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Adapting Viticulture to Climate Change: Impact of Shading in Sicily

Daniele Miccichè [1], Stefano Puccio [1,*], Rosario Di Lorenzo [1], Lucia Turano [1], Francesco Di Carlo [2] and Antonino Pisciotta [1]

[1] Department of Agricultural, Food and Forest Sciences (SAAF), Università degli Studi di Palermo, Viale delle Scienze 11, 90128 Palermo, Italy; daniele.micciche@unipa.it (D.M.); rosario.dilorenzo@unipa.it (R.D.L.); lucia.turano@unipa.it (L.T.); antonino.pisciotta@unipa.it (A.P.)

[2] Cantine Settesoli Soc. Coop. Agricola, S.S. 115, 92013 Menfi (Ag), Italy; f.dicarlo@cantinesettesoli.it

* Correspondence: stefano.puccio01@unipa.it

Abstract: Climate change significantly affects viticulture, with noticeable impacts on yield and quality. The increase in average temperatures, often coupled with decreased precipitation, accelerates the phenological development of grapevines, leading to rapid sugar accumulation and concentration and decreased acidity. This study aimed to evaluate the impact of black shading nets with two levels (26% and 40%) on vine phenology, vegetative growth, yield, and grape ripening, as a potential strategy to mitigate the adverse effects of rising temperatures and reduced precipitation. The research was conducted in southwestern Sicily, in the Menfi (AG) area, using Grillo and Syrah grapevines. Black shading nets were applied during the pea-sized berry stage (BBCH 75). The results demonstrated that shading effectively delayed vine phenology and altered grape ripening, with significant reductions in sugar content (up to 10%) and increases in total acidity (up to 10%) at harvest compared to non-shaded vines. However, shading also reduced berry size, resulting in lower cluster weight and yield per plant (up to 15%). These findings highlight the potential of shading nets as a tool for adapting viticulture to climate change, while emphasizing the need to carefully assess their large-scale applicability, considering economic and operational factors.

Keywords: colored shading nets; global warming; grape quality; vine phenology; *Vitis vinifera*; solar radiation exclusion

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1. Introduction

Climate change is one of the major challenges for global viticulture, with increasing evidence of negative impacts on the thermal and hydric regimes critical for vine development [1,2]. Traditional wine regions, such as those in the Mediterranean, are experiencing higher average temperatures and decreased precipitation, accelerating the phenological cycle and advancing grape ripening [3,4]. This premature ripening can compromise grape quality by increasing total soluble solids and decreasing total acidity, which negatively affects the chemical and organoleptic characteristics of the final product [5,6]. Such changes may compromise the chemical composition and sensory characteristics of grapes, presenting significant challenges for viticulturists striving to maintain consistent quality. To address these issues, adaptive agronomic practices, such as shading nets, are increasingly being explored to mitigate the effects of climate change. Shading nets have emerged as a promising strategy to moderate vineyard microclimates by reducing light intensity and temperature. By altering the microclimatic conditions, shading nets can delay phenological stages, reduce heat stress, and influence grape composition [7]. Studies have shown that shading reduces photosynthetically active radiation (PAR) within the canopy, lowering temperatures and moderating photosynthetic activity. For example, shading treatments on Semillon vines reduced canopy temperatures by nearly 5 °C and net photosynthesis by 40% [8]. Similarly, high shading intensities (e.g., 60–75%) applied to Cabernet Sauvignon vines have significantly decreased PAR, reducing net carbon assimilation while providing substantial protection against excessive heat [9,10]. In addition to its effects on the microclimate, shading influences vegetative growth and reserve accumulation. Reduced photosynthetic activity under shaded conditions often leads to lower carbohydrate production, which may impact vegetative growth and reserve storage for subsequent seasons. For instance, studies on Chardonnay and Aglianico grapevines have demonstrated that higher shading intensities reduced fruit set and total vine yield [11,12]. However, some research has identified compensatory mechanisms, where leaves outside the shaded area maintain or even increase photosynthetic rates, partially offsetting the effects of shading [13]. Additionally, prolonged, high-intensity shading, such as 70%, has been shown to decrease root biomass, starch content, and overall vine vigor [14,15]. Shading also affects grape production and quality, although the effects are complex and cultivar dependent. Excessive shading can reduce berry size, cluster weight, and yield, as observed in studies on Syrah and Cabernet Sauvignon [16,17]. Conversely, moderate shading can protect berries from overexposure, reducing dehydration and preserving their integrity [18]. Furthermore, shading impacts the synthesis of secondary metabolites, such as anthocyanins and flavonols, which are vital for grape color and wine quality. Research on Pinot Noir and Shiraz has shown that while excessive shading reduces anthocyanin concentration, moderate shading can mitigate the degradation of these compounds under high-temperature conditions [19,20]. Despite these findings, there is no universal consensus on the optimal shading percentage or type of net to use. Variations in cultivar responses, environmental conditions, and shading intensity complicate the interpretation of results. For example, high shading percentages (e.g., 70–75%) are often effective in mitigating heat stress but may negatively impact bud fertility and reserve accumulation [21]. On the other hand, lower shading levels (e.g., 26–40%) may strike a balance between reducing heat stress and maintaining sufficient light for photosynthesis, though their long-term effects on vine performance remain uncertain [7,12]. The primary objective of this research is to determine whether lighter shading levels, such as 26%, can effectively mitigate climate-induced stresses, or if higher shading percentages, such as 40%, offer a more suitable balance between immediate protection and long-term sustainability. While the literature frequently supports high shading levels (70% or more) for their immediate protective effects against heat and radiation, concerns persist about their prolonged use. Over time, high-intensity shading could compromise vine vigor, reserve accumulation, and productivity. This study hypothesizes that moderate shading levels, such as 40%, might achieve a better equilibrium, offering adequate protection without the risks associated with excessive shading. By addressing these questions, this research aims to provide practical insights for viticulturists adapting to climate change while ensuring the sustainability of vineyard systems in extreme Mediterranean environments.

2. Materials and Methods

2.1. Trial Location and Vineyard Description

The study was conducted over two consecutive seasons (2021–2022) in two commercial vineyards located in southwestern Sicily, Italy. The vineyards were situated at coordinates 37°35′28″ N, 13°00′44″ E and 37°38′19″ N, 12°59′43″ E, at elevations of approximately 150 m and 305 m above sea level, respectively. The first vineyard was cultivated with Grillo grafted onto 1103P rootstock, while the second was cultivated with Syrah grafted onto 140Ru rootstock (*Vitis vinifera* L.). Both vineyards were oriented NW-SE, with vine spacing of 1.00 m within plants and 2.40 m between rows. Vines were trained to a vertical shoot positioning (VSP) system and pruned to a Guyot system, leaving 10 buds on the fruiting cane and 2 buds on the spur. The soils in both vineyards were predominantly clay–loam. Conventional management practices were employed to control powdery mildew (*Erysiphe necator*) and downy mildew (*Plasmopara viticola*). Irrigation was not provided, as the vineyards relied solely on rainfall during the growing season.

2.2. Macroclimate and Microclimate Data Acquisition

The climate of the region was classified as semi-arid according to the Köppen–Geiger classification system [22–24]. Macroclimatic data for the 2021 and 2022 growing seasons were obtained from an automatic weather station operated by the Sicilian Agrometeorological Information Service (www.sias.regione.sicilia.it, accessed on 3 July 2024), located approximately 10 km from the experimental vineyards. Microclimatic conditions within the canopy were monitored using Elitech RC-51H sensors (San Jose, CA, USA), which were installed at cluster height for each treatment. These sensors recorded temperature and relative humidity continuously at 30-minute intervals from the installation of shading nets until harvest.

2.3. Experimental Design and Shading Treatments

The experimental design followed a randomized complete block structure with three treatments and three replicates per treatment. Each replicate consisted of 50 vines, with 10 buffer vines at each end and 30 interior vines used for data collection. Two shading treatments were compared against an untreated control (UC):

- N26: A black net with a shading factor of 26%, manufactured from high-tenacity, UV-stabilized polyethylene (70 g/m^2, mesh size 7.1 × 1.7 mm; Arrigoni S.p.A., Uggiate Trevano, CO, Italy).
- N40: A black net with a shading factor of 40%, manufactured from the same material but heavier (95 g/m^2, mesh size 0.97 × 1.39 mm).

The nets were installed prior to flowering, at the separated floral button stage (BBCH 57), and initially elevated above the canopy to minimize shading during the flowering stage. As the vines reached the pea-sized berry stage (BBCH 75), the nets were lowered to fully cover the canopy, thereby providing the intended shading effect.

2.4. Vegetative Growth and Phenology

The impact of shading treatments on vegetative growth and phenology was assessed by monitoring the onset of ripening processes and measuring shoot growth. Vineyard inspections were conducted approximately ten days after full bunch closure (BBCH 77) to determine the initiation of ripening, based on visual changes in grape color and signs of berry softening [25]. Due to the differences between the two varieties examined, standardization of sampling times was not feasible. Specific enological objectives and varying maturation durations influenced the timing of sampling. The first sampling occurred seven days after the initiation of ripening for both varieties. The second sampling was conducted approximately 15 days later for Grillo and 25 days later for Syrah. The third sampling coincided with the harvest date. Vegetative growth was assessed at harvest (BBCH 89) by randomly selecting 15 shoots per treatment. Shoots were sampled equally from the cane's proximal, median, and distal sections. Leaf area was determined using a LI-3100C Area Meter (Li-COR Environmental, Lincoln, NE, USA). The total leaf area per vine was calculated by multiplying the measured leaf area per shoot by the number of shoots per vine. During winter dormancy, pruning wood weight was determined by collecting and weighing the pruned material from 30 vines per replicate at the end of each season.

2.5. Leaf Nutritional Status

Leaf nutritional status was evaluated non-invasively immediately after full berry ripening (BBCH 81). Measurements were performed on three leaves per shoot, positioned at basal, medial, and apical locations, using the Dualex 4 Scientific device (Dx4, FORCE-A, Orsay, France). The Dualex 4 Scientific is a portable device designed for the non-destructive measurement of chlorophyll and flavonoid content in leaf epidermis. The device utilizes a combination of wavelengths: one in the UV-A range (315–400 nm) to measure flavonoid absorbance and one in the red range (650 nm) to excite chlorophyll fluorescence. The differential measurement between these wavelengths enables accurate estimation of chlorophyll concentration in leaves. This approach requires no sample preparation or instrument calibration, making it suitable for both laboratory and field use under varying environmental conditions. The parameters assessed included chlorophyll content (CHL), which indicates the amount of chlorophyll in the leaves, the nitrogen balance index (NBI), calculated as the ratio of chlorophyll content to flavonoid content and reflecting the overall nitrogen status, and anthocyanin content (ANT), which measures the concentration of anthocyanins and provides insights into the plant's response to environmental stress [26,27].

2.6. Bunch Damage Assessment

To determine the extent to which shading protects grape bunches from the adverse effects of prolonged direct sunlight exposure, observations were focused exclusively on the Grillo cultivar shortly before harvest. Ten bunches per replicate were randomly selected, resulting in thirty bunches per treatment. Each bunch was examined to classify damage, as described in [28], into sunburn (characterized by brown lesions and epidermal necrosis) or shriveling (loss of turgor and dehydration). The extent of damage was quantified as the ratio of damaged berries to the total number of berries per bunch. This method provided a precise evaluation of the impact of shading treatments in protecting grape bunches from sunlight-induced injuries.

2.7. Grape Yield and Berry Characteristics

The assessment of the average number of bunches per shoot was conducted at the flower bud separation stage (BBCH 57) on thirty vines per replicate. For each plant, the total number of shoots and bunches was recorded, and the average number of bunches per shoot was calculated. To evaluate the effect of shading on grape ripening, three sampling events were performed each season. Sampling methods were designed to account for variability in grape maturation across vines, bunches, and berries [29–32]. For each treatment, 90 vines were selected and 300 berries were sampled in total, with 100 berries per replicate. Berries were collected from clusters at proximal, median, and distal positions on the fruiting cane, as well as from various positions within each bunch (proximal, median, distal). During each sampling event, the level of total soluble solids (TSS - °Brix) was measured using a digital refractometer (model HI96811, Hanna Instruments, Padova, Italy). Total acidity (TA – g/L) and pH were determined through acid/base titration and with a pH meter (model HI99111, Hanna Instruments, Padova, Italy), respectively. Before pressing the berries to obtain must for analysis, 100 berries per replicate were weighed individually. Sampling was carried out according to the previously described procedures. Harvesting was coordinated across all three treatments, based on reaching the target TSS levels for the specified enological goals. These targets were approximately 23.5 °Brix for Syrah and around 22 °Brix for Grillo. Additionally, yield parameters were assessed by counting the number of bunches and measuring the yield per vine in 30 vines per replicate.

2.8. Statistical Analysis

Statistical analysis was conducted to evaluate the effects of treatments (UC, N26, and N40) and years (2021 and 2022) on the parameters of interest. Before performing the analyses, the data were assessed for robustness. Data normality was tested using the Anderson–Darling test, and outliers were identified using Grubbs' test. A two-way analysis of variance (ANOVA) was used to examine significant differences between treatments (T) as the main factor, years (Y), and their interaction (T x Y). This approach allowed for evaluating both main and interaction effects on the measured parameters. The results were evaluated by analyzing average differences between treatments and the interactions between treatments and years via two-way ANOVA and Tukey test for $p < 0.05$. All statistical analyses were performed using Minitab 19 Statistical Software (2010, State College, PA, USA: Minitab, Inc.).

3. Results

3.1. Macroclimatic Data

The two vegetative seasons showed different climatic conditions. In 2021, the average maximum summer temperature (June–September) was 27.59 °C, with a peak of 29.00 °C in August (Figure 1A). In 2022, this average slightly increased to 27.88 °C, with a peak of 29.56 °C in July. The monthly temperatures revealed a consistent trend: in June 2022, the maximum temperature rose to 27.59 °C, an increase of 1.35 °C compared to 26.24 °C in 2021. In July, the temperature reached 29.56 °C, 1.64 °C higher than the 27.92 °C recorded the previous year. However, August experienced a slight decrease to 28.57 °C, compared to 29.00 °C in 2021. September saw an increase to 25.71 °C, 0.53 °C, higher than the 25.18 °C recorded in 2021. Average summer temperatures also increased in 2022. In June, the average temperature rose to 26.62 °C, up by 1.26 °C from 25.36 °C in 2021. July's average temperature increased by 1.50 °C to 28.67 °C (Figure 1B). In contrast, August's average temperature fell to 27.71 °C, which was 0.53 °C lower than the 28.24 °C recorded in 2021. September saw an increase to 25.00 °C, up by 1.17 °C from 24.54 °C the previous year. Data on summer precipitation showed a significant reduction in 2022. Total summer precipitation (June–September) was 158.40 mm in 2021, with 36.20 mm in June, 57.00 mm in July, 0.00 mm in August, and 65.20 mm in September (Figure 1A). In 2022, total summer precipitation dropped to 117.00 mm, with 0.00 mm in June and July, 10.00 mm in August, and 107.00 mm in September (Figure 1B). Despite the reduction in total summer precipitation, the levels in 2022 were closer to the recent regional averages, suggesting that the summer precipitation approached typical values compared to the previous year.

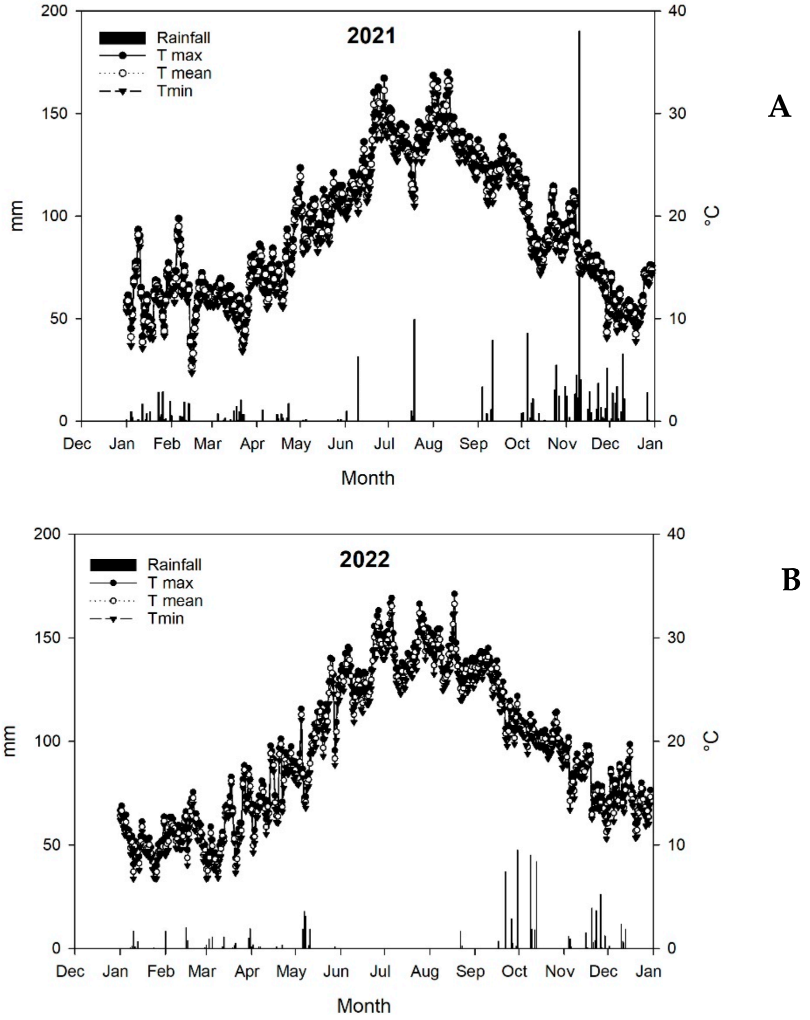

Figure 1. Trends of maximum, average, and minimum temperatures, along with precipitation for the years 2021 (**A**) and 2022 (**B**).

3.2. Microclimatic Data

Microclimatic data indicated that conditions under the UC treatment were generally warmer compared to N26 and N40. Specifically, UC recorded more intervals of 30 minutes where temperatures exceeded 32 °C, 35 °C, and 40 °C. Additionally, the average temperatures during these intervals were higher for UC. For instance, UC experienced 13% more intervals above 40 °C in 2021 and 23.4% more in 2022 compared to N26. The increase was even more pronounced compared to N40, with 63.5% more intervals in 2021 and 105.2% more in 2022. The average temperature during these intervals above 40 °C for UC was 41.3 °C in 2021 and 41.7 °C in 2022, compared to 40.9 °C in 2021 and 41.2°C in 2022 for N26, and 40.5 °C and 40.7 °C, respectively, for N40. Thus, UC had temperatures that were, on average, 0.4 °C higher than N26 in 2021 and 0.5 °C higher in 2022, and 0.8 °C higher than N40 in 2021 and 1.0 °C higher in 2022 (Table 1).

Table 1. High temperature parameters recorded in treatments UC, N26, and N40 during the years 2021 and 2022. This table shows the cumulative hours (∑ h) with temperatures above 32 °C, 35 °C, and 40 °C, and the mean temperatures (T mean) calculated for periods when temperatures exceeded these thresholds in treatments UC, N26, and N40 for the years 2021 and 2022. Different letters on the same row indicate statistically significant differences between treatments (a, b, c), while n.s. indicates no significant difference.

Parameters	Year	UC		N26		N40	
∑ h > 32 °C	2021	1197		1179		1146	
	2022	1172		1149		1079	
∑ h > 35 °C	2021	719		688		528	
	2022	775		709		576	
∑ h > 40 °C	2021	139		123		85	
	2022	158		128		77	
T mean > 32 °C	2021	35.8 ± 0.07	n.s.	35.4 ± 0.07		35.1 ± 0.07	
	2022	36.5 ± 0.08	a	36.2 ± 0.08	b	35.5 ± 0.07	c
T mean > 35 °C	2021	37.4 ± 0.05	a	36.8 ± 0.06	a	36.1 ± 0.06	b
	2022	38.1 ± 0.06	a	37.6 ± 0.06	ab	37.2 ± 0.06	b
T mean > 40 °C	2021	41.3 ± 0.05	a	40.9 ± 0.08	ab	40.5 ± 0.06	b
	2022	41.7 ± 0.08	a	41.2 ± 0.08	b	40.7 ± 0.06	c

3.3. Phenology, Nutritional Status, Vegetative Development, and Vine Vigor

3.3.1. Phenological Stages

Shading significantly influenced the onset of grape ripening across both varieties and years, with particularly pronounced differences observed between the UC and N40 treatment (Table 2). While this trend was evident in both years and varieties, the Grillo cultivar displayed a greater sensitivity to shading compared to Syrah. In 2022, the onset of ripening occurred earlier than in 2021, especially for Grillo, which can be attributed to specific climatic conditions experienced that year. Among the shading treatments, N40 exhibited the most significant delay in ripening in both years. Notably, in 2022, only 42% of Grillo berries reached veraison after 10 days under N40, in contrast to 95% in the UC treatment. For Syrah, N40 also had a pronounced delaying effect in 2022, with a 50% reduction in veraison berries compared to UC ten days after the onset of ripening (Figure 2). The shading treatment N26 also impacted ripening but to a lesser extent. For Grillo, the first assessment showed a 16% reduction in veraison berries compared to UC in both years, which decreased to a 7% reduction in the final assessment. For Syrah, the response to N26 varied by year. In 2021, there was a 16% difference in veraison berries compared to UC at +15 days, while in 2022, UC approached near-complete veraison (100%), with N26 showing a 25% delay.

Table 2. The percentage of berries undergoing veraison was evaluated at two intervals, 10 and 15 days from the start of veraison, for the years 2021 and 2022. Comparison between three treatments: UC (control), N26 (26% shading), and N40 (40% shading) for the Grillo and Syrah varieties.

	Veraison (%)			
	2021		**2022**	
	10	15	10	15
Grillo				
UC	85.6	100	94.7	100
N26	71.2	93.5	80	92.7
N40	52.8	92.1	42.7	88
Syrah				
UC	74.7	97.5	79.3	98.7
N26	62.1	81.4	49.3	73.3
N40	49.2	75.2	28.3	71.1

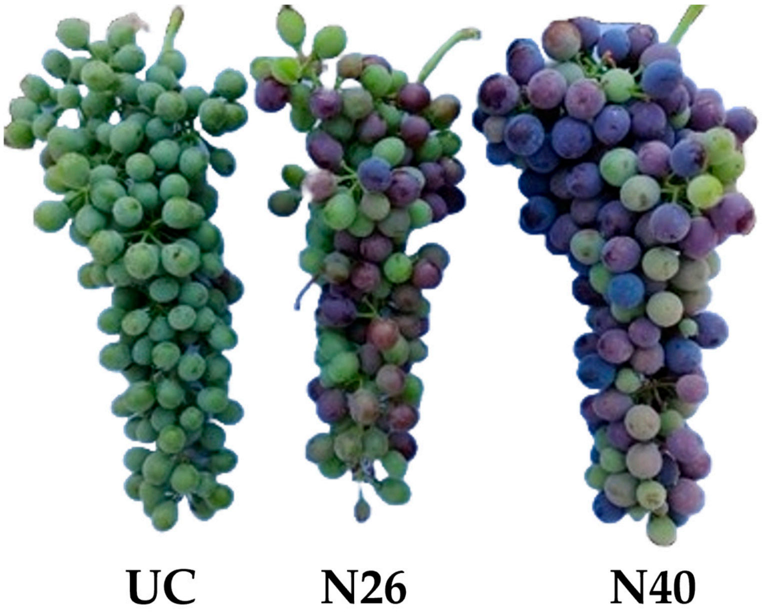

Figure 2. Photograph taken 10 days from the start of the veraison of Syrah grape bunches in 2022. From left to right: N40, N26, and UC.

3.3.2. Leaf Nutritional Status

Shading significantly influenced chlorophyll content in Grillo leaves (Table 3). Specifically, the average chlorophyll content for leaves from N26-treated vines was 33.9 ± 0.44 μg/cm^2, reflecting a 12% increase compared to the untreated control (UC) at 30.2 ± 0.53 μg/cm^2 and a 5.6% increase compared to N40 at 32.1 ± 0.25 μg/cm^2. Similarly, shading also significantly impacted chlorophyll content in Syrah leaves (Table 4). Leaves from vines under N40 treatment exhibited the highest chlorophyll content, with a mean of 30.2 ± 0.34 μg/cm^2, which is 13.9% higher than UC (26.5 ± 0.35 μg/cm^2) and 6.3% higher than N26 (28.4 ± 0.38 μg/cm^2) (Table 4). Regarding leaf anthocyanin content, statistical analysis confirmed a significant reduction in shaded leaves across all years (Table 3). For Grillo, the average anthocyanin content was 63.2% lower in leaves from N26 and 65.8% lower in leaves from N40 compared to UC (Table 4). For Syrah, the reductions were 60.9% in N26 and 78.3% in N40 compared to UC (Table 4). These findings suggest that shading adversely affects anthocyanin production, which may impact the photosynthetic efficiency of shaded leaves. The Nitrogen Balance Index (NBI) was significantly influenced by shading treatments but showed no significant variation between years (Table 3). For Grillo, the average NBI was 3.5% lower in N26 and 16.5% higher in N40 compared to UC. In Syrah, the average NBI was 78.4% and 38.5% higher in N26 and in N40, respectively, compared to UC (Table 4).

Table 3. Significance of each factor and their interactions for Grillo and Syrah. The factors evaluated are year (Y), treatment (T), and their interaction (Y × T). The parameters considered are chlorophyll (Chl), leaf anthocyanins (Anth), and NBI. Significance levels are indicated as follows: ** $p <$ 0.01, *** $p < 0.001$. “n.s.” indicates non-significant.

Parameters	Source	Significance	
		Grillo	Syrah
Chl (μg/cm^2)	Y	n.s.	n.s.
	T	***	***

	Y × T	n.s.	n.s.
Anth (µg/cm^2)	Y	n.s.	n.s.
	T	***	***
	Y × T	n.s.	n.s.
NBI	Y	n.s.	n.s.
	T	**	***
	Y × T	n.s.	n.s.

Table 4. Mean values and standard errors for chlorophyll (Chl), leaf anthocyanins (Anth), and NBI for Grillo and Syrah. Different letters within the same column indicate significantly different values ($p < 0.05$).

	Grillo		Syrah	
Chl (µg/cm^2)				
UC	30.2 ± 0.53	c	26.5 ± 0.35	c
N26	33.9 ± 0.44	a	28.4 ± 0.38	b
N40	32.1 ± 0.25	b	30.2 ± 0.34	a
Anth (µg/cm^2)				
UC	0.038 ± 0.004	a	0.023 ± 0.002	a
N26	0.014 ± 0.002	b	0.009 ± 0.001	b
N40	0.013 ± 0.002	b	0.005 ± 0.001	b
NBI				
UC	34.9 ± 2.12	b	26.9 ± 1.91	c
N26	44.3 ± 3.21	a	48.0 ± 4.46	a
N40	46.1 ± 3.41	a	38.4 ± 3.28	b

3.3.3. Vegetative Growth and Vine Vigor

Shoot length in Grillo cv. did not differ between years; however, significant differences were observed among shading treatments (Table 5). Specifically, while the N26 treatment resulted in a 4.33% increase in average shoot length compared to the untreated control (UC), this increase was not statistically significant. In contrast, the N40 treatment demonstrated an increase in average shoot length, with a 5.34% increase over UC (Table 6). This indicates that the N40 treatment has a significant positive effect on vine shoot length, whereas N26, though showing an increase, did not reach statistical significance. The observed differences in shoot length for N40 are likely due to variations in internode length.

Regarding internode length, statistical analysis revealed a significant effect solely due to shading treatments (T) (Table 5). Specifically, N40 resulted in a significantly longer average internode length compared to UC, with an increase of approximately 10%. Conversely, N26 showed a slight, non-significant decrease in internode length compared to UC, with a reduction of 1.74%. The assessment of average leaf area per vine (m^2) yielded similar values across treatments (Table 6). This consistency in vegetative growth is corroborated by the data on pruning weight, which showed that vines under all treatments had comparable wood weights, ranging from 600 to 700 g (data not shown).

For the cv. Syrah, a two-way ANOVA was conducted to evaluate the effects of the year factor (Y) and the treatment factor (T) on vegetative parameters. The results indicated that the year factor had no significant effect on any of the parameters considered, suggesting that differences between the 2021 and 2022 vintages were negligible. Shading treatments, however, had significant effects on both shoot length and internode length (Table 5). On average, N26 and N40 treatments increased shoot length by 7.7% and 6.0%, respectively, and internode length by 16.3% and 13.0%, respectively, compared to UC (Table 6). No significant differences were found in leaf area per vine and leaf-to-fruit ratio among treatments, indicating that shading had no substantial impact on these parameters (Tables 5 and 6).

Table 5. Significance of each factor and their interactions for Grillo and Syrah. The factors evaluated are year (Y), treatment (T), and their interaction (Y × T). The parameters considered are short length, internode length, leaf area per vine, and leaf area per berry. Significance levels are indicated as follows: * $p < 0.05$, ** $p < 0.01$, “n.s.” indicates non-significant.

Parameters	**Source**	**Significance**	
		Grillo	**Syrah**
Short length (cm)	Y	n.s.	n.s.
	T	*	**
	Y × T	n.s.	n.s.
Internode length (cm)	Y	n.s.	n.s.
	T	**	**
	Y × T	n.s.	n.s.
Leaf area per vine (m^2)	Y	n.s.	n.s.
	T	n.s.	n.s.
	Y × T	n.s.	n.s.
Leaf (cm^2)/berry (g)	Y	n.s.	n.s.
	T	n.s.	n.s.
	Y × T	n.s.	n.s.

Table 6. Mean values and standard errors for shoot length, internode length, leaf area per vine, and leaf area per berry for Grillo and Syrah. Different letters within the same row indicate significantly different values ($p < 0.05$).

	UC		**N26**		**N40**	
Grillo						
Shoot length (cm)	147.5 ± 4.2	b	153.9 ± 5.7	ab	155.4 ± 6.30	a
Internode length (cm)	5.8 ± 0.55	b	5.7 ± 0.32	b	6.3 ± 0.63	a
Leaf area per vine (m^2)	4.6 ± 0.31	n.s.	4.5 ± 0.44		4.6 ± 0.37	
Leaf (cm^2)/berry (g)	9.1 ± 0.36	n.s.	11.1 ± 0.53		11.3 ± 0.48	
Syrah						
Shoot length (cm)	141.8 ± 6.0	b	152.7 ± 8.0	a	150.3 ± 8.0	a
Internode length (cm)	6.2 ± 0.38	b	7.2 ± 0.35	a	7.0 ± 0.42	a
Leaf area per vine (m^2)	2.6 ± 0.52	n.s.	2.8 ± 0.31		2.5 ± 0.33	
Leaf (cm^2)/berry (g)	9.5 ± 0.59	n.s.	9.9 ± 0.50		9.7± 0.51	

3.4. Grape Withering

The nets play a positive role in sunburn effects. In the UC treatment, the percentage of sunburned berries is notably higher at 16.58% (Table 7). In contrast, shading treatments effectively reduce sunburn rates, with N26 and N40 showing lower percentages, at 9.28% and 6.33%, respectively. This indicates that shading nets provide substantial protection, with N40 demonstrating the greatest reduction in sunburned berries. Dehydration rates further illustrate the benefits of shading. The UC treatment exhibits a dehydration rate of 20.38% while shading treatments reduce this rate significantly: N26 to 13.78% and N40 to 14.43%. Notably, the N26 treatment appears slightly more effective in minimizing late-season dehydration compared to N40, although both treatments offer significant improvement over UC. In terms of maintaining healthy berries, shading treatments show a marked improvement. The percentage of healthy berries is substantially higher for shading treatments, with 76.94% for N26 and 79.24% for N40, compared to 63.04% for UC. Among the shading treatments, N40 provides the most notable enhancement in berry health, affirming the advantage of higher shading density in improving grape conditions during the ripening period (Figure 3).

Table 7. Percentage of berries classified as sunburned, dehydrated, or healthy, assessed near harvest for treatments UC, N26, and N40.

Parameters (%)	**UC**	**N26**	**N40**
Sunburn	16.58	9.28	6.33
Dehydration	20.38	13.78	14.43
Healthy berries	63.04	76.94	79.24

Figure 3. Photographs of grape clusters from Grillo cultivar for treatments UC, N26, and N40, taken near harvest. These images provide a visual representation of the percentage of berries affected by sunburn, dehydration, and those remaining healthy, as detailed in Table 6.

3.5. Yield and Fruit Quality

3.5.1. Fruitfulness, Berry Weight, Bunch Size, and Average Yield Per Vine

The analysis of variance (ANOVA) for the average number of bunches per shoot revealed no significant differences among shading treatments (T) and their interaction with the year (Y × T) for either variety (Table 8). However, the year factor (Y) had a notable effect on Syrah (Table 8). Specifically, in 2022, the N26 treatment recorded an average of 1.55 bunches per shoot, representing a 15% reduction compared to the previous year. The UC treatment also showed a decrease to 1.49 bunches per shoot, about 19% lower than in 2021. In contrast, the N40 treatment exhibited a 9% reduction in bunches per shoot, which was not statistically significant. Across both years, Syrah experienced an approximate 14% average reduction in the number of bunches per shoot from 2021 to 2022 (Table 9). Berry weight, a crucial production parameter, demonstrated significant effects due to the interaction between year and treatment (Y × T) (Table 7). For Grillo, the first sampling (seven days post-veraison) in 2021 revealed no significant differences between treatments (Figure 4A). However, at the second sampling (+15 days), UC had a significantly higher berry weight (2.73 ± 0.07 g) compared to N26 (2.37 ± 0.07 g, −13.2%) and N40 (2.44 ± 0.06 g, −10.6%). By the third sampling (+36 days), N26 showed an 18.0% increase in berry weight compared to UC (2.56 ± 0.06 g vs. 2.17 ± 0.06 g), while N40's weight was similar to UC. In 2022, shading effects were more pronounced. At the first sampling, N26's berry weight was 7.7% higher than UC (2.23 ± 0.05 g vs. 2.07 ± 0.07 g), with N40 showing a 1.0% lower weight. By the second sampling, UC maintained a higher berry weight (2.52 ± 0.05 g) compared to N26 (2.36 ± 0.06 g, 6.3% reduction) and N40 (2.19 ± 0.05 g, 13.1% reduction). This trend continued at harvest, where UC had the highest berry weight (2.75 ± 0.07 g), with N26 and N40 showing reductions of 7.3% and 6.9%, respectively (Figure 4B). These results underscore the impact of shading on berry weight, with UC consistently showing the highest berry weight compared to other treatments, especially in 2022. For Syrah, the first sampling in 2021 showed significant differences between treatments, with UC exhibiting an increase of 11% compared to N26 and 10% compared to N40 (Figure 4C). This trend persisted at the second sampling (+26 days), where UC's average berry weight was 1.53 ± 0.03 g, higher than N26 (1.43 ± 0.03 g) and N40 (1.45 ± 0.04 g), with reductions of 6.5% and 5%, respectively. By the third sampling (+47 days), N26 recorded an 18.0% increase in berry weight compared to UC (1.63 ± 0.03 g vs. 1.37 ± 0.03 g), while N40's weight remained similar to UC. In 2022, UC's average berry weight was 16% and 27% higher than N26 and

N40, respectively (Figure 4D). At the second sampling, UC maintained a higher weight (1.64 ± 0.03 g), with N26 and N40 showing reductions of 8.5% and 18.3%, respectively. This trend persisted until harvest, where UC had the highest average berry weight (1.43 ± 0.03 g), with reductions of about 11% for both shading treatments. The variations in berry weight likely contributed to differences in bunch weight for both Grillo and Syrah (Table 8). At harvest, Grillo under UC treatment had an average bunch weight 36% higher (227.3 g) compared to N26 (167.3 g) and about 30% higher than N40 (175.5 g). Consequently, the average yield per vine was higher for UC-treated vines, with reductions of 14% and 22% compared to N26 and N40, respectively (Table 10). Similarly, for Syrah, treatments N26 and N40 resulted in lower bunch weights compared to UC, leading to significant reductions in average yield per plant of 17% (N26) and 20% (N40).

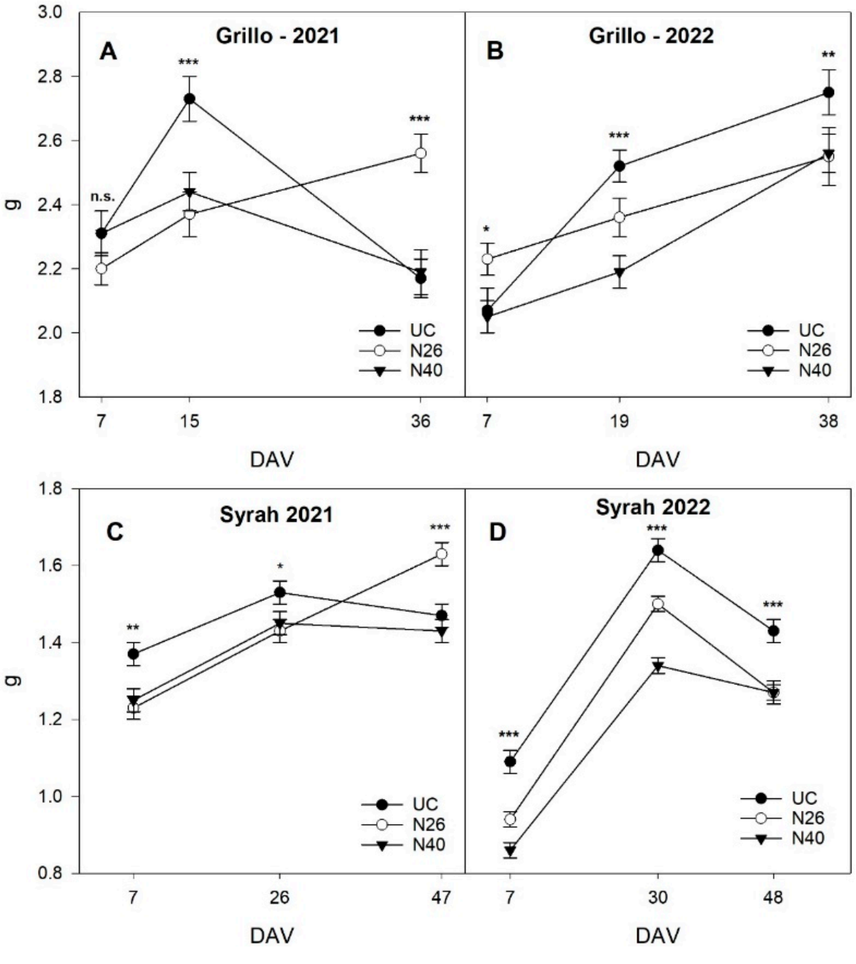

Figure 4. Mean berry weight with standard error for each treatment. Subplot (**A**) illustrates the berry weight for the Grillo variety in 2021, subplot (**B**) for Grillo in 2022, subplot (**C**) for Syrah in 2021, and subplot (**D**) for Syrah in 2022. Significance levels are indicated as follows: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. "n.s." indicates non-significant differences.

Table 8. Significance of each factor and their interactions for Grillo and Syrah. The factors evaluated are year (Y), treatment (T), and their interaction (Y × T). The parameters considered are berry weight, bunch per shoot, bunch weight, and yield per vine. Significance levels are indicated as follows: ** $p < 0.01$, *** $p < 0.001$. "n.s." indicates non-significant.

Parameters	Source	Significance	
		Grillo	Syrah
Berries per bunch	Y	**	n.s.
	T	n.s.	n.s.

	Y × T	n.s.	n.s.
Berry weight (g)	Y	n.s.	***
	T	***	***
	Y × T	***	***
Bunch per shoot	Y	n.s.	***
	T	n.s.	n.s.
	Y × T	n.s.	n.s.
Bunch weight (g)	Y	n.s.	n.s.
	T	***	***
	Y × T	n.s.	n.s.
Yield per vine (kg)	Y	n.s.	**
	T	**	**
	Y × T	n.s.	**

Table 9. Mean values and standard errors for the number of bunches per shoot in the three treatments (UC, N26, N40), for the two cultivars (Grillo, Syrah), and across two years (2021, 2022). Significance levels are indicated as follows: * $p < 0.05$, ** $p < 0.01$, “n.s.” indicates non-significant differences. Different letters within the same row indicate statistically significant differences ($p < 0.05$).

Grillo	**UC**		**N26**		**N40**		**μ**	**Significance**
2021	1.43 ± 0.05		1.43 ± 0.05		1.43 ± 0.05		1.43 ± 0.05	
2022	1.53 ± 0.07		1.38 ± 0.06		1.51 ± 0.07		1.48 ± 0.05	n.s.
Significance	n.s.		n.s.		n.s.		n.s.	
Syrah	UC		N26		N40		μ	Significance
2021	1.83 ± 0.07		1.83 ± 0.07		1.83 ± 0.07		1.83 ± 0.09	
2022	1.49 ± 0.08	a	1.55 ± 0.12	b	1.67 ± 0.09	b	1.57 ± 0.08	n.s.
Significance	**		*		n.s.		*	

Table 10. Mean values and standard errors for bunch per shoot, bunch weight, and yield per vine for Grillo and Syrah. Different letters within the same row indicate statistically significant differences ($p < 0.05$).

	UC		**N26**		**N40**	
Grillo						
Bunch weight (g)	227.3 ± 0.02	a	167.3 ± 0.01	b	175.5 ± 0.01	b
Yield per vine (kg)	4.8 ± 0.62	a	4.2 ± 0.59	ab	3.8 ± 0.51	b
Syrah						
Bunch weight (g)	218.1 ± 0.01	a	185.3 ± 0.02	b	190.0 ± 0.01	b
Yield per vine (kg)	3.8 ± 0.27	a	2.8 ± 0.29	b	3.1 ± 0.21	b

3.5.2. Grape Composition

Total Soluble Solid (TSS - °brix)

The analysis of TSS levels in grapes revealed significant effects for both factors Y and T, but not for their interaction (Y × T) (Table 11). Specifically, UC treatment generally exhibited higher TSS (°Brix) values compared to N26 and N40 across all three measurements for the Grillo variety (Figure 5A). In the first measurement, UC recorded an average value of 13.9 ± 0.21 °Brix, while N26 and N40 reported 12.1 ± 0.34 °Brix and 10.9 ± 0.53 °Brix, respectively, indicating a difference of approximately 14.9% higher for UC compared to N26 and 27.5% higher compared to N40. In the second measurement, UC maintained an average value of 17.5 ± 0.37 °Brix, whereas N26 and N40 recorded 16.8 ± 0.50 °Brix and 16.2 ± 0.18 °Brix, respectively, showing a difference of about 4.2% higher for UC compared to N26 and 8.0% higher compared to N40. At the final measurement, corresponding to harvest time, UC reported an average value of 22.7 ± 0.80 °Brix, while N26 and N40 recorded 21.9 ± 0.16 °Brix and 20.7 ± 0.55 °Brix, respectively, with a difference of about 3.7% higher for UC compared to N26 and 9.7% higher compared to N40. For the Syrah variety, the data indicate that the UC treatment tends to promote higher sugar concentrations during ripening compared to N26 and N40, confirming the general trend observed for Grillo. Specifically, in the first measurement, UC recorded a 21% increase in TSS compared to N26 and a 14% increase compared to N40. In the second measurement, UC showed TSS values of 21.4 °Brix, an increase of 6.5% compared to N26 (20.1 °Brix) and 17.5% compared to N40 (18.2 °Brix), with statistical significance observed only in the comparison with N40. At harvest, UC maintained significantly higher values, reaching 24.6 °Brix compared to 23.7 °Brix for N26, corresponding to a 4% increase. Additionally, UC showed a 6% increase compared to N40, which had a final value of 23.2 °Brix, 1.4 °Brix lower than UC.

Table 11. Significance of each factor and their interactions for Grillo and Syrah. The factors evaluated are year (Y), treatment (T), and their interaction (Y × T). The parameters considered are total soluble solids (TSS), pH, and titratable acidity (TA). Significance levels are indicated as follows: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. "n.s." indicates non-significant differences.

Parameters	**Source**	**Significance**	
		Grillo	**Syrah**
TSS (°Brix)	Y	n.s.	n.s.
	T	***	***
	Y × T	n.s.	n.s.
pH	Y	n.s.	n.s.
	T	n.s.	n.s.
	Y × T	n.s.	n.s.
TA (g/L)	Y	***	***
	T	***	***
	Y × T	**	*

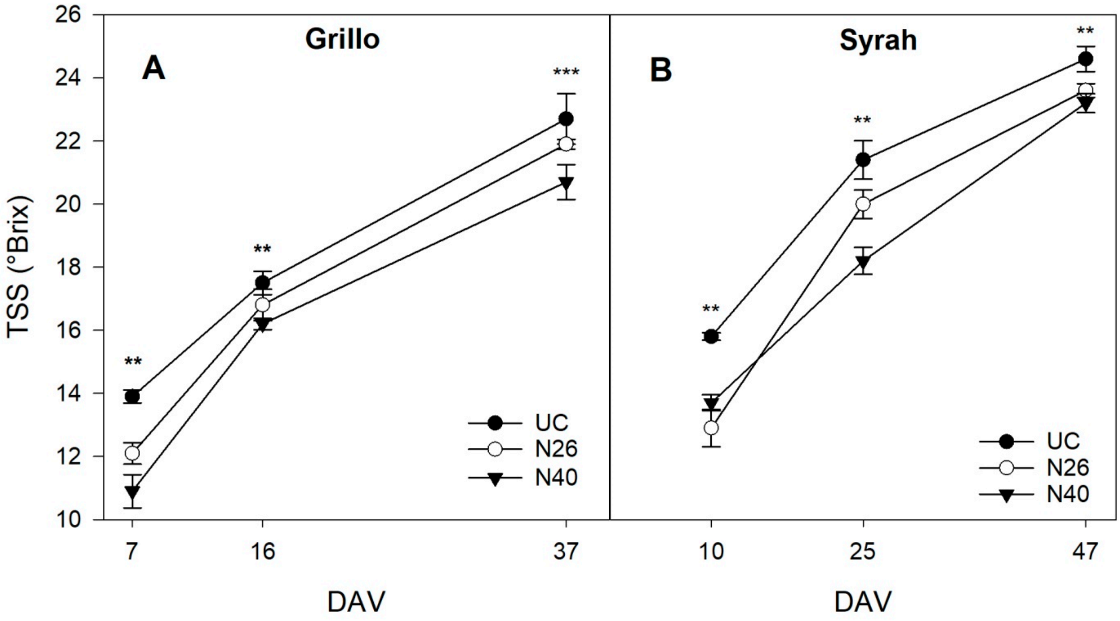

Figure 5. Total soluble solids content (Brix) for the three treatments (UC, N26, N40) across different time points. Subplot (**A**) shows the Brix content for Grillo and subplot (**B**) shows the Brix content for Syrah. Values are presented as means with standard errors. Significance levels are indicated as follows: ** $p < 0.01$, *** $p < 0.001$.

Total Acidity (TA – g/L)

The data show a significant response for both factors Y and T, as well as their interaction (Y × T) (Table 11). Overall, for the Grillo cultivar in both years, the N40 treatment tends to present higher average values compared to UC and N26 in nearly all measurements. In 2021, seven days after full veraison, N40 showed a TA value 32.3% higher than UC and 12.9% higher than N26, while N26 had a TA value 17.2% higher than UC (Figure 6A). These differences, although less pronounced, persisted at 17 days after full veraison. By harvest, the differences were not statistically significant, with N40 having a TA just 1.5% higher than UC and 3.1% higher than N26. UC showed a TA 1.5% higher than N26. In 2022, the N40 treatment promoted higher TA, with significant percentage differences compared to other treatments. At the first measurement, N40 showed a TA value 24% higher than UC and 10.4% higher than N26. N26 had a TA 12.3% higher than UC. This trend continued until harvest, with N40 showing a TA 12.9% higher than UC. In contrast, N26 had values almost identical to UC (Figure 6B).

For Syrah, the analysis of variance revealed a significant effect for TA, not only for the factors Y and T but also for their interaction (Y × T) (Table 11). Specifically, TA analysis for Syrah in 2021 and 2022 shows that N40 tends to present higher average values compared to UC and N26 in nearly all measurements, with more pronounced and significant differences in 2022. In the first measurement of 2021, although differences were not significant, N40 had a higher TA compared to other treatments (Figure 6C). This trend continued until harvest, where N40 showed a TA 18.2% higher than UC and 8.3% higher than N26. N26 had a TA 9.1% higher than UC. In 2022, the differences became even more evident. N26 and N40 showed significantly higher TA values than UC in the first measurement, with N26 recording the highest increase compared to UC, at +36.7% (Figure 6D). However, the evaluation performed 25 days after full veraison showed a trend shift between the two shading treatments, with both maintaining higher values than UC, though N40 showed values 15% higher compared to UC, versus about 8% for N26. At harvest (+48 days), N40 maintained a total acidity 15.4% higher than UC and 13% higher than N26, while N26 showed a significant reduction in acidity, making it not significantly different from UC.

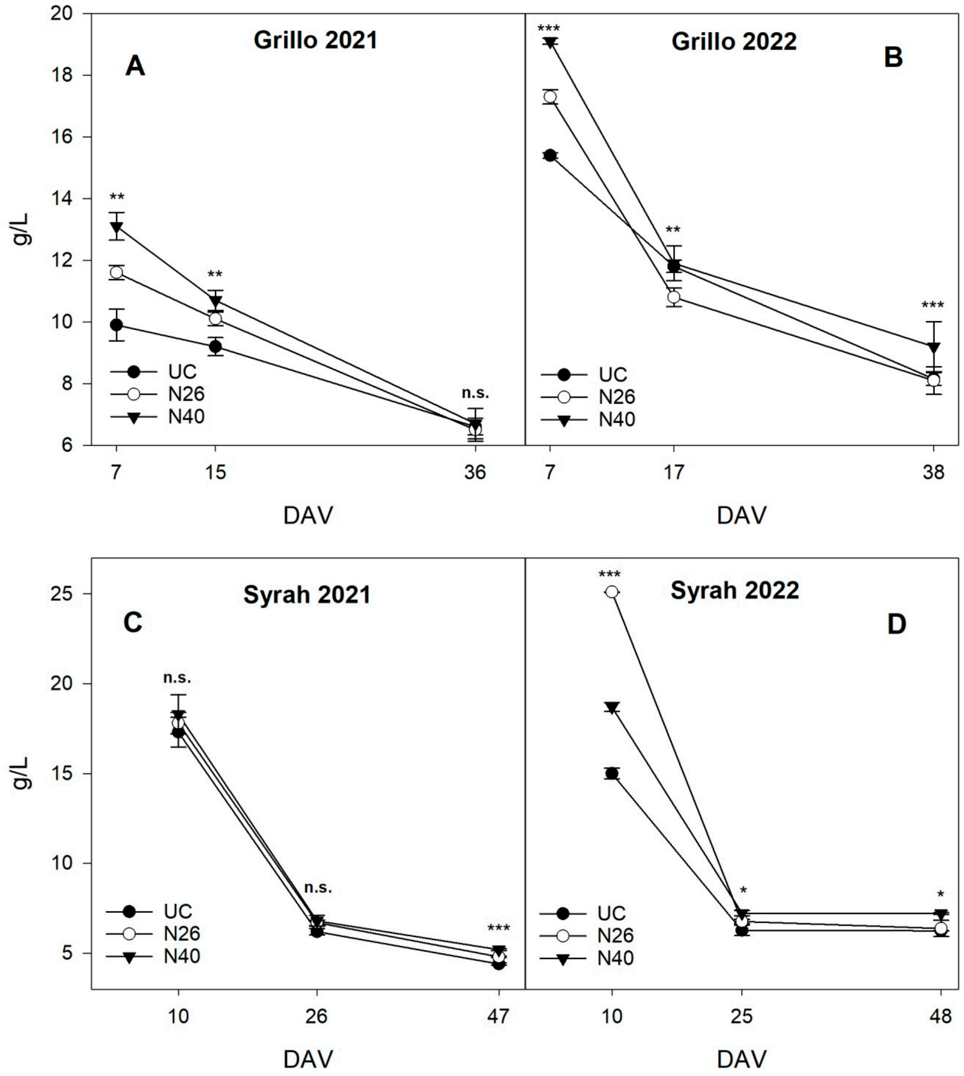

Figure 6. Total acidity (TA) measured for each treatment, presented as means with standard errors. Subplot (**A**) shows the TA for the Grillo variety in 2021, subplot (**B**) for Grillo in 2022, subplot (**C**) for Syrah in 2021, and subplot (**D**) for Syrah in 2022. Significance levels are indicated as follows: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. "n.s." indicates non-significant differences.

4. Discussion

4.1. Macro e and Microclimate Impacts

The precipitation data from 2021 and 2022 highlight significant climatic differences. In 2021, rainfall was anomalous, with most precipitation occurring in the spring and extending partially into the summer. This atypical distribution suggests unique climatic conditions that disrupt normal precipitation patterns. Although the ample spring rainfall may have temporarily eased summer water stress, its irregular distribution underscores the need for careful water resource management. In contrast, 2022 saw precipitation levels return to more typical values for the studied environment. However, the year was marked by reduced rainfall, especially in winter and spring, which posed challenges for water resource replenishment and crop health. Despite summer precipitation approaching historical averages, the overall limited rainfall throughout the year highlighted ongoing challenges in managing water resources and agriculture. Monitoring these fluctuations is crucial for effective management and adaptation to shifting climatic conditions. These trends and challenges are consistent with the impacts of climate change [33–35]. Significant differences in microclimatic conditions between treatments highlight how shading affects temperatures recorded under the covers. The UC treatment exhibited higher average temperatures, with more frequent instances of 30-minute intervals exceeding critical thresholds of 32 °C, 35 °C, and 40 °C compared to N26 and N40. This trend was particularly pronounced during extreme temperature events, with UC recording significantly higher temperatures in both 2021 and 2022. These findings suggest that shading effectively reduces vine exposure to extreme temperatures, influencing the canopy microclimate and potentially mitigating thermal stress.

4.2. Vegetative Growth and Leaf Nutritional Status

Canopy shading had significant repercussions on the physiology of the photosynthetic apparatus. Specifically, there was a marked increase in chlorophyll levels in the leaves of shaded vines. This phenomenon is characteristic of green organs exposed to intense light for extended periods. High irradiance conditions generally result in decreased chlorophyll content, leading to reduced light absorption capacity. This adaptation is presumably a mechanism to avoid or mitigate damage to the photosynthetic apparatus caused by high irradiance [36]. Additionally, our results indicated that UC leaves had significantly more anthocyanins compared to shaded treatments. This suggests that UC leaves were subjected to greater photo-oxidative stress, with higher anthocyanin accumulation likely serving as protection against UV radiation damage [37]. These results align with previous studies on shading effects, which have demonstrated that net use can effectively reduce photo-chemical stress in leaves [14,38]. The monitoring of canopy effects also included the assessment of vegetative growth. Overall, no significant effects on average leaf area per plant (m^2) were observed; however, shaded vines exhibited greater shoot and internode length compared to controls. These responses can be interpreted as adaptations to the altered microclimatic conditions induced by shading. According to established theories on plant responses to shading, increased internode length can be viewed as a strategy to optimize light absorption under reduced light intensity [39]. This phenomenon is consistent with responses observed in other plant species exposed to low red-to-far-red light ratios, where marked stem elongation occurs to achieve better light exposure [40].

4.3. Grape Withering and Yield

Microclimatic results are particularly relevant in light of the increasing frequency of extreme heat events due to climate change. For instance, Zhang et al. [41] report that 2022 was marked by extreme climatic events globally, including unprecedented heat waves and droughts, setting historical records in various regions. In this context, berries are vulnerable to thermal and light stress, leading to noticeable impacts on their sensory characteristics and wine quality. For instance, [36] reports that direct exposure to excessive heat and light causes mesocarp cell death and grape dehydration. Grape dehydration manifested as sunburn and fruit desiccation significantly affects berry weight loss, sugar concentration, organic acid levels, and other wine quality components such as color and aroma [42–45]. Regarding berry weight, the results of this study suggest that the N26 treatment represented an intermediate condition between UC, which was fully exposed to radiation, and the N40 treatment, which provided a higher degree of shading. Under the milder climatic conditions of 2021, the N26 treatment effectively balanced radiation exposure and temperature moderation, reducing dehydration and mesocarp cell death while still permitting sufficient light for photosynthesis and berry growth. Compared to UC, the N26 treatment mitigated the adverse effects of excessive radiation and heat, leading to increased berry weight. Conversely, compared to the N40 treatment, the milder temperatures and lower shading level of N26 allowed for improved light interception, supporting photosynthesis and additional berry growth. This mitigated the constraints on berry enlargement observed under the N40 treatment, where greater shading likely reduced the light required for further berry development. This combination of factors suggests that the moderate shading level provided by the N26 treatment offered optimal conditions for maintaining active physiological processes, enhancing water retention, and supporting additional berry growth, ultimately resulting in higher berry weight compared to the other treatments. In this context, implementing cultivation techniques to counteract or mitigate these effects appears crucial. The results of this study suggest that shading nets could be a valuable tool. The final considerations address the effects of shading on yield components. The results show that canopy coverage at pea berry size (BBCH 75) has significant effects on berry growth, with covered vines reporting significantly lower values at harvest. This result is likely due to reduced light exposure, which, as reported in other studies, results in overall reduced growth [38,46,47]. The direct consequence of this finding is the decrease in average cluster weight for shaded vines, leading to a reduction in average yield per vine.

4.4. Phenological Stages and Grape Quality

Extreme events are not the only issue related to climate change. Various studies indicate that global temperatures have stabilized at generally above-average levels, with a trend towards further increases, exacerbating challenges for viticulture [5,33]. These conditions are significant as the phenological development of the vine is closely dependent on air temperatures [48]. For instance, Jones et al. [49] found that high temperatures advance budburst and flowering, affecting ripening processes. The global importance of this issue is underscored by similar consequences observed in various wine regions worldwide. A study conducted in Bordeaux, France [50], and another in the Douro Valley, Portugal [51], both found a direct correlation between high temperatures and phenological advancement. In this context, shading nets can play a crucial role in delaying vine phenology. In the present study, shaded vines with both types of covers exhibited a clear delay in maturation, likely due to reduced exposure to direct sunlight, which affects photosynthesis and vine metabolism [52].

The significant increase in temperatures has led to grapes maturing under warmer conditions and in shorter times compared to the past, with a rapid increase in sugars and concomitant degradation of organic acids [53]. This phenomenon was previously observed by Kliewer and Lider [54], who demonstrated that clusters exposed directly to sunlight mature more rapidly than those shaded by the canopy. In this study, grapes subjected to shading treatments showed significantly lower sugar values at harvest compared to sun-exposed grapes. These effects are particularly relevant in the context of climate change, considering that many wine regions worldwide are situated in areas highly affected by it. However, it is essential to investigate the causes of these results. Evaluating the ratio of leaf area per gram of berry is crucial, as photosynthesis is the primary source of sugars [55]. Specifically, optimal values of this ratio range from 5 to 15 $cm^2 g^{-1}$ depending on the cultivar, climatic region, and vineyard management techniques [56]. The results of this study show that, for both varieties, there were no differences in this parameter among treatments. This suggests that differences in sugar levels observed between shaded and non-shaded treatments are not attributable to differences in carbohydrate supply to the berries but rather to a clear phenological delay. This response may also be influenced by differences in total acidity (TA), which was higher at harvest in shaded clusters, with N40 demonstrating a greater ability to preserve acids. This response is likely influenced by the lower temperatures recorded under the net, as the role of temperature is well-documented. According to Coombe [57], a 10 °C increase in temperature during growth led to a 50% reduction in tartaric acid content. Similarly, Kliewer and Lider [58] and Lasko and Kliewer [59] found that malic acid synthesis was more sensitive to high temperatures compared to tartaric acid synthesis. In addition to the observed effects on sugar levels and yield components, shading also has implications for the accumulation of secondary metabolites, such as anthocyanins. Shading reduces light exposure, which is critical for anthocyanin synthesis, as demonstrated in several studies [16]. However, under high-temperature conditions, shading can play a protective role by reducing thermal stress and preventing the degradation of anthocyanins already synthesized. For instance, Martínez-Lüscher et al. [9] reported that shaded vines in warm climates exhibited higher anthocyanin concentrations at harvest compared to fully exposed vines, as shading mitigated the heat-induced degradation of these compounds. The timing and intensity of shading also influence its effects. Early and intense shading has been associated with lower concentrations of phenols and anthocyanins, whereas moderate shading in high-temperature environments has been shown to preserve these compounds while maintaining berry quality [14,60]. This dual role of shading, limiting anthocyanin synthesis under reduced light but preserving it under thermal stress, highlights the importance of optimizing shading strategies to balance light interception and temperature regulation.

5. Conclusions

The comparison between the two shading levels tested reveals that 40% shading was more effective in mitigating the negative impacts of extreme temperatures, particularly under hotter conditions, while 26% shading showed advantages primarily in the milder climatic year. Although varying shading levels did not have an immediate effect on bud fertility, further research is needed to evaluate their long-term impacts. Shading influenced berry size and, consequently, cluster size, directly affecting yield. These findings suggest that shading levels below or near 30% may be less suitable for warm environments, such as those studied here, where higher levels of protection are necessary to counteract the increasing frequency of extreme heat events. Furthermore, the results provide preliminary evidence that a shading level of 40% may already represent an optimal compromise, achieving the desired outcomes in terms of thermal stress mitigation and controlled ripening while avoiding the potential drawbacks associated with more intense shading. Higher shading levels (e.g., 70% or more), often recommended in the literature for their immediate protective effects, may pose long-term risks to vine vigor, reserve accumulation, and overall productivity, as highlighted in previous studies. Future research should aim to validate the long-term suitability of moderate shading levels, such as 40%, under diverse environmental conditions and across different cultivars. Additionally, assessing the economic feasibility and large-scale applicability of shading practices will be essential for ensuring the sustainability and productivity of vineyard systems in the context of climate change.

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Data Availability Statement: The datasets generated and analyzed during the current study are not publicly available but can be provided by the corresponding author upon request.

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