that canopy geometry affects net CO_2 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 methoxypyrazines, 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 m^2 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