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Effects of automated fruit-zone irrigation cooling and basal leaf removal on physiology and performances of field grown Sauvignon blanc and Barbera grapevines

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Abstract

Berry dehydration and sunburn are growing concerns for wine grapes cultivated in warm climates. An underexplored method to address this is localized water nebulization at the cluster level for cooling. In 2024, a trial was conducted on Sauvignon blanc (SB) and Barbera rows in Northern Italy, comparing two factors at two levels each: uncooled control (C) versus cooled vines (CL), and non-defoliated (ND) versus defoliated vines (D). Basal defoliation was performed at veraison, while automated cooling was implemented using one fogger per vine, positioned about 10 cm above the cordon, and activated when the air temperature exceeded 33 °C and relative humidity was below 55%. The foggers had a flow rate of 11.2 L/h, with intermittent cooling cycles of 1 min off and 2 min on. Throughout the season, leaf gas exchange, water status, surface cluster temperature, yield components, and grape composition at harvest were measured in both varieties. Out of 51 potential activation days, the system operated on 44 days (86.3%), delivering a total of 145 mm and 183 mm in Sauvignon blanc and Barbera, respectively. The maximum cooling effect on clusters, ranging from − 6 to − 9 °C, was observed when comparing the C-D (warmest) and CL-ND (coolest) treatments, with cooling efficiency unaffected by the presence or absence of basal leaves. Both cooling and maintaining leaf cover effectively reduced cluster sunburn. In Sauvignon blanc, leaf gas exchange and water status were minimally impacted, whereas in Barbera, cooling significantly enhanced leaf function during summer. In Barbera, while ND vines exhibited enhanced sugar and color accumulation at harvest compared to D vines, the CL vines had lower total anthocyanins and phenolics at harvest than C vines, regardless of their unit of expression. This supports the hypothesis that the significant decrease in surface cluster temperature achieved by cooling might not suffice to improve berry pigmentation if berry skin wetting is prolonged, and as a result of an apparent VPD drop, berry transpiration and ripening may be delayed.

Introduction

A consistent feature of global climate change is the increased frequency and intensity of heat waves, defined as the number of days with maximum air temperatures exceeding 35 °C (Fraga et al. 2020). These conditions exacerbate the effects of rapid dehydration and sunburn in plant organs (Marx et al. 2021). Grapevines are not immune to this issue; in Australia, sunburn affects an estimated 5–15% of total grape production (Greer et al. 2006), a concern echoed by South Mediterranean countries (Bucur and Dejeu 2022). Sunburn damage is not always linked to soil water deficits; for instance, in Central-Northern Italy, the past season (2024) has experienced abundant rainfall overall, yet significant local berry sunburn has been reported in many grape-growing districts.

The grapevine berry is a low-transpiring organ with a relatively limited cooling capacity (Rebucci et al. 1997; Zhang and Keller 2015), which helps explain why, under high temperature and intense light, direct sun exposure can raise the surface berry temperature (SBT) by as much as 12–15 °C above the ambient air temperature. It is well known that this

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effect is localized, explaining why SBT and the resulting sunburn damage vary between clusters on the same vine and between berries within the same cluster, depending on the degree of light exposure (Price et al. 1995; Spayd et al. 2002). Critical SBT leading to significant damage is influenced by a multitude of factors, including berry size, shape, and growth stage—hence the presence or absence of color (Gambetta et al. 2021), cluster compactness (Tello and Ibáñez 2018), cultivar (Rustioni et al. 2015), skin thickness (Rustioni et al. 2023), wind speed, water status (Müller et al. 2023), and the amount and composition of epicuticular waxes (Domanda et al. 2024). While a few hours of berry exposure to temperatures between 42 and 49 °C have been reported to cause significant sunburn damage (Rustioni et al. 2015; Gambetta et al. 2021), it is important to emphasize that the interaction of temperature with light and relative humidity can greatly affect the severity of the damage. For instance, when greenhouse-grown Semillon berries were suddenly exposed to high light at temperatures ranging from 25 to 30 °C, no damage was observed; however, when the temperature increased to 38 °C, significant sunburn damage occurred even at low light intensity (Hulands et al. 2014). Moreover, intriguing research on Müller-Thurgau has shown that the combination of heated berries and low relative humidity (RH), which promotes high transpiration, caused initial sunburn symptoms at 44 °C, while the same treatment with high RH, resulting in lower transpiration, reduced this threshold to 41.5 °C (Gambetta et al. 2021).

The typical sign of impending sunburn damage is the loss of the crystalline structure of epicuticular wax, which gives the berries a glossy appearance, unlike the healthy, matte look of unaffected berries (Bhaskar Rao and Markus 2012). The disorder then progresses to sunburn browning (Gambetta et al. 2021) and eventually leads to necrosis (Teker 2023), culminating in berry cracking and shriveling. Recent research by Domanda et al. (2024) has elucidated that the disruption of epicuticular waxes is linked to the rapid degradation of chlorophyll a and the polymerization of phenolics, which in turn accelerates browning.

The impact of sunburn on yield and quality can be severe: yield is significantly reduced, and in a trial where Shiraz wine was produced from 80% shriveled berry lots, the wine was perceived as more alcoholic and associated with dark fruit and dead/stewed fruit characteristics. Additionally, orange pigments and the wine's chemical age were increased compared to the non-shriveled control wine (Chou et al. 2018). In the same variety, shriveled berries resulted in a final wine with fewer total anthocyanins, while terpenes remained unaffected (Suklje et al. 2016).

In addition to the choice of cultivar, various cultural factors can significantly influence the incidence and severity of sunburn in wine grapes. Canopy density, such as the number of shoots per meter of row length, is clearly linked to sunburn damage, as it affects the dynamics and extent of cluster exposure to light. However, the canopy density present when berry sunburn becomes a concern—essentially from fruit set until harvest—is subject to variations due to cultural practices, which can sometimes be difficult to predict. For instance, shoot thinning is expected to reduce canopy density and increase the likelihood of berry sunburn. Yet, research on the long-term changes in canopy growth and density induced by shoot thinning has revealed that, due to growth compensation from the remaining shoots, the final total leaf area per vine—and thus canopy density—may not differ between thinned and un-thinned treatments (Bernizzoni et al. 2011).

Undoubtedly, leaf removal is the summer pruning operation most likely to alter the cluster microclimate. This is especially true when a relatively late and severe basal leaf removal is conducted, suddenly exposing clusters to full sunlight with minimal opportunity for regrowth from lateral buds to restore some fruit shading (Poni et al. 2023). An earlier leaf removal, besides offering a greater chance for new leaf cover to develop, is less likely to result in berry sunburn. Joanna Gambetta et al. (2019) demonstrated in Chardonnay grapes that cluster exposure due to pre-veraison leaf removal is followed by an increased synthesis of photoprotective compounds (flavonoids, carotenoids, and chlorophylls), which is significantly reduced when defoliation occurs at a later stage, such as post-veraison. Row orientation is also known to influence the susceptibility of grapes to sunburn damage, with the west-facing side of a north–south oriented row and the south-facing side of an east–west oriented row being at higher risk (Hunter et al. 2021). Light interception modeling conducted on north–south and east–west oriented rows has shown that at a latitude of 45° N, around 3 PM on June 22, the west-exposed side of north–south oriented rows receives direct radiation of about 600 W m^{-2} and diffuse radiation of about 210 W m^{-2}. In contrast, the same simulation for the south-exposed part of the east–west oriented rows yields 380 W m^{-2} and 215 W m^{-2}, respectively (Canavera et al. 2023).

Assuming the risk of sunburn remains consistently high in a particular area, resorting to cooling irrigation appears quite evident. The emergence of the Internet of Things approach (Farooq and Akram 2021) and the growing awareness of the necessity for water-saving protocols (Gómez-Limón et al., 2002) have raised concerns about traditional over-canopy cooling using high-volume sprinklers (Kliewer and Schultz 1973; Pitacco et al. 1999). Consequently, in recent times, there has been an increase in attempts to employ localized under or within canopy cooling systems (Caravia et al. 2017; Paciello et al. 2017; Deligios et al. 2019; Cogato et al. 2021; Gandolfi et al. 2022; Davide et al.

2023; Valentini et al. 2024) due to the following potential benefits: (i) effective cooling with reduced water usage and enhanced water use efficiency; (ii) relatively easy programming and automation of water supply in response to environmental conditions; (iii) only clusters and basal leaves are wetted, while the rest of the canopy remains relatively dry; (iv) nebulized water, typically provided under on/off intermittency, ensures rapid evaporative cooling and shortens canopy wetting periods. Research conducted in Australia (Caravia et al. 2017) on the application of sprinkler cooling within the cluster zone during the ripening of Cabernet Sauvignon, when air temperatures exceeded 38 °C, preserved berry weight, while changes in grape composition compared to a non-conditioned control were minimal.

We are not aware of any study that has examined the effectiveness of a within-cluster area cooling system, either with or without late-season basal defoliation. Therefore, the objectives of this study were to: (i) describe the setup and automation of a localized cooling system installed on Sauvignon blanc and Barbera rows; (ii) investigate whether and how cooling and leaf removal interact in relation to leaf gas exchange and water status, cluster temperature, yield components, and grape composition.

Materials and methods

Plant material and experimental layout

In 2024, an experiment took place in a 16-year-old vineyard consisting of two adjacent blocks of Sauvignon blanc (clone 297 grafted on 110 R) and Barbera (clone 102R4 grafted on SO4) cultivars, situated at Colle del Podio Farm Estate (Ancarano di Rivergaro, Colli Piacentini wine district, 42°50′ 00″ North, 13°06′ 00″ East, 194 m a.s.l.). The vineyard covers approximately two hectares, with rows aligned North–South and a minimal longitudinal slope. Physicochemical soil analyses for the 0–60 cm depth reveal a texture of 31% loam, 10% sand, and 58% clay, classifying it as Silty Clay Loam. Hydrological constants, calculated according to Saxton & Rawls (2016; 2006), are as follows: wilting point = 19.1% vol., field capacity = 36.6% vol., resulting in available water of 0.170 cm/cm.

Vines are spaced 0.9 m × 2.5 m (in the row and between row spacing, respectively), resulting in a vine density of 4444/ha. They are trained to a spur-pruned permanent cordon with vertical shoot positioning (VSP). The main wire is positioned 90 cm above the ground, topped by three foliage wires (a pair, a single, and another single from bottom to top), creating a total canopy height of no more than 2.3–2.4 m above ground. During winter pruning, each vine typically retains a count bud load of 10–12, distributed across 5–6 two-node spurs. No shoot or cluster thinning was applied during the season. Due to abundant rainfall recorded in the early part of the growing season, vegetative growth was vigorous and prolonged, necessitating shoot trimming twice (on 26 June and 19 August) to prevent procumbent shoots and facilitate vineyard operations. The vineyard is generally dry-farmed, with soil management involving repeated slight tillage under the rows to control weeds and the maintenance of native vegetation between rows through periodic mechanical mowing.

For each cultivar, three adjacent uniform rows, each approximately 100 m in length, were selected and equipped with a cluster cooling system as described below. Within each row, six healthy vines, representative of the cooling (CL) treatment, were randomly selected for detailed agronomic and physiological assessment. An equal number of vines were chosen from three adjacent control (C) rows that were not cooled.

On July 22, the onset of veraison was identified in both varieties by observing initial berry softening and translucency. The following day, July 23, full basal defoliation (D) was manually conducted on half of the vines designated for Control (C) and cooling (CL) treatments. This involved removing all main leaves from node 1 up to one node above any second cluster along a shoot, and any lateral shoots, if present, were also plucked to maximize cluster light exposure. The remaining vines were left non-defoliated (ND). The four resulting treatment combinations were: C-ND (control– non-defoliated); C-D (control– defoliated); CL-ND (cooled– non-defoliated); and CL-D (cooled– defoliated) (Figure S1).

Cooling system: description and setup

The cooling system was installed on three adjacent rows of Sauvignon blanc and Barbera by mounting Super Fogger Micro Sprinklers (Naandanjain Italy, Pomezia, Rome), each equipped with two outlets and operating at a medium pressure of 3 bars (green cover) to deliver a maximum flow rate of 11.2 L/h. Each sprinkler includes a built-in leakage prevention device and a unique filter for added protection. The Super Foggers (SF) were positioned at intervals matching the vine spacing within the row (90 cm), ensuring each sprinkler was centered at mid cordon (Fig. S1). Each SF was connected to the dripper pipeline using 3/8″ connection threads and extended about 10 cm above the cordon. The selected medium pressure SF ensures an average droplet size of approximately 69 microns, aiming to favor homogeneous foliage and cluster wetting during pulsed operation. Since SF was not installed in cases of missing or dead vines, the total number of operational SF sprinklers was 309 for Sauvignon blanc and 297 for Barbera.

Following initial checks using 76 × 22 mm water-sensitive papers (Syngenta Italy, Milano, IT), the intermittent cooling was configured to operate on 1 min on and 2 min off cycles. Automation and programming of the system were managed through the central control irrigation system, SAPIR 2 (Talgil Computing and Control LTD, Kiryat Motzkin, Israel). SAPIR 2 features an internet-enabled controller capable of managing a network of up to 32 outputs. The programming and monitoring of SAPIR 2 are conducted via the DREAM SPOT application platform, accessible on a user's smartphone and/or tablet. The program employs a "start by condition" trigger to activate the system whenever the air temperature (T) exceeds 33 °C and relative humidity (RH) falls below 55%, while a "stop by condition" trigger is set for air T below 31 °C. To ensure system responsiveness between these conditions, "enable by conditions" (granting permission to run the program when the condition is active) and "disable by condition" (denying permission to run the program when the condition is active) pointers were also activated. T and RH are continuously monitored by two built-in analog sensors, recording data at 10 s intervals.

Thermal canopy assessment

Thermal images of clusters and/or leaves were captured using a FLIR E8 Pro infrared camera (FLIR Systems, Inc., Wilsonville, OR, USA), which operates within the 7.5–13 µm wavelength range and offers a spatial resolution of 320 × 240 pixels. In the D treatments, individual clusters were measured, while in the ND treatments, the acquired images included an exposed cluster along with portions of the surrounding leaves. For each labeled vine in each treatment, one image was taken in the afternoon (14:00–16:00) on DOY 206 (24 July) for Sauvignon blanc and on DOY 213 (31 July) for Barbera, standing in front of the west-facing side of the rows. On DOY 236 (23 August), afternoon readings were conducted for both varieties using the same protocol.

All measurements were conducted at a focus distance of approximately 0.5 m, using a wet white paper sheet as a background to ensure the entire cluster silhouette was captured. Each image was then manually processed to isolate the largest inset areas for clusters, while leaf pixels were discarded in the ND treatments. Subsequently, the images were analyzed with the FLIR QuikReport software to calculate the mean, maximum, and minimum cluster temperatures.

Leaf gas exchange and water status

To assess the potential interaction between irrigation and leaf removal levels on leaf function, gas exchange variables—specifically, leaf assimilation rate (A), leaf transpiration rate (E), and stomatal conductance (g_s)—were measured between 11:00 and 13:00 on the east-facing side of the row. This was conducted on two mature mid-shoot leaves (located at nodes 7–10) using an LCi T Pro (ADC Bioscientific Ltd., Hoddesdon, Herts., UK). The leaves were evaluated at ambient CO_2 and relative humidity without altering their natural position, ensuring they received saturating light (PAR > 1.400 µmol·m^{-2}s^{-1}). The same leaves used for gas-exchange measurements were subsequently processed for midday leaf water potential (Ψ_{MD}). They were swiftly enclosed in a transparent bag to minimize transpiration, cut at the petiole with a razor blade, and quickly inserted into the pressure chamber with a well-protruding petiole stub. Pressurization ceased at the first sign of xylem sap appearing at the cut surface.

Yield components and grape composition at harvest

The harvest was conducted manually on 26 August (DOY 239) for Sauvignon blanc and on 11 September (DOY 255) for Barbera. Each test vine was picked individually, with the total number of clusters per vine counted and the mean cluster weight calculated accordingly. Simultaneously, three representative clusters per vine—typically located on the basal, median, and apical portions of the cordon—were taken to the laboratory for further sub-sampling. Each cluster was weighed individually, and a 50-berry subsample was randomly selected from the three clusters by carefully cutting each berry at the pedicel with small, sharp scissors. The remaining berries were crushed, and the musts were immediately analyzed for total soluble solids concentration (TSS, as °Brix), pH, and titratable acidity (TA as g L^{-1}). TSS concentration was determined using a temperature-compensating refractometer (RX-5000 Atago U.S.A., Bellevue, WA). Must pH was measured with a digital PHM82 pH-meter (Radiometer Analytical s.s.s, Villeurbanne Cedex, France), and TA was assessed by titration with 0.1 N NaOH (pH 8.2 endpoint) and expressed as g L^{-1} of tartaric acid equivalents. In Barbera, each 50-berry subsample, while still frozen, was homogenized at 10,000 rpm using the Ultra-Turrax T25 (Rose Scientific, Edmonton, AB, Canada) homogenizer for 1 min. Then, 2 g of the homogenate was transferred to a pre-tared centrifuge tube, enriched with 10 mL of aqueous ethanol (50%, pH 5.0), capped, and mixed periodically for 1 h before centrifugation at 959 g for 5 min. A portion of the extract (0.5 mL) was added to 10 mL of 1 mol/L HCl, mixed, and allowed to stand for 3 h; the absorbance was then measured at 520 and 280 nm using a Jasco V-530 UV spectrophotometer (Jasco Analytical Instruments, Easton, MD, USA). The concentration and content of total anthocyanins and phenolic substances was expressed as mg/g and mg/berry, respectively.

To evaluate the concentrations of tartaric and malic acids in all samples collected at harvest, a portion of the must was diluted fourfold, filtered through a 0.22 µm polypropylene syringe for high-performance liquid chromatography (HPLC) analysis, and then transferred to auto-sampler vials. All solvents used were of HPLC grade. Water of Milli-Q quality, acetonitrile, and methanol were sourced from VWR. Standards for L-(+)-tartaric acid and L-(-)-malic acid were obtained from Sigma-Aldrich. The chromatographic method was developed using an Agilent 1260 Infinity Quaternary LC (Agilent Technology), which included a G1311B/C quaternary pump with an inline degassing unit, a G1329B autosampler, a G1330B thermostat, a G1316B thermostated column compartment, and a G4212B diode array detector (DAD) equipped with a 10 mm path, 1 µL volume Max-Light cartridge flow cell. The instrument was operated using Agilent Chemstation software version A.01.05. The analysis of organic acids employed an Allure Organic Acid Column, 300 × 4.6 mm, 5 µm (Restek). Separation was conducted under isocratic conditions using water, with the pH adjusted to 2.5 using ortho-phosphoric acid, at a flow rate of 0.8 mL/min. The column temperature was kept at 30 ± 0.1 °C, and 15 µL of the sample was injected. Elution was monitored at wavelengths from 200 to 700 nm and detected by UV–Vis absorption with DAD at 210 nm. Organic acids were identified using authentic standards, and quantification was based on peak areas, performed through external calibration with standards.

Statistical analysis

For each cultivar, a two-way ANOVA was conducted on gas exchange and vine performance data using the SigmaStat 10.0 software package (Systat Software, San Jose, CA, USA). The main factors, irrigation and leaf removal, each had two levels. When significant differences were found within the main effects (i.e., C vs. CL and ND vs. D), mean separation was determined using the t-test at $p \leq 0.05$ under protected F conditions. The first-order interaction between irrigation (I) and leaf removal (LR) was analyzed only if the Fisher test indicated significance ($p \geq 0.05$), with interactive means separated using the Student Newman Keuls test at the same probability level. Repeated measures of the same parameters (berry mass, TSS, and TA) taken on different dates from the same individuals throughout the study season were analyzed using the repeated measures ANOVA routine in the XLSTAT 2022.1 software package (Addinsoft, New York, NY, USA).

Results

Weather trends, frequency and amount of water supply

Figure 1 illustrates daily values from DOY 183 (2 July) to DOY 274 (1 October) for maximum air temperature (T_{max}) and relative humidity (RH) as recorded by the SAPIR 2 station. Concurrently, daily rainfall (mm) data is provided by the NetSense weather station. The cooling system was active from DOY 204 to DOY 254, beginning before veraison (estimated at DOY 212 for both varieties) and ending one day after the final harvest of the Barbera variety. This allowed for a potential activation period of 51 days, and as shown in Table 1, the conditions necessary to trigger the cooling system were met on 44 days, accounting for 86.3% of the time. Table 1 also details the number of activation days, the duration of each cooling period, and the total water supplied during each event. Within the set intermittent cooling cycle of 60 s "on" and 120 s "off," the daily duration of foggers in the "on" state ranged from 0 to 118 min, while on particularly hot days, the system ran continuously for over 4 h. The total seasonal activation time slightly exceeded 5000 min. Consequently, the Sauvignon vines received a total of 145 mm/ha, whereas the Barbera vines were supplied with 183 mm/ha (Table 1). Considering that the cooling system supplied water for a total of 31 days in Sauvignon blanc and 44 days in Barbera, the calculated mean daily water supply was 4.7 mm/day and 4.1 mm/day, respectively.

Cluster temperature

The average maximum air temperature and relative humidity on July 24 in Sauvignon were 34.0 °C and 54%, respectively, resulting in a calculated leaf-to-air vapor pressure deficit of 2.45 kPa. Under these conditions, the cooled vines exhibited a significantly lower mean cluster temperature compared to the control vines, with a difference of -3.2 °C. Conversely, the difference in maximum temperature was not substantial enough to be considered significant (Table 2). The mean and maximum cluster temperatures recorded in ND and D vines were quite similar, and no interactions between I and LR were observed.

The same survey was conducted in Barbera on July 31, with the average T_{max} reaching 36.5 °C and RH at 47%, resulting in a VPD of 3.24 kPa. Under such high evaporative demand, the results indicated a greater vine responsiveness to the applied treatment. While cooling proved effective in reducing cluster T_{mean} and T_{max} compared to C (by 5.3 °C less), defoliated vines also exhibited significantly higher cluster heating than the ND vines (Table 2). The significant

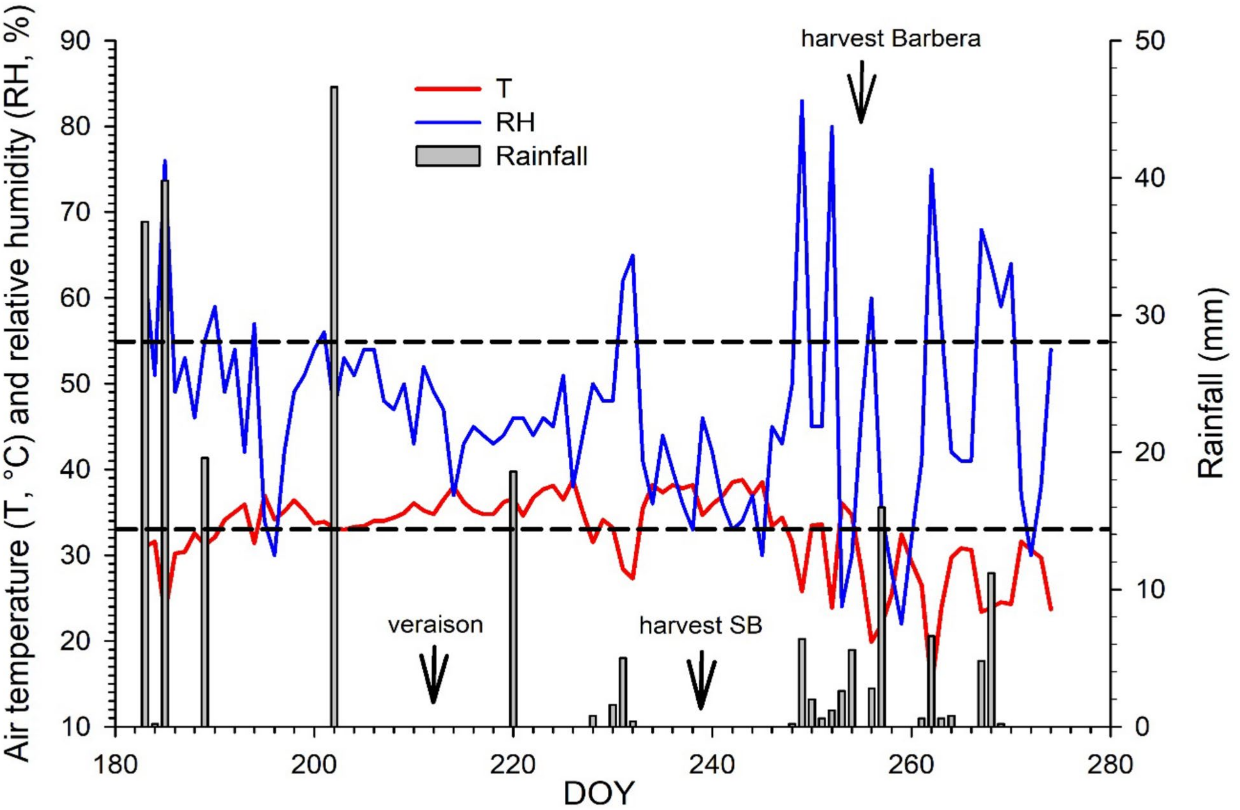


Fig. 1 Daily maximum air temperature (T_{max} as °C), air relative humidity (RH as %) and precipitation (mm) recorded at the experimental site by the SAPIR-2 and Netsense weather stations for the period comprised between DOY 183–274. Horizontal dotted lines identify climatic thresholds chosen for foggers activation (i.e. T max≥33 °C and RH≤55%). *SB* sauvignon blanc

I x LR interaction found for T_{max} (Figure S2) indicated that, in ND, effective cluster T control was achieved regardless of cooling application, and the same was true for the CL-D treatments. As expected, the treatment combination leading to consistent cluster heating (45.6 °C) was C-D.

Readings taken on the afternoon of August 23 reflect conditions of peak evaporative demand, with an average air T_{max} of 38.2 °C and RH at 40%; the calculated VPD was 4.02 kPa. In Sauvignon, cooling resulted in the most significant cluster temperature drop, with T_{mean} and T_{max} decreasing by 8.7 °C and 10.3 °C, respectively. However, another significant I x LR removal interaction was identified for T_{mean} (Figure S2), indicating that a very similar cluster temperature (approximately 32.2 °C) was achieved in the CL treatments, regardless of whether basal LR was performed. Conversely, in the D treatments, cooling led to a 10.2 °C reduction in cluster temperature compared to the uncooled vines. Data collected the same afternoon on Barbera confirmed that cooling significantly reduced cluster T_{mean} and T_{max} compared to C (− 8.1 °C and − 9.1 °C for T_{mean} and T_{max}, respectively), while no significant differences were found across main LF effects, and the I x LR interaction was also non-significant.

Leaf gas exchange and water status

Gas exchange rates observed in mature Sauvignon blanc leaves on July 30 and August 21 were nearly optimal (Table 3). Significant differences in irrigation levels were noted for g_s on July 30 and for E on August 21, while differences in leaf removal levels were rather sporadic. The absence of severe water stress or any condition causing even partial stomatal closure is further supported by the midday leaf water potential measurements, which never fell below -1.1 MPa, and by the generally high leaf g_s rates. No significant I x LR interactions were detected for any of the measured variables.

A different perspective emerged from the assessment of leaf function and water status conducted in Barbera (Table 4). On July 30, measurements indicated generally good leaf function, though notable differences in T_{leaf}, g_s, and Y_{MD} between C and CL levels suggested a mild limitation in the uncooled vines. On the same day, leaf removal showed no effects. By August 21, a hot day with leaf temperatures reaching 46.3 °C in the C treatment, the limitation in leaf function for the uncooled vines was confirmed. When data were combined across the two defoliation levels, the C treatment exhibited a fractional reduction in E, g_s, and

Table 1 Water volume daily supplied to cooled Sauvignon blanc (SB) and Barbera grapevines and expressed on a hectare basis. Calculations refer to an intermittent supply (60 s “on” and 120 s “off” cycles). The chosen fogger type delivers 11.2 L/hours

DOY	Total water supply to SB (m^3/ha)	Total water supply to Barbera (m^3/ha)	Time length of foggers “on” (mins)*	Total time length for each “on–off” cycle (mins)
204	22.06	23.94	24	72
205	20.72	19.00	22	76
206	32.51	33.67	36	108
207	29.20	29.03	32	96
208	41.57	40.10	44	132
209	51.06	50.13	56	168
210	76.95	74.37	84	252
211	47.75	48.93	52	96
212	34.09	36.21	38	104
213	63.14	45.64	58	174
214	23.73	16.16	18	54
215	107.30	45.19	96	288
216	93.49	79.46	82	246
217	79.10	71.97	74	202
218	97.95	82.15	88	264
219	28.05	20.50	30	90
220	22.72	21.10	28	84
221	47.03	59.86	60	180
222	9.92	12.57	12	36
223	15.68	17.36	16	48
224	15.53	15.86	14	42
225	7.05	7.18	6	18
226	53.65	57.31	50	150
227	44.15	48.48	40	120
228	0.00	0.00	–	–
229	8.20	7.03	8	24
230	0.00	0.00	–	–
231	0.00	0.00	–	–
232	0.00	0.00	–	–
233	26.46	27.08	24	72
234	95.65	82.15	88	264
235	8.63	5.98	8	24
236	61.92	59.05	72	216
237	99.53	90.08	92	276
238	94.64	83.20	84	252
239	–	28.73	26	39
240	–	31.42	32	48
241	–	59.40	62	93
242	–	45.49	42	63
243	–	134.08	118	177
244	–	79.91	76	104
245	–	116.57	106	159
246	–	2.09	2	3
247	–	41.30	40	60
248	–	0.00	–	–
249	–	0.00	–	–
250	–	1.79	2	3
251	–	6.43	6	9
252	–	0.00	–	–
253	–	21.54	20	30
254	–	10.02	8	12
Total	1451.23	1829.65	1976	5028

To scale up parcel water supply to a hectare basis, one fogger per vine was considered (i.e. 4444/hectare). DOY = day of year

[*] Until DOY 238, this value includes both varieties

Table 2 Cluster mean (T_{mean}) and maximum (T_{max}) temperature recorded in the afternoon of 24 July for Sauvignon blanc, afternoon of 31 July for Barbera and afternoon of 23 August in both varieties for either cooled (CL) and non-irrigated control (C) vines and for non defoliated (ND) and defoliated (D) vines. Probability values in bold indicate $P < 0.05$

	Irrigation (I)	24 July		31 July		23 August	
		T_{mean}	T_{max}	T_{mean}	T_{max}	T_{mean}	T_{max}
Sauvignon blanc	C	35.9±0.55	37.9±0.81			40.9±0.74	46.5±1.22
	CL	32.7±0.62	36.0±0.63			32.2±0.59	36.2±0.72
	Pr>F	**0.001**	0.065			**0.000**	**0.000**
	Leaf removal (LR)						
	ND	33.9±0.55	36.1±0.64			35.7±1.09	40.0±1.47
	D	34.6±0.84	37.9±0.80			37.5±1.44	42.7±1.63
	Pr>F	0.395	0.086			**0.044**	**0.023**
	I x LR (Pr>F)	0.123	0.617			**0.036**	0.175
Barbera	Irrigation (I)						
	C			37.9±1.06	41.9±1.22	41.0±0.50	48.5±0.83
	CL			32.6±0.41	36.6±0.54	33.1±0.60	39.4±0.86
	Pr>F			**0.000**	**0.000**	**0.000**	**0.000**
	Leaf removal (LR)						
	ND			34.4±0.60	37.1±0.61	37.0±1.05	43.5±1.40
	D			36.1±1.01	41.4±1.30	37.1±1.26	44.4±1.50
	Pr>F			**0.019**	**0.000**	0.458	0.913
	I x LR (Pr>F)			0.052	**0.003**	0.682	0.428

In the CL treatments readings were taken right at the end of cooling period from about 2 to 4 PM. Means represent data taken on one cluster per vine (n=18)

In case of significance of the F test, within column and within factor mean separation was performed by t-test, p=0.05

Table 3 Leaf function and water status assessed on two summer dates as transpiration (E), stomatal conductance (g_s), assimilation (A) and midday leaf water potential (Ψ_{MD}) in Sauvignon blanc grapevines assigned to two irrigation (I) treatments (C=non irrigated control and CL=cooled) and two leaf removal (LR) treatments (ND=non defoliated and D=defoliated). For each treatments mean (main effects) n=18. Pr>F values in bold indicate significance at $p \geq 0.05$

	30 July					21 August				
	T_{leaf} (°C)	E (mmol m^{-2} s^{-1})	g_s (mol m^{-2} s^{-1})	A (µmol m^{-2}-s^{-1})	Ψ_{MD} (-MPa)	T_{leaf} (°C)	E (mmol m^{-2} s^{-1})	g_s (mol m^{-2} s^{-1})	A (µmol m-2-s1)	Ψ_{MD} (-MPa)
Irrigation (I)										
C	38.7±0.26	7.61±0.22	0.518±0.027	11.0±0.39	0.76±0.01	41.6±0.63	7.55±0.32	0.261±0.014	11.1±0.27	1.06±0.018
CL	38.7±0.16	7.08±0.18	0.409±0.016	10.6±0.47	0.79±0.03	42.5±0.21	8.86±0.15	0.258±0.010	11.3±0.39	1.02±0.05
Pr>F	0.963	0.054	**0.001**	0.524	0.293	0.098	**0.002**	0.833	0.639	0.515
Leaf removal (LR)										
ND	38.6±0.16	7.26±0.16	0.452±0.017	10.6±0.40	0.82±0.02	41.8±0.21	8.14±0.19	0.250±0.010	11.3±0.39	1.00±0.05
D	38.8±0.25	7.44±0.25	0.475±0.033	11.0±0.46	0.73±0.02	42.3±0.58	8.26±0.33	0.269±0.010	11.1±0.29	1.07±0.04
Pr>F	0.683	0.446	0.344	0.565	**0.003**	0.500	0.758	0.297	0.642	0.219
I x LR										
Pr>F	0.334	0.154	0.184	0.532	0.090	0.907	0.681	0.624	0.781	0.562

In case of significance of the F test, within-column and within factor mean separation was performed by t-test

A of 24.5%, 59.5%, and 61.5%, respectively, compared to CL. Importantly, these significant differences occurred at a still non-limiting Ψ_{MD}. A week later, the cooling effect was apparent, with significantly lower leaf T in CL treatments, while variations in gas exchange parameters essentially mirrored previous observations, albeit with slightly different magnitudes. Specifically, the fractional reduction in E, g_s, and A for the pooled C treatments was 42.9%, 67.1%, and 51.9%, respectively, compared to the pooled CL treatments. On August 28, there were still no differences among treatments for Ψ_{MD}, which was slightly more negative (about −1.3 MPa) than on the previous sampling date.

Regarding LR effects, it was only at the final measurement date that E, g_s, and A were significantly lower than the rates observed at the D level when data from both water regimes were combined. Specifically, E, g_s, and A decreased in ND by 28.2%, 39.6%, and 24.2%, respectively, compared to D. At no point did a significant I x LR interaction occur for any of the measured variables (Table 4).

Table 4 Leaf function and water status assessed on three summer dates as transpiration (E), stomatal conductance (gs), assimilation (A) and midday leaf water potential (Ψ_{MD}) in Barbera grapevines assigned to two irrigation (I) treatments (C=non irrigated control and CL=cooled) and two leaf removal (LR) treatments (ND=non defoliated and D=defoliated)

	30 July					21 August					28 August				
	T_{leaf} (°C)	E (mmol m^{-2} s^{-1})	g_s (mol m^{-2} s^{-1})	A (μmol m^{-2} s^{-1})	Ψ_{MD} (-MPa)	T_{leaf} (°C)	E (mmol m^{-2} s^{-1})	g_s (mol m^{-2} s^{-1})	A (μmol m^{-2} s^{-1})	Ψ_{MD} (-MPa)	T_{leaf} (°C)	E (mmol m^{-2} s^{-1})	g_s (mol m^{-2} s^{-1})	A (μmol m^{-2} s^{-1})	Ψ_{MD} (-MPa)
Irrigation (I)															
C	40.1±0.27	6.03±0.24	0.224±0.016	10.1±0.56	1.08±0.030	46.6±0.42	3.61±0.61	0.064±0.014	3.7±0.61	1.27±0.03	44.5±0.39	2.64±0.35	0.049±0.009	5.2±0.72	1.32±0.03
CL	38.4±0.28	6.09±0.25	0.331±0.040	11.4±0.41	0.88±0.050	44.3±0.23	4.78±0.35	0.158±0.015	9.6±0.51	1.24±0.03	40.1±0.63	4.62±0.28	0.149±0.016	10.8±0.56	1.35±0.04
Pr>F	**0.000**	0.866	**0.020**	0.087	**0.001**	**0.000**	**0.000**	**0.000**	**0.000**	0.468	**0.001**	**0.000**	**0.000**	**0.000**	0.599
Leaf removal (LR)															
ND	39.5±0.35	6.18±0.21	0.263±0.018	10.8±0.57	1.02±0.044	46.0±0.42	4.87±0.69	0.099±0.020	5.88±0.86	1.25±0.03	42.8±0.76	3.03±0.35	0.075±0.015	6.9±0.96	1.34±0.04
D	38.9±0.31	5.92±0.27	0.293±0.043	10.8±0.46	0.94±0.05	44.9±0.44	5.52±0.58	0.124±0.018	7.42±1.00	1.26±0.03	41.8±0.77	4.22±0.40	0.124±0.020	9.1±0.90	1.34±0.04
Pr>F	0.094	0.459	0.491	0.986	0.147	0.071	0.372	0.244	0.057	0.779	0.168	**0.007**	**0.007**	**0.017**	0.891
I x LR															
Pr>F	0.644	0.400	0.318	0.714	0.930	0.657	0.783	0.445	0.863	0.595	0.933	0.761	0.240	0.867	0.553

For each treatment mean (main effects) n=18. Pr>F values in bold indicate significance at $p \geq 0.05$

In case of significance of the F test, within-column and within factor mean separation was performed by t-test, p=0.05

Yield components, ripening dynamic and grape composition at harvest

In Sauvignon blanc, although the number of clusters per vine recorded in C was higher than in CL due to some variability within the treatment, there was no significant effect on either the final cluster weight or yield per vine (Table 5). Regarding the effects of LR, D resulted in smaller clusters and berries, yet it did not lead to a significant difference in the final yield per vine (Table 5).

Figure 2A–C illustrates the dynamics of fresh berry mass, TSS, and TA in Sauvignon grapes, assessed over four dates between post-veraison and harvest. Initially, there was no difference in berry mass among the treatment combinations, but subsequently, C-ND consistently exhibited larger berry size, which persisted until harvest. The first TSS sampling revealed some differences among treatment combinations, with TSS ranging from 5.8 to 7.2 Brix. These differences tended to diminish over the following dates, except for C-D, which temporarily showed lower TSS on two occasions (Fig. 2B). In contrast, the TA time trends did not reach significance (C).

The effects on the final composition of Sauvignon blanc grapes, when comparing C and CL vines, were specifically related to total acidity and malic acid concentration (Table 5). Total acidity was higher in C vines, while, somewhat unexpectedly, the pooled data for CL vines across defoliation levels showed a significant reduction in malic acid. When examining the main effects related to defoliation, total acidity and malic acid were again the most responsive variables: ND vines retained higher total acidity, driven by increased malic acid at harvest. The main treatment effects on sunburn incidence were pronounced: cooling reduced sunburn incidence by 11.7% compared to no cooling, while the presence of basal leaves decreased sunburn incidence by 9.5% compared to D (Table 5).

In Barbera, the total yield per vine and its main components remained unaffected by the presence or absence of the cooling system (Table 6). In contrast, data pooled over the irrigation levels indicated a lower total yield per vine in D, primarily due to smaller clusters. No significant I x LR interaction was found for the yield components. The time trend for berry mass, represented for the four treatment combinations, showed considerable variability over the last two sampling dates, despite starting with a fairly uniform berry size across the treatments (Fig. 3A). The dynamics of TTS berry accumulation began with a very uniform sugar level (around 5 Brix), and subsequently, C-ND tended to exhibit higher TSS than the other treatments (Fig. 3B). These differences were also reflected in the TA values recorded at the intermediate sampling dates (i.e., DOY 226, 232, 241),

Table 5 Yield components, grape composition and cluster sunburn incidence determined in Sauvignon blanc grapevines assigned to two irrigation (I) treatments (C=non irrigated control and CL=cooled) and two leaf removal (LR) treatments (ND=non defoliated and D=defoliated)

	Clusters/vine	Cluster weight (g)	Berry weight (g)	Yield/vine (kg)	TSS (°Brix)	pH	TA (g/L)	Tartaric acid (g/L)	Malic acid (g/L)	Berry sunburn incidence (%)
Irrigation (I)										
C	31.2±1.8	65.2±4.7	1. 727±0.042	2.00±0.19	21.9±0.35	3.14±0.03	8.26±0.29	7.79±0.26	2.23±0.17	15.1±2.48
CL	25.1±1.3	64.1±4.3	1.573±0.035	1.58±0.15	21.8±0.24	3.16±0.01	7.32±0.18	7.15±0.22	1.45±0.10	3.4±1.14
Pr>F	**0.005**	0.931	**0.002**	0.078	0.879	0.288	**0.004**	0.069	**0.001**	**0.000**
Leaf removal (LR)										
ND	26.7±1.4	71.6±4.8	1,717±0.040	1.90±0.17	21.7±0.35	3.13±0.02	8.17±0.30	7.43±0.25	2.03±0.18	4.6±1.73
D	29.5±1.9	51.4±3.3	1,583+0.030	1.67±0.14	22.0±0.24	3,17±0.02	7.40±0.19	7.53±0.25	1.69±0.16	14.1±2.50
Pr>F	0.151	**0.034**	**0.006**	0.341	0.602	0.154	**0.015**	0.563	**0.167**	**0.000**
I x LR										
Pr>F	0.109	0.781	0.310	0.363	0.175	0.236	0.075	0.874	0.837	0.063

For each treatments mean (main effects) n=18. Pr>F values in bold indicate significance at $p \geq 0.05$

In case of significance of the F test, within-column and within factor mean separation was performed by t-test

where C-D was generally the treatment combination retaining higher TA (Fig. 3C).

Barbera was generally more responsive to cooling and basal defoliation than Sauvignon blanc in terms of grape composition at harvest, with a couple of I x LR interactions also observed (Table 6 and Figure S3). The first interaction involved TSS recorded at harvest, revealing that while cooling resulted in the same TSS level (24.7 Brix) regardless of defoliation (Figure S3), in the absence of cooling, defoliation led to a significantly lower TSS (-3.2 Brix) compared to non-defoliated vines. The second interaction concerned sunburn incidence (Figure S3), showing that a low incidence (2–4%) occurred in non-defoliated vines, whether cooled or not. However, with basal defoliation, cooling was essential to limit berry sunburn to 8.1%, which surged to 29.4% without cooling.

Although irrigation and defoliation levels did not affect TA, D vines exhibited lower malic acid and higher tartaric acid compared to ND vines. Climatization consistently influenced total anthocyanins and phenolics, regardless of whether the data were expressed in terms of concentration (mg/g) or content (mg per berry) (Table 6). At harvest, cooled vines accumulated fewer pigments and phenolics than C vines (Table 6). Regarding leaf removal effects, D vines showed lower total anthocyanins and content compared to ND vines, and this trend, though less pronounced, was also observed in total phenolics.

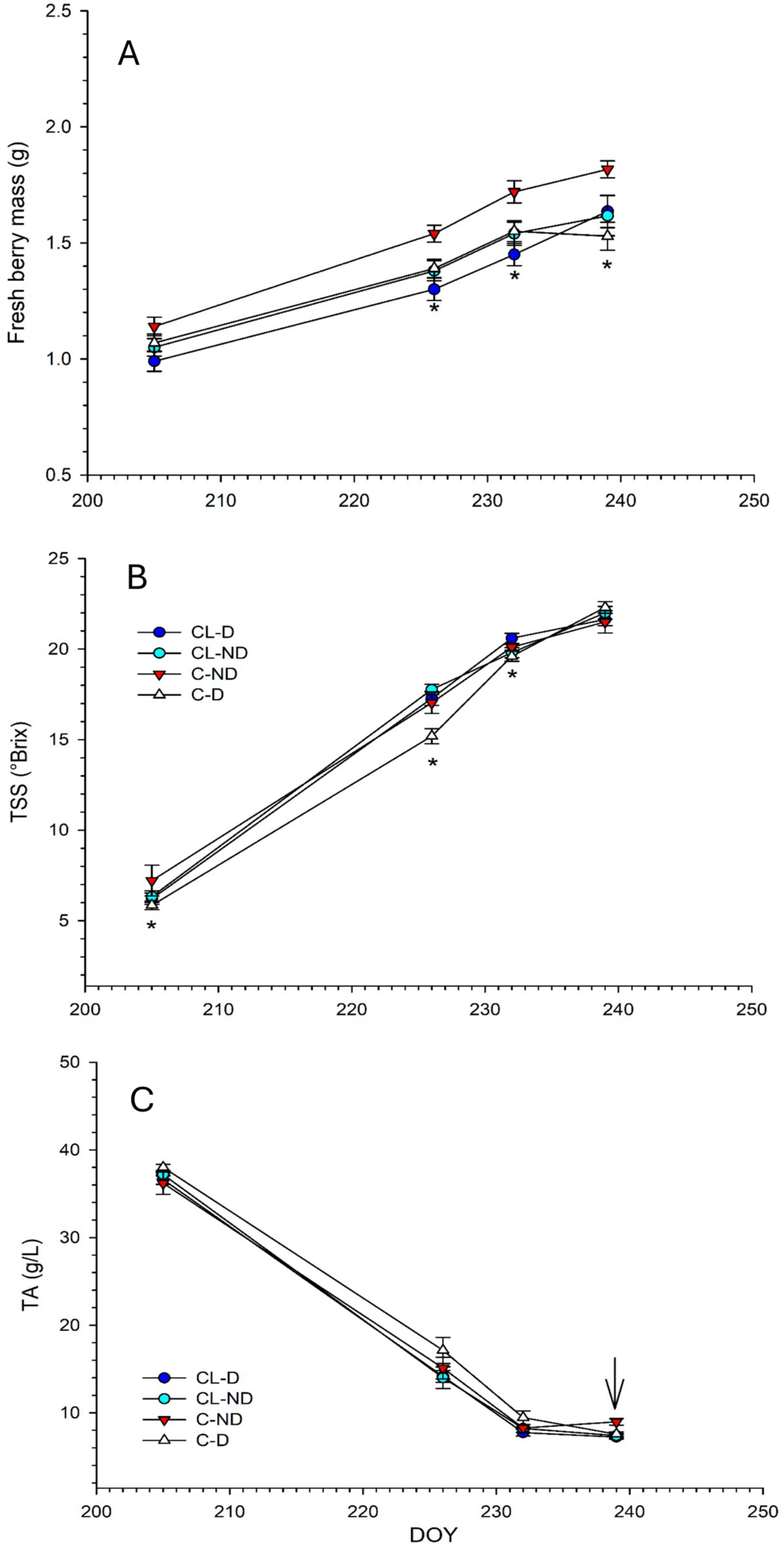
Discussion

Anticipated advantages of an innovative and automated cooling system encompass comprehensive control over cluster overheating, thereby preventing significant berry dehydration and sunburn damage. This system also enhances canopy hydration levels, potentially benefiting gas exchange and promoting the sustainable use of water resources through localized water application, where only the basal part of the canopy is wetted, and the use of an automated activation system. Under cooling conditions, the yield per vine is likely to surpass that of control conditions due to increased berry size and the absence of berry dehydration. However, predicting the response in terms of grape composition is more challenging due to the complex interactions between cluster and leaf temperature and the dynamics of component accumulation within the berry (Poni et al. 2018).

The already intricate scenario described above becomes even more complex in our work as we also introduced the variant of no or basal defoliation. We are unaware of any published work that has previously addressed such an interaction. Indeed, in the absence of cooling, extensive research has shown that relatively early defoliation (at the end of flowering) in Chardonnay, as opposed to late defoliation (at veraison), results in significantly less sunburn damage (Gambetta et al. 2019, 2021) due to higher concentrations of flavonoids in the berries, which act as sunscreen compounds. In our study, defoliation in both varieties was conducted at the onset of veraison, causing a sudden and permanent change in cluster exposure, likely representing a high-risk scenario. In fact, for both cultivars, the incidence of berry sunburn was highest in the C-D treatment combination, although in Barbera, the other three treatment combinations (Figure S3) showed no significant differences. This demonstrates that maintaining at least partial leaf cover around the clusters (Figure S1) during the hottest part of the season can be as effective as cooling in controlling sunburn (Poni et al. 2023).

In our study, the efficiency of the cooling system was evaluated based on the following considerations, all supported by data in Table 2: (i) The cluster temperature

Fig. 2 Time trends of fresh berry mass (**A**), total soluble solids (TSS as Brix) (**B**), and titratable acidity (TA as g/L) (**C**) recorded on Sauvignon blanc grape samples for the four treatment combinations (C-ND, C-D, CL-ND, and CL-D) from veraison until harvest. In the bottom panel, the arrow marks the harvest date. Data were analyzed using Repeated Measure analysis with the XL-STAT package, yielding the following results: fresh berry mass (**A**) showed significant between-subjects (treatments) and time × treatment interaction with F = 71.8 ($p < 0.001$) and F = 7.27 ($p < 0.001$), respectively; TSS (**B**) also exhibited significant between-subjects (treatments) and time × treatment interaction with F = 6.72 ($p < 0.007$) and F = 2.23 ($p < 0.041$), respectively; TA (**C**) was not significant. Within each panel and date, vertical bars represent standard error (SE), while * indicates significant differences among the four treatment combinations on a single date, according to mean separation conducted with the SNK test at $p < 0.05$



remained consistent between CL-ND and CL-D across all dates and cultivars, indicating that the presence of leaves around the cluster did not hinder the cooling effect. Additionally, the hypothesis that foggers positioned near a leaf or cluster might cause water to leak onto the ground, thereby partially reducing the cooling effect, must be dismissed. (ii) When C-ND is used as the standard control treatment, the maximum cooling was observed in CL-ND on August 23, with temperatures dropping by − 7.1 °C and − 8.6 °C for T_{max} in Sauvignon blanc and Barbera, respectively. It is somewhat challenging to compare cluster cooling data from previous studies: Paciello et al. (2017) reported a −7 °C cooling in their treatment, but their temperature measurements were taken "around the canopy." Similarly, Bianchi et al. (2023) did not measure cluster temperature, relying instead on thermo-hygrometers placed at various canopy heights. The most comparable data comes from Valentini et al. (2024), who measured berry temperature using thermocouples and an infrared thermometer, achieving a − 6 °C cooling compared to the uncooled control of Sangiovese and Montepulciano vines grown in pots. In our study, when isolating the effect of defoliation without any cooling (e.g., comparing C-ND and C-D), the presence of leaf cover provided a cooling effect of about 3–4 °C compared to defoliated treatments. However, on the hot day of August 23, T_{mean} and T_{max} did not differ between C-ND and C-D in Barbera. This could be attributed to the relatively sparse canopy in the C-ND treatment (Figure S1), which still allowed some cluster exposure to direct light.

Leaf gas exchange and water status were assessed two and three times over the season for Sauvignon blanc and Barbera, respectively, revealing distinctly different behaviors between the two genotypes. Under non-limiting leaf Ψ_{MD} conditions, the main treatments of irrigation and leaf removal applied to Sauvignon blanc had only sporadic and inconsistent effects on gas exchange (Table 3). In contrast, for Barbera, although leaf Ψ_{MD} showed no differences among treatments on the sampling dates of August 21 and 28, the uncooled treatment experienced a significant limitation in gas exchange. This limitation is likely driven by a stomatal response to very high VPD conditions, and indeed, the partial stomatal closure led to notable leaf overheating (Table 4). Since this response was not observed in Sauvignon blanc, it is hypothesized that cultivar-dependent stomatal sensitivity to increased VPD is a primary controlling factor. Alongside behavior resembling iso-hydric adjustment (Bartlett and Sinclair 2021), VPD-driven stomatal closure might also explain why, in Barbera, the C treatment maintained an Ψ_{MD} similar to the CL treatment.

However, the most novel outcome emerges when comparing C-D and CL-D. Both treatments lack basal leaves up to node 6; however, cooling, besides lowering the cluster

Table 6 Yield components, grape composition and cluster sunburn incidence determined in Barbera grapevines assigned to two irrigation (I) treatments (C = non irrigated control and CL = cooled) and two leaf removal (LR) treatments (ND = non defoliated and D = defoliated)

	Clusters/vine	Cluster weight (g)	Berry weight (g)	Yield/vine (kg)	TSS (°Brix)	pH	TA (g/L)	Tartaric (g/L)	Malic (g/L)	Total anthocyanins (mg/g)	Total anthocyanins (mg/berry)	Total phenolics (mg/berry)	Total phenolics (mg/g)	Berry sunburn incidence (%)
Irrigation (I)														
C	22.6 ± 2.1	74.5 ± 8.1	2.75 ± 0.08	1.64 ± 0.19	25.1 ± 0.74	3.40 ± 0.03	10.5 ± 0.4	8.02 ± 0.23	2.48 ± 0.11	0.887 ± 0.059	2.45 ± 0.19	1.917 ± 0.089	5.28 ± 0.30	16.6 ± 3.1
CL	18.5 ± 1.24	93.1 ± 8.8	2.90 + 0.09	1.65 ± 0.14	24.7 ± 0.61	3.46 ± 0.03	10.7 ± 0.5	7.61 ± 0.22	2.97 ± 0.19	0.662 ± 0.037	1.95 ± 0.14	1.554 ± 0.068	4.57 ± 0.27	5.3 ± 1.1
Pr > F	0.112	0.062	0.101	0.964	0.436	0.011	0.595	0.020	**0.000**	**0.000**	**0.003**	**0.000**	**0.014**	**0.000**
Leaf removal (LR)														
ND	19.9 ± 1.79	104.8 ± 8.0	2.89 ± 0.08	1.94 ± 0.14	25.7 ± 0.74	3.43 ± 0.03	10.8 ± 0.7	7.61 ± 0.19	2.85 ± 0.18	0.813 ± 0.055	2.37 ± 0.18	1.765 ± 0.093	5.14 ± 0.30	3.1 ± 1.0
D	21.2 ± 1.80	63.2 ± 5.9	2.76 ± 0.10	1.35 ± 0.15	24.1 ± 0.55	3.43 ± 0.03	10.3 ± 0.5	8.04 ± 0.26	2.61 ± 0.14	0.702 ± 0.049	1.92 ± 0.15	1.664 ± 0.060	4.57 ± 0.24	18.8 ± 3.7
Pr > F	0.589	**0.000**	0.144	**0.012**	**0.002**	0.911	0.197	**0.021**	**0.047**	**0.014**	**0.004**	0.182	**0.032**	**0.000**
I x LR														
Pr > F	0.961	0.991	0.661	0.666	**0.003**	0.101	0.247	0.069	0.760	0.251	0.372	0.236	0.422	**0.001**

In case of significance of the F test, within-column and within factor mean separation was performed by t-test

For each treatments mean (main effects) n = 18. Pr > F values in bold indicate significance at p ≥ 0.05

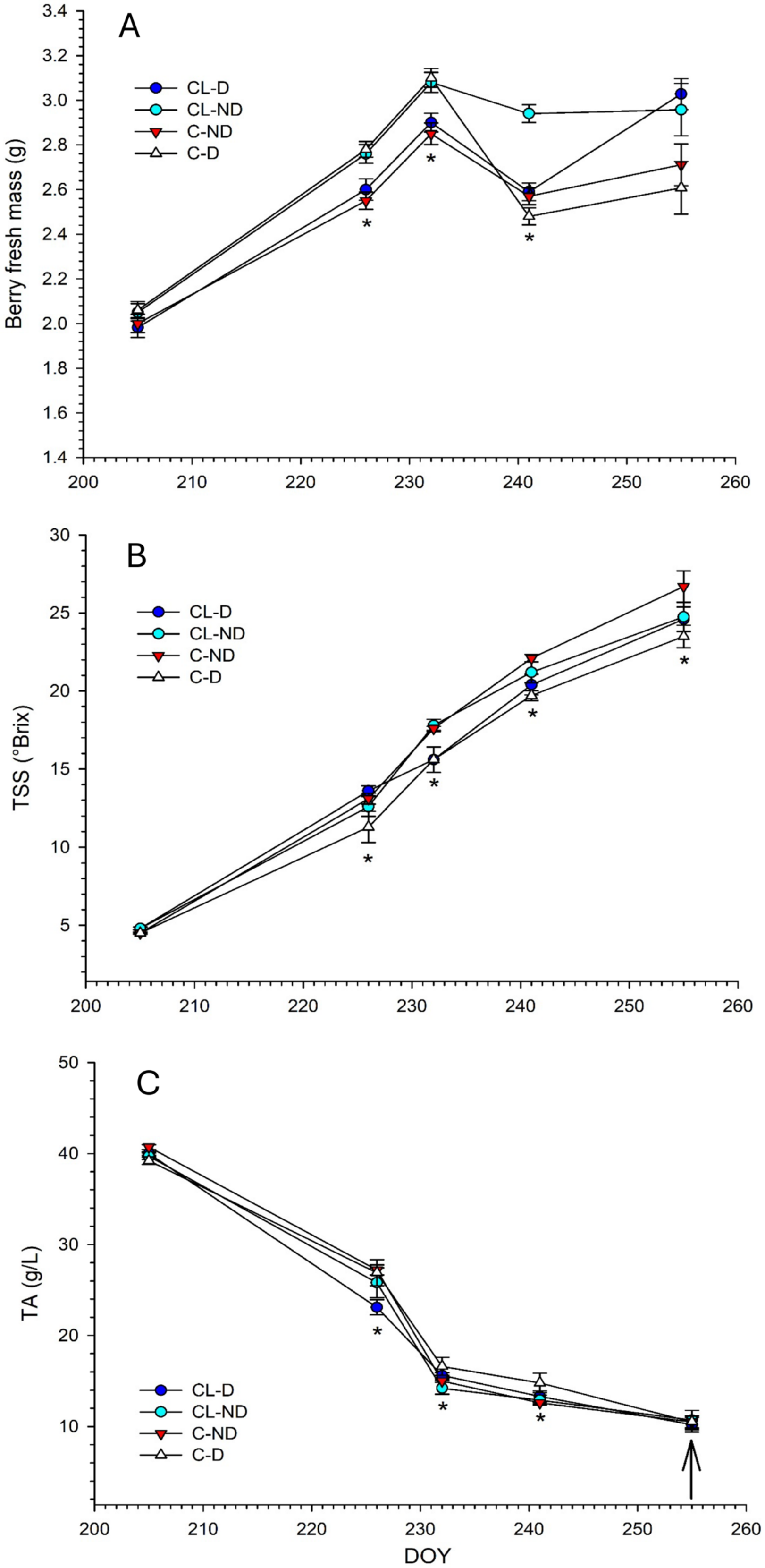


Fig. 3 Time trends for fresh berry mass (**A**), total soluble solids (TSS as Brix) (**B**), and titratable acidity (TA as g/L) (**C**) recorded on Sauvignon blanc grape samples across four treatment combinations (C-ND, C-D, CL-ND, and CL-D) from veraison to harvest. In the bottom panel, an arrow marks the harvest date. Data were analyzed using Repeated Measure analysis with the XL-STAT package, yielding the following results: fresh berry mass (**A**) showed significant between-subjects (treatments) and time × treatment interaction with F = 32.9 ($p < 0.001$) and F = 7.18 ($p < 0.001$), respectively; TSS (**B**) exhibited significant between-subjects (treatments) and time × treatment interaction with F = 7.71 ($p < 0.017$) and F = 2.51 ($p < 0.019$), respectively; TA (**C**) demonstrated a significant time × treatments interaction only, with F = 2.52 ($p < 0.019$). Within each panel and date, vertical bars represent standard error (SE), while * indicates significant differences among the four treatment combinations according to mean separation conducted with the SNK test at $p < 0.05$

temperature, positively influences the function of the upper leaves (approximately nodes 7–10), mitigating the impact of atmospheric water stress. The fact that this difference in leaf function was also observed in the C-ND and CL-ND comparison confirms the effectiveness of our cooling system. A similar effect has been recently reported by Valentini et al. (2024), where the negative effects of a WS treatment, which involved supplying only 50% of the total vine transpiration loss, were almost entirely counteracted by applying nebulization in the cluster zone. This supports the hypothesis that, even in the absence of basal leaves, a cooling system can preserve leaf efficiency and potentially increase leaf longevity.

The sustainability of implementing a cooling system must consider its effects on yield components and grape composition. In Sauvignon blanc, cooling generally did not lead to any noticeable improvement in yield components or grape quality traits. In fact, some responses were contrary to expectations: for example, CL vines had smaller berries and lower TA and malic acid concentrations than C vines. More specifically, C-ND had larger berries than CL-ND, and malic acid levels were lower in both cooled treatments compared to C-ND. Furthermore, unlike previous studies using sprinkler cooling systems (Kliewer and Schultz 1973; Caravia et al. 2017; Paciello et al. 2017), cooling in our Sauvignon vine plots did not delay harvest at all. When considering Sauvignon blanc's response to basal leaf removal, aside from the almost inevitable increase in cluster sunburn due to rapid and full cluster exposure to high light and temperature—which might also explain the lower TA—it is noteworthy that D vines had lower cluster and berry weights. Although the removed leaves are the oldest in the canopy and thus have sub-optimal photosynthetic rates (Poni et al. 1994), it should not be overlooked that these basal leaves are also the largest. Therefore, when data is expressed on a per-leaf basis, it leads to the conclusion that canopy photosynthesis can be significantly reduced (Petrie et al. 2000), thereby imposing some limitations on residual post-veraison berry growth.

Barbera vines demonstrated a greater responsiveness than Sauvignon blanc vines to the treatments applied, both in terms of yield components and the final composition of the grapes (Table 6). Cooling did not significantly impact the main yield components compared to C. Regarding grape composition at harvest, the significant I x LR interaction observed for TSS (Table 6; Figure S3) reveals an intriguing mechanism: In Barbera, cooling overshadowed any effect of LR on the final TSS. In both CL treatments, technological ripening was optimal for Barbera grapes, characterized by high TSS (around 24 Brix) coupled with high TA, a typical trait of this cultivar as shown in Bernizzoni et al., (2009). However, the final concentrations and contents of total anthocyanins and phenolics were somewhat disappointing, with values generally lower than those in the uncooled treatments. Specifically concerning anthocyanins, the efficient cooling achieved by foggers (cluster T_{mean} of 33–35 °C compared to over 40 °C in the uncooled) did not appear to positively influence color accumulation.

This also contradicts the abundant evidence indicating that high temperatures, when combined with high light, rather than high light alone, are primarily responsible for reduced pigmentation in grape berries (Spayd et al. 2002; Tarara et al., 2008; Pastore et al., 2017b; Allegro et al., 2021). This suggests that while color formation is sensitive to canopy manipulation that increases shading around the clusters in the absence of cooling, such sensitivity disappears when cooling is applied to either defoliated or non-defoliated vines. The limited literature available on this topic (i.e., cooling applied in red-grape cultivars) is not exhaustive: an intra-canopy sprinkler system tested at the cluster zone on Cabernet Sauvignon vines (Caravia et al. 2017) showed similar anthocyanin concentrations in both the cooled and uncooled control treatments over two years. In 2015, the cooled treatment had a higher content due to increased berry size. Similarly, in a study on Carignan, Kliewer and Schultz (1973) found little difference in anthocyanin concentration between sprinkled and control treatments. Conversely, in Sangiovese and Montepulciano cultivars, Valentini et al. (2024) reported that cluster fogging combined with a 50% water supply (WS) based on vine water use significantly increased anthocyanin concentration over two seasons compared to a treatment with WS alone.

In our study, the failure of the cooled treatments to increase anthocyanin concentration, despite a significant reduction in surface cluster temperature, shifts the focus to other influencing factors. The most probable factor is the prolonged wetting status that clusters experienced throughout the daily cooling event (Table 1). It has been widely noted that the air VPD surrounding the cluster is the primary driving force behind berry transpiration (Zhang and Keller 2015; Zhu et al. 2019). In grape berries, as in other fleshy fruits, transpiration contributes to fruit weight loss (Rogiers et al. 2004) and influences fruit ripening and solute accumulation (Rebucci et al. 1997). In the latter study, berry transpiration was varied either by altering the VPD around clusters through temperature and relative humidity (RH) adjustments or by applying a drying-accelerating emulsion or a hydrophobic coating (vaseline) over the berry skin. Low berry transpiration in the latter treatment resulted in lower sugar content per berry up to harvest, with berry transpiration and net sugar intake being linearly correlated up to 0.20–0.25 $\text{mmolm}^{-2}\ \text{s}^{-1}$. When berry transpiration was restricted by applying vaseline, sugar accumulation was delayed. A recent experiment by Cabodevilla et al. (2024)

investigated Tempranillo grapevine cuttings exposed to different VPDs, including two treatments with day/night conditions set at 28 °C/18 °C and 43%/58%, with or without the application of the anti-transpirant di-1-p-menthene. When the chemical was present, berry transpiration was significantly reduced, and total anthocyanins decreased from 521 g/L (in the absence of anti-transpirants and with high transpiration) to 364 g/L. Our findings support the hypothesis that the notable decrease in surface cluster temperature achieved through cooling may not suffice to enhance berry pigmentation if the wetting of the berry skin is likely prolonged. Consequently, as a result of the evident VPD reduction, berry transpiration—and subsequently, berry ripening—can be delayed. The hypothesis is consistent with the foundational work of Zhang and Keller (2017), who demonstrated that berry ripening—characterized by solute accumulation and color change—was significantly impaired in Sirah, Merlot, and Concord grapes. This impairment occurred either due to xylem disruption, resulting in blocked xylem backflow, or when berry transpiration was partially inhibited by immersing clusters in a 2% solution of the anti-transpirant Vapor-Gard. These findings further support the notion that the accumulation of sugar and color in ripening grape berries necessitates the removal of excess phloem-derived water, either through transpiration across the berry skin or via xylem backflow.

Examining the primary effects of leaf removal in Barbera, a notable reduction in yield was observed in D vines, primarily due to a decrease in cluster weight (only 54 g compared to 95 g in the C-ND treatment). Since berry weight remained unchanged and it is highly unlikely that fruit set was affected, the reduced yield is evidently a result of the high sunburn rates (Table 5).

Basal leaf removal inhibited sugar accumulation as early as the second sampling date (Fig. 3), and this discrepancy persisted until harvest, with C-D reaching 23.5 Brix compared to 26.8 Brix in C-ND (Table 6). Given that tartaric acid metabolism is relatively temperature-independent (Ford 2012), the higher concentration found at harvest in C-D appears to be a consequence of a ripening delay, further corroborated by the total anthocyanins concentration and content. This seems to stem from two overlapping phenomena: (i) a whole canopy effect suggesting a general ripening delay in the C-D treatment, likely due to a source limitation associated with leaf removal, and (ii) a local effect from increased cluster temperature. Previous studies have clearly demonstrated that in some red cultivars, anthocyanin biosynthesis and degradation are respectively decreased and increased at air temperatures above 35 °C, potentially resulting in cluster temperatures being 10–12° higher (Spayd et al. 2002; Mori et al. 2007; Hulands et al. 2014; Gambetta et al. 2021; Rustioni et al. 2023). In our study, maintaining leaf cover around clusters effectively reduced surface cluster temperature, significantly so on July 31, with a reduction of 1.7 °C (T_{mean}) and 3.7 °C (T_{max}) compared to the D treatment. The study by Yamane et al. (2006) on the sensitivity of the color accumulation process in grape berries to high temperatures applied at various times post-veraison has revealed that the period of greatest sensitivity occurs between one and three weeks after the onset of coloring. Our thermal assessment in July coincides with 10 days after veraison began, suggesting that leaf cover protection at this stage might explain the observed effects. Additionally, it is important to consider that complete leaf removal led to a sudden alteration in the light and thermal microclimate of the cluster, potentially exacerbating the reduction in final anthocyanin concentration. However, it must be acknowledged that the effects of late basal leaf removal on the quantity and composition of anthocyanins remain inconsistent: for example, in cultivars such as Cabernet Sauvignon, Nero d'Avola, Raboso Piave, and Sangiovese, which have distinct anthocyanin and flavonol profiles, the total anthocyanin concentration in berries did not differ between control and late-defoliated vines (Pastore et al. 2017).

A final item that needs to be discussed is the total amount of seasonal water used versus all achieved benefits. Data of water supply through a cooling system might greatly vary in terms of number and flow rate of emitters, above or intra-canopy applications, setting of climate parameters for automated system activation, time length of the chosen intermittency, etc. Average value of mm/day delivered in Sauvignon blanc and Barbera was around 4 due to objective stressful conditions occurring almost every day and to a 60 s/sec120 of/off cycle that was rather generous in terms of supplied water. Comparison with similar work can lead to much lower or higher water supply depending on specific environmental and working condition: Paciello et al., (2017) report 0-8-0.9 mm/d to cool Sauvignon blanc vines grown in Central Italy; however, their calculation is made over a total of 600 atomizers/ha, that is a much lower number than the one expected from vine density (3470 vines/hectare). Conversely, Bianchi et al. (2023) refer 0.27 mm/min in their cooling trial on Chardonnay grown in Northern Italy that is higher than the 0.16 mm/min calculated from our data.

Another theoretical concern when using a nebulization system is whether the water supplied, once it falls to the ground, might contribute to the root water supply, thereby introducing a potential interfering factor. Field studies on canopy cooling have either overlooked this issue (Paciello et al. 2017; Bianchi et al., 2023) or, as in the case of data collected on Semillon (Greer and Weedon 2014), concluded that the fine mist, when in direct contact with the vegetative surface, evaporates quickly without reaching the soil. Several reasons suggest that this latter outcome is applicable to our conditions as well. First, during extended warm dry periods (like the one we were experiencing in our experiment), rainfall less than 5 mm/day may not add any moisture to the soil reservoir, as most of it evaporates before entering the soil (Bos et al. 2009). The equation used in the Farmwest calculator, as discussed in Perera (2021), is: Effective Precipitation (mm) = (rain– 5) × 0.75. Additionally, only 75% of the rainfall over 5 mm is considered effective precipitation. A second and even more robust reason is that, according to Dorsey (1940), the evaporation of water from a water surface—like a swimming pool or an open tank—depends on water temperature, air temperature, air humidity, and air velocity above the water surface. It does not depend on the depth of the water layer. The same book reports that at 30 °C, the water level decreases by 6.8 mm/day, 9.6 mm/day, and 12.9 mm/day when the wind blows at 0, 2 m/s, and 9 m/s, respectively. These numbers should be sufficient to resolve the issue, even considering that our working temperature was not less than 33 °C and that wind velocity is usually higher than 2 m/s. Finally, even if we admit that some water reaches the soil surface, this is a mix of dry tilled soil and native grass, and the soil type is anything but sandy, making it very unlikely that any water can penetrate and reach the root zone.

Conclusions

The automated fruit zone cooling system detailed in this study performed effectively, encountering minimal technical obstacles. The conditions set for system activation ($T_{air} > 33$ °C and $RH < 55\%$) were well-calibrated to achieve a significant cooling effect, regardless of the presence of basal leaves. It is believed that a similar cooling effect could be attained by further reducing the on–off ratio of the intermittent regime from 1:2 to 1:4.

In both cultivars, the cooling option mitigated some negative effects caused by full basal leaf removal, most notably the increased incidence of sunburn. In the more sensitive Barbera, cooling, irrespective of defoliation, unexpectedly maintained the functionality of the leaves located above during the hottest part of the season.

Cooling had a mild impact on the yield of both cultivars, and in Barbera, variations in some yield components (such as smaller clusters) were primarily related to sunburn effects. The impact of cooling on the final grape composition fell short of expectations, especially considering the anticipated benefits from cooler leaves and clusters. Overall, in both cultivars, cooling helped to compensate for some ripening delays triggered by defoliation. However, the lower color achieved by cooled treatments in Barbera suggests that pigmentation is influenced by multiple factors, including T, VPD, and the extent/duration of surface wetting.

Based on the results from the first trial season, adopting cooling does not appear to add sufficient marginal value compared to a standard practice that simply avoids any basal defoliation.

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Author contributions P.B and S.P wrote the main manuscript text; P.B and B.D run the experiment, recorded data and made general supervision; M.G did the analytics.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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