

Research Insight

Open Access

The Role of Canopy Management in Optimizing Grapevine Yield and Quality

Kaiwen Liang ✉

Hainan Institute of Tropical Agricultural Resources, Sanya, 572025, Hainan, China

✉ Corresponding email: kaiwen.liang@hitar.orgTree Genetics and Molecular Breeding, 2024, Vol.14, No.5 doi: [10.5376/tgmb.2024.14.0022](https://doi.org/10.5376/tgmb.2024.14.0022)

Received: 15 Aug., 2024

Accepted: 17 Sep., 2024

Published: 25 Sep., 2024

Copyright © 2024 Liang, This is an open access article published under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Preferred citation for this article:

Liang K.W., 2024, The role of canopy management in optimizing grapevine yield and quality, Tree Genetics and Molecular Breeding, 14(5): 229-238 (doi: [10.5376/tgmb.2024.14.0022](https://doi.org/10.5376/tgmb.2024.14.0022))

Abstract This study explores the critical role of canopy management in optimizing grape yield and quality, emphasizing the principles and practices of enhancing grapevine canopy microclimate to improve production efficiency. Canopy management techniques, including shoot thinning, leaf removal, and pruning systems, contribute to improving light conditions and air circulation within the canopy, thereby optimizing photosynthesis and reducing disease risk. Additionally, the study analyzes the long-term effects of these techniques, such as enhanced sugar accumulation and increased antioxidant content, and examines the potential of automation and precision viticulture technologies to improve management efficiency. Innovative canopy management strategies are particularly essential for achieving sustainable grape cultivation in the face of climate change challenges.

Keywords Canopy management; Grape yield and quality; Photosynthesis optimization; Climate change adaptation; Sustainable viticulture

1 Introduction

Grapevine canopy management is a critical aspect of viticulture that involves the strategic manipulation of the grapevine's foliage to optimize both yield and quality. This practice encompasses a variety of techniques, including shoot thinning, leaf removal, and trellis training systems, all aimed at improving the microclimate around the grape clusters. Effective canopy management can significantly influence the light environment, which is crucial for the regulation of shoot growth and fruit development. By controlling factors such as shoot density and leaf area, viticulturists can enhance the balance between vegetative and reproductive growth, ultimately leading to improved grape yield and quality (Dry, 2000; Smart et al., 2017).

The optimization of yield and quality is of paramount importance in viticulture, as it directly impacts the economic viability and marketability of grape and wine products. Canopy management plays a vital role in this optimization process by influencing key factors such as grapevine water use, berry composition, and the microclimate within the canopy. For instance, practices like shoot trimming and leaf removal can modify the plant's response to soil water availability, thereby preserving wine quality and reinforcing the unique characteristics of the terroir (Pascual et al., 2015; Silvestroni et al., 2016). Additionally, these practices can enhance the grape's sensory attributes and chemical composition, which are essential for producing high-quality wines (Collins et al., 2020; Petoumenou and Patris, 2021).

This study explores the role of canopy management in optimizing grapevine yield and quality. It aims to provide a comprehensive overview of the fundamental principles and practices of canopy management, highlighting its impact on grapevine physiology and fruit development. The study seeks to offer adaptable and efficient canopy management strategy guidelines for various environmental conditions and grapevine varieties. By examining the latest research findings and field trials, it demonstrates how canopy management can be leveraged to achieve the dual goals of high yield and superior grape quality, thereby supporting sustainable viticultural practices.

2 Principles of Canopy Management

Canopy management in viticulture refers to the strategic manipulation of the grapevine's foliage to optimize light exposure, air circulation, and ultimately, the yield and quality of the grapes. Key concepts include the control of shoot number, shoot positioning, and leaf removal, which are essential for managing the microclimate within the

canopy. These practices aim to balance the vegetative and reproductive growth of the vine, ensuring that the canopy is neither too dense nor too sparse. An optimal canopy density, often around three leaf layers, is advocated to minimize shading and enhance the microclimate for fruit development (Dry, 2000; Smart et al., 2017).

The physiological basis of canopy structure in grapevines is rooted in the plant's need to optimize photosynthesis while minimizing stress factors such as excessive shading and poor air circulation. Canopy architecture, including the arrangement and density of leaves, directly influences the vine's ability to intercept light and regulate temperature and humidity around the fruiting zone. Practices such as shoot thinning and leaf removal are employed to modify the canopy structure, enhancing light penetration and reducing the risk of diseases like bunch rot. These adjustments can lead to improved reproductive performance and berry ripening, as seen in studies on varieties like Semillon and Shiraz (Pascual et al., 2015; Silvestroni et al., 2016; Wang et al., 2019).

Light interception is a critical factor in grapevine canopy management, as it directly affects photosynthesis, the process by which plants convert light energy into chemical energy. The amount and quality of light reaching the leaves and fruiting zones determine the vine's photosynthetic efficiency and, consequently, its growth and fruit quality (Wedger et al., 2019). Canopy management techniques such as shoot positioning and leaf removal are designed to optimize light distribution within the canopy, enhancing photosynthetic activity and improving grape yield and quality. For instance, increased light interception through canopy porosity adjustments has been shown to positively impact berry composition and hasten fruit maturity, although excessive exposure can lead to flavonoid degradation (Torres et al., 2020; Petoumenou and Patris, 2021; Mataffo et al., 2023).

3 Techniques in Canopy Management

3.1 Pruning strategies

Pruning is a fundamental technique in canopy management that significantly influences grapevine yield and quality. It involves the selective removal of certain parts of the vine, such as shoots, leaves, or clusters, to optimize the vine's growth and fruit production. Winter pruning is a common practice that helps control vine vigor and balance the ratio of fruit to foliage, which is crucial for maintaining grape quality (Collins et al., 2020). Pruning strategies can also include shoot thinning, which reduces canopy density and improves light penetration, thereby enhancing the microclimate around the fruiting zone (Dry, 2000). These practices are essential for managing the vine's energy distribution, ensuring that resources are allocated efficiently to produce high-quality grapes.

3.2 Training systems

Training systems are designed to shape the grapevine canopy to optimize sunlight exposure and air circulation, which are critical for grape development and disease prevention. Different training systems, such as the Ruakura Twin Two Tier and the Te Kauwhata Three Tier, have been shown to influence canopy architecture and microclimate, thereby affecting yield and fruit composition (Smart et al., 2017). These systems help manage the spatial arrangement of shoots and leaves, reducing shading and promoting uniform ripening of grapes. By adjusting the geometry of the vineyard, training systems can also mitigate the effects of environmental factors, such as temperature and humidity, on grape quality (Pascual et al., 2015).

3.3 Leaf removal practices

Leaf removal is a canopy management practice that involves the strategic removal of leaves to improve light exposure and air flow within the canopy. This technique is particularly effective in reducing the incidence of diseases like *Botrytis cinerea* by decreasing humidity around the fruit clusters (Wang et al., 2019; Mataffo et al., 2023). Leaf removal can be performed at different stages of grape development, such as pre-flowering or pre-veraison, to influence berry composition and ripening (Figure 1) (Gambetta et al., 2020). The removal of leaves can also affect the photosynthetic capacity of the vine, which in turn impacts the sugar accumulation and overall quality of the grapes. By carefully managing leaf area, growers can enhance the microclimate of the canopy, leading to improved grape quality and yield.

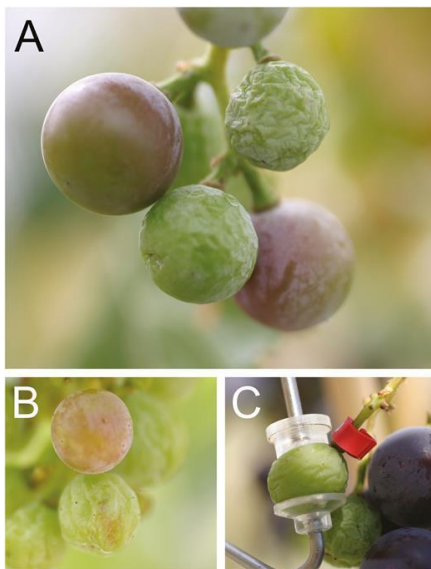


Figure 1 Examples of the hydraulic buffering that occurs at veraison in grapevine (Adopted from Gambetta et al., 2020)

Image caption: When a vine is subjected to water deficit, pre-veraison berries (i.e. green berries) are sensitive to drought-induced shriveling, and berries that are either undergoing veraison (A, B, reddish-green berries) or post-veraison (C, purple berries) are insensitive. Vines shown are under a very severe water deficit ($\Psi_{\text{stem}} < -1.5$ MPa). Photos courtesy of Markus Keller (Adopted from Gambetta et al., 2020)

3.4 Shoot positioning and thinning

Shoot positioning and thinning are critical components of canopy management that help control vine vigor and improve the light environment within the canopy. Proper shoot positioning ensures that shoots are evenly distributed and oriented to maximize sunlight interception, which is essential for photosynthesis and fruit development (Wang et al., 2019). Shoot thinning, on the other hand, involves the removal of excess shoots to reduce canopy density and improve air circulation, which can help prevent disease and promote uniform ripening (Silvestroni et al., 2018). These practices are particularly important in high-vigor vineyards, where excessive shoot growth can lead to shading and reduced fruit quality. By optimizing shoot density and arrangement, growers can enhance the overall performance of the grapevine, leading to better yield and grape quality (Mataffo et al., 2023).

4 Impacts of Canopy Management on Grapevine Yield

4.1 Quantitative effects on cluster and berry development

Canopy management significantly influences the quantitative aspects of cluster and berry development in grapevines. Techniques such as shoot thinning, leaf removal, and cluster thinning have been shown to modify canopy architecture, which in turn affects light interception and microclimate within the canopy. For instance, shoot thinning and leaf removal can decrease the leaf area index, thereby increasing canopy porosity and enhancing light penetration, which positively influences berry ripening and cluster development (Wang et al., 2015). Additionally, the removal of lateral shoots and main leaves before flowering can lead to a reduction in yield potential, as observed in the Swiss white cultivar Petite Arvine, where intensive leaf removal resulted in a 47% decrease in yield potential (Silvestroni et al., 2016). Furthermore, the manipulation of canopy microclimate through practices like shoot number control and vigor management can optimize the balance between shading and light exposure, which is crucial for the development of clusters and berries (Smart et al., 2017). These practices not only affect the size and number of berries but also influence the rachis length, which is a key determinant of bunch compactness and overall yield (Petoumenou and Patris, 2021).

4.2 Long-term impacts on vine health and productivity

The long-term impacts of canopy management on vine health and productivity are profound, as these practices can influence the physiological and structural aspects of the vine. Canopy management strategies such as shoot thinning combined with preanthesis defoliation have been shown to reduce leaf area and yield, but they also

increase sugar concentrations in the grapes, which can have a carryover effect on vine capacity in subsequent years (Wang et al., 2019). This suggests that while certain canopy management practices may initially reduce yield, they can enhance vine health and productivity over the long term by improving grape quality and potentially reducing the need for additional interventions.

Moreover, the control of shoot vigor and the optimization of canopy density can prevent excessive shading, which is associated with primary bud-axis necrosis and reduced shoot fruitfulness (Pascual et al., 2015). By maintaining an optimal light environment within the renewal zone, canopy management can ensure a balance between vegetative growth and fruit production, thereby sustaining vine health and productivity over multiple growing seasons (Mataffo et al., 2023). These practices are essential for adapting to environmental challenges such as climate change, which necessitates improved viticultural techniques to maintain vine performance and fruit quality (Reščič et al., 2016; Buesa et al., 2020).

5 Impacts of Canopy Management on Grapevine Quality

5.1 Influence on grape composition

Canopy management significantly affects the composition of grapes, including sugars, acids, and phenolic compounds. Practices such as shoot thinning and leaf removal can enhance light penetration and air circulation within the canopy, which are critical for the synthesis of sugars and phenolics. For instance, shoot thinning combined with preanthesis defoliation has been shown to increase sugar concentrations in grapes, which is beneficial for wine production (Rienth et al., 2021). Additionally, canopy management can influence the balance of acids in grapes, which is essential for maintaining the desired taste profile in wines. The manipulation of canopy microclimate through practices like leaf removal and shoot thinning can also enhance the phenolic content, contributing to the color and antioxidant properties of the grapes (Silvestroni et al., 2016).

5.2 Effects on aromatic compounds

The aromatic profile of grapes, which is a key determinant of wine quality, is also influenced by canopy management. By altering the microclimate around the grape clusters, canopy management practices can affect the synthesis of aromatic compounds. For example, increased light exposure due to reduced canopy density can enhance the development of desirable aromatic compounds, such as terpenes and norisoprenoids, which contribute to the floral and fruity notes in wines (Smart et al., 2017; Yoshino et al., 2019). Moreover, specific practices like shoot thinning and leaf removal have been associated with changes in the amino acid profile of berries, which can further influence the aromatic complexity of the resulting wine.

5.3 Implications for wine quality

The ultimate goal of canopy management is to improve wine quality by optimizing grape composition and aromatic profiles. Effective canopy management can lead to better ripening of grapes, resulting in wines with enhanced flavor, color, and overall sensory attributes. For instance, canopy division techniques have been shown to improve both yield and wine quality by reducing shading and promoting uniform ripening (Brillante et al., 2018). Additionally, practices that improve the microclimate, such as shoot thinning and leaf removal, can lead to wines with higher concentrations of anthocyanins and other phenolic compounds, which are crucial for the color and mouthfeel of red wines (Petoumenou and Patris, 2021). Overall, strategic canopy management is essential for producing high-quality wines that meet consumer expectations and market demands (Torres et al., 2020).

6 Environmental and Economic Considerations

6.1 Sustainability in canopy management practices

Sustainability in canopy management practices is crucial for maintaining the ecological balance and ensuring long-term productivity in viticulture. Canopy management techniques, such as shoot thinning, leaf removal, and cluster thinning, have been shown to improve grapevine microclimate and reproductive performance, which are essential for sustainable viticulture, especially in hot climates (Jung and McCouch, 2013). These practices not only enhance the quality of the grapes but also contribute to the overall health of the vineyard ecosystem by optimizing water use and reducing the need for chemical inputs (Daryani et al., 2021). Additionally, the use of biostimulants as a sustainable alternative to traditional practices has been explored, offering eco-friendly strategies

to enhance yield and fruit quality while mitigating the impacts of climate change (Rogers and Benfey, 2015). By improving canopy structure and light interception, these practices can lead to better water use efficiency and potentially reduce the environmental footprint of grape production (Kitomi et al., 2020). Overall, sustainable canopy management practices are integral to adapting to environmental challenges and ensuring the resilience of viticultural systems.

6.2 Cost-benefit analysis of different techniques

Conducting a cost-benefit analysis of various canopy management techniques is essential to determine their economic viability and effectiveness in improving grape yield and quality. Techniques such as shoot thinning and leaf removal have been shown to enhance grape quality by improving the microclimate within the canopy, although they may increase labor costs significantly. For instance, while shoot thinning can hasten fruit maturity and improve certain berry traits, it also results in a substantial increase in labor operations cost, which must be weighed against the benefits of improved grape quality (De Dorlodot et al., 2007). Similarly, the use of biostimulants like Sunred® has demonstrated improvements in yield and fruit quality, offering a cost-effective alternative to more traditional growth regulators (Rogers and Benfey, 2015). However, the economic benefits of these practices can vary depending on the specific vineyard conditions and the scale of implementation. Therefore, a comprehensive cost-benefit analysis that considers both the direct costs of implementation and the potential increases in grape quality and yield is crucial for making informed decisions about canopy management strategies (Karnatam et al., 2023; Abdirad et al., 2022).

7 Case Study

7.1 Selection criteria for the case study

The selection of the case study focused on identifying a vineyard renowned for its innovative and effective canopy management practices. The vineyard chosen is located in a region with a challenging climate, which necessitates precise canopy management to optimize grape yield and quality. The vineyard employs a variety of canopy management techniques, including shoot thinning, leaf removal, and cluster thinning, which are well-documented in the literature for their impact on grapevine performance and fruit quality (Wang et al., 2019; Huang and Li, 2024).

7.2 Detailed analysis of a specific canopy management practice in a renowned vineyard

During the harvest phase of the Crimson Seedless grape variety, a comparison of untreated vines (control) and bunches subjected to various pre-harvest canopy management treatments revealed significant effects on the color, size and overall quality of the grapes. As can be seen from the pictures, the untreated grape bunches (Control group) are lighter in color and less ripe; while the grape bunches subjected to specific treatments show significant improvements. For example, grape bunches treated with Kelpak® and LalVigne™ Mature showed a deeper red color, indicating that these treatments can promote the accumulation of pigments, improving the visual appeal and market value of the fruit. In addition, treatment with Ascophyllum nodosum seaweed extract significantly improved the uniformity and ripeness of the fruit, while Ethrel® Top and **Sunred®** treatments further improved the color and gloss of the fruit (Figure 2) (Petoumenou and Patris, 2021). These results indicate that pre-harvest canopy management practices and the application of biostimulants can significantly increase the commercial value of grapes, particularly in terms of color and fruit consistency. For grape growers, combining specific products and processing techniques can not only enhance the appearance of the fruit, but also improve its quality to meet market demand (Petoumenou and Patris, 2021).

7.3 Lessons learned and best practices

The case study highlights several lessons learned and best practices in canopy management. One key takeaway is the importance of tailoring canopy management practices to the specific environmental conditions of the vineyard, such as climate and soil water availability. The combination of shoot thinning and leaf removal proved effective in enhancing grape quality without compromising yield. Additionally, the study underscores the need for ongoing monitoring and adjustment of canopy management strategies to respond to changing environmental conditions and to optimize both yield and quality consistently. These practices can serve as a model for other vineyards

seeking to improve their grape production and wine quality through effective canopy management (Smart et al., 2017; Buesa et al., 2020).

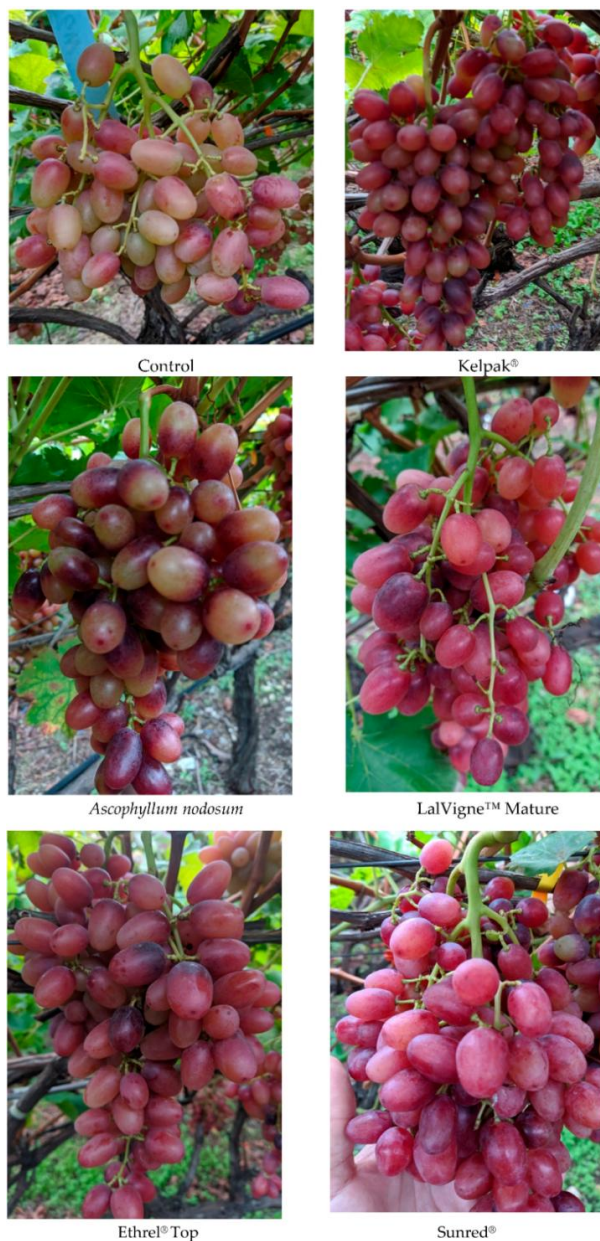


Figure 2 Clusters at harvest of table grape cv. Crimson Seedless after several preharvest canopy applications and compared to cluster from untreated vines (Adopted from Petoumenou and Patris, 2021)

8 Technological Innovations in Canopy Management

8.1 Precision viticulture and remote sensing applications

Precision viticulture and remote sensing technologies have revolutionized canopy management by enabling more accurate monitoring and management of grapevine canopies. These technologies allow for the detailed assessment of canopy microclimate, which is crucial for optimizing grape yield and quality. For instance, remote sensing can be used to evaluate the solar radiation levels within the canopy, which are affected by vineyard geometry and leaf layers, thereby influencing the microclimate and ultimately the grape composition (Buesa et al., 2020). Additionally, precision viticulture tools such as point quadrat analysis and canopy scoring provide quick and effective means to identify problem areas within the canopy, allowing for targeted interventions to improve canopy structure and microclimate (Smart et al., 2017). These innovations facilitate the fine-tuning of canopy management practices to enhance grapevine performance and wine quality.

8.2 Role of automation and robotics in canopy management

Automation and robotics are increasingly being integrated into canopy management to improve efficiency and precision. These technologies can perform tasks such as shoot thinning, leaf removal, and cluster thinning with greater accuracy and consistency than manual labor. For example, automated systems can be programmed to perform shoot thinning and leaf removal, which have been shown to improve canopy porosity and light interception, thereby enhancing berry ripening and reproductive performance (Wang et al., 2019). Moreover, the use of robotics in canopy management can help in maintaining optimal canopy architecture, which is essential for controlling the microclimate and improving grape quality (Pascual et al., 2015; Panda et al., 2021). The integration of automation and robotics not only reduces labor costs but also ensures that canopy management practices are applied consistently across the vineyard.

8.3 Integration of data analytics and decision support systems

The integration of data analytics and decision support systems in canopy management allows for more informed decision-making based on real-time data. These systems can analyze data from various sources, such as remote sensing and field sensors, to provide insights into the optimal canopy management strategies for different environmental conditions. For instance, data analytics can help identify the relationships between soil, plant, and canopy management variables, enabling the adaptation of practices to optimize water use and enhance wine quality (Pascual et al., 2015). Decision support systems can also assist in determining the optimal timing and extent of canopy interventions, such as shoot trimming and leaf removal, to achieve desired outcomes in terms of yield and fruit quality (Silvestroni et al., 2016). By leveraging data analytics, vineyard managers can make more precise and effective decisions, ultimately leading to improved grapevine yield and quality.

9 Future Directions

Canopy management in viticulture presents both challenges and opportunities for optimizing grapevine yield and quality. One of the primary challenges is managing the light environment within the canopy, which significantly influences bud fruitfulness and fruit yield per node. High shoot vigor and canopy shading can lead to primary bud-axis necrosis, reducing the number of fruitful primary shoots and increasing the proportion of less fruitful secondary shoots (Torres et al., 2020). However, opportunities exist in refining canopy management practices such as shoot thinning, leaf removal, and training systems to improve canopy microclimate and enhance grape quality. For instance, shoot thinning and leaf removal have been shown to increase canopy porosity and light interception, positively affecting berry ripening and reproductive performance (Wang et al., 2019). Additionally, innovative practices like leaning grapevine canopies to the west have been explored to improve water use efficiency and yield under Mediterranean conditions, although the effects on grape composition remain minimal (Buesa et al., 2020).

Despite advancements in canopy management, several research gaps remain. There is a need for more comprehensive studies on the interaction between canopy management practices and environmental factors such as soil water availability and climate conditions. For example, while canopy management strategies like shoot trimming have been effective in adapting plant response to soil water availability, their impact on berry and wine quality, particularly the amino acid profile and sensorial attributes, requires further investigation (Pascual et al., 2015). Moreover, the role of biostimulants in enhancing yield and fruit quality under changing climatic conditions is an area ripe for exploration. Products like Sunred® have shown promise in improving anthocyanin accumulation and overall grape quality, suggesting a potential alternative to traditional growth regulators (Petoumenou and Patris, 2021). Addressing these gaps could lead to more sustainable and effective canopy management strategies.

The changing climate poses significant challenges to viticulture, necessitating adaptive canopy management strategies to maintain and enhance grape yield and quality. Climate change impacts, such as increased temperatures and altered precipitation patterns, require innovative approaches to canopy management. For instance, canopy management practices that optimize solar radiation exposure can enhance flavonoid biosynthesis, crucial for grape quality, although care must be taken to avoid degradation of these compounds (Torres et al., 2020). Additionally, strategies that combine shoot thinning with preanthesis defoliation have shown potential in regulating vine yield and improving grape quality by increasing sugar concentrations (Silvestroni et al., 2016). As

climate conditions continue to evolve, the development of canopy management practices that are resilient to these changes will be essential for sustaining grapevine productivity and quality.

10 Conclusion

The role of canopy management in optimizing grapevine yield and quality is pivotal, as it directly influences the microclimate within the vineyard, which in turn affects both the quantity and quality of grape production. Key findings from various studies highlight that effective canopy management practices, such as shoot thinning, leaf removal, and the use of specific training systems, can significantly enhance grape yield and quality. For instance, optimal canopy density, typically around three leaf layers, is crucial for balancing light exposure and shading, which are essential for improving fruit composition and wine quality. Additionally, practices like shoot trimming and cluster thinning have been shown to improve berry ripening and reduce issues like bunch rot, thereby enhancing the overall quality of the grapes.

For viticulturists and industry stakeholders, it is recommended to adopt a tailored approach to canopy management that considers the specific environmental conditions and grapevine varieties. Techniques such as shoot thinning combined with preanthesis defoliation can be particularly effective in increasing sugar concentrations and regulating vine yield over the long term. Moreover, in rainfed vineyards, strategies like reiterate shoot trimming can help adapt plant growth to soil water availability, thereby preserving wine quality without compromising yield. It is also advisable to explore innovative solutions like biostimulants, which have shown promise in enhancing grape color and quality under challenging climatic conditions. By implementing these strategies, viticulturists can optimize grapevine performance, ensuring high-quality grape production that meets market demands.

Acknowledgments

The author sincerely thanks Dr. Green for carefully reviewing the initial draft of the manuscript and providing detailed revision suggestions. The author also extends deep gratitude to the two anonymous peer reviewers for their valuable comments and suggestions on the initial draft of this study.

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.

Reference

- Brillante L., Martínez-Lüscher J., and Kurtural S., 2018, Applied water and mechanical canopy management affect berry and wine phenolic and aroma composition of grapevine (*Vitis vinifera* L., cv. Syrah) in Central California, *Scientia Horticulturae*, 227: 261-271.
<https://doi.org/10.1016/j.scienta.2017.09.048>
- Buesa I., Ballester C., Mirás-Avalos J., and Intrigliolo D., 2020, Effects of leaning grapevine canopy to the West on water use efficiency and yield under Mediterranean conditions, *Agricultural and Forest Meteorology*, 295: 108166.
<https://doi.org/10.1016/j.agrformet.2020.108166>
- Collins C., Wang X., Lesefko S., Bei R., and Fuentes S., 2020, Effects of canopy management practices on grapevine bud fruitfulness, *OENO One*, 54: 313-325.
<https://doi.org/10.20870/oeno-one.2020.54.2.3016>
- Daryani P., Ramandi H., Dezhsetan S., Mansuri R., Salekdeh H., and Shobbar Z., 2021, Pinpointing genomic regions associated with root system architecture in rice through an integrative meta-analysis approach, *Theoretical and Applied Genetics*, 135: 81-106.
<https://doi.org/10.1007/s00122-021-03953-5>
PMid:34623472
- De Dorlodot S., Forster B., Pagès L., Price A., Tuberosa R., and Draye X., 2007, Root system architecture: opportunities and constraints for genetic improvement of crops, *Trends in Plant Science*, 12(10): 474-481.
<https://doi.org/10.1016/j.tplants.2007.08.012>
PMid:17822944
- Dry P., 2000, Canopy management for fruitfulness, *Australian Journal of Grape and Wine Research*, 6: 109-115.
<https://doi.org/10.1111/j.1755-0238.2000.tb00168.x>

- Gambetta G.A., Herrera J.C., Dayer S., Feng Q., Hochberg U., and Castellarin S.D., The physiology of drought stress in grapevine: towards an integrative definition of drought tolerance, *Journal of Experimental Botany*, 71(16): 4658-4676.
<https://doi.org/10.1093/jxb/eraa245>
 PMid:32433735 PMCID:PMC7410189
- Huang J., and Li M.F., 2024, Genomic approaches to enhance disease resistance in grapevine breeding programs, *Molecular Pathogens*, 15(1): 40-49.
<https://doi.org/10.5376/mp.2024.15.0005>
 PMid:39599501
- Jung J., and McCouch S., 2013, Getting to the roots of it: genetic and hormonal control of root architecture, *Frontiers in Plant Science*, 4: 186.
<https://doi.org/10.3389/fpls.2013.00186>
- Karnatam K., Chhabra G., Saini D., Singh R., Kaur G., Praba U., Kumar P., Goyal S., Sharma P., Ranjan R., Sandhu S., Kumar R., and Vikal Y., 2023, Genome-wide meta-analysis of QTLs associated with root traits and implications for maize breeding, *International Journal of Molecular Sciences*, 24(7): 6135.
<https://doi.org/10.3390/ijms24076135>
 PMid:37047112 PMCID:PMC10093813
- Kitomi Y., Hanzawa E., Kuya N., Inoue H., Hara N., Kawai S., Kanno N., Endo M., Sugimoto K., Yamazaki T., Sakamoto S., Sentoku N., Wu J., Kanno H., Mitsuda N., Toriyama K., Sato T., and Uga Y., 2020, Root angle modifications by the *DRO1* homolog improve rice yields in saline paddy fields, *Proceedings of the National Academy of Sciences of the United States of America*, 117(35): 21242-21250.
<https://doi.org/10.1073/pnas.2005911117>
 PMid:32817523 PMCID:PMC7474696
- Mataffo A., Scognamiglio P., Molinaro C., Corrado G., and Basile B., 2023, Early canopy management practices differentially modulate fruit set, fruit yield, and berry composition at harvest depending on the grapevine cultivar, *Plants*, 12(4): 733.
<https://doi.org/10.3390/plants12040733>
 PMid:36840079 PMCID:PMC9959345
- Panda S., Majhi P., Anandan A., Mahender A., Veludandi S., Bastia D., Guttala S., Singh S., Saha S., and Ali J., 2021, Proofing direct-seeded rice with better root plasticity and architecture, *International Journal of Molecular Sciences*, 22(11): 6058.
<https://doi.org/10.3390/ijms22116058>
 PMid:34199720 PMCID:PMC8199995
- Pascual M., Romero M., Rufat J., and Villar J., 2015, Canopy management in rainfed vineyards (cv. Tempranillo) for optimising water use and enhancing wine quality, *Journal of the Science of Food and Agriculture*, 95(15): 3067-3076.
<https://doi.org/10.1002/jsfa.7342>
 PMid:26174077
- Petoumenou D., and Patris V., 2021, Effects of several preharvest canopy applications on yield and quality of table grapes (*Vitis vinifera* L.) Cv. crimson seedless, *Plants*, 10(5): 906.
<https://doi.org/10.3390/plants10050906>
 PMid:33946268 PMCID:PMC8146782
- Reščič J., Mikulič-Petkovšek M., and Rusjan D., 2016, The impact of canopy managements on grape and wine composition of cv. 'Istrian Malvasia' (*Vitis vinifera* L.), *Journal of the Science of Food and Agriculture*, 96(14): 4724-4735.
<https://doi.org/10.1002/jsfa.7778>
 PMid:27129430
- Rienth M., Vigneron N., Darriet P., Sweetman C., Burbidge C., Bonghi C., Walker R.P., Famiani F., and Castellarin S.D., 2021, Grape berry secondary metabolites and their modulation by abiotic factors in a climate change scenario-a review, *Frontiers in Plant Science*, 12: 643258.
<https://doi.org/10.3389/fpls.2021.643258>
 PMid:33828576 PMCID:PMC8020818
- Rogers E., and Benfey P., 2015, Regulation of plant root system architecture: implications for crop advancement, *Current Opinion in Biotechnology*, 32: 93-98.
<https://doi.org/10.1016/j.copbio.2014.11.015>
 PMid:25448235
- Silvestroni O., Lanari V., Lattanzi T., Palliotti A., and Sabbatini P., 2016, Impact of crop control strategies on performance of high-yielding Sangiovese grapevines, *American Journal of Enology and Viticulture*, 67: 407-418.
<https://doi.org/10.5344/ajev.2016.15093>
- Silvestroni O., Lanari V., Lattanzi T., Palliotti A., VanderWeide J., and Sabbatini P., 2018, Canopy management strategies to control yield and grape composition of Montepulciano grapevines, *Australian Journal of Grape and Wine Research*, 25: 30-42.
<https://doi.org/10.1111/ajgw.12367>
- Smart R., Dick J., Gravett I., and Fisher B., 2017, Canopy management to improve grape yield and wine quality - principles and practices, *South African Journal of Enology and Viticulture*, 11: 3-17.
<https://doi.org/10.21548/11-1-2232>
- Torres N., Martínez-Lüscher J., Porte E., and Kurtural S., 2020, Optimal ranges and thresholds of grape berry solar radiation for flavonoid biosynthesis in warm climates, *Frontiers in Plant Science*, 11: 931.
<https://doi.org/10.3389/fpls.2020.00931>

- Wang X., De Bei R., Fuentes S., and Collins C., 2019, Influence of canopy management practices on canopy architecture and reproductive performance of Semillon and Shiraz grapevines in a hot climate, *American Journal of Enology and Viticulture*, 70: 360-372.
<https://doi.org/10.5344/ajev.2019.19007>
- Wedger M., Topp C., and Olsen K., 2019, Convergent evolution of root system architecture in two independently evolved lineages of weedy rice, *The New Phytologist*, 223(2): 1031-1042.
<https://doi.org/10.1111/nph.15791>
PMid:30883803
- Yoshino K., Numajiri Y., Teramoto S., Kawachi N., Tanabata T., Tanaka T., Hayashi T., Kawakatsu T., and Uga Y., 2019, Towards a deeper integrated multi-omics approach in the root system to develop climate-resilient rice, *Molecular Breeding*, 39: 165.
<https://doi.org/10.1007/s11032-019-1058-4>

Disclaimer/Publisher's Note

The statements, opinions, and data contained in all publications are solely those of the individual authors and contributors and do not represent the views of the publishing house and/or its editors. The publisher and/or its editors disclaim all responsibility for any harm or damage to persons or property that may result from the application of ideas, methods, instructions, or products discussed in the content. Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
