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Canopy management and deficit irrigation as a combined strategy to preserve berry quality in *Vitis vinifera* L. under Mediterranean conditions

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ABSTRACT

This study was conducted to determine an optimal irrigation and canopy management strategy to mitigate the effects of climate change on grape quality parameters and yield components in Mediterranean vineyards, primarily to prevent the imbalance between sugars and organic acids in the must. The experiment was conducted in 2021 and 2022 at a commercial vineyard located in Consell (Bodega Ribas, S.A.T., Mallorca, Spain). Two deficit irrigation treatments, moderate deficit irrigation (MDI) and severe deficit irrigation (SDI), were applied in combination with three canopy management treatments control (C), basal leaf removal (L), and basal leaf removal with shading (L+S), by releasing the vine shoots from the wires and hanging them simulating a "curtain" on the south-east side of the canopy. Temperature and radiation in the cluster zone, plant water stress level, and leaf area index were measured during the growing season. Berry weight, total soluble solids, pH, total titratable acidity, tartaric acid, malic acid, and potassium concentration were measured at different berry development and ripening stages, and yield components were determined at harvest. The application of the L+S treatment generated natural shading on the clusters, reducing excess temperature compared to the L treatment, which resulted in greater exposure. The reduction in temperature, combined with the maintenance of moderate water stress, delayed grape ripening, primarily by slowing sugar accumulation in berries, resulting in a final Brix of up to 2.5 °Brix higher. The moderate deficit irrigation treatment combined with a reduction in radiation and temperature at the bunch zone (treatments C and L+S) resulted in a reduction in malic acid degradation, especially during the last weeks of berry ripening. The combination of moderate water stress and shading of clusters after plant defoliation (L+S treatment) maintained a higher cluster weight and no significant yield losses compared to the control treatment in both years. Overall, the combined strategy of moderate water stress and natural shading of the clusters on defoliated vines has been shown to reduce extremely high temperatures in the cluster zone, thereby mitigating negative effects on berry quality and yield losses at harvest.

KEYWORDS: leaf removal, cluster shading, cluster microclimate, berry ripening, yield

INTRODUCTION

In the Mediterranean region, the sustained increase in average temperatures is generating critical impacts on crop productivity and quality, especially during summer, when heat waves are more intense and last longer. Climate change is also increasing the frequency and intensity of drought episodes and extreme rainfall events, putting rain-fed agricultural systems at risk (Arnell *et al*., 2019). Recent projections indicate that the average temperature could exceed the 1.5 °C threshold, while precipitation irregularities will intensify, increasing the vulnerability of Mediterranean agriculture to the risks associated with climate change (IPCC, 2023).

In the wine industry, one of the most concerning consequences of climate change is the advancement of grape berry ripening, a process that not only affects yields but also compromises technological berry parameters, mainly the balance between sugar content and organic acids (van Leeuwen *et al*., 2019). The local impacts of climate change on wine-producing areas require region-specific adaptation measures, with special emphasis on how it modifies the conditions in each region (Santos *et al*., 2020). Compounds essential to technological berry parameters, such as glucose, fructose, potassium, tartaric acid, and malic acid, may be adversely affected by the increased temperatures and water stress, resulting in early berry ripening and unbalanced fruit composition. During the ripening phase, high temperatures alter key cellular mechanisms, such as the degradation of malic acid and the synthesis of tannins, compromising the quality of the berries before they reach optimal ripeness (Rienth *et al*., 2016). Sweetman *et al*. (2014) found that these degradative processes are heightened when high temperatures, over 4 °C above reference values, occur before veraison, leading to a faster decline in malic acid content in berries exposed during early ripening. Besides, severe water stress reduces yield per hectare and berry volume, intensifying the decrease in overall technological berry parameters, leading to quantitative and quality losses of the resulting wine (Gambetta *et al*., 2020). Differences of 0.2–0.4 MPa in stem water potential can cause a significant increase in sugar content, combined with a greater reduction in must acidity, in treatments under more severe water stress (Zufferey *et al*., 2017). Furthermore, extreme water deficits can cause basal leaf fall, exposing clusters to high levels of solar radiation and accelerating ripening and the decline in critical quality parameters (Bahar *et al*., 2011; Spayd *et al*., 2002). Although water stress can limit potassium availability in the soil, the plant often responds by prioritising the transport of this cation to the berry to ensure osmotic adjustment and ROS mitigation (Rogiers *et al*., 2017). High concentrations of this element can lead to the precipitation of tartaric acid as potassium bitartrate, which reduces free acidity and increases pH, potentially compromising the wine's microbiological stability and colour intensity (Mpelasoka *et al*., 2003). The increase in potassium in the berry in response to abiotic stress may be a critical factor in the loss of oenological quality due to its direct impact on the deacidification of the must (Villette *et al*., 2020).

One of the main viticultural practices to avoid fungal infections during the final stages of development is leaf removal, which consists of eliminating basal leaves to enhance air circulation around the clusters and prevent optimal conditions for the fungi inoculation (Asenjo *et al*., 2004). However, in recent years, this practice has posed drawbacks, as it exposes the grapes to higher temperatures and solar radiation, thereby negatively affecting both yield and fruit quality, with a sugar content difference of up to 2.5 °Brix compared to non-exposed vines (Torres *et al*., 2020). To counteract early ripening, various management strategies have been explored. Canopy modification techniques, such as mechanical trimming by removing basal leaves at fruit set, showed slower berry maturation and maintained acidity by managing sunlight exposure (Dokoozlian & Kliewer, 1996; Parker *et al*., 2016). Martínez de Toda and Balda (2013) proposed early leaf removal, at the time the berry measures 3–4 mm in diameter, as a method to slow down ripening slightly, improving technological berry parameters by optimising the leaf area-to-fruit ratio, but having negative consequences in subsequent campaigns. Late pruning performed 23 days after anthesis has also shown a delay in ripening up to 40 days at harvest compared to untreated plants, although yield may be compromised as plant reserves shift (Martínez-Moreno *et al*., 2019). Moreover, the use of different vine training systems has been an important strategy to reduce the direct exposure of clusters to abiotic stresses, having promising results in delaying cluster ripening (Reynolds & Vanden Heuvel, 2009; Palliotti *et al*., 2014). The Sprawl vine training system has been proposed as the most appropriate for current conditions in the Mediterranean basin, rather than the VSP hedgerow, mainly to reduce the cluster's exposure and avoid the negative effects of high radiation and high temperatures (Del Zozzo & Poni, 2024). The artificial shading of clusters has proven to be an interesting option to mitigate the effects of climate change on the main qualitative parameters of wine grape production (Crouchett-Rojas *et al*., 2025; Pallotti *et al*., 2023). Martínez-Lüscher *et al*. (2020) confirmed that artificial shading using nets to reduce solar radiation by 40 % during the cluster ripening improves the must acidity and pH values. In another study, two cluster microclimate coverage treatments were applied using nets with shading factors of 27 % and 32 %, which proved to be an effective tool for obtaining smaller berries, with lower sugar content and reduced acid degradation (Miccichè *et al*., 2023). Regarding irrigation management, applying a moderate deficit irrigation dose (such as 50 % of the crop evapotranspiration) after veraison has been shown to improve the balance of sugars and organic acids and to enhance phenolic content in berries (Girona *et al*., 2009). While severe stress reduces berry size and, consequently, increases the concentration of soluble solids and phenols at harvest, these effects are largely a result of dehydration rather than direct metabolic enhancement (Intrigiolo *et al*., 2016). The timing of deficit irrigation is crucial for the final fruit quality; for instance, water deficit imposed after veraison results in higher titratable acidity and lower pH compared to pre-veraison stress (Caruso *et al*., 2023). Despite the wide range of adaptation strategies explored to mitigate the effects of climate change on grapevine performance, limited research has addressed the

combined effect of deficit irrigation and canopy management strategies, particularly under Mediterranean field conditions. Moreover, while artificial shading has shown promising results, there is limited information on the effectiveness of alternative, low-cost approaches that generate natural shading within the canopy structure. Therefore, the objectives of this work were to study the combined effect of two levels of deficit irrigation with three canopy management techniques on the microclimatic conditions of the cluster zone and how these changes affect the dynamics of technological maturity parameters in berries, such as sugar content, organic acids, phenolic compounds, alongside berry weight and final yield components.

MATERIALS AND METHODS

1. Experimental site and plant material

This study was conducted in the commercial vineyard of Bodegas Ribas S.A.T. (Consell, Mallorca, Spain, 39° 39' 3.82" N, 2° 49' 4.71" E) during the 2021 and 2022 seasons using plants of the Manto Negro cultivar (*Vitis vinifera* L.). The vineyard is located in the Binissalem Denomination of Origin region, with an altitude of 121 meters above sea level and in plain conditions. Vines were planted in 2015 and grafted onto Richter-110 rootstock, using a VSP trellis system with a 67.176° NE–SW orientation, with rows spaced 2.4 m apart and plants spaced 1 m apart. The plants were trained to an arm height of 1.2 m above ground, with 6 spurs and 10 to 12 shoots per plant, and a canopy height reaching 2.2 m above ground. The irrigation system consisted of localised drip irrigation emitters of 3.3 L/h spaced 1 m apart along a lateral irrigation line installed 0.3 m above ground.

Manto Negro is a late-ripening local cultivar from Mallorca. It has a medium disbudding period, and a late veraison period. It presents moderate to low acidity, with limited capacity to retain organic acids during the final stages of ripening, making it particularly vulnerable to acid degradation under high-temperature conditions. This cultivar exhibits very low pigmentation capacity, resulting in wines with moderate to low colour intensity. Despite its moderate to high sugar accumulation potential, the imbalance between sugar content and acidity at harvest makes Manto Negro especially sensitive to the effects of climate change, justifying the need for adapted viticultural management strategies (Escalona *et al*., 2016).

2. Treatments and experimental design

In this experiment, the vines were subjected to two irrigation treatments: moderate deficit irrigation (MDI) and severe deficit irrigation (SDI). The weekly irrigation dose was calculated to cover 80 % of the plant water needs in the MDaI treatment, applied in 2 doses per week, and 40 % of the plant water needs in the SDI treatment, applied in 1 dose per week. The weekly water doses were calculated using the following equation:

$$WD = \frac{ET_P * K_C}{DA * DC} * TC$$

where WD are the weekly water doses per each irrigation treatment (hours), ET_p is the reference evapotranspiration from the SIAR agroclimatic station (L/m^2), K_C is the crop coefficient that was established at 0.4, DA is the area assigned to each dripper (2.4*1 m), DC is the emitter caudal established et 3.3 L/hour, and TC is the treatment coefficient, 0.8 for MDI treatment and 0.4 for SDI treatment.

Irrigation scheduling and water application were set to maintain the plants at two levels of water stress, using midday stem water potential (Ψ) as an indicator. The reference values of Ψ were established between –0.6 and –0.9 MPa for the MDI treatment, and between –1.2 and –1.4 MPa for the SDI treatment (van Leeuwen *et al.,* 2009).

The two irrigation treatments were combined with three canopy management treatments: control (C), leaf removal (L), and leaf removal with cluster shading (L+S). In the C treatment, the canopy was not modified throughout grape development and ripening period. In the L treatment, leaves were removed from the basal zone of the shoots until the second cluster only on the east side of the canopy. Leaf removal was applied at the stage of "pea size", with berry diameter around 7 mm (stage 31, modified E-L system, Dry & Coombe, 2004), corresponding to July 4th for the 2021 campaign and July 11th for the 2022 campaign. In the L+S treatment, the leaf removal was carried out at the same stage as the previous treatment and, in addition, when the berries started to soften (stage 34, modified E-L system, Dry & Coombe, 2004), corresponding to July 29th for the 2021 campaign and July 30th for the 2022 campaign, the vine shoots were allowed to fall on the defoliated side (south-east) simulating a curtain to shade the clusters (see Figure 1 for treatment clarification).

Canopy management treatments were established following a randomised block experimental design. Four blocks were established, and within each block, the irrigation treatment was applied along the rows (5–6 rows per treatment). The three canopy management treatments were established randomly in each block, with a total of 4 replicates per irrigation and canopy management combination.

3. Climate conditions

To evaluate the climate conditions of the vineyard environment, daily temperature, solar radiation, reference evapotranspiration, and rainfall were obtained from the SIAR (Agroclimatic Information System for Irrigation) database at the Inca station (Balearic Islands) (39° 41' 01.7" N, 2° 56' 19.0" E), separated 10.93 km from the experimental vineyard. Mean values for 2021 and 2022 were compared with the corresponding 10-year averages (2011–2020) for the period from April to October, which encompasses the vine growth cycle.

4. Plant water stress monitoring

To monitor plant water status, stem water potential was measured at noon on 4 plants per treatment (1 plant per replicate block) from the start of the campaign until the end of August (June 30

to August 26 in 2021, June 30 to August 29 in 2022). Leaves were bagged in reflective zip bags to prevent transpiration; measurements were taken after 45 minutes of dark adaptation using a Scholander pressure chamber (M-1505D-EXP, PMS Instruments, Albany, Oregon, USA). The accumulated water stress was calculated through the procedure by Myers (1988) using the following modified equation:

$$AWS = \sum_{i=1}^{N} \left(\frac{\Psi_i + \Psi_{i+1}}{2}\right) * \Delta d$$

where AWS is the accumulated plant water stress [MPa*day], Ψ_i is the measured stem water potential [MPa], Δd is the interval between measurements [days].

5. Leaf Area Index monitoring

Leaf Area Index was measured using the Viticanopy® app (De Bei *et al*., 2016). Briefly, the procedure involved taking two pictures per vine (one per arm) at a 10 cm distance from the ground, aligning the irrigation line with the vine arm, then averaging the two values per plant. The measurement images were taken in 12 plants per treatment (3 plants per block), before (26th June 2021 & 4th July 2022) and after (11th July 2021 & 19th July 2022) the leaf removal application. After shading was applied in the L+S treatment, images could not be taken because the new shoot arrangement was incompatible with the application system requirements.

6. Cluster microclimate measurements

Temperature and radiation in the cluster zone were recorded during the experiments using HOBO Pendant® sensors (model UA-002-64, Bourne, MA) placed inside the plant canopy in the bunch zone. Each sensor was placed in a random plant per treatment. The sensors were placed on the third internode of a vine shoot to measure the temperature and radiation of the cluster zone. Temperature and radiation measurements were recorded every ten minutes. The excess accumulated temperature above 35 °C and the accumulated radiation during berry growth and ripening were calculated using the following equations:

$$AT = \sum_{\substack{i=1 \\ T_i > 35\,°C}}^{N} (T_i/6)$$

where AT is the accumulated temperature above 35 °C [°C*hour], T_i is the registered temperature [°C], dividing by six is used to convert data from ten-minute ranges to hours.

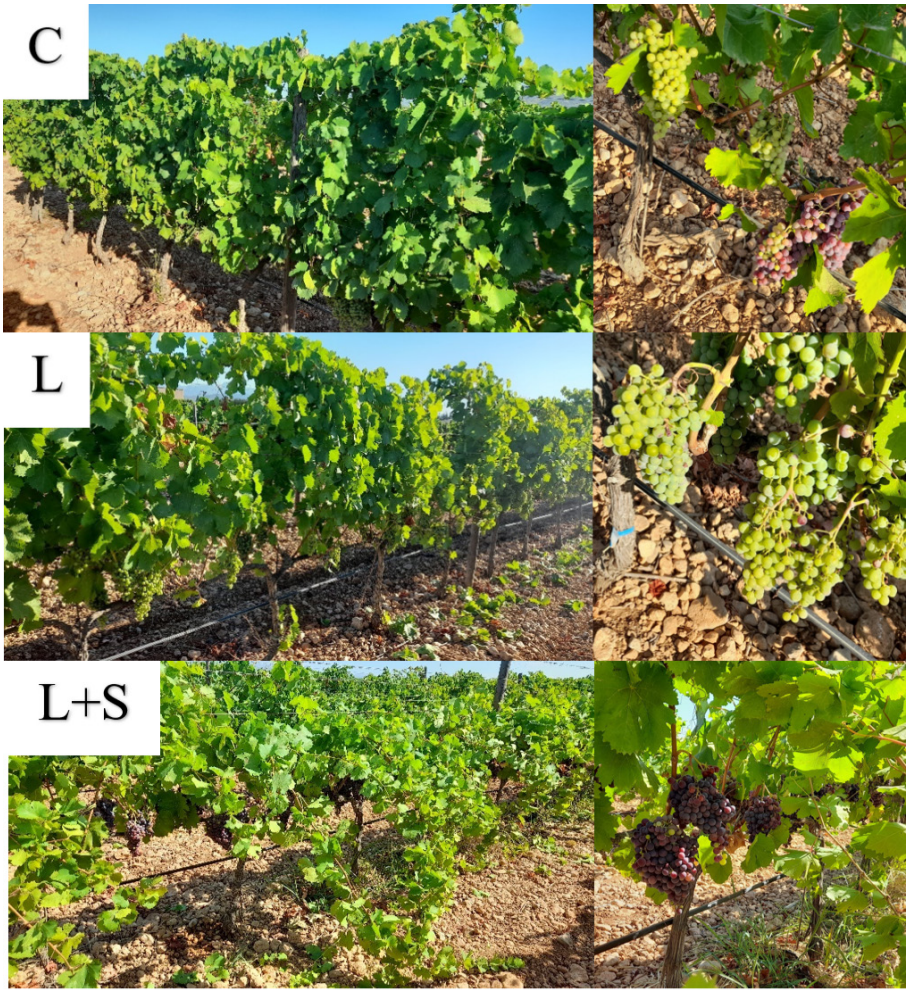


FIGURE 1. Canopy management treatments. Entire plant and cluster area pictures in the three canopy management treatments applied (control, C; leaf removal, L; leaf removal and shading, L+S).

$$AR = \sum_{i=1}^{N} (R_i * 0{,}0079 * 1/1000 * 1/6)$$

where AR is the accumulated radiation [kWh/m^2], R_i is the registered light intensity [lx], dividing by six is used to convert data from ten-minute ranges to hours.

7. Technological berry parameter analyses

To monitor grape development and ripening, berry sampling was carried out at 5 moments: initial sampling at the pea-sized stage of the berry (just before defoliation), at the application of leaf removal, 1 week after applying leaf removal, 1 week after applying shading, and harvest. For each sampling, 100 berries were randomly sampled from each replicate block of irrigation and canopy management treatments and stored in a portable cooler for subsequent laboratory processing.

On each sampling date, berry weight was estimated by weighing the 100 berry samples on an electronic balance and dividing by the number of berries. After that, each sample was smashed in its respective zip bag, and the resulting sample must was transferred to a 50 mL tube for analysis. Total soluble solids concentration, pH, total titratable acidity, tartaric acid, malic acid and potassium ions concentration were measured in fresh must. Total soluble solids (TSS) were measured using a handheld refractometer (ZUZI ® AOC, La Rioja, Spain). The pH was measured using a pH meter (CRISON PH BASIC 20, Barcelona, Spain). The titratable acidity was determined by acid-base neutralisation using sodium hydroxide (NaOH 0,1 M) and the colour change of bromothymol blue (C27H28Br2O5S 0.4 %) at pH 7 as an indicator (Method OIV-MA-AS313-01). Tartaric acid, malic acid, and potassium ions concentration in the must samples were measured using different enzymatic kits (BioSystems, Barcelona, Spain) in the Ribas winery laboratory following the manufacturer's indications.

In addition, in 2022, berry samples were collected at harvest to evaluate the phenolic profile of the berries using the Glories method (Glories & Augustin, 1993). Briefly, whole berries were crushed, and the resulting paste was macerated with two acidic solutions (tartaric acid at pH 3.2 and hydrochloric acid at pH 1) to extract phenolic compounds from the seeds and skins of the berries. The compounds measured were IPT (index of total phenolic compounds), total and extractable anthocyanins, and tannins from the skins and seeds, using a spectrophotometer (MULTISKAN SkyHigh, Thermo Scientific™, Waltham, Massachusetts, United States).

8. Yield and yield components

At harvest, the number of clusters per plant was counted, and the yield per plant was measured using a dynamometer (KERN HDB 5K5N, KERN & SOHN, Balingen-Frommern, Germany), and average cluster weight was estimated based on the two previous parameters.

9. Data analysis

A linear mixed-effects model (two-way factorial design), comparing the effects of irrigation, canopy management, their interaction, and the "block" as a random factor, was carried out to verify significant differences among treatments in the measured parameters. When significant effects were detected, a post-hoc analysis was performed using Tukey's test to identify differences among treatments. Additionally, using the technological berry parameters from each season, Pearson correlation analyses were performed with the accumulated temperature above 35 °C and the accumulated radiation recorded for each sampling date and treatment combination. All statistical analyses were performed using lme4, lmerTest and emmeans packages on RStudio (R version 4.2.0, Posit co.).

RESULTS

1. Vineyard climatic conditions

The environmental conditions recorded in 2021 and 2022 were compared with the 10-year average (Table S1). From May to September, mean daily temperatures were above the historical average, with 2022 standing out with the highest value of 22.57 °C recorded in August. For solar radiation, June, July, September, and October 2022 exceeded the 10-year mean, reaching a peak of 25.7 MJ/m^2 in June. Accumulated precipitation during the vegetative period (April–October) was lower than average in both years, with 2022 particularly notable for the absence of rainfall in June and July (Table S1).

2. Plant water status and leaf area

Stem water potential measurements during the 2021 season showed no significant differences between irrigation treatments after the end of June, indicating uniform water stress levels. By July, water stress increased, with values declining to –1 to –1.5 MPa, and later recovering in August. In the 2022 campaign, initial measurements also showed no differences, but by mid-July, MDI treatments maintained higher water potential than SDI treatments, with significant differences ($p < 0.05$) observed by the end of July. An irrigation system error in early August temporarily eliminated differences, but they reappeared by the end of the month, with MDI/C and MDI/L showing higher values than SDI treatments (Table S2).

The results for accumulated plant water stress in the 2021 season (Figure 2A) did not show significant differences among irrigation treatments. However, during 2022 (Figure 2B), accumulated stem water stress values showed a significant effect of the irrigation, with MDI treatment showing higher accumulated values than SDI ($p < 0.05$).

As shown in Figure 3A–3B the LAI values 7 days before the L treatment application, did not show significant differences among treatments, indicating that the plants had a similar vegetative development. As expected, the leaf removal in the L and L+S treatments resulted in lower LAI values than

the control. In the second measurement, seven says after the defoliation application (on July 11th), the results showed significant differences ($p < 0.001$) between the MDI/C treatment, with 1.56 ± 0.07 m^2 leaf/m^2 soil, and L and L+S treatments, remarking the low values from the MDI/L and SDI/L treatments, with 1.20 ± 0.05 and 1.23 ± 0.05 m^2 leaf/m^2 soil, respectively.

As in the 2021 season, the initial LAI values for 2022 showed no significant differences among treatments, indicating that plants started the season with similar levels of vegetation (Figure 3C–D). In the second LAI measurement, one week after leaf removal, the results showed a similar trend as in 2021 season, with significant differences ($p < 0.001$) between the MDI/C treatment (1.69 ± 0.05 m^2 leaf/m^2 soil) and the others, except for the SDI/C treatment (1.53 ± 0.04 m^2 leaf/m^2 soil).

3. Microclimatic conditions

Cluster zone temperature data recorded during the 2021 season showed significant differences among treatments. The L+S treatment had 6 or 7 fewer days with temperatures above 35 °C, and maximum temperatures were 1 to 3 °C lower than in the L treatment (Table S3). In the 2022 season, the sensors registered a higher number of days with temperatures above

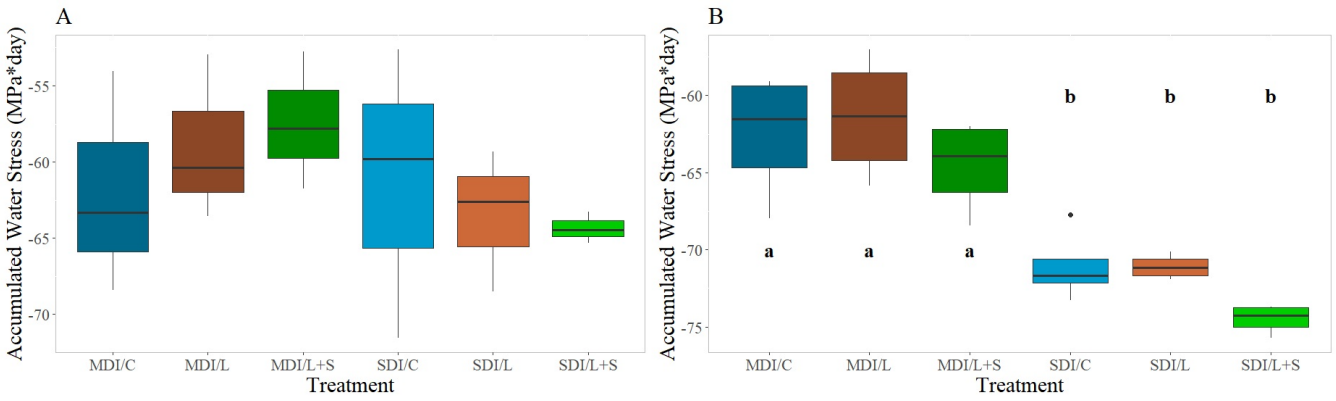


FIGURE 2. Accumulated water stress [MPa*day] during the 2021 (A) and 2022 (B) growing seasons. Boxplots represent the median, interquartile range, and minimum–maximum values (n = 4). Different letters indicate significant differences among treatments ($p < 0.05$) using Tukey's test.

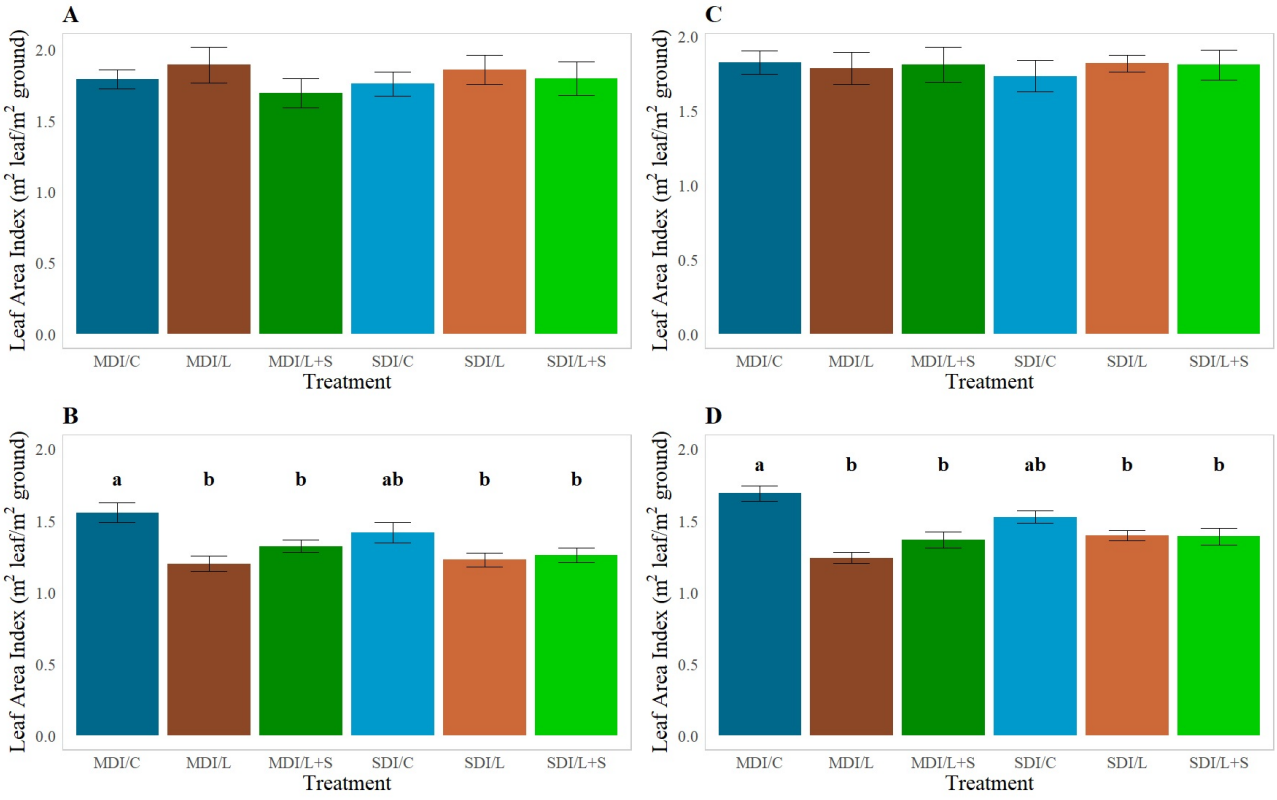


FIGURE 3. Leaf Area Index results [m^2 leaf/m^2 ground] 7 days before (A & C) and 7 days after (B & D) leaf removal application for 2021 (A, B) and 2022 (C, D) campaigns. Bars indicate mean value (n = 12) ± SE. Different letters indicate significant differences among treatments ($p < 0.05$) using Tukey's test.

35 °C compared to 2021, but the treatment MDI/L+S showed a notable reduction in the maximum temperatures registered in the cluster zone, reaching almost 5 °C below the control and 9 °C below the MDI/L treatment.

The results of the temperature accumulation above 35 °C in 2021 (Figure 4A) showed the highest values in the SDI/L and MDI/L treatments, reaching more than 3000 cumulative °C*hour at harvest. The L+S treatment showed intermediate accumulation values, differing from the C treatment mainly by a greater temperature accumulation during the period between leaf removal and shading. In 2022 (Figure 4B), the MDI/L treatment accumulated more than 4000 °C*hour, clearly higher than the others, among which MDI/C showed the lowest accumulation, with values below 2000 °C*hour.

The pattern of radiation accumulation in the clusters was similar to that of temperature accumulation, particularly in 2021 (Figure 4C). In that season, the SDI/L and MDI/L treatments recorded the highest cumulative radiation, both exceeding 600 kWh/m^2 at harvest. In contrast, the 2022 season (Figure 4D) displayed a different pattern, with accumulated radiation values not fully matching the trends observed for temperatures above 35 °C (Figure 4B) but keeping the MDI/C and MDI/L+S treatments with the lowest accumulated radiation, both with accumulated radiation below 400 kWh/m^2.

4. Berry weight and sugar content

At the beginning of the 2021 season, the berry weight was affected by irrigation treatment ($p < 0.01$), although these differences became non-significant by July. In 2022, no differences were observed at the start of the season, indicating similar initial berry size across treatments. In both years, this similarity persisted until the 3rd sampling date, during the ripening stage. From that point onwards, both water availability and canopy management affected berry weight (Table 1). In 2021, during ripening, MDI/C and MDI/L+S treatments maintained significantly higher berry weights than SDI/L and SDI/C. A similar pattern was observed in 2022, with both MDI/C and MDI/L+S treatments showing higher values compared to all severe deficit irrigation treatments (Table 1). At harvest in 2021, berry weight was significantly affected by irrigation, canopy management and their interaction, with MDI/C and MDI/L+S showing the highest berry weights. However, in 2022, only MDI/L+S treatment (2.7 ± 0.07 g) was significantly higher than all SDI treatments at harvest.

Notably, in both seasons, the combination of severe deficit irrigation with leaf removal and shading (SDI/L+S) mitigated the reduction in berry weight, resulting in values higher than SDI/C and SDI/L and not significantly different from MDI/C at harvest (Table 1).

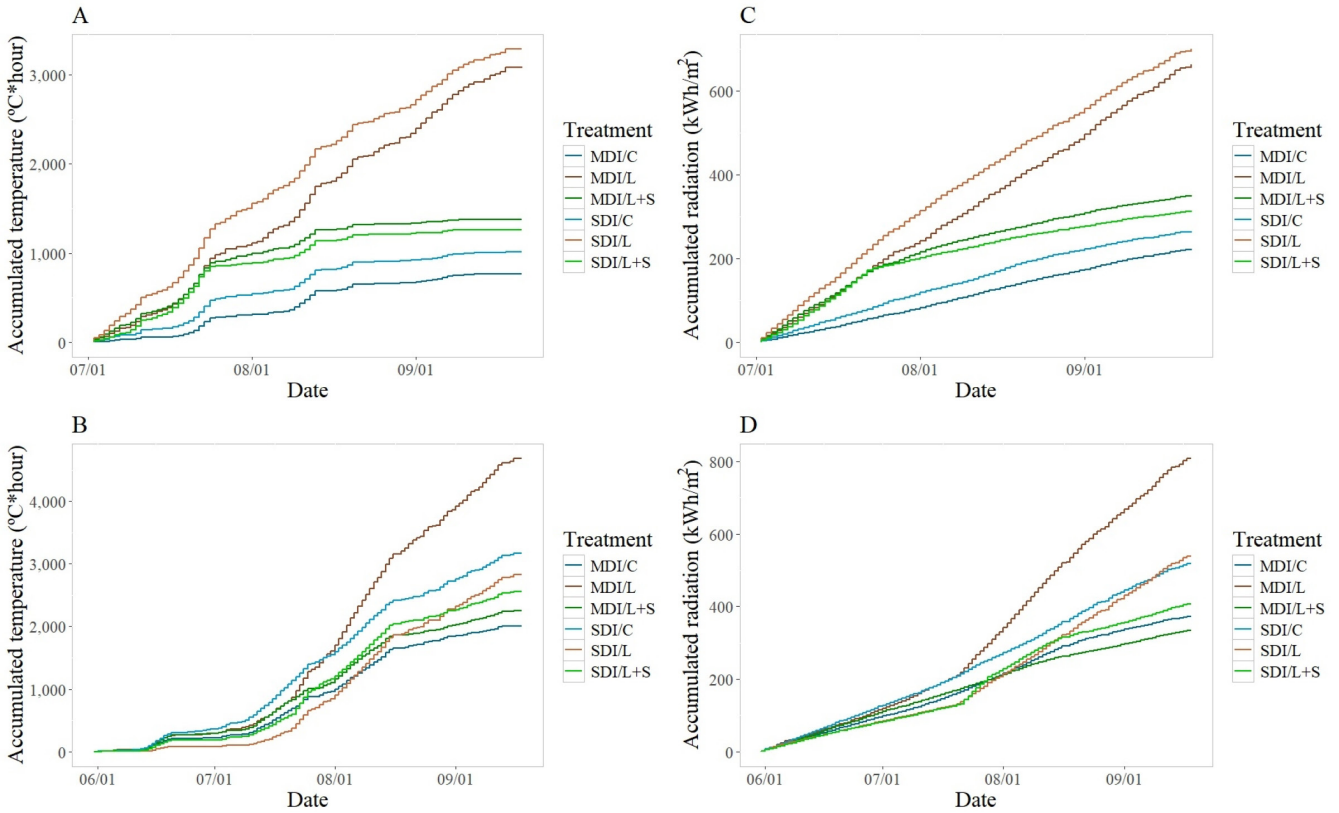


FIGURE 4. Accumulated temperature above 35 °C [°C*hour] (A & B) and accumulated solar radiation [kWh/m²] (C & D) per campaign and treatment. Recorded throughout the grape ripening period during the 2021 (A & C) and 2022 (B & D) growing seasons.

TABLE 1. Average berry weight [g] and total soluble solids [°Brix] for 2021 and 2022 campaigns. Values represented are means (n = 4) ± SE and analyse of variance (AOV) per irrigation treatment (I), canopy management treatment (C) and interaction (I * C). Asterisks (*) indicate the significance of the factor (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$). Different letters indicate significant differences ($p < 0.05$) using Tukey's test.

	2021									
	2nd July		23rd July		10th August		7th September		23rd September	
	BW	TSS	BW	TSS	BW	TSS	BW	TSS	BW	TSS
MDI/C	1.15±0.02a	3.98±0.03b	1.65±0.02	12.1±0.47a	2.63±0.04a	19±0.52a	2.81±0.03a	25.5±0.17a	2.72±0.07a	26.18±0.41a
MDI/L	1.09±0.04ab	4±0.05b	1.58±0.05	10.53±0.43b	2.55±0.13ab	17.68±0.21bc	2.64±0.15ab	24.93±0.31a	2.4±0.04b	25.55±0.46abc
MDI/L+S	1.1±0.02ab	4±0b	1.6±0.04	10.45±0.2b	2.58±0.04ab	17.08±0.48c	2.76±0.03a	24±0.68ab	2.7±0.07a	25.18±0.15bc
SDI/C	0.99±0.05c	4.2±0.08a	1.5±0.03	12.28±0.22a	2.27±0.13c	18.53±0.38ab	2.55±0.04bc	24.7±0.57ab	2.46±0.1b	24.73±0.97c
SDI/L	1.05±0.02bc	4.23±0.11a	1.62±0.04	12.18±0.28a	2.38±0.1bc	17.53±0.29bc	2.42±0.07c	25.2±0.82a	2.45±0.09b	25.95±0.46ab
SDI/L+S	1.04±0.03bc	4.26±0.09a	1.55±0.09	11.68±0.36a	2.52±0.04ab	16.9±0.47c	2.66±0.1ab	23.68±0.71b	2.64±0.07a	25.18±0.52bc
AOV I	**	***	-	***	**	-	**	-	**	-
AOV C	-	-	-	**	-	***	*	*	***	**
AOV I * C	-	-	-	-	-	-	-	*	**	*
	2022									
	27th June		11th July		29th July		30th August		18th September	
	BW	TSS	BW	TSS	BW	TSS	BW	TSS	BW	TSS
MDI/C	0.75±0,04	4.5±0.17	0.92±0.02	5.35±0.06c	1.74±0.02a	15.88±0.19abc	2.03±0.05a	25.8±0.18ab	2.08±0.05ab	25.48±0.17bc
MDI/L	0.76±0.02	4.45±0.05	1±0.03	5.48±0.13bc	1.6±0.05ab	15.48±0.13bc	1.77±0.05b	25.65±0.23ab	1.98±0.06ab	25.28±0.36bc
MDI/L+S	0.76±0.03	4.5±0.1	0.95±0.02	5.3±0.09c	1.51±0.0ab	14.9±0.37c	2.14±0.03a	24.35±0.39b	2.15±0.03a	24.9±0.17c
SDI/C	0.82±0.06	4.7±0.1	0.91±0.03	5.93±0.05a	1.48±0.0b	17.03±0.19a	1.71±0.05bc	26.6±0.24a	1.69±0.06cd	26.9±0.17a
SDI/L	0.82±0.02	4.6±0.08	0.99±0.02	5.85±0.1ab	1.43±0.05b	16.33±0.39ab	1.53±0.03c	26.88±0.58a	1.6±0.02d	27.45±0.53a
SDI/L+S	0.8±0.03	4.65±0.05	0.9±0.04	5,95±0.13a	1.4±0.03b	16.85±0.24a	1.84± 0.04b	25.73±0.3ab	1.89±0.04bc	26.23±0.15ab
AOV I	-	-	-	***	***	***	***	***	***	***
AOV C	-	-	-	-	*	-	***	**	***	*
AOV I * C	-	-	-	-	-	-	-	-	_	_

Regarding sugar accumulation, at the beginning of the 2021 season, irrigation had a strong effect on reducing total soluble solids (TSS; $p < 0.001$), but this effect was replaced by the effect of canopy management from the second sampling onwards, which persisted until harvest (Table 1). During late ripening (fourth sampling date), the SDI/L+S treatment showed significantly lower TSS (23.68 ± 0.71 °Brix) than MDI/C (25.5 ± 0.17 °Brix) and SDI/L (25.2 ± 0.82 °Brix). In 2022, the effects of irrigation on reducing TSS became significant from the second sampling date onwards ($p < 0.001$), and this effect was further reinforced by canopy management from the fourth sampling date. At that moment, the MDI/L+S treatment showed significantly lower TSS values (24.35 ± 0.39 °Brix) than SDI/C (26.6 ± 0.24 °Brix) and SDI/L (26.88 ± 0.58 °Brix) treatments. Towards harvest, TSS values increased steadily until reaching maximum levels in both campaigns. In 2021, the most notable differences were observed between SDI/C (24.73 ± 0.97 °Brix) and MDI/C (26.18 ± 0.41 °Brix), while in 2022, all MDI treatments surpassed SDI/C and SDI/L treatments (Table 1).

5. pH, acidity and potassium content

The pH values did not show substantial differences among treatments (Table 2). However, in July 2021, MDI/L (2.86 ± 0.02) and MDI/L+S (2.86 ± 0.01) showed higher pH than most other treatments. At harvest, pH values showed a significant effect of irrigation, with SDI/C (3.97 ± 0.07) and SDI/L+S (3.97 ± 0.04) reaching lower values than the MDI/C (4.06 ± 0.04) treatment. However, in 2022, no differences were observed despite a progressive increase in pH during ripening (Table 2).

Analysis of grape titratable acidity showed a significant irrigation effect throughout the 2021 season. By mid-July, TTA declined, with significant differences between MDI/L and MDI/L+S compared to SDI/C and SDI/L. As the season progressed, the three MDI and the SDI/L+S treatments showed significantly higher TTA values, with the SDI/L recording the lowest value (5.06 ± 0.18 g TA/L) and MDI/L+S the highest (5.93 ± 0.09 g TA/L) (Table 2). At harvest, acidity continued to decline, showing clear effects of both canopy management and irrigation.

In contrast, 2022 showed a significant irrigation effect only on the third sampling date (29 July), when MDI/L+S had the highest acidity (7.54 ± 0.24 g TA/L), differing significantly from SDI/C (6.58 ± 0.22 g TA/L) and SDI/L+S (6.45 ± 0.12 g TA/L). However, at the fourth sampling date (30 August) and at harvest (18 September), the irrigation effect observed in the previous samplings disappeared with no differences among treatments (Table 2).

Regarding organic acids, tartaric acid concentrations were similar across treatments at the pea-size stage (first sampling date) in both seasons, with no effect of irrigation or canopy management. In July, values increased notably in both seasons, but in 2022 only, the SDI/C treatment with 9.8 ± 0.1 g/L, showed significant differences compared to the MDI/L and MDI/L+S treatments, with 9.04 ± 0.11 and 9.13 ± 0.14 g/L, respectively. As ripening progressed, these differences disappeared until the grapes were fully ripe (4th sampling, 1 week after the shading treatment was applied). At this stage, MDI treatments tended to show lower tartaric acid concentrations than SDI treatments in both seasons, with MDI/L+S recording the lowest values in 2021 (4.69 ± 0.12 g/L) and MDI/C and MDI/L+S differing significantly from the remaining treatments in 2022. At harvest, the effects of canopy management were consistent for both seasons. In both years, the L+S canopy treatment under MDI conditions tended to maintain tartaric acid concentrations closer to those of the control, partly mitigating the reductions observed in defoliated treatments (Table 3).

Irrigation clearly influenced the malic acid content of the berries in both seasons, with the effect more evident from veraison onwards (Table 3). Significantly higher values were observed in the moderate deficit irrigation treatments. In addition, canopy management also influenced malic acid concentration from this point onwards. The treatments MDI/L (1.76 ± 0.06 g/L) and MDI/L+S (1.69 ± 0.09 g/L) continued to show the highest values during fruit ripening of 2021, with significant differences compared to the SDI/L and SDI/L+S treatments, while in 2022 the treatments MDI/L (1.21 ± 0.03 g/L) and MDI/L+S (1.23 ± 0.12 g/L) showed significant differences with the MDI/L, SDI/ and SDI/L+S treatments. At harvest, in 2021, SDI treatments were significantly lower than MDI/C and MDI/L+S (1.68 ± 0.03 and 1.56 ± 0.03 g/L, respectively), while in 2022 SDI/L+S again showed the lowest values compared with MDI/C (1.26 ± 0.04 g/L) and MDI/L+S (1.29 ± 0.11 g/L).

Potassium values were recorded in both campaigns, but with very moderate treatment effects. Differences were only found in July 2021, with MDI/L+S (1867 ± 11 mg/L) showing the lowest values and significant differences compared to MDI/C and SDI treatments. In 2022, the effect of the irrigation treatment was observed during ripening and harvest (4th and 5th sampling), with significant differences between MDI/L+S (2077 ± 76 mg/L) and SDI/C (2491 ± 72 mg/L) treatments (Table S4).

6. Phenolic content

Concerning the phenolic content of berries during the 2022 campaign, the results revealed clear irrigation effects but no significant canopy management effects on total anthocyanins, extractable anthocyanins, and skin tannins, with higher values under severe deficit irrigation compared to moderate deficit irrigation treatments (Table 4). Notably, the SDI/L and SDI/L+S treatments showed the highest values of these compounds, differing significantly from the MDI/L treatment. However, the Total Polyphenol Index (IPT), seed tannins, and anthocyanin extractability were not significantly affected by either irrigation or canopy management (Table 4).

7. Correlation analyses of grape technological berry parameters

The correlation matrix heatmap shows Pearson correlation coefficients, indicating the strength of the linear relationships between variables. Environmental variables showed a strong influence on must quality parameters in both seasons, with consistent trends between 2021 (upper part) and 2022

TABLE 2. Values of pH and total titratable acidity [g TA/L] for 2021 and 2022 campaigns. Values represented are means (n = 4) ± SE and analysis of variance (AOV) per irrigation treatment (I), canopy management treatment (C) and interaction (I * C). Asterisks (*) indicate the significance of the factor (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$). Different letters indicate significant differences ($p < 0.05$) using Tukey's test.

2021										
	2nd July		23rd July		10th August		7th September		23rd September	
	pH	TTA	pH	TTA	pH	TTA	pH	TTA	pH	TTA
MDI/C	2.47±0.02	34.93±0.41bc	2.93±0.03a	18±1.12bc	3.41±0.02	5.74±0.16ab	3.91±0.03	3.56±0.1a	4.06±0.04a	2.96±0.16bc
MDI/L	2.47±0.01	34.73±0.46bc	2.86±0.02b	20.38±1.13a	3.38±0.02	5.79±0.2ab	3.89±0.02	3.49±0.1ab	4.01±0.03ab	3.21±0.09a
MDI/L+S	2.47±0	34.35±0.04c	2.86±0.01b	19.73±0.23ab	3.35±0.02	5.93±0.09a	3.85±0.05	3.43±0.12ab	4.02±0.03ab	3.13±0.07ab
SDI/C	2.46±0.01	36.26± 0.32a	2.92±0.01a	17.55±0.55c	3.41±0.04	5.48±0.23bc	3.91±0.06	3.27±0.09b	3.97±0.07b	3.04±0.06abc
SDI/L	2.48±0.03	35.79±0.87ab	2.92±0.01a	17.23±0.52c	3.42±0.02	5.06±0.18c	3.9±0.04	3.32±0.11ab	4±0.06ab	2.98±0.1bc
SDI/L+S	2.47±0.01	35.87±0.22ab	2.89±0.02ab	17.87±0.83bc	3.37±0.03	5.66±0.06ab	3.83±0.04	3.32±0.1ab	3.97±0.04b	2.89±0.16c
AOV I	-	***	-	**	-	**	-	*	**	**
AOV C	-	-	*	-	-	-	-	-	-	-
AOV I * C	-	-	-	-	-	-	-	-	-	**
2022										
	27th June		11th July		29th July		30th August		18th September	
	pH	TTA	pH	TTA	pH	TTA	pH	TTA	pH	TTA
MDI/C	2.51±0.01	34.99±0.29	2.61±0.02	33.75±0.52	3.24±0.02	6.96±0.16ab	3.96±0.02	2.6±0.26	4.05±0.03	2.68±0.19
MDI/L	2.5±0.01	34.59±0.05	2.58±0.01	33.66±0.52	3.22±0.02	7.16±0.22ab	3.95±0.02	2.68±0.06	4±0.03	2.7±0.12
MDI/L+S	2.51±0.01	35.86±0.45	2.6±0.01	33.56±0.32	3.19±0.02	7.54±0.24a	3.9±0.02	2.98±0.23	4.02±0.05	2.79±0.13
SDI/C	2.51±0.003	35.48±0.43	2.6±0.02	34.22±0.47	3.28±0.01	6.58±0.22b	4.01±0.02	2.67±0.27	4.07±0.06	2.79±0.13
SDI/L	2.5±0.01	35.25±0.43	2.61±0.01	33.61±0.27	3.22±0.03	6.98±0.2ab	3.93±0.06	2.89±0.1	3.98±0.03	2.87±0.24
SDI/L+S	2.5±0.004	35.11±0.31	2.59±0.02	33.52±0.5	3.25±0.01	6.45±0.12b	3.93±0.02	2.73±0.08	4±0.04	2.63±0.11
AOV I	-	-	-	-	-	**	-	-	-	-
AOV C	-	-	-	-	-	-	-	-	-	-
AOV I * C	-	-	-	-	-	-	-	-	-	-

TABLE 3. Tartaric acid concentration [g/L] and malic acid concentration [g/L] for 2021 and 2022 campaigns. Values represented are means (n = 4) ± SE and analyse of variance (AOV) per irrigation treatment (I), canopy management treatment (C) and interaction (I * C). Asterisks (*) indicate the significance of the factor (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$). Different letters indicate significant differences ($p < 0.05$) using Tukey's test.

2021										
	2nd July		23rd July		10th August		7th September		23rd September	
	TA	MA	TA	MA	TA	MA	TA	MA	TA	MA
MDI/C	4.8±0.49	23.32±0,08ab	6.67±0.2	8.83±0.4bc	4.43±0.06	2.86±0.08a	4.94±0.13b	1.76±0.06a	4.95±0.06c	1.68±0.03a
MDI/L	4.52±0.14	23.19±0,22b	7.3±0,33	9.72±0.43ab	4.54±0.04	2.6±0.16ab	4.81±0.1bc	1.6±0.06ab	5.32±0.09a	1.36±0.07b
MDI/L+S	4.69±0.17	23.51±0.23ab	7.12±0.09	9.94±0.37a	4.34±0.03	2.79±0.07a	4.69±0.12c	1.69±0.09a	4.83±0.09c	1.56±0.03a
SDI/C	4.36±0.43	23.81± 0,2ab	6.94±0.1	8.41±0.34c	4.52±0.07	2.46±0.08b	4.88±0.03bc	1.48±0.12abc	4.95±0.05c	1.31±0.11bc
SDI/L	4.79±0.3	23.91±0,28a	6.9±0.15	8.41±0.26c	4.45±0.06	1.93±0.2c	5.19±0.07a	1.22±0.17c	5.11±0.06b	1.18±0.18c
SDI/L+S	4.22±0.13	23.93 ± 0,36a	6.98±0.16	8.26±0.42c	4.44±0.1	2.42±0.08b	4.98±0.08ab	1.33±0.15bc	4.95±0.14c	1.29±0.11bc
AOV I	-	**	-	***	-	***	**	***	-	***
AOV C	-	-	-	-	-	**	-	-	***	**
AOV I * C	-	-	-	-	-	-	*	-	**	-
2022										
	27th June		11th July		29th July		30th August		18th September	
	TA	MA	TA	MA	TA	MA	TA	MA	TA	MA
MDI/C	10.83±0.8	20.51±0.09	9.41±0.28ab	20.49±0.23	4.62±0.03	2.94±0,1a	4.5±0.01c	1.21±0.03a	4.77±0.05cd	1.26±0.04ab
MDI/L	10.22±0.34	20.75±0.25	9.04±0.11b	20.83±0.11	4.83±0.1	2.78±0,17a	5.01±0.07b	0.85±0.07c	5.04±0.08bc	1.08±0.11abc
MDI/L+S	11.5±0.52	20.68±0.31	9.13±0.14b	20.63±0.38	5.16±0.25	2.96±0,09a	4.39±0.12c	1.23±0.12a	4.57±0.11d	1.29±0.11a
SDI/C	9.99±0.48	20.98±0.09	9.8±0.1a	20.47±0.2	4.8±0.12	2.46±0,11ab	5.1±0.05a	0.94±0.05ab	5.61±0.09a	0.98±0.05abc
SDI/L	10.15±0.28	21.2±0.49	9.33±0.07ab	20.6±0.32	5±0.12	2.38±0,17ab	5.05±0.06ab	0.66±0.14bc	5.44±0.12a	0.85±0.13bc
SDI/L+S	10.09±0.54	20.65±0.27	9.54±0.08ab	20.02±0.16	4.76±0.14	2.08±0,15b	4.89±0.05ab	0.83±0.05bc	5.3±0.06ab	0.86±0.06c
AOV I	-	-	**	-	-	***	***	***	***	***
AOV C	-	-	*	-	-	-	***	***	**	-
AOV I * C	-	-	-	-	-	-	**	-	-	-

(lower part) (Figure 5). Accumulated temperature (AT) and accumulated radiation (AR) showed significant positive correlations with berry weight (BW), total soluble solids (TSS), pH, and potassium (K), and negative correlations with titratable acidity (TTA) and organic acids (TA and MA). In 2021, pH (PH) and total soluble solids (TSS) showed high correlation coefficients with both AT and AR (0.71 and 0.77, respectively), which were further strengthened in 2022, reaching even higher values.

8. Yield components

Yield per plant showed a similar trend across both seasons, although significant differences were observed only in 2022 (Figure 6B). Under MDI conditions, defoliated plants (MDI/L) showed lower yield than defoliated and shaded ones (MDI/L+S), which recorded the highest yield (3.74 ± 0.31 kg/plant). MDI/L+S did not differ significantly from the MDI control and was the only treatment with yields significantly higher than those of all SDI treatments.

Averaged cluster weight followed a similar trend to yield, with significant differences observed in both seasons. In 2021, the MDI/L+S treatment showed the highest values (0.26 ± 0.02 kg), differing significantly from MDI/L, SDI/C, and SDI/L+S (0.19 ± 0.02 kg, 0.2 ± 0.02 kg and 0.19 ± 0.02 kg, respectively; Figure 6C). A similar trend was observed in 2022, where the MDI/L+S treatment (0.42 ± 0.02 kg) showed significant differences compared with the MDI/L, SDI/C, and SDI/L treatments (0.27 ± 0.03 kg, 0.28 ± 0.03 kg, and 0.28 ± 0.02 kg, respectively; Figure 6D).

DISCUSSION

This study evaluated the effects of two deficit irrigation strategies combined with three canopy management techniques on grape technological parameters and yield in 'Manto Negro' vines under Mediterranean conditions.

The application of moderate deficit irrigation (MDI) had a positive impact on fruit quality compared with severe

TABLE 4. Phenolic compounds and anthocyanin extractability for the 2022 campaign. Values represented are means (n = 4) ± SE and analysis of variance (AOV) per irrigation treatment (I), canopy management treatment (C) and interaction (I * C). Asterisks (*) indicate the significance of the factor (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$). Different letters indicate significant differences ($p < 0.05$) using Tukey's test.

	IPT	Total anthocyanins [mg/L]	Extractable anthocyanins [mg/L]	Skin tannins [mg/L]	Seed tannins [mg/L]	Anthocyanin extractability
MDI/C	24.74±2.45	106.97±11.54b	94.5±9.45ab	3.78±0.38ab	24.58±2.46	11.15±4.98
MDI/L	27.33±0.57	108.72±11.82b	91.875±7.67b	3.68±0.31b	27.2±0.57	14.46±4.53
MDI/L+S	24.78±1.85	112.44±16.7ab	93.625±12.65ab	3.75±0.51ab	24.63±1.84	15.81±3.99
SDI/C	24.82±3.47	147±13,95ab	124.47±7.462ab	4.98±0.3ab	24.6±3.53	14.44±3.9
SDI/L	26.77±0.7	161.44±21.56a	125.56±12.77a	5.02±0.51a	26.58±0.7	21.14±3.17
SDI/L+S	25.33±3.32	163.41±24.08a	126.28±15.04a	5.05±0.6a	25.12±3.35	21.3±4.97
AOV I	-	**	**	**	-	-
AOV C	-	-	-	-	-	-
AOV I * C	-	-	-	-	-	-

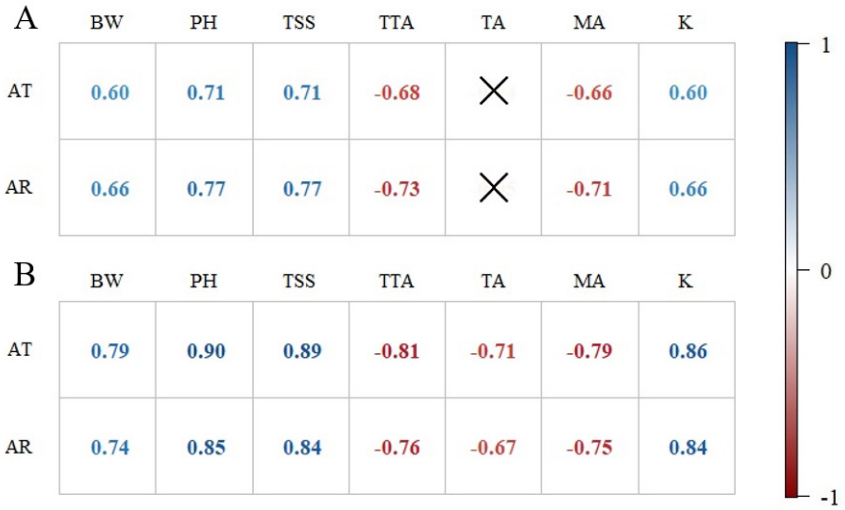


FIGURE 5. Heat map of Pearson correlation coefficients between technological berry parameters and the accumulation of temperature above 35 °C and radiation for 2021 (A) and 2022 (B) seasons. Positive correlations are shown in blue and negative correlations in red; crosses indicate non-significant correlation between parameters ($p > 0.05$). Abbreviations: BW, berry fresh weight; PH, must pH; TSS, total soluble solids; TTA, total titratable acidity; TA, tartaric acid; MA, malic acid; K, potassium; AT, accumulated temperature above 35 °C; AR, accumulated radiation.

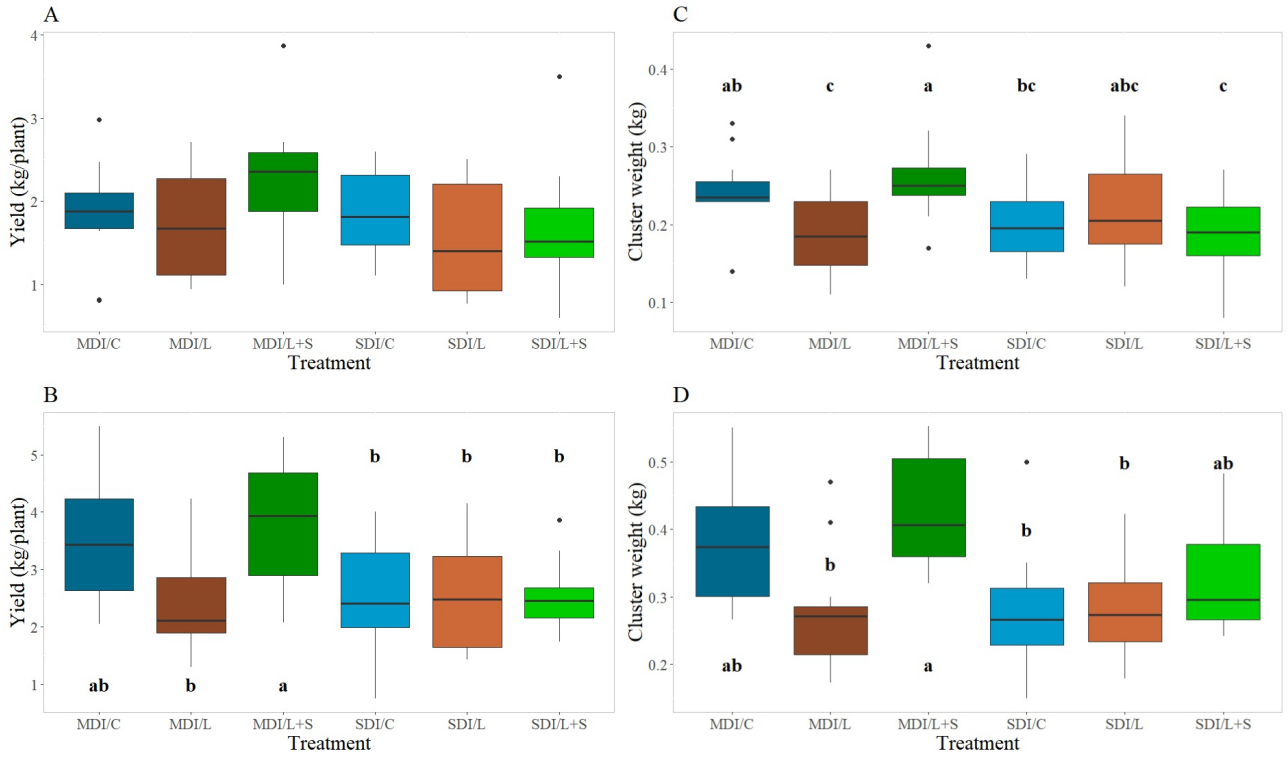


FIGURE 6. Yield [kg/plant] and average cluster weight [kg] at harvest for 2021 (A & C) and 2022 (B & D) campaigns. Boxplots represent the median, interquartile range, and minimum–maximum values (n = 12). Different letters indicate significant differences among treatments ($p < 0.05$) as determined by Tukey's test.

deficit irrigation (SDI), resulting in higher berry weight and must total acidity, together with a slight reduction in total soluble solids concentration. These results agree with previous studies showing that severe water stress promotes a significant increase in sugar accumulation in grape berries, with increases exceeding 5 % compared to plants under more moderate stress (Romero *et al.*, 2022; Gambetta *et al.*, 2020). Severe water restriction has also been associated with enhanced organic acid degradation, leading to differences of over 3 g TA/L between treatments, along with an increase in must pH (Poni *et al.*, 2018; Geng *et al.*, 2022). Additionally, during the 2022 season, plants subjected to severe deficit irrigation exhibited higher concentrations of phenolic compounds, particularly anthocyanins and tannins, in the berry skin. These findings align with those reported by Gambetta *et al.* (2020), who observed higher phenolic concentrations in vines under water stress within a stem water potential range of –1.1 to –1.4 MPa compared with plants under less water stress. Water stress during the post-veraison phase is the main limiting factor for berry enlargement. During this period of fruit ripening, berry volume determines the concentration of their main compounds. As berry volume decreases, sugars, must pH, and phenolic compounds such as tannins and anthocyanins in the fruit increase due to a dilution effect, further highlighting the imbalance in berry composition, with increases of around 50 % reported under severe stress conditions (Berhe, 2022).

In addition to irrigation treatments, the effects of cluster exposure were studied by modifying the canopy of the plants through leaf removal and natural shading. Although the effects of defoliation and shading on grape quality have been well documented, the combined effects of water availability, berry temperature and radiation exposure on fruit development, yield, and quality parameters remain incompletely understood. When severe water stress is combined with canopy modifications (leaf removal, late pruning, shoot thinning, and shoot trimming) during fruit development and the ripening period, reductions in berry number per bunch, bunch weight, or yield have frequently been reported (Cameron *et al.*, 2024). The severity of yield reductions depends on both the intensity and timing of the practices applied, with the greatest impacts occurring when shoot reductions exceed 25 % or when interventions are applied at advanced phenological stages, such as veraison (EL 34; Dry & Coombe, 2004). Fruit-zone leaf removal is commonly used to improve cluster microclimate, improving the exposure of the fruit zone in denser canopies, thus reducing cluster disease incidence (Guidoni *et al.*, 2008; Poni *et al.*, 2018). However, under current Mediterranean climatic conditions, increasing the bunch exposure may also increase sunburn during a heat wave (Gambetta *et al.*, 2021) and exacerbate the negative effects of excessive temperature and radiation on the fruit (Dokoozlian & Kliewer, 1996; Asenjo *et al.*, 2004). The intensity and timing of defoliation may affect the final effects on fruit composition, and it is generally recommended not to exceed 30 % leaf area removal and to apply the technique before veraison (Verdenal *et al.*, 2018; Torres *et al.*, 2021). In this study, leaf removal was applied at the green berry stages (EL 32; Dry & Coombe, 2004), before cluster compactness in both seasons. At this stage, the accumulation of malic acid in the berry is approaching its maximum, after which

degradation processes dominate as grape berries start to soften (Possner & Kliewer, 1985). In plants under severe water restriction (SDI treatment), higher accumulation of temperature and radiation was recorded, especially in 2022, probably due to higher basal leaf loss than in 2021. As seen in a study by Bahar *et al*. (2011), after applying extreme water stress (below –2 MPa) to the plants, they began to dry out the basal leaves in order not to compromise the younger leaves, which leads to the loss of a certain percentage of leaf cover and therefore leaves the clusters more exposed. These modifications of the cluster microclimate trigger the ideal conditions for the berries to dehydrate, especially in the leaf removal treatment under severe deficit irrigation, increasing their sugar concentration in the pulp, with differences of up to 2 °Brix between the treatments with greater and lesser exposure to temperature (Martínez-Lüscher *et al*., 2020; VanderWeide *et al*., 2021).

Berry weight loss and sugar accumulation were observed in final samplings of both seasons, with the severe deficit irrigation combined with bunch defoliation treatment showing the lowest values. Leaf removal followed by natural shading, applied at the onset of ripening, reduced both accumulated temperature and radiation in both seasons. In both years, the differences between the MDI/L+S and the SDI/L treatment were statistically significant, with the greatest differences observed in the 2022 season, with 0.55 g/berry and 2.59 °Brix. In fact, the reduction in berry weight observed under leaf removal was mitigated when combined with shading under both irrigation regimes, particularly under moderate deficit irrigation. Similar results have been reported in other studies, where the combination of shading and higher irrigation levels (40 and 80 % of ET_C, respectively) led to increased berry weight up to 0.2 g per berry (Martínez-Lüscher *et al.*, 2020).

Regarding sugar accumulation, berry dehydration in the leaf removal treatment was accompanied by an increase in sugars from veraison to harvest, especially under severe deficit irrigation, due to a concentration effect. However, when leaf removal was combined with shading, sugar accumulation in the berries was reduced, likely through a reduction in skin transpiration caused by lower exposure to high temperatures and radiation. Notably, the combination of shading with moderate deficit irrigation resulted in the lowest sugar levels among all treatments, confirming that bunch shading together with moderate water stress can slow sugar accumulation in the berry. These results agree with other studies reporting lower sugar content in shaded clusters compared to more exposed ones (Crouchett-Rojas *et al*., 2025; Pallotti *et al*., 2023; Liu *et al*., 2024). It is worth noting that in these studies, shading was achieved using nets or shielding boxes as a covering system. In contrast, the shading approach applied in the present work relied solely on natural canopy development, without additional material costs, representing an easily adoptable strategy to mitigate excessive radiation and temperature on clusters during development and ripening.

In addition to the increase in TSS, the combination of severe water deficit and leaf removal showed the lowest values of acidity parameters, particularly malic acid concentration. Conversely, moderate water deficit combined with leaf removal and shading maintained the highest malic acid levels during the ripening and harvest. The slower malic acid degradation under the leaf removal and shading treatment can be explained by the reduction in berry transpiration due to lower cluster zone temperature and radiation (Possner & Kliewer, 1985; Sweetman *et al*., 2014; Friedel *et al*., 2015). These results are consistent with other studies examining cluster shading strategies; for instance, after applying a defoliation of more than 50 % of the leaf area, the pH increased by 0.1 and the acidity was reduced to 1 g TA/L compared to the untreated plants (Basile *et al*., 2015; Mataffo *et al*., 2023). The results of our study confirm the strong relationship between malic acid concentration and must titratable acidity from fruit set to harvest, a pattern commonly observed across grape varieties (Plantevin *et al*., 2024). These findings indicate that canopy architecture, particularly shoot arrangement, plays a central role in regulating the thermal and radiative environment of the cluster zone. By maintaining these parameters within an optimal physiological range, the metabolic degradation of malic acid, via cellular respiration, can be effectively modulated (Rienth *et al*., 2016). Consequently, managing the spatial distribution of vegetation is not merely a structural choice but a strategic intervention to decouple sugar accumulation from acid loss, thereby buffering the fruit against the imbalances typically triggered by extreme temperature peaks.

The effects of the different treatments on fruit quality described above were corroborated by Pearson correlation analysis, which showed that most parameters, particularly in the 2022 season, were significantly correlated with temperature and radiation accumulation. Specifically, cumulative temperature above 35 °C and radiation in the cluster zone were strongly related to key technological berry parameters, such as sugar content, pH, and malic acid concentration.

Leaf removal with or without subsequent bunch shading did not have a major impact on grape phenolic content during the 2022 season. This differs from previous studies reporting that high temperatures and radiation on the cluster significantly reduced the synthesis of phenolic compounds during the later stages of berry ripening. For instance, differences up to 10 °C in maximum temperature between treatments resulted in losses of over 50 % of certain phenolic compounds, mainly anthocyanins (Mori *et al*., 2007; Tarara *et al*., 2008). The lack of a clear response to the effect of plant canopy management on phenolic compound concentration may be due to a compensatory interaction with the water-stress treatment applied to the plants. In fact, irrigation treatment alone showed significant effects on total and extractable anthocyanins, as well as seed tannins.

This agrees with studies that found that increasing plant water stress up to a certain threshold (Ψ_{Leaf} = –1.12 MPa) favours the synthesis of phenolic compounds, reaching concentrations close to 150 % compared to plants with less water stress (Girona *et al*., 2009). Furthermore, irrigation management plays a central role in establishing the phenolic content in berries.

In both campaigns, primarily in 2022, the effects of deficit irrigation combined with canopy management highlighted the importance of maintaining moderate water stress while reducing cluster exposure to minimise yield losses. Moderate deficit irrigation, when combined with leaf removal and bunch shading resulted in the highest bunch weight values and the highest production per plant in 2022. These findings are consistent with the other studies, where it has been verified that severe water regime (stem water potential between –1.1 and –1.4 MPa) can lead to significant production losses up to 40 % compared to fully irrigated plants (Gambetta *et al*., 2020). Moreover, excessive temperature and radiation (increases of approximately 0.8 °C and 0.4 MJ/hm^2) can reduce cluster mass due to increased water loss through the berry skin (Oliveira *et al*., 2014; Martínez-Lüscher & Kurtural, 2021).

The application of leaf removal and shading treatments may pose practical limitations compared to conventional canopy management, particularly when integrated with crop operations. This treatment requires additional labour and occupies space in the rows, potentially interfering with routine plant maintenance. However, this modification is mainly carried out at veraison, when most crop management tasks have already been completed. This modification of the canopy structure could also affect plant and cluster health, but, as with cultivation practices, this treatment is applied after veraison, when disease and pest pressure are reduced. Moreover, leaf removal performed before shading the bunches promotes ventilation within the bunch, helping to prevent the proliferation of fungal diseases. Harvest operations may also be affected. In most wineries in Mallorca and other Mediterranean areas, hand-harvesting is preferred to maintain must quality as much as possible, which is totally compatible with this canopy management practice.

CONCLUSION

Concluding, the results of this study demonstrate that implementing moderate water deficit in combination with early leaf removal followed by natural cluster shading can effectively mitigate some of the negative impacts of climate change on berry quality and yield in 'Manto Negro' cv. under Mediterranean conditions.

The results confirmed that applying moderate deficit irrigation improved berry quality, with higher berry weight, lower total soluble solids, and reduced malic acid degradation. In contrast, severe water stress promoted a significant increase in total soluble solids and must pH, while accelerating the degradation of organic acids. In addition, the study of the berry phenolic profile in 2022 showed that greater water deficit stress was associated with higher concentrations of anthocyanins and tannins in the skins.

The combination of a moderate deficit irrigation strategy with defoliation and natural cluster shading can improve microclimate conditions in the bunch zone, reducing berry exposure to high temperatures (above 35 °C) and solar radiation during ripening. This integrated approach proved to be the most effective strategy for delaying sugar accumulation, slowing malic acid degradation, and maintaining high berry and bunch weight at harvest. In addition, in 2022, this strategy significantly increased plant yield.

Overall, the integration of moderate deficit irrigation with targeted canopy management emerges as a robust strategy to improve grape berry composition while maintaining vineyard productivity, offering a relevant adaptive approach under increasing climate variability and water scarcity in Mediterranean viticultural regions. However, future research should focus on its applicability to other cultivars, environments, and training systems, as well as how microclimate modification may affect bunch health and oenological capacity.

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