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Article

IMPACT OF ASYMMETRICAL WEST-SIDE CANOPY SHADING WITH ANTI-HAIL NETS ON VINEYARD MICROCLIMATE, YIELD AND WINE COMPOSITION

IMPACTO DO SOMBREAMENTO ASSIMÉTRICO DA FACE OESTE DA CANÓPIA COM REDES ANTIGRANIZO NA MODULAÇÃO DO MICROCLIMA, NO RENDIMENTO E NA COMPOSIÇÃO DO VINHO

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SUMMARY

In warm arid viticultural regions, excessive solar radiation and high temperatures during ripening increasingly compromise berry composition and wine quality. These effects are expected to intensify under climate warming. In hail-prone areas such as Mendoza, Argentina, anti-hail nets are widely adopted for crop protection and may also offer an opportunity for vineyard microclimate modulation. This study evaluated the effects of commercial anti-hail nets on canopy microclimate, yield, and wine composition in a *Vitis vinifera* L. cv. 'Malbec' vineyard over three consecutive seasons. Three treatments were compared: an uncovered control (CO), a moderate symmetrical shading treatment using standard anti-hail nets providing 17% radiation exclusion on both canopy sides (M1), and an intensified asymmetrical configuration combining 17% shading on the east side with reinforced 50% shading on the west side (M2). Anti-hail nets significantly buffered the canopy microclimate by reducing leaf temperature and the accumulation of hours above 35 °C during peak thermal periods. Shading intensity was the main factor associated with observed vine responses. Moderate shading (M1) preserved yield stability while improving the sugar–acid balance and enhancing wine chromatic characteristics during the 2017 season. In contrast, intensified west-side shading (M2) promoted excessive vegetative vigor, increased the pruning weight-to-yield ratio, and reduced wine chromatic expression, indicating that excessive radiation attenuation may limit color-related ripening processes. Overall, moderate differential shading could potentially be an effective multifunctional strategy to mitigate thermal stress while preserving wine typicity in arid viticultural regions.

RESUMO

Em regiões vitivinícolas quentes e áridas, a radiação solar excessiva e as temperaturas elevadas durante a maturação têm vindo a comprometer a composição das uvas e a qualidade dos vinhos no contexto das alterações climáticas. Em zonas propensas à ocorrência de granizo, como Mendoza, Argentina, as redes antigranizo são amplamente utilizadas para proteção da produção e podem igualmente contribuir para a modulação do microclima da canópia. O presente estudo avaliou os efeitos de redes antigranizo comerciais sobre o microclima da canópia, o rendimento e a composição das uvas e dos vinhos numa vinha de *Vitis vinifera* L. cv. 'Malbec' ao longo de três vindimas consecutivas. Foram comparados três tratamentos: um controlo sem cobertura (CO), um sombreamento simétrico moderado com redes padrão proporcionando 17% de exclusão da radiação em ambos os lados da canópia (M1) e uma configuração assimétrica intensificada, combinando 17% de sombreamento no lado leste com 50% no lado oeste (M2). As redes antigranizo atenuaram o microclima da canópia, reduzindo a temperatura foliar e a acumulação de horas acima de 35 °C durante os períodos térmicos críticos. A intensidade do sombreamento foi o principal fator associado às respostas da videira. O sombreamento moderado (M1) manteve o rendimento e favoreceu um equilíbrio mais adequado entre açúcares e acidez, bem como melhores características cromáticas nos vinhos. Em contraste, o sombreamento intensificado no lado oeste (M2) promoveu maior vigor vegetativo, aumentou a razão peso da lenha de poda/rendimento e reduziu a expressão cromática dos vinhos. De modo geral, o sombreamento diferencial moderado mostrou potencial como estratégia multifuncional para mitigar o stress térmico sem comprometer a tipicidade dos vinhos em regiões vitivinícolas áridas.

Keywords: Heat stress mitigation, microclimate modification, vegetative–reproductive balance, chromatic characteristics, Malbec.
Palavras-chave: Mitigação do stresse térmico, modificação do microclima, equilíbrio vegetativo–reprodutivo, características cromáticas, Malbec.

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INTRODUCTION

Climate change constitutes one of the main current challenges for viticulture, especially in arid and semi-arid regions, where the increase in air temperature, the greater frequency of heat waves, and the intensification of extreme climatic events affect both the productivity and the quality of grapes intended for winemaking (Van Leeuwen *et al.*, 2019; Yu *et al.*, 2022; Dominguez *et al.*, 2024). In particular, the increase in temperature during the ripening period has been associated with advances in key phenological stages, such as veraison and harvest, imbalances in the source–sink relationship, and modifications in berry and wine composition, compromising the typicity, stability, and aging potential of the final product (Torres *et al.*, 2020; Gutiérrez-Gamboa *et al.*, 2021, 2024). In red cultivars like 'Malbec', these conditions often lead to an excessive decoupling between sugar accumulation (technological maturity) and the expression of phenolic-related quality attributes (chromatic maturity) associated with color expression, a phenomenon that threatens the emblematic wine profile of high-altitude regions.

In western Argentina, the province of Mendoza concentrates the country's largest viticultural area, and is characterized by a semi-arid climate with high incident radiation, low precipitation, and marked thermal variability that intensifies during the summer period. These conditions predispose the occurrence of thermal and radiative stress during critical stages of the vine cycle, particularly under recent warming scenarios (Van Leeuwen *et al.*, 2019; Dominguez *et al.*, 2024). In this region, hail represents one of the most structurally limiting climatic risks for wine production, with frequent events that generate significant losses in yield and quality (Bechis *et al.*, 2022). Recent climate models and observational analyses suggest that the frequency and severity of convective storms, including hailstorms, could intensify due to climate change, although with variable responses depending on the region, reinforcing the need for multifunctional adaptation strategies at the vineyard scale (Van Leeuwen *et al.*, 2019; Raupach *et al.*, 2021).

The use of anti-hail nets has been consolidated as an effective tool to reduce mechanical damage caused by hail in vineyards. While these structures act as a physical barrier originally designed for hail protection, they also modify the crop microclimate by altering the quantity, distribution, and spectral quality of incident radiation, as well as air temperature and relative humidity within the canopy (Avenant and Avenant, 2022; Pallotti *et al.*, 2023; Domanda *et al.*, 2024). These microclimatic modifications can influence canopy functioning, including processes related to gas exchange, water status, and water use efficiency, with consequences for vegetative growth, yield, and grape quality (Villalobos-Soublett *et al.*, 2021; Gutiérrez-Gamboa *et al.*, 2024; Gu *et al.*, 2025).

In this context, artificial shading using nets already adopted in commercial vineyards has been proposed as an adaptation strategy to global warming, aimed at mitigating the negative effects of excess radiation and high temperatures on vine physiology and berry composition (Martínez-Lüscher *et al.*, 2017, 2020; Miccichè *et al.*, 2025), as well as on wine composition and attributes related to quality perception (Martínez-Lüscher *et al.*, 2020; Lu *et al.*, 2021; Crouchett-Rojas *et al.*, 2025). Recent studies indicate that partial shading can reduce canopy and cluster temperature, improve water use efficiency, and modulate ripening kinetics, especially in warm and semi-arid regions (Caravia *et al.*, 2016; Miccichè *et al.*, 2023; Tiffon-Terrade *et al.*, 2023; Gutiérrez-Gamboa *et al.*, 2024).

However, most studies have evaluated the effect of shading homogeneously across the vineyard or the entire canopy, mainly under controlled experimental conditions (Martínez-Lüscher *et al.*, 2017; Miccichè *et al.*, 2025; Gu *et al.*, 2025), while differential exposure according to cardinal orientation has received limited attention under commercial vineyard conditions. Canopy orientation determines contrasting patterns of radiation interception throughout the day, particularly in near north-south oriented row-trained (Gouot *et al.*, 2019; Zarrouk *et al.*, 2024). In the southern hemisphere, the west-facing side of the canopy receives the greatest solar radiation during afternoon, coinciding with daily peaks in air temperature and evaporative demand (Van Leeuwen *et al.*, 2019; Torres *et al.*, 2020). This combination has been associated with greater leaf thermal stress and alterations in the synthesis of phenolic compounds associated with berry and wine color expression. Despite this, there is a lack of empirical evidence regarding how asymmetrical shading, specifically on the west-facing side, can modulate these effects in commercial vineyard conditions.

In this framework, differential shading of the west-facing side of the canopy emerges as a management alternative with potential to reduce the impact of thermal excess without compromising total light interception in the vineyard. When this shading is implemented using anti-hail nets, the practice acquires a multifunctional character, integrating protection against extreme climatic events and thermal stress mitigation (Pallotti *et al.*, 2023; Crouchett-Rojas *et al.*, 2025). Nevertheless, concerns persist regarding the possible effects of net use on vegetative growth and vine balance, limiting its adoption as an integral agronomic tool (Forte *et al.*, 2022; Domanda *et al.*, 2024; Reta *et al.*, 2025).

Based on the premise that selective west-side shading may decouple the ripening process from extreme afternoon thermal peaks while preserving vine balance under appropriate shading intensity, the aim of this study was to evaluate the effect of differential shading of the west-facing side of the canopy, using anti-hail nets, on microclimate, vegetative–reproductive balance, yield, and grape and wine composition in a cv. 'Malbec' vineyard in southern Mendoza, Argentina.

MATERIALS AND METHODS

Site and plant material

The study was conducted in an experimental *Vitis vinifera* L. cv. 'Malbec' vineyard located in San Rafael, south of Mendoza, Argentina (34° 39' 47" S, 68° 23' 35" W; 650 m a.s.l.), over three consecutive growing seasons (2015–2016, 2016–2017 and 2017–2018), corresponding to the 2016, 2017, and 2018 harvest seasons, respectively. The vineyard was planted in 1999 with own-rooted vines on a loamy-textured soil composed of 46% sand, 30% silt, and 24% clay (USDA classification, Gee and Bauder, 1986), with a sedimentation volume 93.76 ± 0.60%, according to the method by Nijensohn and Pilasi (1962). The soil exhibited neutral to slightly alkaline pH (7.84 ± 0.16, determined in saturated soil paste), and was classified as non-saline (electrical conductivity of the saturated extract: 3.64 ± 0.48 mS/cm) and non-sodic (sodium adsorption ratio, SAR: 4.17 ± 0.61), following standard soil salinity assessment procedures (Richards, 1973).

Rows were oriented NNE-SSW (24º 8' 45" relative to geographic north), with a planting density of 2667 plants/ha (2.5 m between rows and 1.5 m between plants). Although vineyard rows were not strictly north-south oriented, the western canopy side remained exposed to greater afternoon solar radiation during the warmest part of the day. Vines were trained to a vertically shoot positioned (VSP) system and spur-pruned to 20 buds per plant (≈53340 buds/ha). Irrigation was supplied via a drip system with 2 L/h emitters spaced every 0.75 m. Irrigation was applied uniformly across treatments throughout the study. During the growing season, from budburst to leaf fall, the applied irrigation amount was approximately 680 mm.

To characterize the environmental conditions, data were obtained from an automatic weather station (THP 933, Nimbus, Argentina) located 120 m from the site. Maximum, mean, and minimum air temperatures and precipitation were recorded, and the following bioclimatic indices were calculated: Huglin heliothermal index (HI), cool night index (CI), and Winkler index (WI). These values were compared to a 72-year historical series (1950-2021).

Experimental design and treatments

The experiment followed a randomized complete block design with three treatments and four replications (12 experimental units in total). Each experimental unit (EU) consisted of five consecutive vines. The treatments were: **CO** (control) vines without net protection; **M1** (Intermediate Shading) protection with a black anti-hail net with 17% nominal shading factor installed on both sides of the canopy; and **M2** (Asymmetrical/Intense Shading): protection consisting of a black anti-hail net with a 17% nominal shading factor on the east-facing side and a 50% shading factor net on the west-facing side, intended to increase shading on the west-facing side of the canopy during afternoon hours (Figure 1). In both M1 and M2, the nets were installed using the Grembiule system, which protects the fruit zone while allowing canopy management (Nahüel, 2013). Nets were installed during the winter preceding the beginning of the experiment and remained in place throughout the three growing seasons.

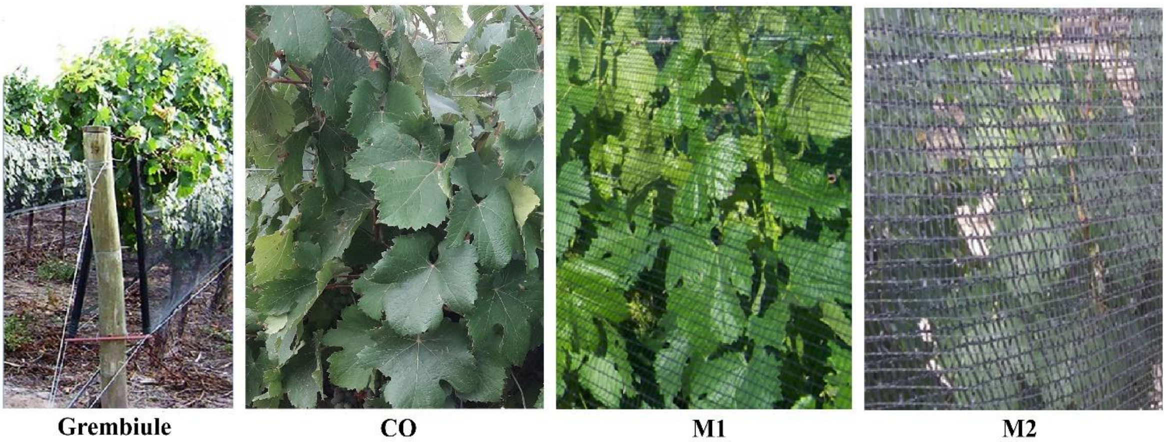

Figure 1. Evaluated treatments: CO (control, without protection), M1 (17% hail net on the east and west sides), and M2 (17% hail net on the east side and 50% hail net on the west side). Grembiule: hail net installation system applied in the M1 and M2 treatments.

Microclimatic and canopy measurements

Detailed microclimatic measurements were performed during the 2017 growing season, corresponding to the second experimental season, when the vineyard experienced representative warm conditions suitable for characterizing canopy thermal and radiative responses under the evaluated treatments. During the second season, in the maturity phase (February 7, 2017), the Photosynthetic Photon Flux Density (PPFD; µmol/m²/s) incident on the west side of the row was measured at 0.25 m from the canopy center, both above the foliage and below the net. External radiation was simultaneously recorded as a reference. Measurements were performed with a linear quantum sensor (LI-191, LI-COR, Lincoln, NE, USA) connected to a light meter (LI-250A, LI-COR, Lincoln, NE, USA). Simultaneously, leaf temperature was determined using a digital infrared thermometer (GM 300, BENETECH, China) with a resolution of 0.1 °C, positioned 10 cm from the leaf surface and held perpendicularly. These measurements represent a single-season and snapshot-based characterization of canopy microclimatic conditions and were used descriptively rather than to infer interannual variability.

Furthermore, air temperature and relative humidity were recorded over 42 consecutive days during the 2017 season, from veraison (stage 35, Eichhorn and Lorenz scale modified by Coombe, 1995) until harvest. Wireless thermo-hygrometers (Klima Logger, TFA Dostmann GmbH & Co. KG, Germany) connected to a digital data logger (Klima Data 30.3015) were used. One thermo-hygrometer was installed per experimental unit (n = 4 per treatment). Sensors were placed at cluster level (≈1 m above ground) in the center of the canopy, above the permanent cordon, and measurements were made every 30 min. Accordingly, microclimatic interpretation in this study is restricted to the conditions evaluated during the 2017 growing season and was used descriptively rather than to infer interannual variability.

Vegetative growth

During the study, in winter, pruning wood weight was determined for each plant in the EU using an electronic scale (SC 102 ACUARIO, Balcoppan, Córdoba, Argentina). The Ravaz Index was calculated (yield/pruning weight) to assess the source-sink balance.

Yield components and yield

For each season, harvest timing was determined when treatment CO reached 23 °Brix (ATC-1E, ATAGO, Tokyo, Japan). At harvest, the number of clusters per plant was counted and total production per plant was determined with an electronic scale (SC 102 ACUARIO, Balcoppan, Córdoba, Argentina). From these variables, cluster weight was estimated and berry weight was determined by random sampling of 100 berries per replicate.

Must and wine chemical composition

Grapes from each replicate (totaling 12 EU) were harvested and processed separately for micro-vinification under controlled conditions (20 ± 2 °C). Micro-vinifications and wine composition analyses were conducted only during the 2017 season, which provided representative warm conditions for evaluating enological responses under the different shading treatments. For each EU, a 2.6 kg sample was destemmed and crushed, and the must was fermented in disinfected glass containers. In the must, total soluble solids (°Brix), pH (827 PH LAB, Metrohm, Switzerland), and titratable acidity (titration with 0.1 N NaOH) were determined. In the resulting wines, alcohol content (% v/v), pH and titratable acidity (TA), expressed as g/L of tartaric acid, were determined (Nazrala *et al.*, 2009). Additionally, absorbance (*A*) at 420, 520, and 620 nm was measured using a visible light spectrophotometer (Spectronic 601, Milton Roy Company, USA). These data were used to calculate Color Intensity (CI = $A_{420} + A_{520} + A_{620}$) and Hue (H = A_{420} / A_{520}), following the methods described by Glories (1984).

Statistical analysis

Data were analyzed using mixed linear models (Infostat ® 2020 software; National University of Córdoba, Córdoba, Argentina). Treatments and seasons were treated as fixed effects, while experimental units were considered as random effects. Mean comparisons were performed using Fisher's LSD test ($p<0.05$). For repeated measurements over time, including air temperature and relative humidity time-course data, appropriate covariance structures were modeled to account for temporal correlation among observations, and the final model structure was selected based on information criteria and model fit diagnostics within the Infostat mixed-model procedure (Di Rienzo *et al.*, 2017). Residual diagnostics were performed to verify model assumptions.

RESULTS AND DISCUSSION

The implementation of differential shading using anti-hail nets was associated with substantial shifts in the vineyard's microclimate, which subsequently modulated the canopy, productive and qualitative performance of cv. 'Malbec' vines.

The following sections detail the impact of these radiative and thermal modifications on canopy status, yield components, and the chemical profile of both must and wine across three consecutive seasons.

The trial was characterized by significant inter-annual variability (Table I).

The first growing season (2016) aligned with historical means - Winkler III, while the subsequent 2017 and 2018 seasons were notably warmer -

Winkler IV (Cabré *et al.*, 2016). According to the multicriteria climate classification, the site was defined as warm (HI +2) with very cool nights (CI +2) (Tonietto and Carbonneau, 2004).

Table I

Thermal conditions, bioclimatic indices, and precipitation during the 2016, 2017, and 2018 seasons in an experimental Malbec vineyard located in southern Mendoza, Argentina

Season	T_{max} (°C)	T_{min} (°C)	T_{med} (°C)	HI	CI (°C)	WI	P (mm)
2016	26.4	11.5	18.9	2669	11.8	1884 (III)	524
2017	29.2	11.4	20.3	3069	11.3	2171 (IV)	427
2018	29.6	10.7	20.1	2993	8.6	2141 (IV)	149
Historical mean	27.6	10.7	19.2	2745	10.9	1939 (III)	262

Maximum (T_{max}), mean (T_{med}), and minimum (T_{min}) temperatures, Winkler Index (WI) and precipitation (P, mm) during the three growing seasons (October to April), Huglin Index (HI) (September to March), and Cool Night Index (CI) (March).

Microclimatic effects of differential west-side shading

Anti-hail nets induced marked microclimatic modifications at the canopy level, particularly when differential shading was applied to the west side of the row. In north–south oriented systems in the Southern Hemisphere, this side of the canopy is typically exposed to the highest radiation and thermal loads during the afternoon, creating a window of elevated environmental stress (Gouot *et al.*, 2019; Zarrouk *et al.*, 2024). During the 2017 growing season, incident photosynthetic photon flux density (PPFD) measured on the west side of the canopy showed a significant reduction under the intensified west-side shading treatment (M2) compared to both the control (CO) and the moderate shading (M1). This result indicates that the asymmetrical net configuration in selectively attenuated radiation during peak heat hours without excessive shading of the entire canopy (Figure 2).

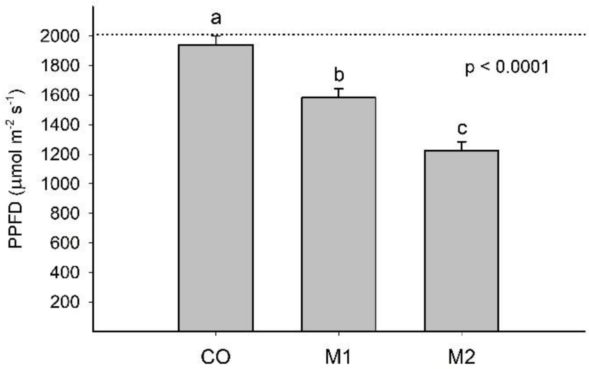

Figure 2. Photosynthetic photon flux density (PPFD, µmol/m²/s) incident on the canopy at midday on 07/02/2017 in response to west-side shading intensity in an experimental ‘Malbec’ (*Vitis vinifera* L.) vineyard located in southern Mendoza, Argentina. Bars indicate standard error. Means followed by the same letter are not significantly different (Fisher’s LSD test, p<0.05). CO: uncovered control; M1: symmetrical shading (17% on both sides); M2: asymmetrical west-side shading (50% on the west side). The dotted line indicates the reference ambient PPFD.

This reduction in incident radiation was associated with a significant decrease in leaf temperature (T_{Leaf}) measured at midday during the 2017 growing season, when PPFD and leaf thermal load are near their daily maximum. Such thermal moderation is relevant, as previous research indicates that high T_{Leaf} could induce partial stomatal closure and reduce carbon assimilation under conditions of high atmospheric evaporative demand (Gouot *et al.*, 2019; Torres *et al.*, 2020). Accordingly, differential shading reduced radiative heat gain and was associated with lower leaf temperature under the evaluated conditions.

The spatial modification of the canopy microclimate under west-side shading was associated with lower T_{Leaf} values compared to the control, as summarized in Table II, in agreement with previous reports describing similar thermal reductions under shade or photo-selective nets in warm and arid viticultural regions (Martínez-Lüscher *et al.*, 2017; Miccichè *et al.*, 2023; Storchi *et al.*, 2024). From a canopy perspective, the observed leaf temperature remained within ranges generally considered below thresholds commonly associated with heat stress in grapevines (typically below 35 °C) under the conditions evaluated in 2017 (Ghiglieno *et al.*, 2020; Lu *et al.*, 2021).

Table II

Midday leaf temperature on 07/02/2017 in response to west-side shading intensity in an experimental 'Malbec' (*Vitis vinifera* L.) vineyard located in southern Mendoza, Argentina

Treatment	**Leaf temperature (°C)**
CO	31.73 ± 0.18 a
M1	31.33 ± 0.18 a
M2	30.77 ± 0.18 b
p-value	0.0015

Values are means ± standard error. Means followed by the same letter are not significantly different (Fisher's LSD test, $p<0.05$). CO: uncovered control; M1: symmetrical shading (17% on both sides); M2: asymmetrical west-side shading (50% on the west side).

Regarding air temperature (T_{air}) and relative humidity (RH), nets slightly modified the canopy microclimate during the 2017 growing season, particularly during the afternoon period (Figure 3). The most consistent effect was associated with reduced exposure to thermal extremes. During the monitoring period, CO accumulated 28.5 hours above 35 °C, whereas symmetrical (M1) and asymmetrical west-side shading (M2) treatments accumulated 21.0 and 19.5 hours, respectively (Figure 4). Repeated measures analysis during the monitoring period indicated significant differences between shaded treatments and the control. Similar thermal buffering effects under shading nets have been reported in warm viticultural regions (Van Leeuwen *et al.*, 2019; Pallotti *et al.*, 2023; Crouchett-Rojas *et al.*, 2025).

In parallel, shaded treatments exhibited higher RH values during the 2017 ripening period (Figure 3). These differences were associated with lower T_{air} and reduced incident radiation under shaded conditions. Similar responses have been reported under shading in arid and hyper-arid viticultural environments (Avenant and Avenant, 2022; Gutiérrez-Gamboa *et al.*, 2024). However, the magnitude of these effects depends on canopy architecture and net radiative transmittance, emphasizing the importance of adjusting shading intensity and spatial deployment according to local climatic conditions (Martínez-Lüscher *et al.*, 2017; Zarrouk *et al.*, 2024).

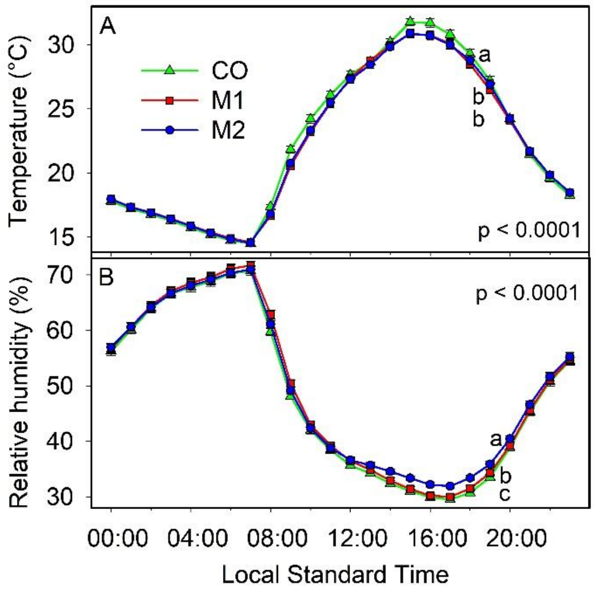

Figure 3. Diurnal course of air temperature (A) and relative humidity (B) in response to west-side shading intensity in an experimental 'Malbec' (*Vitis vinifera* L.) vineyard located in southern Mendoza, Argentina. Values are means recorded from 24/01/2017 to 06/03/2017. Bars indicate standard error. Statistical analysis of repeated measurements over time was performed using mixed linear models. Means followed by the same letter are not significantly different (Fisher's LSD test, p<0.05). CO: uncovered control; M1: symmetrical shading (17% on both sides); M2: asymmetrical west-side shading (50% on the west side).

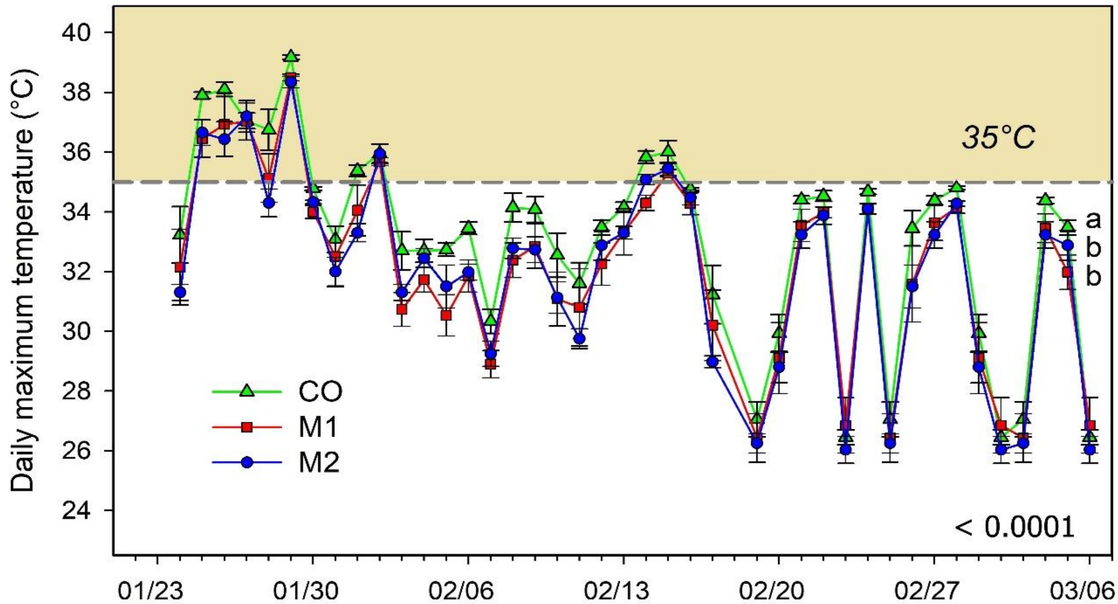

Figure 4. Daily maximum air temperature recorded within the canopy from 24/01/2017 to 06/03/2017, in response to west-side shading intensity in an experimental 'Malbec' (*Vitis vinifera* L.) vineyard located in southern Mendoza, Argentina. Bars indicate standard error. Statistical analysis of repeated measurements over time was performed using mixed linear models. Means followed by the same letter are not significantly different (Fisher's LSD test, p<0.05). CO: uncovered control; M1: symmetrical shading (17% on both sides); M2: asymmetrical west-side shading (50% on the west side).

Yield and its components: sensitivity to shading intensity

Yield components exhibited a strong interaction between treatment and season (Table III), indicating that treatment responses varied according to seasonal climatic conditions. During the first season, characterized by higher-than-average rainfall and lower thermal demand, no significant differences were found between treatments. These results suggest that the agronomic effects of shading may become more evident under conditions of high thermal and radiative stress (Tiffon-Terrade *et al.*, 2023; Crouchett-Rojas *et al.*, 2025). In contrast, within the 2017 and 2018 seasons, berry weight was higher (up to 10%) in both net treatments, although this response did not translate into significant differences in total yield.

The increase in berry size under the nets was associated with localized reductions in water loss and transpiration typically linked to west-side solar exposure, which was associated with the maintenance of cell turgor during berry expansion (Avenant and Avenant, 2022; Zarrouk *et al.*, 2024). However, M2 showed a significant reduction in cluster weight and total yield (10-14%) across the second and third seasons compared to CO and M1. This decline, despite the presence of larger berries, is consistent with a lower number of berries per cluster under the intensified shading treatment. Consequently, while moderate shading (M1) maintained yield stability across seasons, excessive radiation exclusion in M2 was associated with a reduction in productive performance (Storchi *et al.*, 2024; Reta *et al.*, 2025).

Table III

Yield components and yield in response to west-side shading intensity during the 2016, 2017 and 2018 seasons in an experimental 'Malbec' (*Vitis vinifera* L.) vineyard located in southern Mendoza, Argentina

Season (Se)	Treatment (Tr)	Berry weight (g)	Cluster weight (g)	Yield per vine (Kg)
2016	CO	1.30 ± 0.03	72.2 ± 2.1	2.689 ± 0.084
	M1	1.27 ± 0.03	74.9 ± 2.1	2.725 ± 0.084
	M2	1.26 ± 0.03	75.4 ± 2.1	2.680 ± 0.084
	p-value	0.4835	0.5143	0.9802
2017	CO	1.13 ± 0.02 b	78.6 ± 2.4 a	2.575 ± 0.081 a
	M1	1.14 ± 0.02 ab	77.5 ± 2.4 a	2.698 ± 0.081 a
	M2	1.18 ± 0.02 a	70.5 ± 2.4 b	2.208 ± 0.081 b
	p-value	0.0489	0.0431	0.0004
2018	CO	1.17 ± 0.02 b	87.3 ± 2.6 a	2.819 ± 0.072 a
	M1	1.27 ± 0.02 a	89.7 ± 2.6 a	2.913 ± 0.072 a
	M2	1.29 ± 0.02 a	76.7 ± 2.6 b	2.536 ± 0.072 b
	p-value	<0.0001	0.0024	0.0020
Se	2016	1.28 ± 0.01 a	74.2 ± 1.2 b	2.698 ± 0.042 a
	2017	1.15 ± 0.01 b	75.6 ± 1.4 b	2.494 ± 0.050 b
	2018	1.25 ± 0.01 a	84.6 ± 1.4 a	2.756 ± 0.050 a
	p-value	<0.0001	<0.0001	0.0007
Tr x Se	p-value	0.0022	0.0108	0.0497

Values are means ± standard error. Means followed by the same letter are not significantly different (Fisher's LSD test, p<0.05). CO: uncovered control; M1: symmetrical shading (17% on both sides); M2: asymmetrical west-side shading (50% on the west side).

Vegetative expression and productive balance

The increase in pruning weight and the subsequent decrease in the Ravaz Index under shaded conditions indicate a progressive shift toward greater vegetative vigor, which was particularly marked in the third season (Table IV). The significant treatment × season interaction indicates that these responses varied according to seasonal conditions. In 2017–2018, M2 reached its peak vegetative expression, representing a 29% increase over the control (p<0.0001).

This cumulative response across seasons suggests that sustained attenuation of thermal stress not only affects current-season growth, but also promotes the accumulation of perennial reserves and canopy biomass over time, as observed in other arid viticultural systems (Villalobos-Soublett *et al.*, 2021; Miccichè *et al.*, 2023).

This enhanced vigor may be associated with the reduction in incident radiation and T_{air} under shaded conditions (Avenant and Avenant, 2022; Gutiérrez-Gamboa *et al.*, 2024). However, the concomitant increase in pruning weight and decrease in the Ravaz Index under M2 indicate a shift away from an optimal vegetative–reproductive balance. The Ravaz Index values observed under M2 during 2017–2018 (≈4.4) were below the range commonly considered balanced for quality-oriented viticulture (5–10), suggesting excessive vegetative development relative to crop load (Keller, 2015; Torres *et al.*, 2020). This pattern suggests an imbalance between vegetative growth and reproductive development, a condition that may compromise both yield and quality objectives in viticulture (Van Leeuwen *et al.*, 2019; Storchi *et al.*, 2024).

Table IV

Vegetative expression and balance index in response to west-side shading intensity during the 2016, 2017 and 2018 seasons in an experimental 'Malbec' (*Vitis vinifera* L.) vineyard located in southern Mendoza, Argentina

Season (Se)	Treatment (Tr)	Pruning weight (Kg)	Ravaz Index
2016	CO	0.464 ± 0.02	6.0 ± 0.3
	M1	0.474 ± 0.02	5.9 ± 0.3
	M2	0.473 ± 0.02	5.8 ± 0.3
	p-value	0.9247	0.8368
2017	CO	0.442 ± 0.02 b	5.9 ± 0.2 a
	M1	0.481 ± 0.02 ab	5.7 ± 0.2 a
	M2	0.500 ± 0.02 a	4.4 ± 0.2 b
	p-value	0.0325	<0.0001
2018	CO	0.447 ± 0.01 c	6.3 ± 0.2 a
	M1	0.491 ± 0.01 b	6.0 ± 0.2 a
	M2	0.580 ± 0.01 a	4.4 ± 0.2 b
	p-value	<0.0001	<0.0001
Se	2016	0.470 ± 0.01 b	5.9 ± 0.1 a
	2017	0.474 ± 0.01 b	5.3 ± 0.2 b
	2018	0.506 ± 0.01 a	5.6 ± 0.2 ab
	p-value	0.039	0.0215
Tr x Se	p-value	0.0117	0.0029

Values are means ± standard error. Means followed by the same letter are not significantly different (Fisher's LSD test, p<0.05). CO: uncovered control; M1: symmetrical shading (17% on both sides); M2: asymmetrical west-side shading (50% on the west side).

Overall, the vegetative imbalance observed under intense west-side shading suggests a threshold beyond which the benefits of thermal mitigation may be constrained by reduced radiation within the fruiting zone. For 'Malbec', a cultivar particularly susceptible to the decoupling of technological and phenolic maturity, such microclimatic conditions may negatively affect berry composition and subsequent wine quality (Dominguez *et al.*, 2024; Crouchett-Rojas *et al.*, 2025). These results indicate that while west-side shading may contribute to thermal stress mitigation, excessive radiation attenuation may reduce vine balance and fruit quality, with implications for chromatic characteristics addressed in the following section (Torres *et al.*, 2020; Reta *et al.*, 2025).

Must and wine composition: Decoupling and chromatic stability

Must composition was notably influenced by shading intensity. Because the treatment × season interaction was not significant for must composition variables, treatment and season effects are presented separately in Table V. The control treatment reached the highest total soluble solids (23.6 °Brix), whereas the asymmetrical high-shading treatment (M2) exhibited a lower sugar concentration at harvest (22.8 °Brix; p=0.0156). This reduction in soluble solids, along with the lower must pH observed under both net configurations, suggests a relative decoupling between sugar accumulation and acid-base balance during ripening. This response is consistent with the warm thermal conditions observed during the study period (Table I), under which anti-hail nets attenuated extreme afternoon temperatures (>35 °C; Figure 4), potentially moderating sugar accumulation (Torres *et al.*, 2020; Gu *et al.*, 2025). As reported by Lu *et al.* (2021) and Storchi *et al.* (2024), moderate shading may prevent excessive sugar accumulation, potentially favoring a more synchronized ripening process.

Regarding wine composition, shading intensity markedly affected chromatic characteristics (Table VI). Moderate shading (M1) resulted in the highest color intensity (1.859 ± 0.115), whereas intense west-side shading (M2) caused a significant decrease. This pattern indicates that radiation exclusion beyond a critical threshold may override the benefits of thermal mitigation, as minimum light levels are required to sustain optimal chromatic development in red wines. Consistent with previous studies, excessive radiation attenuation may limit the expression of wine color charactristics derived from berry composition, resulting in reduced color intensity despite lower thermal stress, as reflected by CI and H values (Martínez-Lüscher *et al.*, 2017; Gouot *et al.*, 2019; Domanda *et al.*, 2024). Conversely, M1 appeared to provide an optimal radiation window, sufficiently high to promote color development while low enough to prevent thermally driven losses of chromatic compounds.

Table V

Must chemical composition in response to west-side shading intensity during the 2016, 2017 and 2018 seasons in an experimental 'Malbec' (*Vitis vinifera* L.) vineyard located in southern Mendoza, Argentina

		°Brix	**pH**	**TA (*)**
Treatment (Tr)	CO	23.6 ± 0.2 a	3.69 ± 0.02 a	4.12 ± 0.04
	M1	23.3 ± 0.2 ab	3.63 ± 0.02 ab	4.15 ± 0.04
	M2	22.8 ± 0.2 b	3.61 ± 0.02 b	4.25 ± 0.04
	p-value	0.0156	0.0294	0.0616
Season (Se)	2016	22.7 ± 0.2 b	3.68 ± 0.02 ab	4.17 ± 0.04
	2017	23.4 ± 0.2 a	3.65 ± 0.02 a	4.18 ± 0.04
	2018	23.5 ± 0.2 a	3.60 ± 0.02 b	4.17 ± 0.04
	p-value	0.0068	0.0385	0.9386
Tr x Se	p-value	0.1696	0.9131	0.1241

Values are means ± standard error. Means followed by the same letter are not significantly different (Fisher's LSD test, p<0.05). CO: uncovered control; M1: symmetrical shading (17% on both sides); M2: asymmetrical west-side shading (50% on the west side). TA (*): Titratable acidity, expressed as g/L of tartaric acid.

Chromatic characteristics were significantly affected by shading intensity, as reflected by changes in color intensity (CI) and hue (H) (Table VI). Moderate shading (M1) exhibited the highest CI values and maintained lower H compared to the reinforced west-side shading treatment, indicating a more intense and red-oriented chromatic profile. In contrast, the increase in H and the reduction in CI observed under intensified shading (M2) suggest a shift toward less favorable chromatic expression, consistent with light-limited conditions for color development. Similar responses have been reported under excessive shading or reduced irradiance, where color intensity decreases and hue increases despite thermal mitigation, particularly in warm-climate viticulture (Martínez-Lüscher *et al.*, 2017; Gouot *et al.*, 2019; Miccichè *et al.*, 2025). It should be noted that enological variables were evaluated only in the 2017 season, which was among the warmest years of study.

Table VI

Wine chemical composition and chromatic attributes in response to west-side shading intensity during the 2017 season in an experimental Malbec (*Vitis vinifera* L.) vineyard located in southern Mendoza, Argentina

Treatment	H	CI	pH	TA (*)	Alcohol (% v/v)
CO	0.526 ± 0.007 b	1.662 ±0.115 ab	3.80 ± 0.03 a	3.78 ± 0.02 b	13.35 ± 0.21 a
M1	0.523 ± 0.007 b	1.859 ±0.115 a	3.71 ± 0.03 b	3.87 ± 0.02 a	12.75 ± 0.21 ab
M2	0.551 ± 0.007 a	1.324 ±0.115 b	3.68 ± 0.03 b	3.89 ± 0.02 a	12.40 ± 0.21 b
p-value	0.0302	0.0266	0.0295	0.0022	0.0279

Values are means ± standard error. Means followed by the same letter are not significantly different (Fisher's LSD test, $p<0.05$). CO: uncovered control; M1: symmetrical shading (17% on both sides); M2: asymmetrical west-side shading (50% on the west side). TA (*): Total titratable acidity, expressed as g/L of tartaric acid. H: hue (A_{420} / A_{520}), CI: color intensity:(A 420 nm + A 520 nm + A 620 nm), chromatic attributes calculated according to Glories (1984).

In parallel, both shaded treatments exhibited lower wine pH and higher titratable acidity compared to the control, which may indicate a mitigation of malic acid thermal respiration, a process typically accelerated by high berry temperatures under high solar exposure. The preservation of organic acidity is particularly relevant for 'Malbec' wines, as acid balance strongly influences color expression and overall chromatic perception (Torres *et al.*, 2020; Lu *et al.*, 2021). Within this framework, M1 showed the most balanced response among the evaluated treatments, combining moderated alcohol content (12.75% v/v vs. 13.35% in CO), improved acidity retention, and enhanced chromatic attributes. Accordingly, moderate asymmetrical west-side shading may contribute to improving wine balance and typicity in arid regions, where excessive radiation often compromises color development despite advanced technological maturity (Pallotti *et al.*, 2023; Dominguez *et al.*, 2024; Crouchett-Rojas *et al.*, 2025). Enological responses should be considered within the temporal scope of the 2017 vintage.

CONCLUSIONS

Asymmetrical shading of the canopy's west side using anti-hail nets effectively buffered the vineyard microclimate against extreme ambient conditions, confirming its potential as a targeted mitigation strategy for warm-climate viticulture. Among the evaluated configurations, moderate shading (17%, M1) provided the most balanced response, maintaining yield stability while showing improved sugar–acid balance and wine chromatic characteristics during the 2017 season. This treatment was associated with moderated thermal conditions and did not promote excessive vegetative vigor, preserving a favorable vegetative–reproductive balance relative to the control.

In contrast, intensified west-side shading (50%, M2), although effective in reducing thermal extremes, was associated with higher vegetative growth and lower wine chromatic expression in 2017, suggesting that excessive radiation attenuation may compromise vine balance and color-related wine attributes under arid conditions. Nevertheless, reinforced west-side shading may represent a valuable alternative in specific situations, such as vineyards or regions characterized by recurrent high pH and low natural acidity, where stronger thermal mitigation could help preserve acid balance at the expense of reduced chromatic intensity.

Overall, this study supports the use of anti-hail nets as a multifunctional adaptation tool under warm arid viticultural conditions. Beyond their primary protective role against hail damage, these structures were associated with changes in the balance between technological and color-related ripening processes, potentially contributing to the preservation of wine typicity, natural acidity, and chromatic quality under increasing thermal pressure in arid viticultural regions.

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