments reveal that, despite depressed photosynthesis, shaded grapevine leaves can maintain non-structural carbohydrate pools due to reduced sink demand, but this accumulation constrains full photosynthetic recovery when leaves are re-exposed to sun (Gallo et al., 2024). Hormonal regulation by abscisic acid and gibberellin can shift carbon allocation by increasing non-structural carbohydrates in leaves, enlarging phloem area, and up-regulating sugar transporter genes in leaves and berries, thereby accelerating hexose accumulation in fruit or enhancing stem growth (Figure 2) (Murcia et al., 2016; Li et al., 2021).

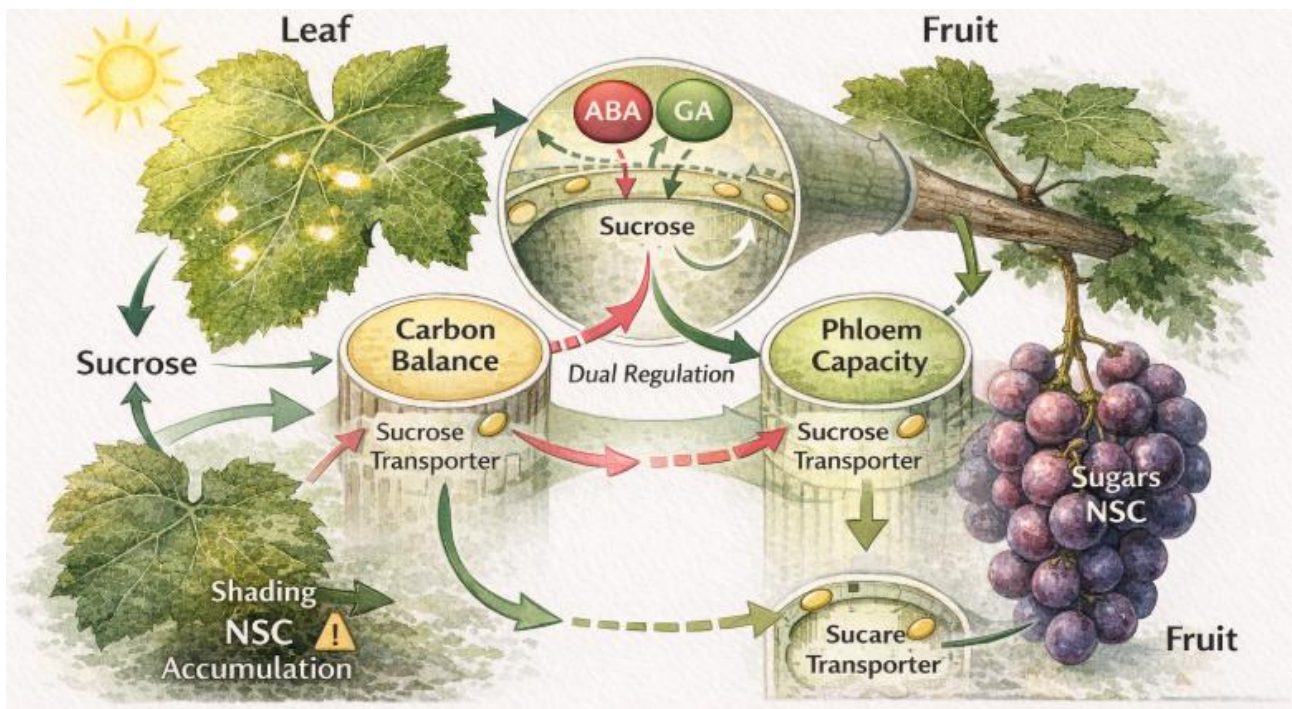


Figure 2 Mechanisms of photosynthate transport and hormonal regulation in grapevines, highlighting phloem function and carbohydrate allocation (Adopted from Li et al., 2021)

Canopy structure shapes P_n , G_s and T_r by modifying light and water status, with open, well-lit canopies generally enhancing photosynthesis but increasing transpirational demand. Strong vertical gradients in radiation and water potential create sharp differences in photosynthesis among canopy layers, so mid-canopy leaves in mixed light often dominate carbon gain. These physiological patterns control carbohydrate accumulation and transport, where adequate, well-distributed active leaf area and effective phloem function are critical for sustaining fruit sugar accumulation and overall vine performance.

5 Effects of Canopy Structure on Fruit Quality

5.1 Influence on sugar accumulation

Canopy structure, through its effects on source-sink balance and microclimate, strongly regulates the rate and extent of sugar accumulation in berries. Shoot thinning, which reduces crop load and increases canopy porosity, consistently hastened ripening and increased total soluble solids (TSS) by about 2.5 Brix in Cabernet Sauvignon, although it reduced yield (Torres et al., 2020). Similarly, early or cluster-zone leaf removal often increases berry sugar and final wine alcohol, indicating that greater light exposure and a higher leaf-to-fruit ratio can accelerate sugar accumulation when temperature is not excessive (Stefanović et al., 2021). These responses show that structural manipulations of the canopy can shift the trajectory of berry sugar dynamics.

Conversely, increasing shading within the canopy tends to slow sugar accumulation and delay maturity. Partial canopy shade that reduced solar radiation by ~75% lowered leaf net assimilation and resulted in berries with reduced TSS and delayed phenological development compared with unshaded vines (Lu et al., 2021). Artificial canopy shading applied at fruit set likewise decreased sugar concentration at harvest and increased must acidity, pointing to a general slowing of ripening under reduced light and temperature (Micciché et al., 2023). Late-season canopy reduction by shoot trimming can also decrease final TSS without major changes in yield, providing a tool to moderate excessive sugar in warm climates (Assefa et al., 2025).

5.2 Regulation of organic acids and flavor compounds

Canopy structure alters berry temperature and light, thereby modifying organic acid degradation and acid-sugar balance. Shading treatments that reduce irradiance and berry temperature generally increase titratable acidity and lower pH at harvest, as shown for partially shaded Cabernet Sauvignon and shaded Nero d'Avola. In contrast,

cluster-zone leaf removal typically lowers titratable acidity, even when TSS is unchanged, reflecting faster organic acid catabolism in warmer, better-exposed berries (Anić et al., 2021; Yao et al., 2024). These changes in acids interact with sugar levels to define harvest ripeness and wine freshness.

Flavor and aroma compounds are also highly sensitive to canopy-driven microclimate. Increased exposure from shoot thinning and leaf removal decreased methoxypyrazines (green, herbaceous notes) in warm-climate Cabernet Sauvignon, improving sensory maturity despite only modest flavonoid gains (Torres et al., 2020). In semi-arid conditions, partial canopy shading enhanced fruity and floral wine aroma by increasing esters and β -damascenone, while also altering C6/C9 and fatty acid precursors in berries. Full cluster shading from veraison to harvest changed volatile profiles in Cabernet Sauvignon, with higher total volatiles and shifts toward fruity, herbaceous, floral, and mushroom notes compared with exposed clusters (Liu et al., 2024).

5.3 Effects on color and secondary metabolites

The relationship between canopy structure and berry color is complex, as light and temperature can both stimulate and degrade pigments. In warm climates, increased cluster exposure via leaf removal or shoot thinning hastened maturity but did not consistently raise total anthocyanins at harvest, and flavonols were the only group clearly upregulated with higher solar radiation (Torres et al., 2020). Excessive exposure crossed degradation thresholds for some flavonoids, indicating that there is an optimal range of radiation for color development beyond which anthocyanins and other compounds decline. By contrast, early leaf removal in Eastern Serbia increased anthocyanins and total phenolics in Cabernet Sauvignon skins and wines, particularly under temperate warm conditions where overexposure risk was lower (Stefanović et al., 2021).

Moderate shading can also enhance or preserve color and phenolic quality under very hot, high-radiation conditions. Partial canopy shade increased berry and wine anthocyanin concentrations in a semi-arid site, while reducing flavonols, suggesting that lower temperatures favored anthocyanin stability despite reduced light. Full cluster shading from veraison decreased anthocyanins, phenols, and tannins, showing that excessive shade can suppress phenolic synthesis when light becomes limiting (Liu et al., 2024). Cluster-zone leaf removal at different stages often increases berry anthocyanins and flavonols across cultivars and seasons, though it may reduce certain aroma-related norisoprenoids, emphasizing trade-offs between color and specific flavor precursors (Yao et al., 2024).

Across these studies, canopy structure modulates sugar accumulation, acid metabolism, aroma formation, and phenolic composition by reshaping light and temperature around clusters. Practices that open the canopy tend to increase TSS, lower acidity, and adjust volatile and phenolic profiles toward riper styles, while shading slows sugar accumulation, preserves acids, and can either enhance or depress color depending on climate severity. Effective canopy design therefore requires cultivar- and climate-specific balancing of exposure to optimize soluble solids, flavor, and secondary metabolites simultaneously.

6 Canopy Management Practices and Their Regulatory Effects

6.1 Effects of pruning methods

Winter pruning primarily regulates bud number, potential crop load, and the renewal zone light environment that determines bud fruitfulness for the next season. Lighter winter pruning with more buds retained can increase shoot number but may reduce individual shoot vigor and modify bud microclimate (Collins et al., 2020). Delayed winter pruning, performed when apical shoots already bear unfolded leaves, can postpone budburst by 15-30 days and partially shift ripening into cooler periods without large yield penalties (Gatti et al., 2016). Such late pruning also altered seasonal canopy phenology and increased cumulative carbon gain per vine through higher and more sustained canopy net CO₂ exchange.

Double pruning and very late winter pruning have been proposed as tools to adapt to both excessive summer heat and spring frost risk. In Brazilian ‘Syrah’, a double-pruning strategy that induced a winter harvest improved sugar and phenolic accumulation and reduced rot incidence compared with the traditional summer harvest (Favero et al., 2020). A review on frost mitigation shows that two-step delayed winter pruning exploits acrotony to “sacrifice”

apical shoots to frost while preserving basal buds, thereby reducing damage and sometimes delaying maturity into a cooler window (Poni et al., 2022). These approaches modify canopy structure and functioning over the whole cycle, with cascading effects on photosynthesis and berry quality.

6.2 Leaf removal and shoot thinning techniques

Leaf removal and shoot thinning are key summer pruning operations used to adjust canopy density, fruit exposure, and the source–sink balance. Pre-bloom leaf removal and shoot trimming, applied at different positions along the shoot, differentially altered fruit set, berry number per bunch, berry weight, and composition by modifying local source leaves and assimilate supply (Mataffo et al., 2023). Basal defoliation at fruit set in Cabernet Sauvignon increased single-leaf photosynthesis, changed berry temperature profiles, and shifted soluble solids, titratable acidity, and phenolic composition, with moderate defoliation often favoring higher Brix and extractable anthocyanins (Figure 3) (Cataldo et al., 2021).

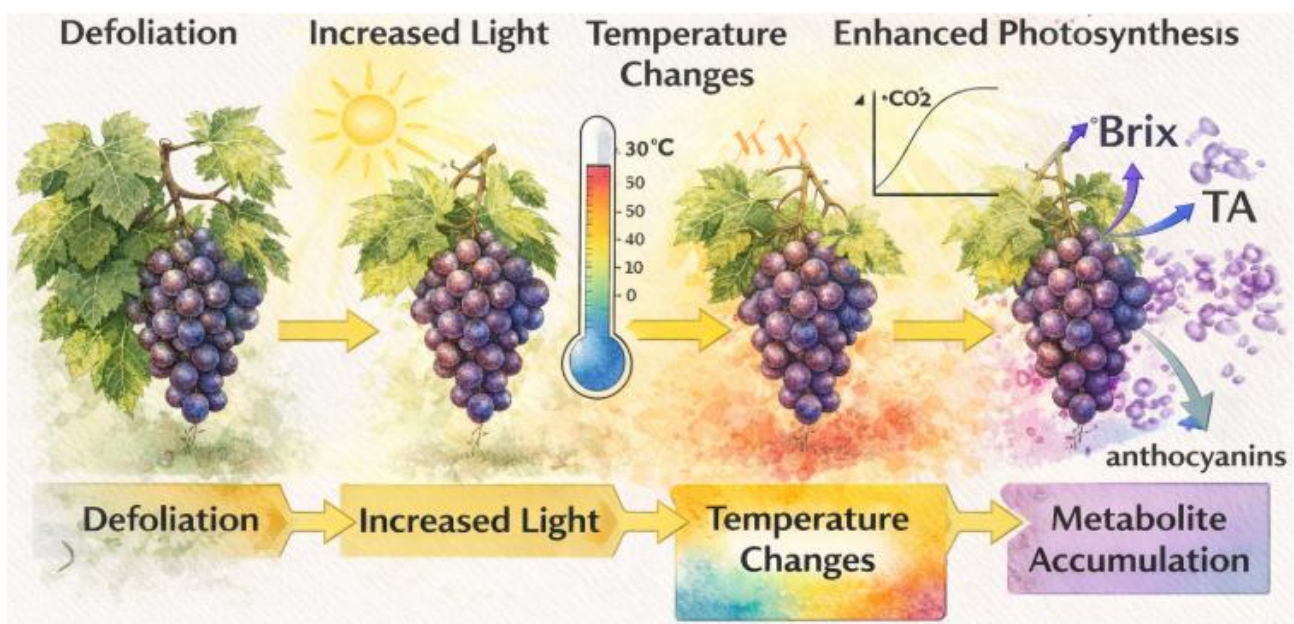


Figure 3 Effects of basal defoliation on fruit-zone microclimate and berry composition, including changes in temperature, photosynthesis, and metabolite accumulation (Adopted from Cataldo et al., 2021)

Shoot thinning and its combination with defoliation can open the fruiting zone and reduce leaf layer number, but their effects on yield and composition are not uniform across climates and seasons. In Montepulciano, shoot thinning alone reduced canopy density but did not consistently reduce yield or improve fruit composition, whereas shoot thinning combined with pre-flowering defoliation decreased yield, reduced *Botrytis* incidence, and improved berry composition, with carry-over effects on yield the following year (Silvestroni et al., 2018). A broader study showed that leaf removal and shoot thinning modify bud light interception and carbohydrate status, thereby influencing bud fruitfulness and inflorescence primordia size, which link current-season canopy management to future yield potential (Collins et al., 2020).

6.3 Training systems and shoot positioning

Training systems and shoot positioning define canopy geometry, affecting total leaf area, exposed leaf area, and the proportion of sunlit versus shaded leaves. A comprehensive review highlights that divided canopy systems and alternatives to classical VSP can simultaneously increase yield and improve fruit composition by optimizing the light microclimate of leaves and clusters (Reynolds and Heuvel, 2009). Recent whole-canopy gas-exchange work comparing VSP, single high wire, and pergola structures in Sangiovese showed that, per unit leaf area, single high wire canopies achieved higher net CO₂ exchange and better drought resilience, whereas pergola attained superior fruit maturity at similar yields (Del Zozzo et al., 2024).

Shoot orientation and trellis form interact strongly with cultivar architecture to determine light interception and fruit exposure. Three-dimensional modeling of VSP versus non-positioned systems (gobelet and bilateral free cordon) demonstrated that free-standing canopies can have higher light interception and a greater proportion of sunlit leaf area at intermediate LAI, particularly benefiting cultivars with procumbent shoots (Louarn et al., 2008). In a humid Chinese region, a single-curtain system increased cluster-zone PPFD, improved leaf chlorophyll content and mid-shoot photosynthetic capacity, and enhanced assimilate allocation to fruit compared with a pergola system, resulting in higher soluble solids and more favorable vegetative–reproductive balance (Du et al., 2023). Thoughtful choice of training and shoot positioning thus provides a structural framework within which pruning, leaf removal, and thinning can fine-tune canopy function and fruit quality.

7 Interactive Effects of Environmental Factors and Canopy Structure

7.1 Influence of light intensity and climatic conditions

Light intensity and thermal regime interact with canopy structure to shape photosynthesis and berry composition. Row orientation modifies the angle and timing of solar radiation on canopy walls, creating distinct patterns of leaf water potential and photosynthetic activity among orientations and canopy sides (Hunter et al., 2020). In Shiraz, canopies oriented north-south or east-west showed the highest average photosynthesis, while south- and southwest-facing sides had lower photosynthetic output under less favorable radiation and temperature conditions. At the berry level, different orientations and exposure patterns generate contrasting pulp temperatures, which in turn drive differences in sugar ripening and skin phenolics (Hunter et al., 2021).

Climate warming increases the risk of radiative excess and high berry temperatures, which can accelerate sugar ripening but compromise acid balance and color stability (Miccichè et al., 2023). In warm regions, porous or divided canopies that temper afternoon heat loads can support better phenolic accumulation than highly exposed VSP walls, especially when combined with adjusted row orientation (Reynolds and Heuvel, 2009). Shading nets applied at fruit set reduced berry temperature, delayed phenology, increased must acidity and decreased pH, illustrating how reduced light and moderated heat can slow ripening and modify grape composition under hot conditions. Such findings highlight the need to match canopy openness and exposure with local radiation and temperature regimes.

7.2 Regulation of canopy structure by water and nutrient supply

Water availability strongly regulates canopy size, density, and thus microclimate. In potted Sangiovese, reduced irrigation to 50%-35% of full supply decreased net CO₂ exchange and transpiration, especially in VSP and pergola geometries, while single high-wire canopies maintained higher photosynthetic efficiency and drought resilience (Figure 4) (Del Zozzo et al., 2024). Field trials combining six trellis systems with three irrigation levels showed that higher applied water increased leaf area, berry size, and yield, whereas low water (25% ET replacement) limited vegetative growth but enhanced berry anthocyanin and flavonol concentrations (Yu et al., 2022). These responses indicate that irrigation regimes co-define canopy architecture and its functional quality in warm climates.

Nutrient status, particularly nitrogen, interacts with water to control vigor and canopy development. Reviews of deficit irrigation and vine mineral nutrition emphasize that limited water combined with moderate nitrogen can reduce canopy size, berry size, and disease incidence, while accelerating ripening and improving color (Keller, 2005). Growth is more sensitive than photosynthesis to both water and nitrogen shortage, so controlled deficits can restrain excessive canopy expansion and prevent overly dense, shaded canopies. However, severe water or nitrogen limitation may reduce assimilate supply and lead to excessive fruit exposure, suggesting that water-nutrient management must be finely tuned to sustain a functional canopy structure.

7.3 Adaptability of canopy structures in different ecological regions

The suitability of canopy systems differs among ecological regions, depending on temperature, radiation, and water availability. In Californian warm climates, single high-wire and high-quadrilateral trellises achieved greater yields and higher berry anthocyanin derivatives than conventional VSP, while increased crown porosity in VSP raised flavonol levels but was associated with lower photosynthetic capacity and translocation efficiency (Yu et al.,

2022). In Brazilian tropical conditions, VSP training provided higher vine water status but lower berry Brix compared with a modified Geneva Double Curtain, illustrating a trade-off between water relations and fruit exposure in a hot, seasonally dry region (Favero et al., 2010). Reviews of training systems under climate change propose re-evaluating divided and high-wire systems, particularly in warm and sub-tropical zones where VSP often requires intensive manipulation to avoid overexposure and rapid ripening (Del Zozzo and Poni, 2024).

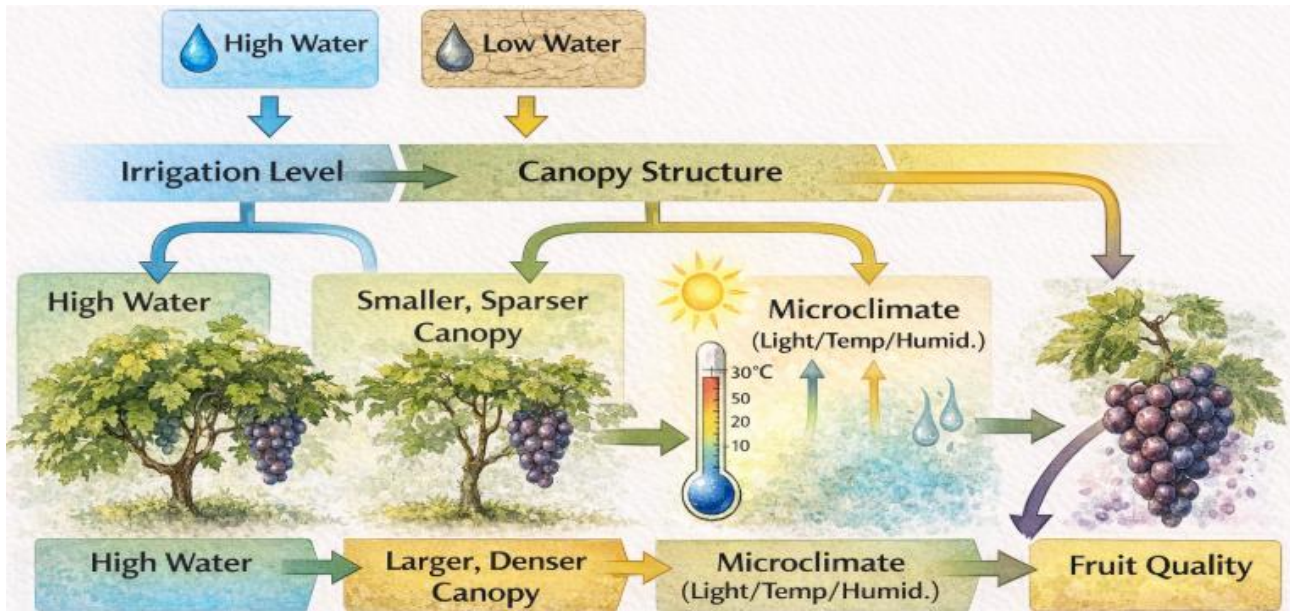


Figure 4 Conceptual model illustrating how water availability regulates canopy structure, microclimate, and physiological processes affecting grapevine performance (Adopted from Del Zozzo et al., 2024)

In humid, rainy regions, canopy structures must also address disease pressure and excess vigor. For the ‘Miguang’ grape in a rainy Chinese region, a single-curtain system improved cluster-zone light, leaf photosynthetic capacity, and assimilate distribution to fruit compared with a pergola, while simultaneously decreasing vegetative growth (Du et al., 2023). Systematic reviews of climate-change adaptation highlight that combining location, training system, irrigation, and canopy management at multiple scales allows region-specific compromises between water use and productivity (Naulleau et al., 2021). Across cool, temperate, and warm areas, training choices therefore need to integrate local climate, water resources, and disease risk to select canopy architectures that maintain photosynthetic efficiency and fruit quality under changing environments.

8 Case Study: Effects of Typical Canopy Management Systems on Grape Quality

8.1 Comparison of photosynthetic efficiency under different training systems

Training system geometry shapes how efficiently grape canopies convert intercepted light into carbon gain. In potted Sangiovese, whole-canopy gas exchange showed that, when expressed per unit leaf area, the single high wire (SHW) system achieved about 24% higher net CO₂ exchange than both VSP and pergola under well-watered conditions, highlighting superior photosynthetic efficiency of more elevated, sprawling canopies (Del Zozzo et al., 2024). Under progressive water deficit, SHW maintained higher NCER/leaf area and transpiration/leaf area, while VSP and pergola exhibited stronger declines in light saturation point and quantum yield, indicating lower drought resilience and efficiency.

Training systems also differ in how they reconcile photosynthetic efficiency with fruit ripening and composition. Despite lower NCER/leaf area than SHW, the pergola system reached the best fruit maturity at comparable yields, suggesting a favorable balance between light interception, evaporative cooling, and source–sink relations. A broader review confirms that divided or non-VSP systems (e.g., pergola, high wires, GDC) can improve overall efficiency by enhancing light distribution and balancing dry-matter partitioning, while conventional VSP often achieves good control of vigor but may require multiple canopy operations to maintain internal light and avoid excessive berry heating in warm climates (Del Zozzo and Poni, 2024).

8.2 Empirical analysis of moderate leaf removal on fruit quality improvement

Moderate basal leaf removal is widely used to alter cluster microclimate without excessively reducing source capacity. In Cabernet Sauvignon, removal of four basal leaves at fruit set (LR4) increased single-leaf photosynthesis and resulted in grapes with higher Brix and greater extractable anthocyanins and polyphenols compared with the untreated control, showing that a modest reduction in leaf area can enhance both technological and phenolic ripeness (Cataldo et al., 2021). A more severe treatment (removal of eight leaves) increased titratable acidity and did not further improve color compounds, indicating that beyond a certain threshold defoliation may cool clusters and slow sugar and phenolic accumulation.

Regional trials in continental Croatia likewise demonstrated quality gains from moderate cluster-zone defoliation in Merlot. Basal leaf and lateral removal at berry set increased UV radiation in the fruiting zone, which did not change sugar concentration but significantly reduced titratable acidity and enhanced skin phenols, anthocyanins, flavonols, and flavan-3-ols, particularly in the cooler ripening season (Anić et al., 2021). A multiyear transcriptomic analysis of pre-flowering defoliation further showed consistent up-regulation of genes involved in flavonoid biosynthesis and hormonal signaling across sites and cultivars, supporting the robustness of early leaf removal in improving composition when carefully calibrated to climate and vigor (Zenoni et al., 2017).

8.3 Successful regional practices of canopy optimization

Successful canopy optimization strategies are strongly region- and climate-specific, combining training choice with targeted summer operations. In rainy eastern China, a single-curtain (SCT) system outperformed a pergola for ‘Miguang’ by increasing photosynthetic photon flux density in the cluster zone, enhancing chlorophyll and leaf area of mid-shoot leaves, and promoting assimilate allocation to fruit, which translated into higher berry soluble solids and lower titratable acidity under humid, low-light conditions (Du et al., 2023). In cold semiarid Ukraine, free-growing shoots on a 1.2-m cordon created a canopy with optimal leaf index and relatively low transpiration, improving photosynthetic apparatus activity and yield stability in dry years, thus enabling non-irrigated production (Shtirbu et al., 2022).

In warm and hot regions, canopy modifications increasingly aim to buffer heat and radiation while maintaining efficient photosynthesis. Leaning VSP canopies 30° toward the west in a temperate-warm Spanish site increased morning radiation on Bobal vines and reduced afternoon heating, resulting in musts and wines with higher acidity, lower pH, and greater color intensity, anthocyanins, polyphenols, and aroma esters than standard VSP (Ferrer-Gallego et al., 2024). Systematic reviews of adaptation strategies underline that combining such architectural changes with irrigation and other levers at multiple scales offers the most promising path to maintain productivity and quality under climate change while respecting local constraints and grower capacity (Naulleau et al., 2021).

9 Conclusions and Future Perspectives

Research on canopy structure in grapevines shows that training system, geometry and density jointly determine light interception, whole-canopy gas exchange and, ultimately, fruit composition. Systems such as single high wire, high quadrilateral or pergola can achieve higher whole-canopy net CO₂ exchange per unit leaf area and better drought resilience than traditional VSP, while still reaching good fruit maturity in warm climates. Across systems, the best predictor of photosynthesis is the amount and timing of direct light intercepted by the canopy, whereas transpiration is tightly related to vapor pressure deficit, highlighting the central role of canopy architecture in mediating climate effects. Canopy manipulation techniques including defoliation, shading nets, and early canopy management at pre-bloom further refine this structural control over microclimate and source–sink balance. Basal defoliation at fruit set can increase single-leaf photosynthesis, adjust berry temperature, and improve soluble solids and anthocyanin extractability when severity is moderate. Shading nets and altered training height or leaning reduce berry temperature and slow ripening, often preserving acidity and preventing flavonoid degradation under hot conditions. Early leaf removal or shoot trimming at specific positions along the shoot modulates fruit set, bunch compactness and berry composition, showing that both the amount and spatial distribution of leaf area are critical for balancing yield and fruit quality.

Despite extensive work, several limitations constrain the current understanding and application of canopy-based strategies. Many studies evaluate single levers (e.g., training system alone or a specific defoliation regime) under narrow climatic and cultivar conditions, making it difficult to generalize results or predict performance under future climates. Systematic reviews emphasize that most adaptation studies lack multi-lever and multi-scale approaches, and rarely quantify economic feasibility, restricting their usefulness for decision-makers in commercial vineyards. There is also incomplete coverage of the diversity of canopy forms and their long-term physiological impacts. Reviews indicate that classical systems such as VSP and goblet, though widely used, may be less aligned with future climate demands, yet empirical comparisons with alternative systems in different regions remain limited. Evaluations often focus on a few compositional traits (sugars, basic phenolics) and short time frames, while long-term effects on carbohydrate reserves, vine longevity, and cumulative yield are less frequently addressed. These gaps hinder precise recommendations on optimal canopy structures across ecologically contrasting regions.

Future research needs to integrate canopy architecture with other adaptation levers, especially under projected climate scenarios. Systematic assessments show that combining changes in training system, irrigation regime, soil and floor management, and canopy manipulation leads to more robust adaptation strategies than any single intervention alone. Modelling tools that couple gas exchange, water status, leaf temperature and radiation load can be expanded to simulate how alternative trellis designs, shading devices and reflective treatments interact with heatwaves and water scarcity. Such approaches could guide site-specific canopy designs that maintain photosynthesis while protecting fruit quality. At the application level, regionally tailored canopy systems offer promising prospects. Reviews of training systems under warming suggest re-evaluating high-wire, divided and non-VSP canopies in warm and semi-arid areas, while using more exposing systems in newly suitable cool regions to accelerate ripening. Recent work also points to using berry skin flavonols as practical indicators of canopy architecture and radiation exposure, supporting precision management of leaf area and porosity in the field. Coupling these physiological indicators with remote sensing and decision tools could enable dynamic canopy management that sustains photosynthetic efficiency and fruit quality across increasingly variable ecological conditions.

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Conflict of Interest Disclosure

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