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 CO_2 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”