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An Automatic Cooling System to Cope with the Thermal–Radiative Stresses in the Pignoletto White Grape

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Abstract

Recent climatic extremes, characterized by hot and dry summers, threaten grape yield and berry composition, increasing the need for sustainable mitigation strategies. In this study, a fruit-zone cooling system was tested to reduce sunburn damage and improve vine performance. The system integrates proximal sensors and an automatic misting actuator, triggered when the air temperature exceeds 35 °C. Over two seasons (2022–2023), trials were conducted on Pignoletto vines subjected to four treatments: control (C), misted without defoliation (C + FOG), defoliated (DEF), and defoliated plus misted (DEF + FOG). The effects on microclimate, yield, berry sunburn, and berry composition were evaluated. Misting consistently reduced both air and berry temperature. Treated vines showed increased yield, mainly due to reduced sunburn and higher cluster weight. Although no clear differences in technological maturity were observed, misted vines tended to retain higher acidity under extreme heat. Flavonol synthesis was unaffected by cooling but stimulated by increased light exposure, being higher in defoliated vines. Volatile compounds analysis highlighted misting's moderating effect on oxidative stress and aroma profile shifts, particularly during the hotter season. Overall, the cooling system proved effective in mitigating summer stress, offering a promising tool for preserving yield and berry composition in white cultivars under climate change.

Keywords: aroma compounds; climate change; phenolic maturity; precision irrigation; sunburn damage; *Vitis vinifera* L.

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1. Introduction

Pignoletto (*Vitis vinifera* L.) is a white Italian variety cultivated in the Bologna area (Italy) for the production of the Protected Designation of Origin (PDO) Colli Bolognesi Pignoletto wine. In recent decades, many of the most suitable vineyard areas in Italy have been frequently exposed to intense solar radiation, high vapor pressure deficits (VPDs) and high temperatures, especially during the ripening period [1]. As reported by several authors, in conditions of water scarcity and thermo-radiative excess (multiple summer stresses), Pignoletto cv. shows a near-isohydric behavior [2,3] characterized by its ability to maintain relatively stable leaf water potential despite fluctuations in soil moisture and atmospheric vapor pressure deficit [4,5]. This results in slightly conservative water use to environmental stimuli, primarily due to stomatal behavior aimed at limiting water loss [6,7]. However, the occurrence of multiple summer stresses, leading to leaf photoinhibition and necrosis, exposes grape clusters to direct sunlight. This exposure can result in a significant yield reduction due to sunburn, which often manifests as berry browning and/or tissue lesions [8–10]. Indeed, this damage is exclusively observed on exposed bunches and specifically on berries facing direct sunlight, while shaded parts remain unaffected [11–15]. Excessive light radiation and heat are the primary triggering factors for sunburn injuries [16–19]; however, light is considered the crucial initiator, as high temperatures alone in the field do not induce this phenomenon [13,14].

Beyond yield, the quality traits of sunburnt grapes are also compromised, leading to lower organoleptic quality. In berries affected by sunburn, elevated temperatures activate malic acid respiration pathways, resulting in a loss of total acidity and an increase in pH. Major abiotic factors such as temperature, water availability, solar radiation, and atmospheric CO_2 concentration can profoundly affect grapevine physiology and berry development by regulating the biosynthesis and degradation of both primary and secondary metabolites, including phenolics and volatile aroma compounds [20]. For instance, sunburn not only reduces the concentration of key varietal monoterpenes such as linalool, geraniol, and nerol, thereby diminishing the floral and fruity aroma profile, but also leads to an increase in lipid-derived volatiles like (E)-2-hexenal and hexanol, which contribute to herbaceous and green aromas and are also considered stress volatiles [21]. Alkanes, belonging to the hydrocarbon fraction of grapevine volatile organic compounds, show seasonal variability. Their prevalence in spring has been linked to leaf age since young leaves emit hydrocarbons but not alcohols. Although less studied in berries, alkanes may still contribute, directly or indirectly, to the organoleptic profile of wines [22]. The concentration of total soluble solids is also typically reduced by sun exposure [11–21]. Furthermore, these affected berries may exhibit lower amounts of phenolic compounds and anthocyanins, causing atypical color [23], alongside a reduced content of yeast assimilable nitrogen (YAN), which can hinder the development of secondary aromas in wines [22]. These effects are striking when the bunches are directly exposed to light and heat due to a lack of vegetative vigor or because of canopy management choices such as late defoliation [24–26], which is largely applied during the season, mainly to reduce cluster rot infections [27]. Both cluster light exposure and temperature have been reported to affect the content of methoxypyrazines (MPs) in berry at harvest [28]. In particular, direct sunlight causes the degradation of MPs and the consequent reduction in unpleasant vegetative aromas both in grapes and in wine [29,30]. Moreover, cluster light exposure stimulates the production of flavonols, which could contribute to the bitter sensation in the grape and wine, as reported by Allegro and colleagues [26]. This result, obtained specifically in the Pignoletto variety, highlights the importance of grape cluster exposure to light precisely around veraison, when flavonol accumulation begins. Today, some short-term agronomic techniques, such as foliar application of kaolin and zeolite [31,32] and smart irrigation [33–35], allow for the mitigation of the negative effects of climate change on grapes. In particular, kaolin and zeolite treatments proved effective not only in reducing the daily maximum temperature of grape berries but also in enhancing the accumulation of anthocyanins, while the application of mist irrigation was extensively studied in the 1970s and proved to be an effective method for reducing water stress in plants [36]. Therefore, ultra-fine misting systems have been developed to evaporatively cool the air inside the canopy of grapevines, reducing both water consumption, leaf wetting and, consequently, plant diseases [37]. Starting from these assumptions, a fully automated fruit-zone cooling system was implemented in the experimental vineyard of the University of Bologna, characterized by the presence of summer heatwaves. The primary objective of this study was to optimize the microclimatic conditions surrounding grape clusters during the most crucial phenological phase, ripening. In particular, we aim to test whether, in wine-growing regions characterized by high temperatures or frequent heat waves during ripening, the exposure of grape clusters to solar radiation—often intensified around veraison due to the aging of basal leaves—and its negative effects on grape composition and yield can be mitigated through misting.

The system's performance was evaluated on the Pignoletto cultivar, with a specific focus on dissecting the effects of misting on yield, alleviating sunburn damage and unravelling the intricate interplay of light and temperature on the yield and compositional attributes, flavanols and volatile organic compounds of grape berries. This scientific investigation aims to contribute valuable insights to the understanding of viticultural practices under challenging climatic conditions.

2. Materials and Methods

2.1. Plant Material and Experimental Design

Trials were carried out in the 2022 and 2023 seasons in a four-year-old vineyard at the experimental station of the University of Bologna (Bologna, 44°32′ N, 11°22′ E). Plant material consisted of *Vitis vinifera* L. Pignoletto vines, clone Cab3, grafted onto K5BB rootstock, spaced at 1.20 m within a single row and 2.7 m between rows (oriented northeast to southwest), and trained to bilateral Guyot VSP system. Winter pruning left 10 buds per plant, while during spring, 10 shoots per vine were left. The experimental design comprised 48 labeled vines, distributed across three blocks along the row. Within each block, 4 uniform vines per treatment were monitored (12 vines each treatment). The vines underwent a targeted intervention involving the manual removal of basal leaves and the application of water nebulization to the fruit zone, following the scheme outlined in Table 1: non-defoliated control (C); non-defoliated vines treated with water nebulization in the bunch zone (C + FOG); vines subjected to defoliation (DEF); vines subjected to both defoliation and nebulized water spray (DEF + FOG).

Table 1. For clarity and improved interpretation of the upcoming figures and tables, the theses derived from the relationship between the defoliation and misting factors will be labeled as indicated below.

	NO FOG	FOG
NO DEF	C	C + FOG
DEF	DEF	DEF + FOG

Defoliation was carried out at veraison on DOY 216 and 222 for 2022 and 2023, respectively, coinciding with the simultaneous standardization of cluster numbers. It involved removing all main and lateral leaves from the six basal nodes of each shoot to expose the clusters to direct sunlight [25]. The soil management was carried out as follows: the inter-row was covered with ILMIX (S.I.S, San Lazzaro, BO, Italy), and mowed during the season to avoid excessive evapotranspiration, while in the under-row, an offset-type cultivator tilled the soil periodically. The vineyard was not irrigated and the viticultural practices typical for the Emilia Romagna region were applied.

2.2. Fruit-Zone Cooling System Characteristics

The cooling system was implemented in open-field conditions, following the detailed description provided by Valentini and colleagues [35]. It included a control unit (iFarming srl, Ravenna, RA, Italy) equipped with sensors for canopy temperature and humidity, as well as a misting system (RIVULIS F.L.F. nozzles, Rivulis Irrigation, Gvat, Israel) installed 10 cm below the cordon. A semi-automatic mesh filter was installed upstream of the fogger pipeline to improve water quality and prevent nozzle clogging. The F.L.F. foggers were also equipped with a built-in leakage prevention device. The system was activated when the canopy temperature reached 35 °C, a threshold established according to the criteria proposed by Pastore and colleagues [38]. Based on a planting density of 1.2 m × 2.7 m and one nebulizer per vine, totaling 3086 emitters per hectare, each vine received 0.81 mm of water per hour. The water application cycle consisted of 5 min of activation followed by 15 min of inactivity, with a maximum of three cycles per hour. As previously reported by Matthias and Coates [37], misting systems have been developed to cool the canopy air evaporatively; therefore, nebulized water was not available for use at ground level. The system was activated on day of year (DOY) 216 (August 4) during the 2022 season and on DOY 222 (August 10) during the 2023 season (Supplementary Material Figure S1).

2.3. Climate Data Acquisition

Weather conditions were recorded from veraison to harvest by a meteorological station annexed to the experimental vineyard (iFarming Srl, Ravenna, RA, Italy). Moreover, for the microclimate detail, three digital thermal probes and relative humidity sensors (iFarming, Ravenna, RA, Italy) were placed in the fruit zone within the canopy (30 cm above the cordon). Each sensor was then connected to a control unit to analyze in real time the microclimate data recorded by the sensor every 10 min during the seasons to activate the cooling system. Mean berry temperature was measured around midday using an infrared thermometer (mod. Raynger ST, Raytek, Santa Cruz, CA, USA) on DOY 217 and 232 (2022 season) and on DOY 225 and 235 (2023 season).

2.4. Yield Attributes and Berry Composition at Harvest

At the time of harvest, the yield of tagged vines was weighed, and the number of clusters was counted. The incidence of necrosis was determined by estimating the percentage of clusters affected by sunburn damage out of the total number of clusters per vine. The severity of necrosis was assessed based on the percentage of affected berries per cluster. Furthermore, 30 berries per vine (360 berries per treatment) were collected during the harvest to scan the following parameters: total soluble solid concentration (TSS), using a self-compensating Maselli R50 refractometer (Misure Maselli, Parma, Italy); must pH and titratable acidity (TA), using a Crison titrator (Crison Instruments, Barcelona, Spain).

2.5. Analysis of Berry Flavonols at Harvest

Flavonols were extracted from the skins of 20 berries by immersing the peeled skins in 100 mL of methanol for a duration of 24 h within a light-protected environment at a temperature of 20 °C. Subsequently, 5 mL of the resulting supernatant underwent an acid hydrolytic process, leading to the cleavage of flavonol glycosides [39]. For the analytical phase, a High-Performance Liquid Chromatography (HPLC) mod. Waters 1525,142 equipped with a diode array detector (DAD) and a reversed-phase column (RP18,250 × 4 mm, 5143 µM) with a pre-column (Phenomenex, Castel Maggiore, Bologna, Italy) was employed. Quantification was achieved by measuring absorbance at 370 nm [39]. The contents of flavonols were expressed in milligrams per kilogram of berries (mg kg^{-1}).

2.6. Analysis of Berry Aromatic Compounds at Harvest

The volatile molecule profiles were detected by the Solid Phase Microextraction (SPME) combined with the Gas Chromatography and Mass Spectrometry (GC/MS) technique, as described by Gottardi and colleagues [40]. A CAR/PDMS, 75 µm fiber (SUPELCO, Bellefonte, PA, USA) was used to perform the solid-phase microextraction (SPME). The samples were placed in vials (5 g of frozen grapes) and kept for 30 min at 4 °C; also, 2 ppm of chlorobenzaldehyde (as internal standard) was added to the samples. To perform the SPME, the samples were incubated for 5 min at 45 °C. Then, the fiber was exposed to the vial headspace for 20 min at 45 °C. The volatile molecules adsorbed were desorbed in the gas chromatograph (GC) injector port in splitless mode at 250 °C for 50 min. The headspace of the volatile compounds was analyzed using the GC 6890N, Network GC System with mass spectrometry 5970 MSD (Agilent Hewlett–Packard, Geneva, Switzerland). The column used was J & W CP-Wax 52 CB (50 m × 320 m × 1.2 m). The initial temperature was 40 °C (1 min), which then increased by 4.5 °C/min up to 65 °C. The temperature was then increased by 10 °C/min up to 230 °C and remained constant for 17 min. Compounds were identified by comparison using a NIST 11 (National Institute of Standards and Technology) database. The gas carrier was helium at 1.0 mL/min flow. All the analyses were performed in triplicate.

2.7. Statistical Analysis

Data were processed by analysis of variance over the year using the mixed procedure of SAS v 9.0 (SAS Institute, Inc., Cary, NC, USA) and treatment comparisons were analyzed using Tukey's test with a cut-off at $p \leq 0.05$. Volatile organic compounds are expressed as the average of three replicates and the raw data were analyzed using a principal component analysis (PCA) performed by Statistica software (version 8.0, Statsoft, TULSA, OK, USA).

3. Results

A fruit-zone cooling system was employed to evaluate the effectiveness of nebulized water in mitigating sunburn damage to Pignoletto throughout the 2022 and 2023 seasons, marking the first-ever field testing of the device. In detail, the 2022 season was marked by persistent heatwaves [41] in the initial half of August, as also evidenced by elevated Vapor Pressure Deficit (VPD) values recorded at the vineyard layer by the meteorological station (Figure 1A). More precisely, in the first part of the month (from DOY 216 to 223), when the clusters were exposed to sunlight, air temperatures surpassed 35 °C, prompting the activation of the cooling system (Table 2). In contrast, the latter part of the month witnessed substantial rainfall and a decline in VPD (Figure 1A). To provide detailed insights, the experimental station recorded a cumulative rainfall of 101 mm during the period of misting system activation. Conversely, the 2023 season was characterized by intense air temperature and persistent heatwaves, evident in the elevated daily VPD values, particularly noticeable after DOY 230 (Table 3, Figure 1B).

Table 2. Year 2022. Range temperature (Range Air T) and average maximum temperature (Maximum Air T) recorded on untreated vines between 11:00 and 19:00. The misting system's impact is depicted by the number of mist cycles per day and the resulting drop in air temperature close to the cluster zone (Drop Air T), measured in FOG-treated vines compared to the untreated vines.

DOY	Range Air T (°C)	Average Maximum Air T (°C)	Mist Cycle Per Day (n)	Drop Air T in FOG (°C)
216	37.0–40.6	37.7	3	−3.3
217	38.1–41.6	39.1	12	3.8
218	39.0–41.6	38.5	6	2.4
222	33.6–35.1	33.9	6	1.1
223	34.1–35.6	33.7	6	1.5
229	36.8–37.6	35.1	3	0.4
232	33.9–35.6	33.5	3	1.6

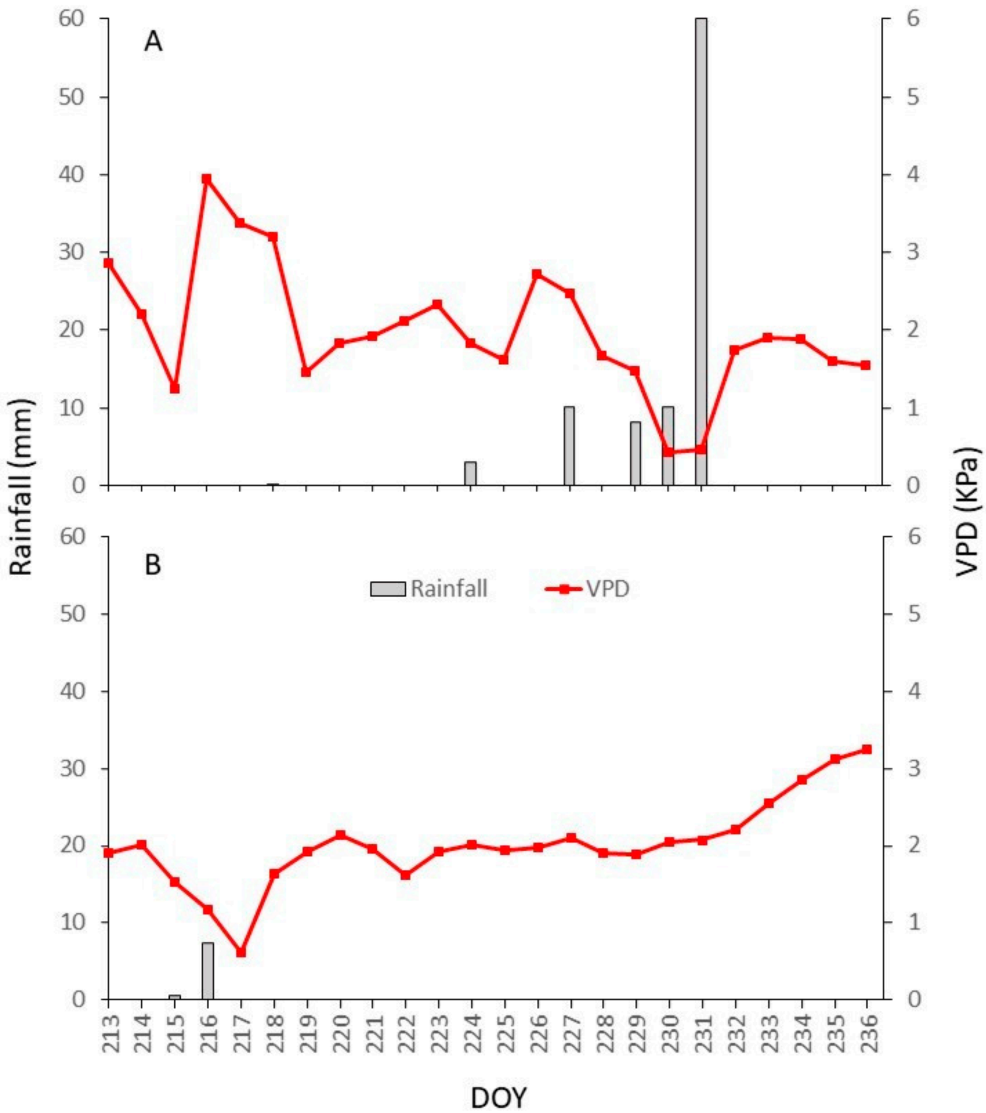

Figure 1. The trend of daily vapor pressure deficit (red line, VPD) and the rainfall (grey bars, Rainfall) at a meteorological station during the test period (2022, (**A**); 2023, (**B**)).

A closer analysis of the precipitation pattern during 2023 indicates that the initial days of August (DOY 215-DOY 218), coinciding with the defoliation process (DOY 216), experienced relatively higher humidity. This was followed by a decrease in rainfall, with only 10 mm recorded from the pre-veraison stage to harvest (Figure 1B).

In summary, during the 2022 season, the misting system was activated promptly as the grape clusters were exposed to the sun. In contrast, in the 2023 season, system activation (DOY 224) occurred two days after defoliation (DOY 222), reflecting a noticeable temperature disparity between the two years during veraison.

The misting system was in operation for 7 days during the 2022 season and 12 days in the 2023 season, as outlined in Tables 2 and 3. The nebulizer cycles per day ranged from 3 to 12 in 2022 and 4 to 16 in 2023. In particular, the system maintained an average of 6 cycles per day during the 2022 season and 13 cycles per day for the year 2023. Given that each cycle dispenses water for 5 min, we can estimate the mist volume generated in the cluster zone over the two years. This varied from 0.81 to 3.24 mm in 2022 and 1.33 to 5.33 mm in the warmer 2023, totaling 10.8 mm and 47.7 mm across the two seasons, respectively (Tables 2 and 3).

Table 3. Year 2023. Range temperature (Range Air T) and average maximum temperature (Maximum Air T) recorded on untreated vines between 11:00 and 19:00. The misting system's impact is depicted by the number of mist cycles per day and the resulting drop in air temperature close to the cluster zone (Drop Air T), measured in FOG-treated vines compared to the untreated vines.

DOY	Range Air T (°C)	Average Maximum Air T (°C)	Mist Cycle Per Day (n)	Drop Air T in FOG (°C)
224	32.1–37.1	34.2	16	3.7
225	33.5–37.7	34.7	14	3.3
226	31.9–36.2	34.7	12	1.3
227	29.8–36.4	34.9	12	0.8
228	30.7–38.2	35.6	14	1.2
229	29.1–35.3	34.4	4	0.5
230	30.9–38.2	35.2	14	1.1
231	31.3–38.7	35.9	14	0.9
232	34.7–38.0	36.0	14	0.9
233	32.0–39.7	37.3	14	2.2
234	33.0–40.8	38.5	16	2.4
235	34.8–41.9	39.9	16	2.1

No direct correlation is apparent between the number of system activations and the temperature decrease around the grape cluster area in nebulized vines. However, a discernible trend emerges in FOG, indicating a temperature reduction with an increase in misting cycles compared to untreated vines. During the hottest days of 2022, with temperatures ranging between 37 and 41.6 °C and an average maximum exceeding 39 °C, the system achieved a temperature reduction ranging from 3.3 to 3.8 °C (Table 2). Comparable thermal peaks in 2023 were observed after August 20th (DOY 234 and 235). Even with 16 activations (equivalent to almost an hour and a half of continuous misting), the air temperature dropped by just over 2 degrees, stabilizing between 36 and 37 degrees Celsius (Table 3). It is worth noting that on August 23rd (DOY 235), the average maximum air temperature in untreated vines reached 39.9 degrees between 11 am and 7 pm. This underscores that 2023 was indeed characterized by a warm and dry season.

The temperature of the berries (Tables 4 and 5), whether they were exposed to direct radiation or shielded from it, consistently remained cooler for an extended duration after water delivery compared to the canopy. Analyses of berry temperature, measured with an infrared thermometer at solar noon on two representative days in each year (one being an extremely warm and dry day, DOY 217 and DOY 235, and the other a moderately warm day, DOY 232 and 225, respectively, in the 2022 and 2023 seasons), revealed a significant third-degree interaction among all the factors examined—FOG × DEF × DOY (YEAR). In 2022, the berry temperatures recorded in vines subjected to FOG consistently remained below the critical threshold of 35 °C, demonstrating a noteworthy distinction from the temperatures observed in vines without FOG treatment (Table 4), showing thermal reduction ranging from 1.8 to 9.5 degrees Celsius in both sets of observed data. The two days, marked by different climatic conditions, exhibit distinct behavior of the clusters under direct exposure. In detail, there are no differences between the DEF and NO DEF treatments on the 217th day of the year, while for DOY 232, the temperature value for DEF + FOG is the absolute minimum (Table 4). Similar observations, as mentioned above, were also evident in 2023, where clusters subjected to misting demonstrated a significant cooling effect on DOY 225 and 235 (Table 5). As reported above, there were no differences between the DEF and NO DEF treatments (Table 5).

Table 4. Berry temperatures (°C) recorded on vines with foliage and vines subjected to basal leaf defoliation, as well as on vines subjected to or without nebulization of the cluster zone during the 2022 season (DEF = defoliated; NO DEF = not defoliated; FOG = nebulized; NO FOG = untreated with misting).

DOY		NO FOG	FOG
217	NO DEF	35.1 a	30.9 b
	DEF	39.0 a	29.5 b
232	NO DEF	33.2 a	31.4 a
	DEF	35.8 a	28.2 b

Different letters indicate significant differences between treatments and for each date according to Tukey's test ($p \leq 0.05$).

Table 5. Berry temperatures (°C) recorded on vines with foliage and vines subjected to basal leaf defoliation, as well as on vines subjected to or without nebulization of the cluster zone during the 2023 season (DEF = defoliated; NO DEF = not defoliated; FOG = nebulized; NO FOG = untreated with misting).

DOY		NO FOG	FOG
225	NO DEF	32.8 a	30.6 b
	DEF	35.4 a	28.1 b
235	NO DEF	35.9 a	33.3 b
	DEF	37.4 a	35.4 b

Different letters indicate significant differences between treatments and for each date according to Tukey's test ($p \leq 0.05$).

A comprehensive analysis of ripening curves over both trial years revealed no significant differences between treatments, except for berry mass evolution in the 2023 season (Figure 2). Notably, defoliated treatments showed a discernible decrease in berry size leading up to harvest in 2023 (Figure 2B). This decline in berry mass coincided with a rise in vapor pressure deficit (VPD) at the end of August (Figure 1B). Worth noting is the sudden decline in the DEF + FOG treatment, which seemed to maintain the same growth rate as the NO DEF group's berry until DOY 244, only to undergo a drastic reduction at harvest. At harvest, a marked difference is apparent between the two groups, DEF and NO DEF, as illustrated in Figure 2B, in contrast to the preceding year (Figure 2A). Despite these differences in berry size, both years showed similar trends in technological maturity parameters, including soluble solids, pH, and titratable acidity. The recorded values were consistent with the expected characteristics of the variety and growing region, and no statistically significant differences among treatments were detected for these variables in either season (Figure 2C–H).

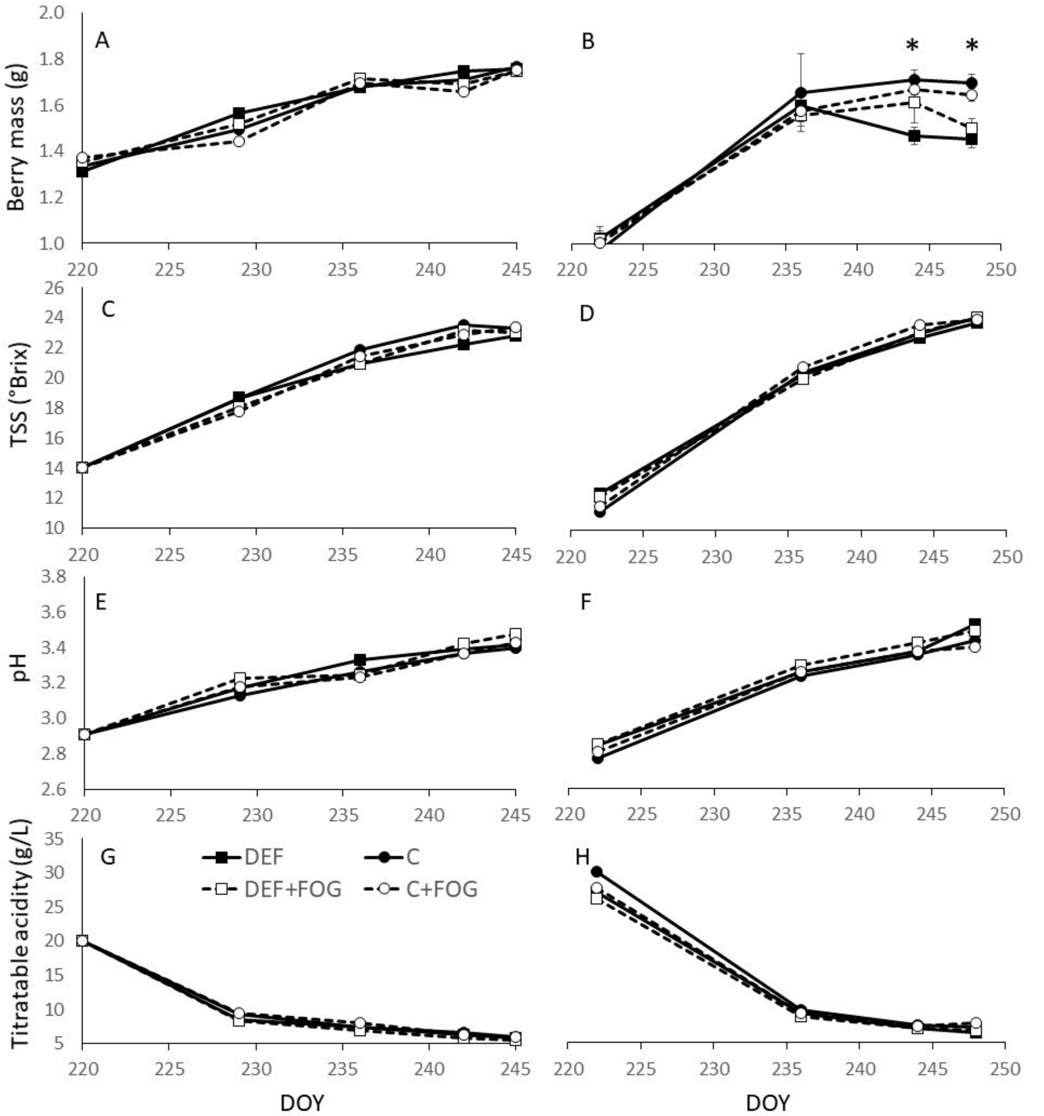

Figure 2. Trends of berry mass ((**A**), 2022 and (**B**), 2023), soluble solids ((**C**), 2022 and (**D**), 2023), pH ((**E**), 2022 and (**F**), 2023), and titratable acidity ((**G**), 2022 and (**H**), 2023) in the two test years. The asterisk indicates a significant difference between treatments ($p = 0.01$). In (**B**), standard error bars are included to better illustrate the intra-treatment variability.

While no statistical differences were observed among treatments in terms of technological maturity, variations in yield at harvest were evident (Table 6). The table below highlights significant disparities in yield production between the FOG and NO FOG treatments over the two years of the trial (Table 6). The efficacy of the misting system in ensuring higher yields, even under direct solar exposure, is emphasized. Although, in 2022, this outcome correlates with the average bunch mass being higher in FOG than in NO FOG, these differences do not appear significant in 2023. A more comprehensive explanation of this interaction is provided in the Supplementary Materials (Table S1), indicating a tendency for an increase in grape cluster weight even during the warmest season. As also shown in Figure 2, berry mass at harvest differs only in season 2023 (Table 6, Supplementary Materials Table S2), showing a sensible reduction in DEF. The analysis reveals that the warmer and drier conditions of the 2023 season had a discernible impact on various yield components, particularly influencing parameters associated with heat damage. Notably, the assessment of sunburn, including both the incidence and severity of necrosis, was conducted through direct observations of the grapes during harvest (Table 6). Regarding the influence of treatments on the incidence of necrosis, discernible disparities are apparent, particularly in the context of fruit-zone misting. The empirical findings, as delineated in Table 6, underscore a significant reduction in the prevalence of necrotized berries during the two-year observation period in FOG. In contrast, defoliated vines show a dissimilar trend over the years concerning damage incidence. Specifically, in 2022, the wettest year, defoliated vines exhibit a higher number of affected berries compared to the driest year, where the incidence of sunburn appears to be less pronounced (Supplementary Materials Table S3). Concerning the severity of sunburn damage, the results reveal an interaction between YEAR×DEF and YEAR×FOG treatments (Table 6, Supplementary Materials Tables S4 and S5), emphasizing a higher percentage of compromised clusters in thesis exposed to direct radiation and without FOG. This outcome is specifically noticeable in the 2023 season, characterized by harsh climatic conditions. A statistical difference between the two years was observed in terms of soluble solids content (TSS) at harvest (Table 6), with a higher concentration of sugar in 2023. Although no differences were found among treatments in terms of pH, interactions concerning titratable acidity emerged (Table 6).

Table 6. Yield components and berry composition at harvest in the 2022 and 2023 seasons. The table shows the effects of defoliation (DEF vs. NO DEF) and misting (FOG vs. NO FOG) treatments.

Parameter		2022		2023		Significance			
		NO FOG	FOG	NO FOG	FOG	YEAR	DEF	FOG	INTERACTIONS
Cluster (n)	NO DEF	21	21	30	30	*p* = 0.0005	ns	ns	ns
	DEF	21	21	30	30				
Yield (kg)	NO DEF	2.85	3.20	3.28	3.72	ns	ns	*p* = 0.05	ns
	DEF	2.89	3.35	3.07	3.29				
Cluster weight (g)	NO DEF	130	150	109	124	ns	ns	ns	YEAR × FOG (*p* = 0.083)
	DEF	140	158	104	114				
Berry mass (g)	NO DEF	1.77	1.75	1.63	1.58	ns	ns	ns	YEAR × DEF (*p* = 0.017)
	DEF	1.76	1.75	1.42	1.45				
Necrosis incidence (%)	NO DEF	53	41	3	3	ns	ns	*p* = 0.043	YEAR × DEF (*p* = 0.011)
	DEF	45	35	32	17				
Necrosis severity (%)	NO DEF	3	2	6	2	ns	ns	ns	YEAR × DEF (*p* = 0.045) YEAR × FOG (*p* = 0.040)
	DEF	4	4	16	6				
TSS (°Brix)	NO DEF	23.4	23.4	24.0	23.9	*p* = 0.054	ns	ns	ns
	DEF	22.8	23.0	23.6	24.0				
pH	NO DEF	3.39	3.42	3.41	3.37	ns	ns	ns	ns
	DEF	3.41	3.48	3.49	3.46				
Titratable acidity (g/L)	NO DEF	6.00	5.92	7.23	7.81	ns	ns	ns	YEAR × DEF (*p* = 0.081) YEAR × FOG (*p* = 0.035)
	DEF	5.73	5.48	6.45	6.75				
Flavonols (mg/kg)	NO DEF	3.6	2.3	5.6	6.3	ns	ns	ns	YEAR × DEF (*p* = 0.006)
	DEF	7.9	8.7	39.4	39.3				

Mean comparisons were conducted using Tukey's test ($p \leq 0.05$). The statistical significance of the main factors (YEAR, DEF, FOG) and of their interactions is indicated by the corresponding *p*-values (actual values shown). Abbreviations: ns = not significant; TSS = total soluble solids.

In detail, the misting system appears to have shown no effect on grape acids in the wetter year but resulted in a significant increase in the warmer year (Supplementary Materials Table S6). Conversely, exposed clusters exhibited a decrease in acidity compared to non-defoliated ones, with a more pronounced effect in 2023 (Supplementary Materials Table S7). The YEAR×DEF interaction is also evident for the flavonols (Table 6, Supplementary Materials Table S8), wherein the defoliation technique exerts an increasing influence. Notably, this effect is particularly pronounced in the warmer year. Of particular interest is the observation that, regardless of the misting treatment applied, the warmer year consistently exhibits a higher flavonoid content in the exposed clusters.

A clear distinction in volatile compound profiles was observed between the two trial years (2022 and 2023) across all treatments, as illustrated in Figure 3. Aldehyde concentrations consistently increased from 2022 to 2023 in all treatments. For instance, the C treatment showed an increase from 61.69% in 2022 to 81.93% in 2023. Similar upward trends were noted in the DEF, DEF + FOG and FOG treatments. In contrast, alcohol concentrations showed an opposite trend, being relatively high in 2022 (particularly in DEF + FOG and C, around 20% across all samples), but significantly lower in 2023 (decreasing to 5.58%). Benzene derivatives also showed a clear increase in 2023, with concentrations nearly doubling across all treatments compared to 2022. The FOG treatment exhibited the most pronounced change. Acidic compounds remained relatively stable between years, although some treatment-specific shifts were noted (Figure 3). For instance, DEF had the highest acid concentration in 2022 but the lowest in 2023. Ketone relative abundances showed an overall decreasing trend, dropping from approximately 0.60% in 2022 to below 0.15% in 2023. A distinct qualitative change was observed in the presence of alkanes, which were absent in 2022 but appeared in 2023 across all treatments, with the highest value in DEF. Terpenes and esters, were more prominent in 2022. Terpenes were particularly elevated in the DEF treatment in 2022 but nearly undetectable in 2023.

Overall, the 2023 harvest was characterized by a general increase in aldehydes and benzenes, a noticeable reduction in alcohols and ketones, and the new appearance of alkanes. Within each year, higher aldehyde concentrations were observed in FOG samples in 2022, which also exhibited lower levels of alcohols. This trend was reversed in 2023.

A Principal Component Analysis (PCA) was performed using the quantified volatile compounds from the 2022 and 2023 seasons to explore the overall variation in volatile composition across the different experimental treatments. The PCA biplot is displayed in Figure 4A,B, encompassing both the scores and loadings of the initial two principal components (PC1 and PC2), which collectively accounted for the preponderance of variance (80.42 and 78.35% in 2022 and 2023, respectively) in the dataset.

In 2022 (Figure 4A), the four treatments demonstrated distinct clustering within the two-dimensional space defined by the first two principal components. At the same time, PC1 (Factor 1) clearly separated the defoliated samples (DEF and DEF + FOG) from the non-defoliated ones (C and C + FOG). The presence of FOG was found to be associated with higher levels of C6 compounds such as hexanal and 3-hexenal, while C was associated with 4-hexen-1-ol and decanoic acid ethyl ester. DEF samples exhibited a stronger correlation with compounds such as acetic acid, acetophenone, 2-hexen-1-ol and 3-hexen-1-ol, while DEF + FOG was associated with compounds such as 2-penten-1-ol, 1-octen-3-ol, decanoic acid, 3,7-dimethyl-1,6-octadien-3-ol.

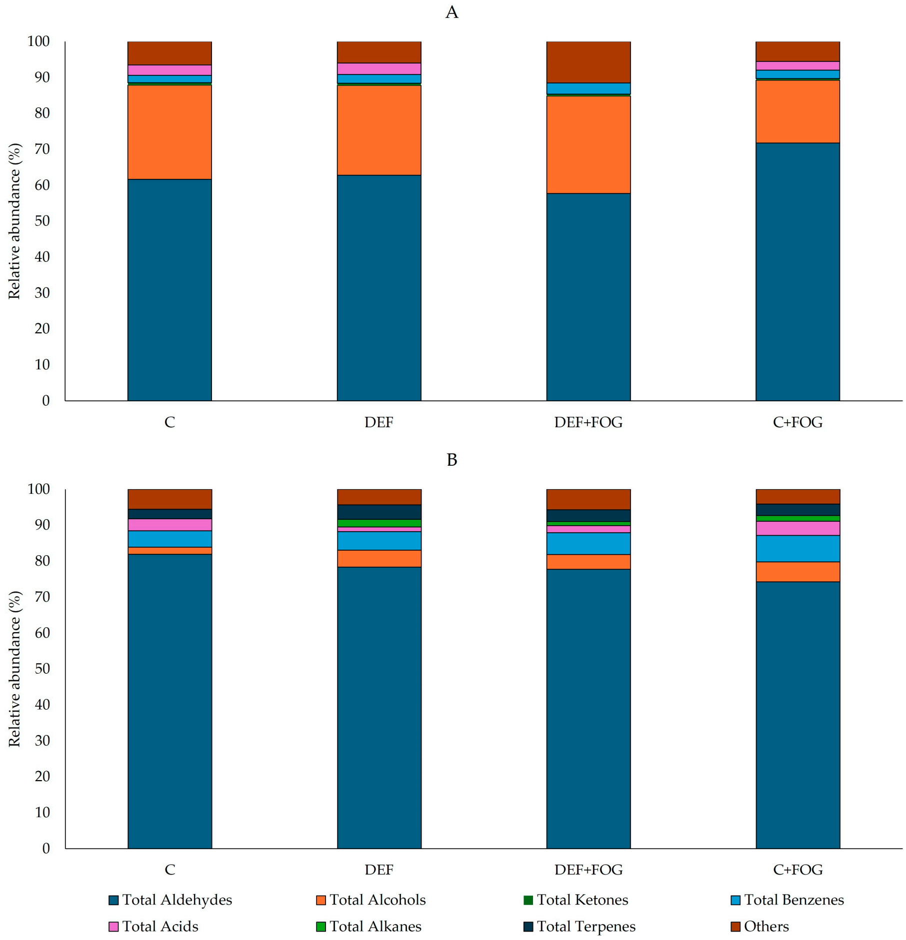

Figure 3. Average relative abundance (%) of key volatile compounds in berry samples from the 2022 (**A**) and 2023 (**B**) harvests, categorized by experimental treatment (C = non-defoliated control; C + FOG = non-defoliated vines treated with water nebulization in the bunch zone; DEF = vines subjected to defoliation; DEF + FOG = vines subjected to both defoliation and nebulized water spray.

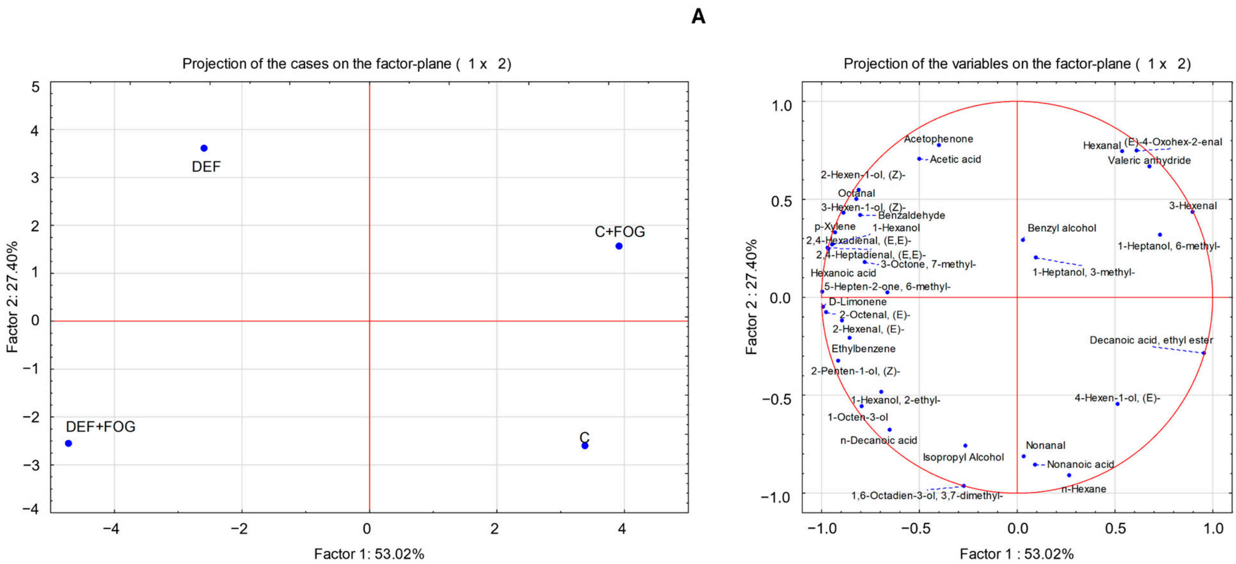

Figure 4. *Cont*.

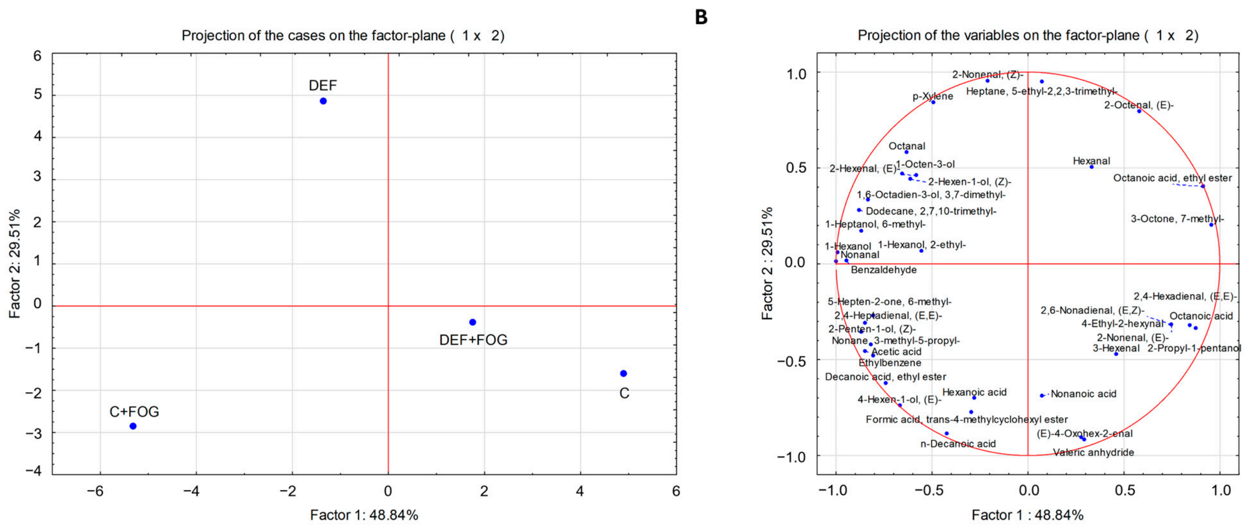

Figure 4. Principal Component Analysis (PCA) of volatile compounds in grape samples across 2022 (**A**) and 2023 (**B**) treatments.

A similar pattern of sample distribution was observed in 2023 (Figure 4B), though with certain variations. In this case, PC2 (Factor 2) largely separated DEF (at positive PC2 values) from C + FOG (at negative PC2 values). While DEF remained distinctly separated from the control, indicating that this treatment persisted in significantly affecting the volatile profile, the treatments C + FOG and DEF + FOG manifested a closer proximity with C. This suggests the potential for an interaction or a combined effect of both treatments, aligning their volatile profiles more closely with the control. Molecules such as 3-hexenal, 2-nonenal, octanoic acid, nonanoic acid, 2,4-hexadienal were associated with both control and DEF + FOG. In contrast, DEF was characterized by octanal, 2-nonenal, 2-hexenal. Lastly, C + FOG was characterized by acetic acid, 4-hexen-1-ol, and decanoic acid ethyl ester.

4. Discussion

The principal aim of this study was to assess the efficacy of a water mist cooling system in mitigating sunburn damage to Pignoletto white grape. Additionally, this research aimed to unravel the rule of mist in the intricate influence of light and temperature on the ripening process of white grape berries. Notably, while prior studies have established the impact of cluster exposure on Pignoletto in relation to radiation [26], our investigation was exclusively focused on unveiling the consequences of thermal modulation through misting system on vine behavior. Subsequently, this study delved into an in-depth exploration of the effects of temperature and light on yield production and berry composition, with a specific emphasis on the roles played by bunch exposure and/or bunch cooling. This nuanced analysis aimed to contribute novel insights to the existing body of knowledge [23,25,38,42].

The system was specifically designed to target the cluster, setting it apart from traditional sprinkler solutions assessed in *Vitis vinifera* L. and other species [43–46]. In grapevines, automate overhead sprinklers are typically focused on preventing leaf overheating and preserving their functionality based on available knowledge on energy balance [47]. Moreover, the threshold sprinkler activation is fixed at different levels according to the varieties: 27 °C in both Pinot noir and Chardonnay [47], 30 °C for Cardinal, Carignan and Riesling [45], 32 °C in Chardonnay, Riesling and Chenin Blanc [48], 35 °C in Semillon [49]. Our system, in agreement with Caravia and colleagues [50], operates in the cluster zone but differs in two attributes: it is arranged below the cordon and not inside the canopy to avoid direct interference between fog and foliage; and it has the thermal limit set at 35 and not 38 °C. This departure is noteworthy, considering that numerous metabolic processes tend to slow down or cease at 35 °C, including flavonoid synthesis [38,51].

In summary, the 2022 and 2023 seasons were characterized by different climatic conditions. In 2022, persistent heatwaves in August prompted system activation in the first part of the month, while in 2023, intense solar radiation and heatwaves were observed during the second half of the trial period. The misting system demonstrated a discernible trend in reducing temperatures around the cluster area during warm days, with a significant temperature reduction in both seasons. In addition, misting resulted in a sustained cooling effect on berry temperatures, maintaining cooler conditions compared to untreated vines. This effect was similar to those reported in more recent research works obtained by misting systems aimed at water resource conservation [49,50,52].

Misting emerged as a pivotal factor in amplifying yields, underscoring its efficacy in enhancing grape production, even when faced with direct solar exposure. This outcome bears particular relevance for viticulturists seeking methodologies to optimize yield among climatic adversities. In detail, vines subjected to misting exhibited a substantial increase in yield, attributable to a mitigated incidence of sunburn damage and a concurrent enhancement in cluster weight. In particular, increases in average cluster and/or berry weight have been reported in Semillon [49], Riesling [45], and Cabernet Sauvignon [50]. In contrast, no difference in yield and berry size was observed in Chardonnay treated with a high-pressure spray system, at about 70 Bar [53]. In addition to the latest research, over two trial seasons, an analysis of the positive effects exerted by the treatment on sunburn damage was shown. It is well known that in a climate change scenario, the phenomena of both berry dehydration and necrosis exert a direct influence on cluster mass, particularly when clusters are directly exposed to solar radiation [24,50,54]. In our trial, the misting system significantly reduced the prevalence of necrotized berries over the two years, underscoring its role in mitigating sunburn damage. Furthermore, the most noteworthy findings emerged in the second year of the experiment, which were associated with elevated temperatures and a concurrent reduction in recorded rainfall. Indeed, the heightened evaporative demand in 2023 has been unequivocally established as a contributing factor that accentuated the severity of sunburn damage in defoliated vines. Significantly, it also underscored the decisive role of misting in alleviating injury.

Grapevine canopy management serves as a crucial tool in influencing the microclimate around berry clusters and this manipulation has far-reaching effects on berry quality traits. It is well known that exposure to sunlight enhances the levels of sugars and flavonoids [55] and the specific response is not only dependent on the grapevine genotype but also on the berry temperature [24,56–58]. Leaf removal around the clusters is a widely employed practice to regulate berry illumination and temperature, particularly in cooler regions where very high temperatures are not common [59], but its use in warm regions is controversial due to the negative effect exerted by the thermal excess. As previously stated, Italy is undergoing a precipitous climate shift marked by an increase in temperatures during the grape ripening phase [60]. Consequently, defoliation practices expose clusters to high solar radiation, which may exert a discernible influence on berry mass, as observed in our study, where defoliated vines exhibited a diminished berry size during the hottest season. Moreover, in certain hilly areas, the current climatic conditions may induce early senescence and abscission of basal leaves, resulting in unintended exposure of the clusters to direct sunlight. Although the treatments did not impact sugar content or pH, a positive effect of grape cooling was observed in terms of total acidity. This finding aligns with reports from other authors [52,53] and appears to be attributed to the pronounced cooling action on the cluster zone and the grapes themselves, thereby slowing down malic acid respiration [61].

Defoliation during veraison significantly affects light and temperature exposure while exerting only a limited impact on the source–sink balance [25]. Its influence on flavonoid biosynthesis in berries is noteworthy but strongly dependent on grapevine genotype [62,63]. In particular, flavonol synthesis is enhanced under high radiation levels, where flavonols may act as antioxidants and natural sunscreens [24,64]. Moreover, Preys et al. [65] reported a correlation between flavonol concentration and the perceived bitterness of the resulting wines. Our research outcomes are consistent with those reported by Allegro and colleagues [26], who observed a similar response in Pignoletto cultivated in northern Italy, where increased cluster light exposure after leaf removal led to reduced titratable acidity and enhanced flavonol levels. While the application of nebulized water positively influenced titratable acidity, it did not exhibit a substantial impact on the overall flavonol content. The noticeable increase in flavonols in defoliated vines, even in the presence of misting, suggests a significant role for light-dependent modulation, emphasizing the predominant influence of light over temperature effects.

The analysis of volatile compound profiles across different treatments and years reveals clear patterns influenced by defoliation, misting, and seasonal climatic conditions. Aldehyde concentrations increased significantly in the warmer year (2023), indicating enhanced oxidative stress and lipid peroxidation [66]. FOG had a mitigating effect, slightly reducing aldehyde levels compared to NO-FOG treatments. Conversely, alcohol levels declined under defoliation and in response to the intense heat of 2023, likely due to reduced activity of alcohol dehydrogenase (ADH), an enzyme sensitive to environmental stress [67]. Nebulization helped preserve alcohol levels in 2022, especially in DEF + FOG samples, highlighting its role in maintaining enzymatic activity and metabolic balance under heat stress. Benzene derivatives, which are often products of aromatic amino acid degradation, especially when berries are exposed to higher temperature [68], showed higher levels in 2023, with no significant differences among treatments. This suggests an enhanced pathway activity or increased thermal degradation of aromatic amino acids in the second year. Terpene levels, which are known to be light-sensitive [20], were higher during the cooler year (2022) in defoliated samples, reflecting enhanced biosynthesis due to increased sunlight. However, they dropped drastically in 2023, likely suppressed by extreme temperatures, indicating their vulnerability to thermal stress even in the presence of misting. Esters showed minimal variation across treatments in 2022, though their reduction in 2023 suggests possible heat-related suppression of biosynthetic activity. Ketones, associated with microbial or lipid degradation, followed a similar trend, showing a marked decrease in the hotter season, especially in misted treatments. Finally, alkanes, absent in 2022, appeared only in 2023 and were most abundant in defoliated vines. Their emergence is strongly associated with cuticular damage and sunburn, supporting their role as indicators of structural stress caused by excessive heat and solar exposure [15]. In summary, the vintage 2023, which was characterized by higher heat and dryness, had the strongest overall impact, notably reducing compounds sensitive to metabolic and environmental disruption. Looking at the single treatments, defoliation amplified oxidative and thermal stress, while misting served as a partial buffer.

5. Conclusions

Our study aimed to assess the efficacy of a water mist cooling system in mitigating sunburn damage to Pignoletto white grape and to unravel the intricate influence of light and temperature on grape berry ripening. The designed misting system, specifically targeting the cluster, demonstrated a discernible trend in reducing temperatures around the cluster during warm days, significantly cooling berry temperatures in both seasons. Misting emerged as a pivotal factor in amplifying yields, showcasing its efficacy in enhancing grape production, even under direct solar exposure. This outcome is particularly relevant for viticulturists facing climatic adversities. Vines subjected to misting exhibited a substantial increase in yield, attributed to a mitigated incidence of sunburn damage and a concurrent enhancement in cluster weight. Additionally, our study explored the effects of defoliation during veraison, confirming its significant influence on light and temperature exposure, impacting flavonoid biosynthesis. The increase in flavonols in defoliated vines, even with misting, underscores the crucial role of light-dependent modulation, emphasizing its predominant influence over temperature effects. In summary, our research highlights the multifaceted impact of misting on grapevine canopy management, with positive effects on yield, sunburn damage mitigation and berry composition. Furthermore, the analysis of volatile compounds revealed that the warmer 2023 vintage significantly impacted the aromatic profile, notably reducing metabolites particularly sensitive to environmental and metabolic disruption. Defoliation exacerbated oxidative and thermal stress, triggering marked shifts across several volatile classes. In contrast, misting acted as a mitigating factor, helping to preserve specific compounds (e.g., alcohols in 2022) and moderating the overall aroma alterations induced by stress. Notably, in 2023, the volatile profile of defoliated and misted vines (DEF + FOG) more closely resembled that of the control, underscoring the system's role in stabilizing the aromatic composition under extreme conditions. These findings reinforce the potential of misting not only in improving yield and limiting sunburn, but also in safeguarding key aroma compounds that are essential for grape and wine quality. Additional investigation is needed to better characterize the oxidized fraction of flavonols, which may contribute to berry browning.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae11091128/s1. Table S1: Cluster weight interaction (YEAR × FOG); Table S2: Berry mass interaction (YEAR × DEF); Table S3: Necrosis incidence interaction (YEAR × DEF); Table S4: Necrosis severity interaction (YEAR × DEF); Table S5: Necrosis severity interaction (YEAR × FOG); Table S6: Titratable acidity interaction (YEAR × FOG); Table S7: Titratable acidity interaction (YEAR × DEF); Table S8: Flavonols' interaction (YEAR × DEF). Figure S1: Fruit cooling system details.

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