DOI: https://doi.org/10.20870/oeno-one.2026.60.4.10343

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VITICULTURE ORIGINAL RESEARCH ARTICLES

Anti-hail net colour and installation system impacts on vegetative growth, yield, and berry composition (cv. Malbec)

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Article number: 10343

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Associate editor:
Roberta De Bei

Received:
14 August 2026

Accepted:
07 October 2026

Published:
29 October 2026

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ABSTRACT

Anti-hail nets are used worldwide as a physical barrier to protect grapevines from hail damage. Beyond this protective role, they also modify the vineyard microclimate. These effects are relevant in warm and arid wine-growing regions, where vineyards are frequently exposed to both hailstorms and heat stress. However, the effects of anti-hail nets on yield, growth and berry quality have been scarcely studied. This study evaluated, in San Rafael, Mendoza, Argentina, over three growing seasons (2018–2019, 2019–2020, 2020–2021), the combined effects of two anti-hail net colours (Black and Pearl) and two installation systems (Grembiule and Modified) on vegetative growth, yield components, and berry composition of *Vitis vinifera* L. cv. Malbec. Each variable was measured on one or more seasons. Results showed that under both installation systems, the Black net increased vegetative growth. Both the Black net and the Grembiule system improved yield components, with the Black–Grembiule combination increasing yield by 16 % compared with the Pearl–Grembiule treatment. At harvest, berries from vines grown under the Black net had higher titratable acidity and lower pH, whereas those from the Pearl net showed higher berry sugar. Tannin and anthocyanin concentrations were higher in berries from vines grown under the Grembiule system. In regions prone to hail events, selecting both net colour and installation system according to environmental conditions to optimise vine growth, yield, and fruit quality provides an additional tool to buffer the negative effects of climate change at the vineyard scale.

KEYWORDS: shading net, adaptation strategy, climate change, berry maturity, phenolics, vegetative growth

INTRODUCTION

Viticulture in warm and arid regions faces increasing challenges due to rising temperatures, prolonged droughts, and more frequent extreme events, such as hailstorms (Cabré & Nuñez, 2020). Hailstorms are unavoidable events that cause substantial economic losses in agricultural systems across the world. Hail damage threatens grapevine productivity, fruit quality, and vineyard sustainability. Consequently, many viticultural regions prone to hailstorms have widely adopted anti-hail nets (Kim *et al*., 2023). While primarily used for hail protection, anti-hail nets alter vineyard microclimate by modifying light transmittance and thermal conditions. The magnitude of these effects depends on both net characteristics and the installation system.

In recent years, the use of shade nets to protect vines from extremely hot and dry conditions has received increasing attention (Gutiérrez-Gamboa *et al*., 2024; Pallotti *et al*., 2023). Several studies have assessed the impact of shade nets on grapevine microclimate, water status, berry composition, and yield (Villalobos-Soublett *et al*., 2021; Jafari Burki *et al*., 2022; Miccichè *et al*., 2023). However, anti-hail nets differ from shade nets, particularly in their tissue density, radiation transmittance, spectral characteristics, and thermal properties (Pallotti *et al*., 2023). For instance, shade nets reduce incoming radiation by 30–95 %, whereas anti-hail nets generally reduce it by only 8–40 % (Crouchett-Rojas *et al*., 2025; Nahüel *et al*., 2026). Despite the widespread use of anti-hail nets over recent decades, relatively few studies have assessed their effects on grapevine performance (Salazar *et al*., 2018; Ruland *et al*., 2023; Domanda *et al*., 2024; Nahüel *et al*., 2026).

Net characteristics and installation systems determine the effects on vineyard microclimate and grapevine performance. Darker nets (*e.g.*, black) generally reduce transmittance more than lighter-coloured nets, resulting in lower canopy and berry temperatures, with reductions of approximately 1.0 °C in daily mean canopy temperature and 3.5–6.0 °C in cluster temperature. These effects improve water status and increase titratable acidity by up to 1.8 g/L (Martínez-Lüscher *et al*., 2020; Lu *et al*., 2021). In contrast, lighter-coloured nets (*e.g.*, pearl or white) allow greater light transmittance and maintain sugar accumulation close to that of uncovered vines, while effects on yield and yield components may vary with shading intensity and environmental conditions (Villalobos-Soublett *et al*., 2021; Miccichè *et al*., 2023; Domanda *et al*., 2024).

The installation system modifies vine architecture and radiation distribution within the canopy. The most widespread installation system in vertically shoot-positioned (VSP) vineyards is the Grembiule (Figure S1). In balanced vineyards or under low-vigour conditions, this system improves water status, increasing midday leaf water potential by 0.20–0.30 MPa, while decreasing canopy maximum air temperature at cluster level by up to 2.0 °C and VPD by 0.25 kPa compared with uncovered vines (Nahüel *et al*., 2026). However, a key characteristic of the Grembiule system is that the net is placed close to the canopy, limiting its expansion. In high-vigour varieties and/or environmental conditions that favour vigour, it may lead to high-density canopies and unfavourable microclimatic conditions (Ruland *et al*., 2023). To overcome this limitation, a modification has been introduced, hereafter referred to as the Modified system (Figure S1), in which the net is attached in the middle of the interrow, providing additional space for canopy development. However, a recent study showed that this modified system leads to unfavourable microclimatic conditions, with afternoon canopy air temperature up to 2.0 °C higher than in uncovered vines and higher VPD during the central hours of the day (Nahüel *et al*., 2026).

Despite the differences in canopy architecture and microclimate generated by the installation systems, few studies have evaluated their effects on vegetative growth, yield, and berry composition (Pallotti *et al*., 2023; Ruland *et al*., 2023; Domanda *et al*., 2024). Furthermore, the effects of net colour and its interaction with the installation system on vine performance remain scarcely explored. Although previous studies have evaluated anti-hail net characteristics or installation systems separately, little information is available on how both factors interact to influence vegetative growth, yield components, and berry composition, particularly under warm and arid viticultural conditions. This study aimed to evaluate the combined effect of anti-hail net colour (Black and Pearl) and installation system (Grembiule and Modified) on vegetative growth, yield components, and berry composition of *Vitis vinifera* L. cv. Malbec. This knowledge will contribute to developing viticultural strategies that optimise hail protection while adapting to other environmental constraints in warm and arid viticultural regions.

MATERIALS AND METHODS

1. Site and plant material

The experiment was carried out during three consecutive growing seasons (2018–2019; 2019–2020, and 2020–2021) in an own-rooted Malbec experimental vineyard planted in 2000 at the Experimental Station Rama Caída – National Institute of Agricultural Technology (34°39’47.62” S, 68°23’35.92” W, 724 m a.s.l.), Mendoza, Argentina. Vines were trained in a vertical shoot positioning (VSP) system and spur-pruned to 16 buds per plant. Rows were oriented north–south, with 2.5 m between rows and 1.5 m between vines. The vineyard was drip-irrigated with 1.6 L h^{-1} emitters spaced at 0.75 m. Fertilisation and irrigation programs were the same for all treatments.

Meteorological data, including temperature, relative humidity and precipitation, were registered with an automatic weather station (THP 933, Nimbus, Argentina) located close to the vineyard. Based on these data, Huglin’s Heliothermal Index (HI; Huglin, 1978), the Winkler Index (WI; Amerine & Winkler, 1944) and the Cool Night Index (CI; Tonietto & Carbonneau, 2004) were calculated and compared with historical values comprising more than 70 years. The WI and

HI were calculated using a base temperature of 10 °C for the period from 1 October to 30 April and expressed as °C days (Cabré *et al*., 2016). For HI, a latitude coefficient of d = 1.00 was used, whereas CI was calculated as the mean minimum air temperature during March (Tonietto & Carbonneau, 2004). Historical records classify the region as region III according to the WI, warm (HI +2), and with very cool nights (CI +2; Cabré *et al*., 2016; Tonietto & Carbonneau, 2004).

2. Experimental design and treatments

The experiment consisted of the combination of two anti-hail net colours (Black and Pearl), with two installation systems (Grembiule and Modified) and a control without protection, resulting in five treatments: Black–Grembiule (BG), Pearl–Grembiule (PG), Black–Modified (BM), Pearl–Modified (PM), and control (CO) plants. The experiment followed a completely randomised block design with five replicates, using the winter pruning weight measured prior to the start of the first experimental season as the blocking factor. Each replicate consisted of 15 vines distributed across three adjacent rows (five consecutive vines per row), totalling 75 vines per treatment. Measurements were performed on the three central vines of each experimental unit.

Both anti-hail nets (AgriNet, Mendoza, Argentina) were fabricated with UV-stabilized high-density polyethylene. The nets consisted of cylindrical monofilament woven in a leno pattern with orthogonal warp and weft yarns, a mesh aperture of 3.5 × 7 mm and 2.6 yarns cm^{-1} in both directions. The light transmission characteristics of each net are described in Nahüel *et al.* (2026), with incident PAR reduced by approximately 37 % and 11 % under the Black and Pearl nets, respectively. In the Grembiule system, the net was placed over the canopy on both sides of the VSP and supported by metal separators of 0.40 and 0.65 m at the upper and lower positions, respectively, with lateral wires used to support and tension the lower part of the net. In the Modified system, metal separators and lateral wires were not used; instead, the nets from adjacent rows extended toward the middle of the interrow and were joined by metal tensioners approximately 0.65 m long (Figure S1). In the Grembiule system, the nets allow all operations to be performed and remain permanently installed throughout the whole season; they are only laid down before mechanical harvest and pruning. Whereas in the Modified system, the net was automatically lifted when the machinery passed by a system of metallic bars that were coupled to the tractor (Figure S2). Similarly to the Grembiule, the nets are only laid down for harvest and pruning.

Each season, all treatments were harvested on the same day when control grapes reached between 23 and 24 °Brix. The effects of treatments on canopy microclimate (*i.e.*, air temperature, relative humidity, VPD, wind speed, and radiation) and leaf water potential were evaluated through the entire season from budburst to harvest. Here, we present the daily evolution of these variables for flowering, veraison, and harvest. The methodology and sensors used to characterise canopy microclimate have previously been reported in detail (Nahüel *et al.*, 2026).

3. Carbon isotope discrimination

Carbon isotope composition ($\delta^{13}C$) was determined in leaves and berries at the end of the cycle as an estimate of intrinsic water use efficiency (van Leeuwen *et al.*, 2009). During the 2019–2020 season, berry $\delta^{13}C$ was determined from a composite sample of 50 berries randomly collected on the central vines of each experimental unit immediately before harvest. During the 2020–2021 season, four fully expanded leaves per experimental unit (two from each canopy side) were collected at harvest. Samples were oven-dried at 55 °C until constant weight (3 and 8 days for leaves and berries, respectively) and ground to a fine powder using an analytical mill (IKA® A11 basic, IKA Werke GmbH & Co. KG, Germany). Approximately 3.0 mg ± 0.5 of sample was weighed into tin capsules (6 × 4 mm). Carbon isotope composition was determined relative to the V-PDB standard using an isotope ratio mass spectrometer (Thermo Scientific DELTA V coupled via ConFlo IV to a Flash 2000 elemental analyzer) with an analytical precision of ±0.1 ‰.

4. Vegetative growth

Shoot length was measured in 2019–2020 on two shoots emerging from a randomly selected spur on the central plant of each replicate. Shoots were measured twice a week from budburst to mid-December when shoots were trimmed. Total leaf area (TLA) was measured in 2018–2019 and in 2019–2020 on one plant per replicate. The selected vine was completely defoliated after harvest and before leaf fall. The primary and secondary leaves were separated and measured by placing them without overlapping on a white surface and capturing them with a digital image (Bustos Morgani *et al.*, 2022). Images were analysed with CobCal ®v2.1 software (Ferrari *et al.*, 2009) to estimate the total leaf area. Pruning weight and shoot number were recorded during winter each season. Single shoot weight was calculated by dividing pruning weight by shoot number.

5. Yield components, vine balance, and berry primary composition

Before bloom, two primary basal inflorescences per replicate were selected, tagged, and enclosed in tulle bags until pea-size stage (stage 31 of the modified Eicchorn and Lorenz scale; Coombe, 1995). After fruit set, bags were removed and calyptras counted to estimate the number of flowers per inflorescence. The number of berries per bunch was registered on the same tagged basal bunches before harvest, and the percentage of berry set was calculated (Keller *et al.*, 2010). From veraison (stage 35) to harvest, 50 berries per replicate were randomly sampled every ten days to follow berry weight and maturity. Berries were weighed and then crushed by hand to measure total soluble solids (TSS) concentration with a refractometer (PAL-1, ATAGO, Tokyo, Japan), pH with a pH meter (pH330, WTW, Weilheim, Germany) and total acidity (TA) by acid-base titration. At harvest, the number of clusters per plant and yield per plant were registered and whole-vine average cluster weight was calculated across all harvested clusters (incorporating both basal and distal clusters on primary shoots). Ravaz Index (RI) and leaf-to-fruit ratio (LFR) were calculated to estimate vine balance.

6. Berry secondary metabolite composition

At harvest, 50 berries per replicate were sampled and stored at –18 °C until analysis. The skins of the 50 berries were manually separated, washed with water, dried with filter paper, weighed, and lyophilised for 24 h (Biobase BK-FD10P, Shandong, China). Then, freeze-dried skins were ground to a fine powder using a household electric grinder (Atma, MC8141N, Buenos Aires, Argentina). The extraction method proposed by Pérez-Navarro *et al.* (2019) was followed. Briefly, 1 g of skin powder was sampled, and 25 mL of a solvent mixture of $CH_3OH/H_2O/HCOOH$ (50:48.5:1.5 *v/v/v*) was added. The extraction was carried out by sonication for 15 min at 10 °C (Cole-Parmer 8891, Vernon, Hills, USA) and then centrifuged for 5 min at 5000 rpm and 5 °C (Sorvall SS-3 Automatic Centrifuge, DuPont Inst., CT, USA). The supernatant liquid was separated, and a second extraction was performed over the pellet. Both supernatants were combined and stored at –20 °C until analysis. The extract was centrifuged (11,000 g, 5 min) in a microcentrifuge (Model 134 D, Gelec, Buenos Aires, Argentina) and used for analysis. Absorbance was measured with a UV–Visible Spectrophotometer (Lambda 25; PerkinElmer, Hartford, CT, USA). Tannins and anthocyanins were quantified following the methods described by Harbertson *et al*. (2002). Tannins were determined by protein precipitation and expressed as milligrams of (+)-catechin equivalents per gram of dry skin, whereas anthocyanins were determined by the pH differential method and expressed as milligrams of malvidin-3-glucoside equivalents per gram of dry skin.

7. Statistical analysis

Data were analysed using linear mixed-effects models by statistical software (InfoStat 2020, National University of Córdoba, Córdoba, Argentina). Model assumptions were verified by inspecting residuals for normality and homogeneity of variance. Net colour, installation system, time, and interactions were treated as fixed effects, whereas blocks were considered random effects. Whenever the interaction between net colour and installation system was significant, treatment means were compared by Fisher's least significant difference (LSD) test ($p \leq 0.05$). When this interaction was not significant, the main effects were analysed and subsequently compared with the uncovered control using the same procedure. For repeated-measures analyses, replicate was included as a random effect to account for within-subject correlation. Shoot length was analysed as a function of days after budbreak, including treatments, their interaction as fixed effects and blocks as a covariate. Complementarily, to assess differences in berry weight at harvest between each treatment and the control, orthogonal contrast analysis by a linear mixed model was used (Di Rienzo *et al.*, 2017). Regressions between TSS and pH, and between GDD and sugar per berry, were fit using a sigmoidal model, whereas a regression between TSS and TA was fit with an exponential decay function. Regressions were performed with TableCurve2D (Version 5.01, Systat Software Inc. 2002).

RESULTS

1. Meteorological and microclimatic conditions

Relative to the historical climatic classification described for the study region, the three growing seasons presented higher values of WI, HI, maximum and minimum temperatures than the historical mean. In the 2019–2020 and 2020–2021 growing seasons, the warmer thermal conditions were reflected in the viticultural climate classes HI +3 (very warm) and CI +1 (cool nights), respectively (Table 1). Annual rainfall was lower than the historical average in the 2018–2019 and 2019–2020 seasons, but higher in 2020–2021 (Table 1). During the growing season (from October to April), the minimum mean temperature ranged between 11.2 and 11.8 °C, the maximum mean temperature between 29.0 and 30.2 °C, and the average temperature between 20.0 and 20.8 °C. Although the historical WI (1,939 °C days) places the region in Winkler Region III, all three experimental seasons accumulated between 2,111 and 2,301 °C days, corresponding to Winkler Regions IV and V (Table 1).

The daily evolution of canopy microclimate and vine water status showed different responses to net colour and installation system across phenological stages (Figure 1). PPFD inside the canopy was lower under Black than Pearl nets, with reductions of approximately 30 % and 27 %, respectively, relative to the control. Canopy air temperature was mainly affected by the installation system, with Grembiule reducing maximum air temperature by up to 1.06 °C compared to control vines. In contrast, the Modified system increased afternoon air temperature by up to 2.0 °C relative to the control. Similarly, Grembiule reduced VPD_{max} by 5.5–9.4 % compared with the control, while the Modified system showed higher VPD during the central hours of the day. Midday leaf water potential also showed less negative values under Grembiule than the control, whereas the Black net also showed higher values than control vines at veraison. At harvest, midday leaf water potential was similar between Black and Pearl nets and higher than control.

TABLE 1. Maximum (T_{max}), mean (T_{mean}) and minimum temperature (T_{min}), Huglin Index (HI), cool night index (CI), Winkler Index (WI), and rainfall during the three growing seasons (from October to April). San Rafael, Mendoza.

Season	T_{max} (°C)	T_{min} (°C)	T_{mean} (°C)	HI	CI	WI (°C d)	Rainfall (mm)
2018–2019	29.0	11.2	20.0	2959	9.8	2111	184
2019–2020	30.0	11.6	20.8	3161	13.7	2301	76
2020–2021	30.2	11.8	20.2	3083	12.4	2184	435
Historical mean (1950–2021)	27.6	10.7	19.2	2745	10.9	1939	262

2. Carbon isotope discrimination

No interaction between net colour and installation system was found for berry (p = 0.366) or leaf (p = 0.5772) carbon isotopic composition ($\delta^{13}C$). During 2019–2020, berry $\delta^{13}C$ was only affected by net colour (Figure 2b), while no effect of installation system was observed (Figure 2a). Pearl net presented a higher value than Black net, while control vines showed an intermediate value. In 2020–2021, leaf $\delta^{13}C$ was affected by both net colour and installation system (Figures 2c and 2d). According to the results obtained in the previous season in berries, leaves under Pearl net showed less negative $\delta^{13}C$ values (–26.45 ‰) than those under Black net (–27.10 ‰), and control vines were intermediate and did not differ significantly between net colours. Regarding the installation system, leaves under the Modified system showed a higher value (–26.55 ‰) than the Grembiule system (–27.00 ‰). Pearl net showed higher $\delta^{13}C$ values in berries during 2019–2020 and leaves during 2020–2021, while the Modified system exhibited higher $\delta^{13}C$ values in leaves in the 2020–2021 season.

3. Vegetative growth

All anti-hail treatments increased shoot growth compared to control plants. By the time of shoot trimming, shoot length and growth rate were higher in the plants under BM treatment, followed by BG, PG, and PM treatments, while the control vines showed the shortest shoots (Figure 3). Final shoot length was increased by about 31 % by Black net compared to control (0.98 *vs* 0.75 m) and 23 % above the Pearl net (0.80 m) (Table 2). Net colour affected total leaf area (TLA) and primary leaf area (PLA) independently of the installation system, while secondary leaf area was unaffected (Table 2). TLA under the Black net was 30 % above the control (4.85 *vs* 3.72 m^2) and 14 % above the Pearl net (4.20 m^2). PLA under the Black net was 29 % above the control (3.89 *vs* 3.01 m^2) and 17 % above Pearl (3.31 m^2). No differences were observed between the two installation systems on TLA or PLA.

An interaction between net colour and installation system was found for pruning and shoot weight (Table 2). The BM treatment showed the highest pruning and shoot weight, whereas PM and BG were intermediate, and PG did not differ from the control for pruning weight. Pruning weight increased in BM by 41 % and by 16 % in PM and BG treatments compared to the control. Single shoot weight increased in BM by 38 % and by 12 % to 17 % in BG, PG, and PM compared to the control.

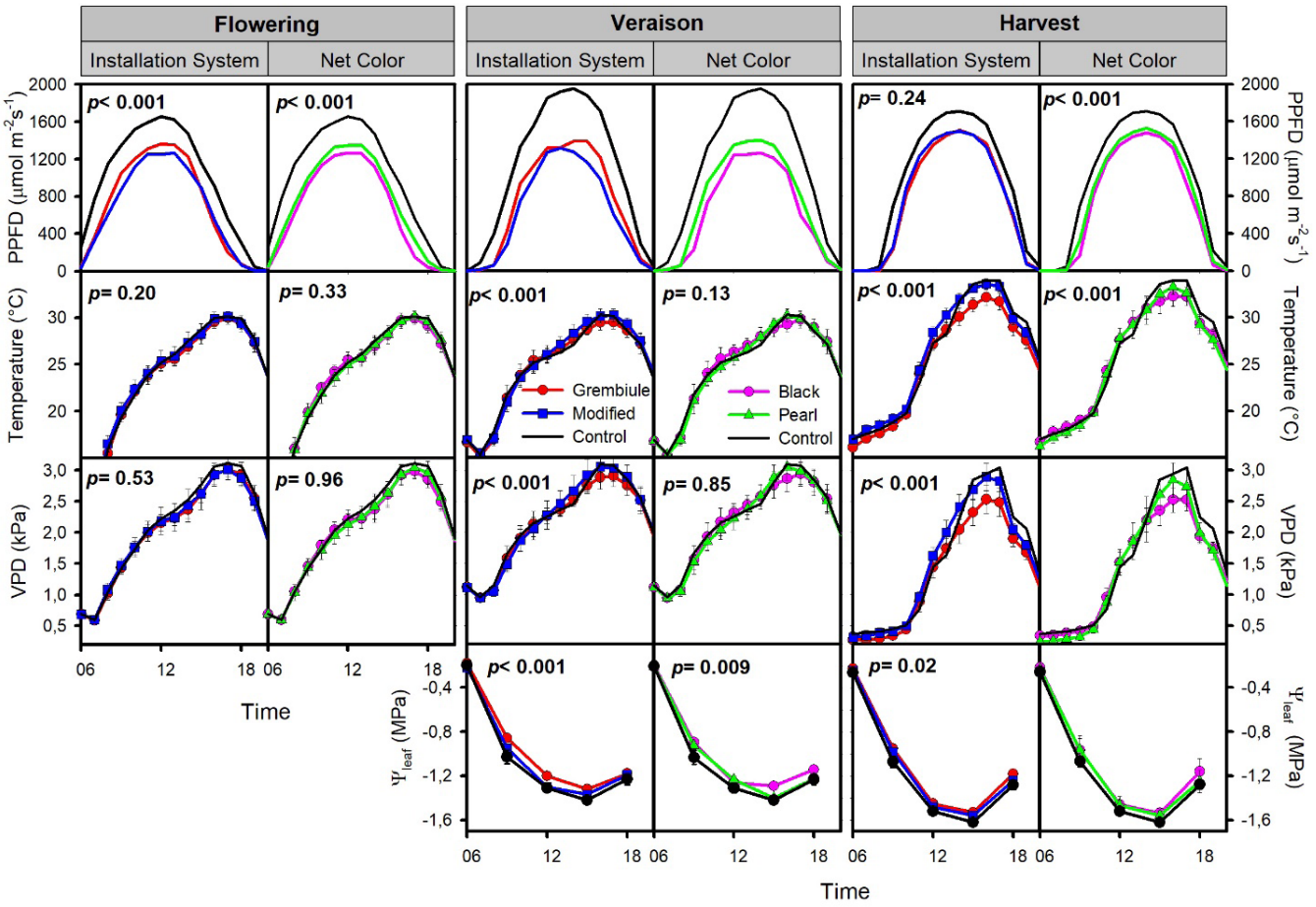


FIGURE 1. Evolution of photosynthetic photon flux density (PPFD), air temperature, and VPD measured at canopy level and leaf water potential for three main phenological stages in Malbec control vines (CO), under two anti-hail net colours (Black or Pearl), and with two installation systems (Grembiule and Modified).

4. Yield components and vine balance

For variables evaluated at harvest involving yield and its related indices (bunch weight, total yield, and Ravaz index), control values are based on the first two seasons only. The third season was excluded from statistical comparisons involving the control because a severe hailstorm occurred days prior to harvest, causing total yield loss in uncovered vines.

A simple effect of net colour and installation system was observed for the number of flowers per inflorescence and the number of berries per bunch (Table 3). Black net showed 9.6 % more flowers per inflorescence and 14 % more berries per bunch than Pearl, whereas control vines showed intermediate values. Similarly, the Modified system showed 9 % more flowers per inflorescence and 13.7 % fewer berries per bunch than the Grembiule system, whereas control vines showed intermediate values. Fruitset was affected by the interaction between net colour and installation system. The BG and PM treatments showed 10 % higher fruitset than PG (Table 3). The number of bunches per shoot and bunches per vine was similar between BG and control, which showed 5–10 % higher than the remaining treatments. Black net increased bunch weight compared to Pearl net, whereas no statistical comparison with the control was performed for this variable. The installation system had no effect (Table 3). Berry weight at harvest was not affected by the treatments (Table 3). The berry number and berry weight recorded on tagged basal inflorescences were therefore not directly comparable with the whole-vine average bunch weight measured at harvest. However, when analysing the evolution of berry weight from veraison, a significant interaction was found (Figure S3). We observed that BM, PM, and PG showed higher berry

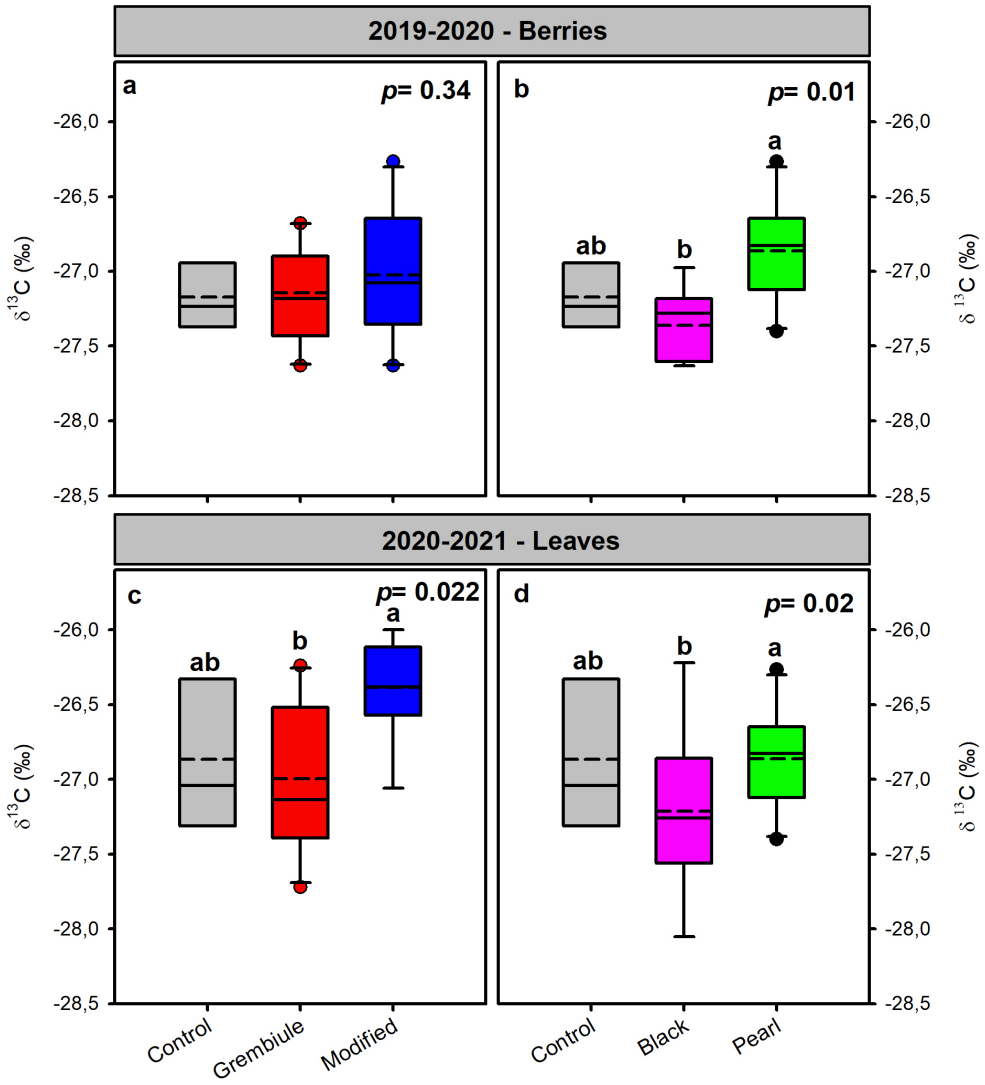


FIGURE 2. Carbon isotope composition ($\delta^{13}C$) in Malbec berries (a and b) and leaves (c and d) of control vines and vines grown under anti-hail nets colours (Black and Pearl) and installation systems (Grembiule and Modified) during the 2019–2020 and 2020–2021 growing seasons in Mendoza, Argentina. Box plots represent the 25th and 75th percentiles; the solid horizontal line represents the median, and the dashed line represents the mean value. Points show the outliers, and whiskers show the 5th and 95th percentiles. Within each factor, different letters indicate significant differences according to Fisher's LSD test ($p < 0.05$).

weight during maturity than BG and control vines. This was confirmed with orthogonal contrast analysis, which showed a 6 % increase in berry weight in PG, BM, and PM compared to the control (Table S1). No difference in berry weight was observed between BG and control.

An interaction was found between net colour and installation system for yield (Table 3). Plants under BG presented higher yield than BM, PM and PG. Control plants were excluded from the overall comparison for yield because of complete yield loss in the third season. The Ravaz index (RI) was affected by the interaction between net colour and installation system. BM reduced RI by 14 % compared with PG and by 23 % compared with BG, whereas no statistical comparison with the control was performed because the control was excluded from the overall comparison (Table 3). Finally, the leaf-to-fruit ratio was only affected by net colour, with no effect of the installation system. LFR in Black net was 19 % above the control and 13 % above Pearl.

5. Berry chemical composition

No interaction was found between net colour and installation system for berry chemical composition. The net colour affected the concentration of TSS, pH, TA, and sugar per berry at harvest, while no effect of installation system was observed on those variables (Table 4). Vines under the Black net showed lower values of TSS during maturity in the three seasons compared to Pearl net and control (Figures S3D, S3E, S3F). This was confirmed at harvest, when the Pearl net showed the highest TSS, the Black net the lowest, and the control intermediate values (Table 4). Accordingly, during the three seasons we observed that the Black net showed lower increases in sugar per berry than the Pearl net and the control (Figure 4A). Sugar per berry under the Pearl net was 7 % higher than the control and 5 % higher than the Black net (Table 4).

Total acidity (TA) evolution was also affected by net colour. We observed a slight decrease in TA under Black net compared to the control across the three seasons, while the

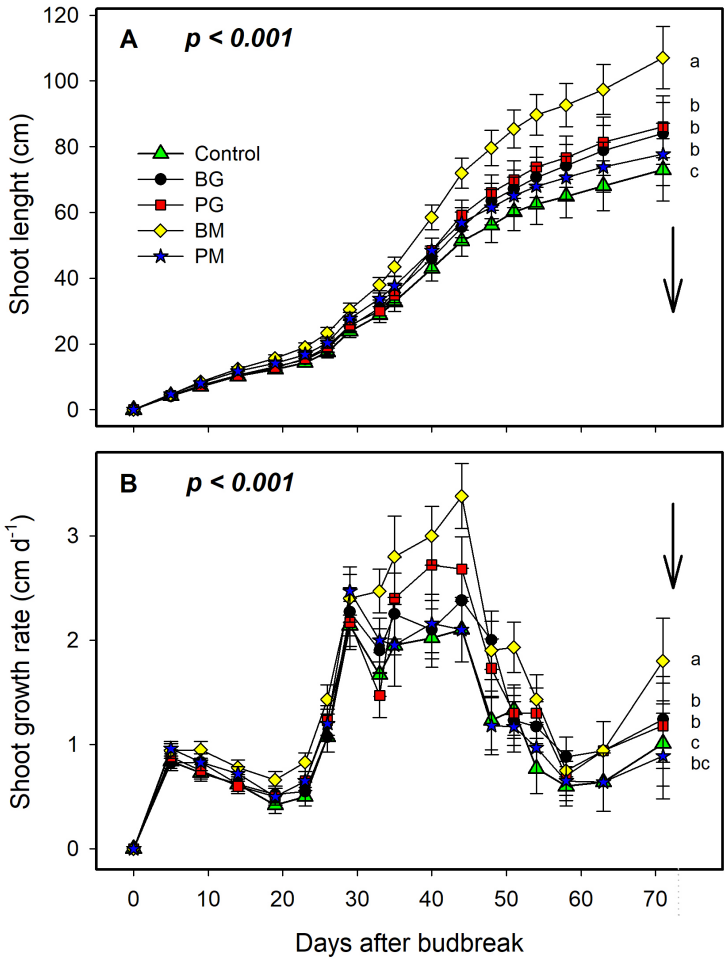


FIGURE 3. Seasonal evolution (2019–2020) of shoot length (A) and shoot growth rate (B) of Malbec vines under different anti-hail net colours (Black and Pearl), installation systems (Grembiule and Modified) and uncovered control plants (CO): Black-Grembiule (BG), Pearl-Grembiule (PG), Black-Modified (BM), and Pearl-Modified (PM). The arrow indicates the moment of shoot trimming. Different letters indicate statistically significant differences between treatments at $p \leq 0.05$ (Fisher test).

Pearl net was intermediate (Figure 4B). This was reflected at harvest when the Black net showed a 12.7 % higher TA than control vines (4.69 *vs* 4.16 g L^{-1}) and 6.6 % above Pearl (4.40 g L^{-1}) (Table 4). We observed a delay in the pH increase under both colours across the three seasons evaluated. Under the Black net, the pH increase was slower than the control, while the Pearl net was intermediate (Figure 4C). At harvest, the pH was 0.05 and 0.03 lower under Black and Pearl nets, respectively, compared to control vines (Table 4).

Total tannin concentration in berry skins at harvest was affected by the interaction of net colour and installation system. However, anthocyanins were only affected by the installation system (Table 4). We observed that PG showed the highest concentration of total tannins, followed by BG. In contrast, BM and PM resulted in lower total tannin levels, similar to the control. Specifically, BG and PG treatments increased total tannins in berry skin by 20 % and 41 %, respectively (Table 4). Similar results were observed regarding anthocyanins, which were higher in the Grembiule system, followed by the Modified system, while the control plants showed the lowest value. The Grembiule system led to a 48 % increase in total anthocyanins, while the Modified system resulted in a 16 % increase (Table 4). Expressing tannins and anthocyanins on a per-berry basis yielded the same statistical pattern as the analysis based on concentrations expressed per gram of skin.

DISCUSSION

The use of anti-hail nets is an adaptive strategy in regions prone to hail damage. This study explored the impact of anti-hail net colour and installation system on the vegetative development, yield components, and berry composition of *Vitis vinifera* L. cv. Malbec grapes under warm and dry climatic conditions.

1. Black net and Grembiule system were associated with improved water status and increased vegetative growth

The differences in $\delta^{13}C$ indicate adjustments in intrinsic water-use efficiency (WUE_i) among treatments. Carbon isotope composition integrates the balance between net carbon assimilation and stomatal conductance over time (Medrano *et al*., 2015; Santesteban *et al*., 2015) and has been widely validated as an indicator of whole-season WUE_i (Bchir *et al*., 2016) and vine water status (Gaudillère *et al*., 2002; Spangenberg *et al*., 2020). The lower $\delta^{13}C$ values recorded under the Black net and the Grembiule system indicate a less water-demanding environment, as shown by the higher leaf water potential (Figure 1), lower canopy VPD, air temperature, and water stress integral during the whole season (Nahüel *et al*., 2026). During the three seasons, irrigation was managed to provide non-limiting water conditions, as reflected by $\delta^{13}C$ values, which

TABLE 2. Primary (PLA), secondary (SLA) and total leaf area (TLA), shoot length, pruning, and shoot weight for Malbec plants under two different anti-hail net colours (Black and Pearl) and two installation systems (Grembiule and Modified) and uncovered control plants (CO). Within each factor and season, different letters indicate significant differences ($p < 0.05$).

		PLA (m^2)	SLA (m^2)	TLA (m^2)	Shoot length (m)	Pruning wt. (g)	Shoot wt. (g)
Colour (C)	Black	3.89 ± 0.13 a	0.96 ± 0.06	4.85 ± 0.15 a	0.98 ± 0.04 a	-	-
	Pearl	3.31 ± 0.13 b	0.89 ± 0.06	4.20 ± 0.15 b	0.80 ± 0.04 b	-	-
	CO	3.01 ± 0.16 b	0.71 ± 0.07	3.72 ± 0.20 b	0.75 ± 0.05 b	-	-
	p-value	**0.002**	0.415	**0.005**	**0.004**	-	-
System (Sys)	Grembiule	3.48 ± 0.13	0.88 ± 0.06	4.35 ± 0.15	0.85 ± 0.04	-	-
	Modified	3.73 ± 0.13	0.97 ± 0.06	4.70 ± 0.15	0.93 ± 0.04	-	-
	CO	3.01 ± 0.16	0.71 ± 0.07	3.72 ± 0.20	0.75 ± 0.05	-	-
	p-value	0.169	0.272	0.126	0.187	-	-
Interaction (C × Sy)	CO	-	-	-	-	378 ± 21 c	22.4 ± 1 c
	BG	-	-	-	-	441 ± 21 b	25.9 ± 1 b
	PG	-	-	-	-	420 ± 21 bc	25.2 ± 1 b
	BM	-	-	-	-	534 ± 21 a	30.9 ± 1 a
	PM	-	-	-	-	440 ± 21 b	26.2 ± 1 b
	p-value	0.515	0.523	0.440	0.664	**0.034**	**0.025**
Season (Se)	2018–2019	3.47 ± 0.13	0.4 ± 0.06 b	3.9 ± 0.15 b	0.7 ± 0.04 b	485 ± 24 a	25.5 ± 1 b
	2019–2020	3.49 ± 0.13	1.3 ± 0.06 a	4.7 ± 0.15 a	1.0 ± 0.04 a	496 ± 22 a	31.0 ± 1 a
	2020–2021	nd	Nd	Nd	nd	394 ± 18 b	24.6 ± 1 b
	p-value	0.905	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Interactions	***p-value***	0.244*	0.470***	0.462*	0.406*	0.441***	0.150***

Values are means ± SE. Sample size was n = 10 for PLA, SLA, TLA, and shoot length (5 replicates × 2 seasons), and n = 15 for pruning weight and shoot weight (5 replicates × 3 seasons). Interaction *p*-values refer to the relevant interaction for each variable (* C × Se; ** Sy × Se; *** C × Sy × Se).

TABLE 3. Yield and yield components, Ravaz Index, and leaf area to fruit ratio (LFR) of Malbec plants under different anti-hail net colours (Black and Pearl), installation systems (Grembiule and Modified), and uncovered control vines (CO). Main effects and their interactions are presented when significant. Within each factor and season, significant differences are indicated by different letters ($p < 0.05$).

		Flowers per inflorescence	Fruitset (%)	Berries per bunch	Berry weight (g)	Bunch weight (g)	Bunches per shoot	Bunches per vine	Yield (kg)	Ravaz Index	LFR (m^2 kg^{-1})
Colour (C)	Black	229 ± 7.8 a	-	107 ± 4.8 a	1.33 ± 0.01	86.68 ± 0.81 a	-	-	-	-	1.67 ± 0.05 a
	Pearl	209 ± 7.8 b	-	94 ± 4.8 b	1.35 ± 0.01	83.78 ± 0.81 b	-	-	-	-	1.48 ± 0.05 b
	CO	222 ± 8.6 ab	-	106 ± 5.6 ab	1.27 ± 0.02	81.47 ± 1.60	-	-	-	-	1.40 ± 0.07 b
	p-value	**0.016**	-	**0.010**	0.168	**0.005**	-	-	-	-	**0.014**
System (Sy)	Grembiule	210 ± 7.8 b	-	107 ± 4.8 a	1.33 ± 0.01	85.58 ± 0.81	-	-	-	-	1.57 ± 0.05
	Modified	229 ± 7.8 a	-	94 ± 4.8 b	1.34 ± 0.01	84.88 ± 0.81	-	-	-	-	1.58 ± 0.05
	CO	222 ± 8.8 ab	-	106 ± 5.6 ab	1.27 ± 0.02	81.47 ± 1.60	-	-	-	-	1.40 ± 0.07
	p-value	**0.022**	-	**0.011**	0.454	0.503	-	-	-	-	0.856
Interaction (C × Sy)	CO	-	47.5 ± 1.9 ab	-	-	-	1.93 ± 0.03 a	32.5 ± 0.56 a	2.80 ± 0.08	6.9 ± 0.4	-
	BG	-	47.6 ± 1.9 a	-	-	-	1.98 ± 0.03 a	33.4 ± 0.56 a	2.88 ± 0.06 a	7.0 ± 0.3 a	-
	PG	-	42.7 ± 1.9 b	-	-	-	1.80 ± 0.03 b	29.9 ± 0.56 b	2.50 ± 0.06 c	6.3 ± 0.3 a	-
	BM	-	46.1 ± 1.9 ab	-	-	-	1.80 ± 0.03 b	30.9 ± 0.56 b	2.68 ± 0.06 b	5.4 ± 0.3 b	-
	PM	-	47.8 ± 1.9 a	-	-	-	1.80 ± 0.03 b	30.0 ± 0.56 b	2.53 ± 0.06 bc	6.4 ± 0.3 a	-
	p-value	0.503	**0.007**	0.132	0.356	0.894	**0.007**	**0.022**	**0.028**	**0.001**	0.814
Season (Se)	2018–2019	nd	nd	nd	1.33 ± 0.02	79.05 ± 0.96 b	1.77 ± 0.03 b	32.9 ± 0.43 a	2.61 ± 0.04 b	5.9 ± 0.3	1.39 ± 0.05 b
	2019-2020	205 ± 7.8 b	50.7 ± 1.7 a	103 ± 4.8	1.35 ± 0.02	91.38 ± 0.96 a	2.00 ± 0.03 a	32.0 ± 0.43 a	2.88 ± 0.04 a	6.4 ± 0.3	1.76 ± 0.05 a
	2020–2021	233 ± 7.8 a	41.4 ± 0.8 b	96.9 ± 4.8	1.33 ± 0.02	85.25 ± 0.96 b	1.82 ± 0.03 b	29.0 ± 0.43 b	2.31 ± 0.22 c	6.5 ± 0.3	nd
	p-value	**0.001**	**<0.0001**	0.190	0.535	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**	0.168	**<0.0001**
Interaction	***p-value***	0.020* / 0.877**	0.724 ***	0.137* / 0.320**	0.971***	0,168 *	0.299 ***	0.473 ***	0.348 ***	0.313 ***	0.029 *

Values are means ± SE. Sample size was n = 20 for flowers per inflorescence, fruitset and berries per bunch; n = 15 for berry weight, bunch weight, bunches per shoot, bunches per vine, yield, and Ravaz Index; and n = 10 for LFR. Control values for bunch weight, yield, and Ravaz Index correspond to the first two seasons only. Interaction *p*-values refer to the relevant interaction for each variable (* C × Se; ** Sy × Se; *** C × Sy × Se).

were within the range corresponding to no water stress (van Leeuwen *et al.*, 2023). Despite the differences in $\delta^{13}C$ being relatively small (*i.e.*, around 0.6 ‰), they were enough to illustrate the changes produced by treatments in water status according to microclimate conditions.

Pruning weight increased under most of the protection treatments, except for the Pearl-Grembiule treatment (PG). The greatest increase was observed in BM, where pruning weight was 41 % higher than the control. Specifically, a greater primary and total leaf area and shoot length were observed in plants under Black net, regardless of the installation system, with increases of 29 %, 30 %, and 31 %, respectively, compared with the control. This enhanced vegetative growth is related to the vine water status, reflected by lower values of $\delta^{13}C$ (Figure 2) and higher values of leaf water potential under Black nets and the Grembiule system (Nahüel *et al.*, 2026). Furthermore, as detailed previously, Black nets significantly reduced incident solar radiation and air temperature at the canopy level, reducing evapotranspiration and increasing leaf water potential, which is consistent with other studies using shade nets (Caravia *et al.*, 2016; Greer *et al.*, 2010; Villalobos-Soublett *et al.*, 2021; Avenant & Avenant, 2022; Jafari Burki *et al.*, 2022). In addition, the enhanced vegetative growth might suggest an acclimation to lower incident radiation, which would be reflected by a higher internode elongation and individual leaf area (González *et al.*, 2019).

Other studies have reported a decrease in pruning weight under anti-hail nets with a higher degree of shade (Ruland *et al.*, 2023). Such discrepancies highlight that the vine's physiological response to netting depends on the environmental conditions. For instance, in warm and dry regions, the effects of nets reducing heat and water stress may outweigh any negative impacts associated with light reduction (van Leeuwen *et al.*, 2019). Furthermore, studies with shading nets have shown that the effects on vegetative growth depend on both the shading percentage and net colour (Salazar *et al.*, 2018; Villalobos-Soublett *et al.*, 2021; Jafari Burki *et al.*, 2022). The use of Black net appears to be adequate for warm and dry conditions, with limited water availability for irrigation. However, under more humid and non-limiting water conditions, it could lead to excess vigour and canopy density. Our values of pruning weight, individual shoot weight, and balance indexes were within the ranges that could be considered optimal, indicating moderate and controlled vigour. This suggests that in arid environments, Black anti-hail nets and the Grembiule system improve vine water status without inducing excessive vegetative growth (Nahüel *et al.*, 2026).

2. Black net and Grembiule system increased yield under moderate vine vigour

It is interesting to note that during the third season, a hailstorm occurred on February 26, 2021, generating 100 % yield loss in control vines while no damage was observed in the rest of the treatments. Independently of the system or net colour used, the use of nets is essential to ensure yield in regions prone to hail like the one in the present study. Growers usually associate the use of Black net and the Grembiule system with excessive canopy shading, a reduction in yield due to lower bud fertility, number of flowers per inflorescence and berries per bunch. Contrary to these expectations, in this study, the combination of both, Black net and Grembiule system (BG), resulted in a higher yield, mainly due to the increased number of bunches per shoot and vine. This contrasts with previous results for Malbec, where netting reduced bunch number and yield (Ruland *et al.*, 2023). The Black net resulted in more flowers per inflorescence, berries per bunch and bunch weight than the Pearl net. This unexpected outcome suggests that the microclimatic modifications induced by the Black net, particularly the reduction in air temperature and water stress during critical reproductive development stages (Nahüel *et al.*, 2026), may have compensated for any potential negative effects of light reduction on flower induction and fruit set (Gutiérrez-Gamboa *et al.*, 2024). These results indicate that, under moderate vine vigour, Black net did not compromise yield formation.

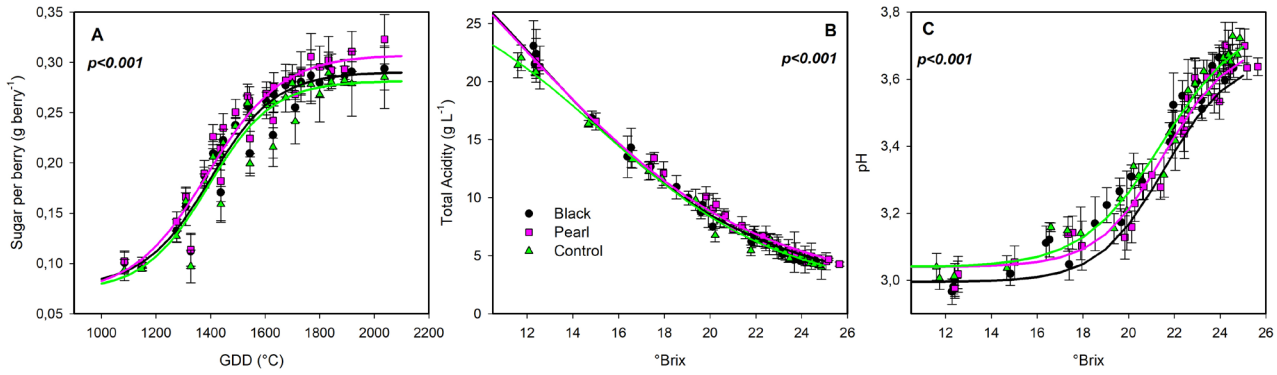


FIGURE 4. Evolution of sugar per berry (A) as a function of growing degree days (GDD), and evolution of total acidity (B) and pH (C) as a function of total soluble solids (TSS) for Malbec plants without net protection (Control), Black and Pearl nets. Each point is the mean of 5 replicates ± standard deviation. One regression was fit for all seasons (2018–2019; 2019–2020; 2020–2021) simultaneously.

The installation system significantly affected the yield components. The Modified system showed more flowers per inflorescence than the Grembiule, suggesting that after budbreak and during early spring, a more open canopy might improve flower induction and formation. By contrast, Grembiule system promoted a higher fruit set, berry number per bunch, and yield than the Modified system and control. This enhanced performance likely resulted from reduced air temperature, VPD, and water stress integral (Nahüel *et al*., 2026). These conditions might have reduced inflorescence temperature during flowering and fruit set, which can favour pollen viability and fertilisation (Keller *et al*., 2010; Salazar *et al*., 2018; Pallotti *et al*., 2023; Gutiérrez-Gamboa *et al*., 2024), improved assimilate allocation, and promoted greater berry retention (Ghiglieno *et al*., 2020; Basile *et al*., 2015). Furthermore, shading could improve yield by reducing the number of shrivelled berries (Oliveira *et al*., 2014), although contrasting responses to shading intensity have been observed among cultivars (Ghiglieno *et al*., 2020; Villalobos-Soublett *et al*., 2021). The lower fruit set observed in the Modified system might be related to a higher shading intensity, as shown in previous studies (Basile *et al*., 2015; Downey *et al*., 2006). These findings indicate that installation design can modify yield formation by affecting vine microclimate.

3. Black net increased acidity and decreased pH, while Grembiule increased phenolic content

All treatments were harvested on the same day, based on TSS accumulation on control vines. Vines under the Pearl net showed higher TSS during maturity than the Black net (*i.e.*, 1 °Brix lower), while control vines were intermediate. Net colour affected pH and total titratable acidity (TA), whereas the installation system affected anthocyanin and tannin content. The Black net resulted in the lowest pH and the highest TA, while the Pearl net showed intermediate pH values and no significant differences in TA compared to the control. Black net showed 0.7 °Brix less at harvest compared to the rest of the treatments, which might partially explain this higher TA and lower pH. However, Black net showed lower values of pH and higher TA at the same values of TSS during the whole maturity period (Figures 4A and 4B). As previously shown, Black nets significantly reduce the canopy heat load, thereby lowering the berry temperature during ripening (Nahüel *et al*., 2026). Low berry temperatures reduce the degradation rate of malic acid, resulting in higher acidity and lower pH (Spayd *et al*., 2002; Cohen *et al*., 2008; Cohen *et al*., 2012; Sweetman *et al*., 2014; Martínez-Lüscher *et al*., 2020; Lu *et al*., 2021). Pearl nets, by allowing higher radiation transmittance and generating higher air temperatures than Black nets, likely explain their impact on these variables.

TABLE 4. Total soluble solids (TSS), pH, total acidity (TA), sugar per berry, tannins, and anthocyanins (expressed as mg per g of skin) at harvest for Malbec plants under different anti-hail net colours (Black and Pearl), installation systems (Grembiule and Modified), and uncovered control plants (CO): Black-Grembiule (BG), Pearl-Grembiule (PG), Black-Modified (BM), and Pearl-Modified (PM). Within each factor and season, significant differences are indicated by different letters ($p < 0.05$).

		TSS (°Brix)	pH	TA (g L^{-1})	Sugar per berry (g)	Tannins (mg g^{-1})	Anthocyanins (mg g^{-1})
Colour (C)	Black	24.3 ± 0.2 b	3.66 ± 0.01 c	4.69 ± 0.09 a	0.292 ± 0.003 b	-	25.5 ± 1.20
	Pearl	25.0 ± 0.2 a	3.68 ± 0.01 b	4.40 ± 0.09 b	0.306 ± 0.003 a	-	27.2 ± 1.21
	CO	24.7 ± 0.3 ab	3.71 ± 0.01 a	4.16 ± 0.12 b	0.286 ± 0.005 b	-	20.02 ± 1.36
	p-value	**0.001**	**0.027**	**0.010**	**0.006**	-	0.159
System (Sy)	Grembiule	24.6 ± 0.2	3.66 ± 0.01	4.57 ± 0.09	0.297 ± 0.003	-	29.60 ± 1.20 a
	Modified	24.7 ± 0.2	3.67 ± 0.01	4.53 ± 0.09	0.301 ± 0.003	-	23.20 ± 1.21 b
	CO	24.7 ± 0.3	3.71 ± 0.01	4.16 ± 0.12	0.286 ± 0.005	-	20.02 ± 1.36 c
	p-value	0.738	0.506	0.717	0.434	-	**<0.0001**
Interaction (C × Sy)	CO					17.21 ± 0.76 c	
	BG					20.70 ± 0.76 b	
	PG					24.23 ± 0.76 a	
	BM					18.53 ± 0.76 c	
	PM					18.45 ± 0.79 c	
	p-value	0.946	0.894	0.457	0.442	**0.035**	0.616
Seasons (Se)	2018–2019	24.7 ± 0.2 a	3.69 ± 0.01 a	4.71 ± 0.18	0.299 ± 0.004 ab	18.48 ± 0.73 b	30.7 ± 1.37 a
	2019–2020	25.1 ± 0.2 a	3.64 ± 0.01 b	4.45 ± 0.06	0.308 ± 0.004 a	17.41 ± 0.71 b	26.0 ± 1.34 b
	2020–2021	24.1 ± 0.2 b	3.68 ± 0.01 a	4.48 ± 0.04	0.290 ± 0.004 b	25.54 ± 0.71 a	22.5 ± 1.34 c
	p-value	**0.0004**	**0.0002**	0.297	**0.013**	**<0.0001**	**<0.0001**
Interaction	***p-value***	0.277 *	0.401 *	0.267 *	0.105 *	**0.128 *** **	**0.130 ** **

Values are means ± SE. Sample size was n = 15 for all variables (5 replicates × 3 seasons). Interaction *p*-values refer to the relevant interaction for each variable (* C × Se; ** Sy × Se; *** C × Sy × Se).

The Grembiule system showed the highest anthocyanin and tannin content in berries, while the Modified system showed intermediate anthocyanin values and no significant difference in tannins compared to the control. In earlier studies, the Grembiule system effectively reduced canopy temperature during the hottest hours of the day, which could be related to the higher phenolic concentration found in the berries at harvest (Gouot *et al*., 2019). This thermal buffering observed in the Grembiule system likely promoted the synthesis and preservation of phenolic compounds (Martínez-Lüscher *et al*., 2020). No differences in phenolics were found between the Modified system and control vines (Gouot *et al*., 2019). Elevated temperatures during ripening can inhibit the biosynthesis of anthocyanins and tannins and enhance their degradation (Cohen *et al*., 2012; Gouot *et al*., 2019; Lu *et al*., 2021). Thus, more favourable thermal conditions under the Grembiule system supported the higher phenolic concentration. Interestingly, net colour alone had no significant effect on anthocyanin content, underscoring the importance of the installation system and its effects on microclimate, rather than the exclusive spectral properties related to nets, in modulating phenolic accumulation (González *et al*., 2015; Gouot *et al*., 2019; Torres *et al*., 2020; Miccichè *et al*., 2023).

4. Anti-hail nets can provide additional benefits according to environmental conditions

The results showed how the interaction between colour and installation system modulated the canopy microclimate (Nahüel *et al*., 2026) and, consequently, vegetative growth, yield, and berry composition. In warm and dry climates, Black net, especially when installed using the Grembiule system, promoted vegetative growth, supported yield formation, and enhanced fruit composition through microclimate modification. In contrast, Pearl net generated higher sugar accumulation, suggesting its suitability for cloudier, cooler conditions. These different responses highlight that the selection of protection strategies in terms of colour and installation systems must be adapted to site-specific conditions, vigour, cultivar traits, landscape, and oenological objectives. Importantly, our findings diverge from some results obtained in other regions, where netting had no significant effects on berry quality (Domanda *et al*., 2024) or yield (Pallotti *et al*., 2023), while other studies reported similar responses in yield and acidity (Storchi *et al*., 2024), reinforcing the idea that shading effects are highly context-dependent. Sunburn is a major concern in warm, arid vineyards, and anti-hail nets may help reduce its incidence (Oliveira *et al*., 2014). Although sunburn was not assessed in the present study, the observed reduction in canopy temperature suggests that anti-hail nets could also provide some protection against sunburn. As vineyard resilience and sustainability become increasingly important, strategies for protecting vineyards from environmental hazards and biotic and abiotic stresses should align with production and oenological goals, as well as market demands, particularly in regions with pronounced climatic constraints (Gutiérrez-Gamboa *et al*., 2021; Gutiérrez-Gamboa *et al*., 2024; Pallotti *et al*., 2023). As viticulture adapts to the challenges of climate change, anti-hail nets have emerged not only as a tool to protect against hail but also to provide additional benefits for fine-tuning vine performance while mitigating climate-related risks. The integration of installation systems and anti-hail net colour into vineyard design will be key to achieving physiological balance, stable yields, and optimal fruit quality in future production scenarios (Gutiérrez-Gamboa *et al*., 2024; Pallotti *et al*., 2023).

CONCLUSIONS

Our results indicate that anti-hail nets can modify berry maturity and composition by modulating the vine microclimate in warm and arid conditions. While the primary purpose of anti-hail nets is to protect vineyards during hailstorms, as demonstrated in the third season of our experiment, we also showed that the colour of the net and the installation system offer additional benefits. Specifically, our findings showed that, under moderate vigour, Black nets, particularly when used with the Grembiule system, were associated with greater vegetative growth and yield, and with higher acidity and phenolic concentration at harvest. In contrast, Pearl nets increased sugar accumulation, although they were associated with lower acid retention than Black nets under high temperatures. In the current climate change scenario, the colour of the net, along with the installation system, provides additional opportunities to modulate berry composition by altering air temperature, VPD, and leaf water status. This study contributes to a deeper understanding of how anti-hail net colour and installation systems can buffer environmental stresses in dry and hot conditions, modulating vegetative growth, yield, and berry oenological potential.

ACKNOWLEDGEMENTS

This study is part of Cesar Gabriel Nahüel's PhD thesis at the Facultad de Ciencias Agrarias, Universidad Nacional de Cuyo. The authors are grateful to L. Martínez and H. Lázaro for discussing statistical methods, to V. Gimenez, A. Gómez, M. Vico, R. Osorio and D. Nahüel for technical assistance in the field, and to AgriNet (Argentina) for providing the anti-hail nets used in this study.

FUNDING

This research was funded by projects MZASJ-1251306, PEI505, PE I517, PDI060 and PE-L01-I002 of the National Institute of Agricultural Technology (INTA

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