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Use of White Non-Woven Polyester Sheets (TNTs) to Control Photoinhibition, Berry Dehydration, and Extreme Heat in the Vineyard

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Abstract

The protection of leaves from photoinhibition and berries from dehydration and sunburn has become an increasingly important objective in response to the rising frequency and intensity of heat waves worldwide. This research investigated the effect of a white nonwoven geotextile sheet (TNT) installed in the fruiting zone in the white cultivar 'Verdicchio' (*Vitis vinifera* L.) during critical summer periods with the aim of protecting leaves and berries from extreme heat. The study was conducted over two seasons (2020–2021) in a rainfed vineyard in central Italy using a randomized block design. Physiological and yield parameters were recorded. Vines protected with TNT did not show any changes in net photosynthesis, stomatal conductance, and water use efficiency, compared to unshielded vines. However, TNT reduced leaf temperature and increased berry total acidity and malic acid concentration while reducing sugar content, leading to wines with higher freshness and reduced alcohol levels. The use of TNTs shows significant potential as a practical tool for viticulturists to mitigate the effects of excessive heat, allowing for better management of berry ripening and ultimately improving final wine characteristics. Additionally, TNT is economically feasible, especially if applied only to the afternoon-exposed side of the canopy, and its cost can be amortized, especially in vineyards affected by frequent heat waves and/or dedicated to the production of premium wines.

Keywords: leaf gas exchange; temperature; chlorophyll fluorescence; grape composition; *V. vinifera*

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1. Introduction

In recent decades, adverse weather events throughout the entire grapevine growing and production cycle have increased significantly in viticultural areas worldwide. Spring frosts, summer hailstorms, torrential rains, flooding, and especially very high air temperature and heat waves are becoming more frequent, making vineyard management more difficult, requiring appropriate and adaptive management techniques, preferably preventative ones [1,2]. Regardless of the grape variety, the negative consequences of high temperature and heat waves can be summarized as follows: (a) yield loss caused by

severe dehydration of the berries, leading to grape sunburn [3,4]; (b) poor grape chemistry quality due to the rapid degradation of organic acids and varietal aromas, including primary precursors [5,6]; (c) poorly polymerized tannins and abundant flavonoids, especially quercetin, accumulation in the berry skin resulting in excessive bitterness and astringency in wines [7]; (d) high sugar content resulting in highly alcoholic wines [8]; (e) leaf photoinhibition phenomena with chlorosis and necrosis [9]; (f) risks to vine survival [10–13]. Under multiple summer stress conditions, i.e., high temperature and radiative regimes and water scarcity, the resulting wines are unexpressed and unrecognizable and characterized by poor longevity [11]. Therefore, under these conditions, the primary objective is to protect the clusters during critical periods with readily deployable and cost-effective techniques. Among those capable of providing a protective function and allowing full recovery after heat waves is the use of screening nets, including photo-selective ones [14–17] and shade films [18].

This study describes the results of a two-season trial aimed to assess the effect of the application of a white non-woven geotextile sheet (TNT) to the fruiting zone of the white cultivar 'Verdicchio' during summer. The hypothesis tested was whether the TNT would increase the reflection of radiant energy and hence cool down the canopy. The goal of this research was to determine whether TNTs could protect the canopy from leaf photoinhibition and the berries from dehydration and sunburn, as well as analyze their effects on yield and grape composition.

2. Materials and Methods

2.1. Plant Material, Site Location, and Experimental Design

The study was conducted in 2020 and 2021 in a rainfed commercial vineyard located near Serra S. Quirico (Ancona, Marche Region, central Italy, 43°27′0.5″ N, 13°03′53″ E, elevation 296 m a.s.l.). The vineyard was a six-year-old planting of 'Verdicchio' (*V. vinifera* L.) indigenous to the area, grafted on 'SO4' rootstock. Vines were trained to a Guyot system with a bud-load of 9–10 nodes per vine on a hilly terrain with an average slope of about 20%. Vine spacing was 3 m between rows and 1 m between vines (3330 vines per hectare) with a North-East to South-West rows orientation. The fruiting cane was positioned 0.8 m above ground with three pairs of surmounting catch wires, for a canopy wall extending about 1.2 m above the fruiting cane. Pest management was carried out according to local standard practices.

Two rows were selected to establish a completely randomized block design, with each row serving as a block. Thirty vines within each block were randomly assigned to the following two treatments: (a) control, no TNT (C); (b) positioning of a white TNT on the fruit zone. The TNT (1 m wide and 30 g/m^2 density) was installed at the BBCH 79 growth stage (majority of berries touching), which occurred on June 30th in 2020 and 24th in 2021, and was removed 3 weeks before harvest. The sheet was placed on the canopy side exposed in the afternoon, which is more sensitive to thermal and radiative stress (Figure 1). Weather conditions were monitored using an automatic meteorological station of the Regional Meteorological-Hydro-Pluviometric Information System (SIRMIP) provided by the Civil Protection Service of the Marche Region, located near the trial site.

2.2. Gas Exchange and Chlorophyll Fluorescence Measurements and Canopy Light Characteristics

Single-leaf gas-exchange measurements were taken twice daily at 12.00–13.00 and 15.00–16.00 solar time on clear days at BBCH 85 (softening of berries), which occurred on the 31st of July in 2020 and 24th of July in 2021. Measurements were taken on both the sun-exposed side of the canopy and under the TNT. For each treatment, twenty leaves on 10 vines were selected from primary shoots, located at nodes five or six above the

distal cluster. These measurements were performed using a portable, open system, LCA-3 infrared gas analyzer (ADC Bio Scientific Ltd., Herts, UK) equipped with a broad leaf chamber featuring a 6.25 cm^2 window, and all readings were taken at ambient relative humidity with an air flow adjusted to 350 mL min^{-1}. Net photosynthesis (P_n), transpiration rate (E), and stomatal conductance (g_s) were calculated from the inlet and outlet CO_2 and H_2O relative concentrations. Intrinsic water use efficiency (WUEi) was then derived as the P_n/g_s ratio. Moreover, the amount of radiation transmitted through the TNT was measured using a 1 m linear quantum sensor (mod. RG99, Silimet, Modena, Italy) equipped with 10 photosynthetic active radiation (PAR) sensors. To further investigate the photochemical apparatus, chlorophyll fluorescence was also measured on the same leaves used for gas exchange analysis with a lightweight portable continuous excitation fluorometer, Handy-PEA (Hansatech Instrument, Norfolk, UK). After 30 min of dark adaptation, the leaves were exposed to actinic light of 3000 µmol photons $m^{-2} \cdot s^{-1}$. Fluorescence parameters, such as Fo (ground fluorescence), Fm (maximum fluorescence), and Fv (variable fluorescence, Fm-Fo), were collected using the method described by [19]. Fv/Fm ratio, indicating the maximum quantum yield of PSII [19], was calculated automatically by the Handy-PEA fluorimeter. Other parameters were also determined, such as the area over the fluorescence curve between Fo and Fm, which indicates the pool size of plastoquinone on the reducing side of PSII [20]. Simultaneously, on the same leaves used for the gas exchange readings, the temperature of the upper side of the leaves was measured using an infrared thermometer (Model TM909L9, Assi-control, Varese, Italy).



Figure 1. Vineyard of cv. 'Verdicchio' showing the installation of the TNT on the fruiting zone. The TNT was installed at the end of June and removed at the end of the summer.

2.3. Yield and Grape Composition

Harvest was carried out on September 24 and 21 in 2020 and 2021, respectively. Vines (n = 26 per treatment) were individually harvested, and the number of clusters per vine as well as the total mass were recorded. The average cluster weight was then calculated. At harvest, three samples of 300 berries per treatment on each block were randomly collected, and their fresh weight was recorded. After crushing, the total soluble solids content (°Brix) in the must was measured using a temperature-compensating refractometer. Titratable acidity was determined by titration with 0.1 N NaOH to an end point of pH 8.2 and expressed as g/L of tartaric acid equivalent. The must pH was measured using a PHM82 standard pH meter (Radiometer, Copenhagen, Denmark). Yeast assimilable nitrogen (YAN)

content in the must was measured according to a method based on the reaction with formaldehyde with amino functions [21]. The incidence of sunburn damage was assessed at harvest as a percentage of affected clusters of the total. A cluster was deemed sunburnt when a minimum of 10 berries were showing visual symptoms. Cluster compactness was visually estimated on 200 clusters per treatment using OIV code 204 (OIV 1983), where number 1 indicates "berries in grouped formation with many visible pedicels" and number 9 indicates "misshapen berries". At winter pruning, canes from 26 representative vines per treatment were weighted to estimate pruning mass.

2.4. Statistical Analysis

Two-way analysis of variance (ANOVA) was used to assess treatment and year effects on yield components, grape composition, gas exchange, and chlorophyll fluorescence parameters using SigmaStat software package version 3.5 (Systat Software, Inc., San Jose, CA, USA). The year was considered a random variable, and the error term for the treatment factor was the year × treatment interaction mean square. Treatment comparison was performed each year by the *t*-test. Visual ratings of cluster compactness were transformed to the square root before analysis.

3. Results

3.1. Meteorological Data

The 2020 season was characterized by moderate daily maximum temperatures, with peaks of 27.3 °C in May, 32.9 °C in June, 34.6 °C in July, 34.5 °C in August, and 30.5 °C in September (Figure 2). The accumulated heat totaled 1748 growing degree days (GDD, base 10 °C from 1 April to 30 September), with 409 GDD in July (24% of the total) and 445 GDD in August (25%). There were only two days with temperatures exceeding 35 °C, 39 days with temperatures greater than 30 °C, and 22 nights with temperatures above 20 °C, classified as tropical nights [22]. The total rainfall during the growing season was 431.6 mm, and the majority of the rain was concentrated in June (88.8 mm), August (70.2 mm), and September (108.4 mm).

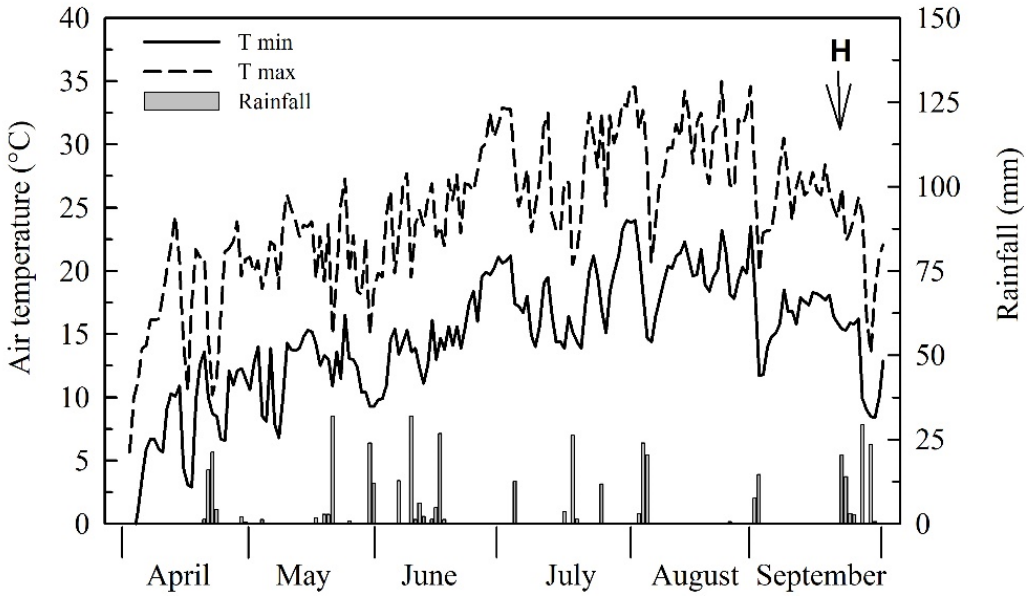


Figure 2. Seasonal trends of minimum and maximum air temperature and rainfall recorded from April to September in the 2020 season. H = harvest time.

Compared to 2020, the 2021 season was characterized by higher daily maximum temperatures with peaks reaching 25.9 °C in May, 35.6 °C in June, 36.1 °C in July, 35.3 °C

in August, and 29.6 °C in September (Figure 2). The accumulated heat totaled 1836 GDD, with 453 GDD in July (25% of the total) and 454 GDD in August (25%). There were six days with temperatures exceeding 35 °C, 44 days with temperatures greater than 30 °C, and 36 tropical nights. Total rainfall during the growing season was 214 mm, almost half compared to 2020, with the majority concentrated in May (56.8 mm) and September (61.8 mm). April, June, July, and August were almost dry with only 23, 12, 31, and 29 mm of rain, respectively.

3.2. Physiological Parameters

Measurements carried out on the 31st of July 2020 between 12:00–13:00 and 15:00–16:00 solar time highlighted that the TNT reduced PAR values by 39% and 48% in the first and second measurement, respectively, compared to the control. Leaf temperature was also reduced with a difference of 2.6 °C compared to the control in the morning and 3.2 °C at mid-afternoon (Table 1).

Table 1. Measures of photosynthetic active radiation (PAR, μmol $m^{-2} \cdot s^{-1}$), leaf temperature (TL, °C), net photosynthesis (P_n, μmol$m^{-2} \cdot s^{-1}$), stomatal conductance (g_s, mmol $m^{-2} \cdot s^{-1}$), water use efficiency (WUE = P_n/g_s), maximum quantum yield of photosystem II (Fv/Fm, arbitrary unit), and area (arbitrary unit). Measurements were collected from 20 leaves chosen as the 5th or 6th leaf above the distal cluster on a shoot of the medial 'Verdicchio' vines under the TNT and control in the 2020 season.

	PAR	T_L	P_n	g_s	WUE	Fv/Fm	Area
			12:00–13:00				
Leaves under the TNT	1149 b	31.4 b	9.6 a	245 a	39.2 a	0.77 a	28,900 a
Control	1883 a	34.0 a	11.7 a	280 a	40.8 a	0.70 a	27,800 a
			15:00–16:00				
Leaves under the TNT	913 b	31.9 b	8.5 a	210 a	40.5 a	0.78 a	25,600 a
Control	1760 a	34.1 a	9.2 a	227 a	40.9 a	0.73 a	26,900 a

Values followed by different letters are significantly different at $p < 0.05$ (*T*-test).

At the same time, the leaves under the TNT did not show significant variation in P_n, g_s, and WUE, compared to control leaves during both end-morning and mid-afternoon measurements (Table 1). In both treatments, no photoinhibition was found, since Fv/Fm and area parameters showed no significant variation. However, Fv/Fm values always resulted in higher than 0.70, indicating a good quantum yield of PSII and absence of photoinhibition.

On the 24th of July 2021, leaves under the TNT showed a reduction in PAR availability compared to the control, with −36% at the end of the morning and −41% at mid-afternoon (Table 2), as well as a decrease in leaf temperature of approximately 4–5 °C. P_n, g_s, and WUE did not show any differences. However, a slight photoinhibition was observed, as Fv/Fm values in both measurement intervals dropped below 0.65 (Table 2). Nevertheless, despite these down-regulations of PSII activity, initial PSII photodamage and diminished non-radiative energy dissipation, only a few sporadic leaves from unshielded control vines showed yellowing and/or necrosis phenomenon (Figure 3). This behavior could be linked to the fact that, before measurements, the days with temperature around 30 °C were limited, precisely four consecutive days with air temperature variable from 29 to 31 °C (Figure 2), probably not sufficient to cause chronic photoinhibition in the leaves.

3.3. Vine Yield and Grape Composition at Harvest

At harvest 2020, which occurred on the 24th of September, total yield and the related components did not show significant variations among treatments, such as the pruning

weight (Table 3). In TNT-covered vines, there was no incidence of sunburn on clusters, while in the control vines, 13.8% of clusters were affected (Figure 3 and Table 3).

Table 2. Photosynthetic active radiation (PAR, µmol $m^{-2} \cdot s^{-1}$), leaf temperature (TL, °C), net photosynthesis (P_n, µmol $m^{-2} \cdot s^{-1}$), stomatal conductance (g_s, mmol $m^{-2} \cdot s^{-1}$), water use efficiency (WUE = P_n/g_s), maximum quantum yield of photosystem II (Fv/Fm, arbitrary unit), and area (arbitrary unit) on medial leaves of primary shoot of 'Verdicchio' vines under the TNT and control in 2021 season.

	PAR	T_L	P_n	g_s	WUE	Fv/Fm	Area
			12:00–13:00				
Leaves under the TNT	1250 b	32.2 b	6.2 a	171 a	36.0 a	0.78 a	25,600 a
Control leaves	1956 a	37.4 a	6.4 a	182 a	34.2 a	0.64 b	24,600 a
			15:00–16:00				
Leaves under the TNT	1120 b	30.8 b	4.8 a	155 a	29.5 a	0.80 a	22,800 a
Control leaves	1890 a	35.8 a	4.1 a	146 a	28.6 a	0.63 b	21,500 a

Values followed by different letters are significantly different at $p < 0.05$ (*T*-test).



(**a**) (**b**)

Figure 3. Depiction of foliage of uncovered 'Verdicchio' vines affected by photoinhibition with chlorosis (**a**) and cluster with evident sunburn in control vines (**b**).

Table 3. Yield components measured at harvest and pruning weight in control and TNT-covered 'Verdicchio' vines in the seasons 2020 and 2021.

	2020		2021		Year × Treatment Interaction [a]
	Control	TNT	Control	TNT	
Yield/vine (kg)	4.70	4.35	3.25 b	3.96 a	*
Number of clusters/vine	10.4	9.7	9.6	10.1	ns
Cluster weight (g)	455	448	336 b	392 a	*
Berry weight (g)	2.8	2.9	2.3 b	2.9 a	*
Number of berries/cluster	160	151	143	137	ns
Number of seeds/berry	2.3	2.4	2.5	2.6	ns
Rachis length (cm)	21.3	21.0	21.9	22.3	ns
Cluster compactness [b]	7.2	7.0	7.1	7.3	ns
Sunburn clusters (%)	13.8 a	0 b	24.9 a	1.3 b	**
Pruning weight (kg/vine)	1.34	1.39	1.51	1.62	ns

[a] In the case of a significant year × treatment interaction, letters indicate means separation within rows and years by *t*-test. *, **, and ns indicate significance at $p < 0.05$, 0.01 or no significance, respectively. [b] Rated according to the OIV 204 standard.

In the 2021 season vintage, the control vines showed a lower yield (−18%) compared to TNT-covered vines, together with a reduction in berry and cluster weight due mainly to berry dehydration (Table 3). The TNT protected the clusters from sunburn damage, with only 1.3% of clusters affected compared to the 25% measured in the control (Figure 3 and Table 3).

The chemistry of grapes from TNT-covered vines in 2020 showed a similar must pH and a significantly higher content of organic acids, especially malic acid (+0.55 g/L) and YAN (+88 mg/L), compared to the control. (Table 4). At harvest 2021, total soluble solids were significantly lower in clusters from TNT vines, and organic acids, malic acid, and YAN were significantly higher; must pH resulted in lower values (Table 4), indicating a delay of the ripening process.

Table 4. Grape composition measured at harvest in 'Verdicchio' vines shielded with a TNT and unshielded (control) in 2020 and 2021 vintages.

	2020		2021		Year × Treatment Interaction [a]
	Control	TNT	Control	TNT	
Total Soluble Solids (°Brix)	23.0	22.4	23.6 a	21.8 b	*
Titratable Acidity (g/L)	6.6 b	7.1 a	6.1 b	7.0 a	*
Malic Acid (g/L)	2.03 b	2.58 a	2.01 b	2.60 a	*
Must pH	3.10	3.04	3.18 a	3.06 b	*
YAN (mg/L) [b]	196 b	284 a	156 b	202 a	**

[a] In the case of a significant year × treatment interaction, letters indicate means separation within rows and years by *t*-test. *, ** indicate significance at $p < 0.05$, 0.01, respectively. [b] YAN = yeast assimilable nitrogen.

4. Discussion

It is generally accepted that shading influences the microclimate beneath the net by reducing canopy and cluster temperatures [23–25]. Several authors have reported increased chlorophyll content due to reduced photoinhibition as a result of the lower irradiance and cooler leaf temperatures [18,26–28]. In this trial, the basic physiological activity of leaves covered by TNTs during the hottest periods of summer was not affected (Tables 1 and 2). At the same time, leaf photoinhibition, typically occurring under several consecutive days with air temperature above 30 °C, was mitigated, avoiding chlorosis and necrosis in the leaves, in agreement with the studies above. During the hottest hours of the day, typically at midday at the latitude of the trial, leaves covered with a TNT did not show reductions in P_n, g_s, and WUE (Tables 1 and 2). This indicates that the PAR available under the TNT was sufficient to saturate chloroplasts and to keep the stomata open, maintaining normal gas exchange while cooling canopy temperatures. The use of the white TNT, with the inherent high light reflection, effectively protected clusters from sunburn, in accordance with other findings [3,29]. Considering that cluster number per vine remained unchanged between treatments, the increased berry size and yield recorded in 2021, which was drier and hotter than the previous year, in TNT-covered vines is likely related to the cooler canopy microclimate and reduced berry dehydration (Table 3). These results support the notion that vine netting can enhance yield, especially in hot and dry seasons, as also shown in other studies [17,24,30].

The greater yield recorded in 2021 in the TNT vines could have caused the observed delay in technological ripening of the grapes (lower total soluble solids, must pH, and higher organic acids) (Table 4). On the other hand, the absence of an effect on technological ripening in 2020 is likely related both to the fact that leaves under the TNT maintained normal activity comparable to the control and to the exposure of uncovered parts of the canopy, in agreement with previous studies [27]. The increased YAN is also notable,

since levels above 150 mg L^{-1} are essential for consistent alcoholic fermentation and for enhancing primary aroma development (Table 4). In their survey, Bouloumpasi et al. [31] reported that amino acid content in grapes across various varieties in Greece is generally negatively correlated with temperature, particularly during the ripening period. Although their study focused primarily on climate and growing regions, it helps explain the results of this trial, where shading the fruiting zone and thereby cooling the canopy microclimate led to higher nitrogen content in the grapes on both vintages.

Finally, it has been previously reported that a major drawback of shading is the reduction in vine growth due to decreased photosynthesis and hence carbohydrate assimilation [16,23,27]. However, in this study, no differences in pruning weight were observed between treatments, as vines' assimilation and sugar production were not compromised (Table 3). This is likely because the TNT covered only the fruiting zone while leaving the upper canopy exposed, thereby ensuring adequate carbohydrate supply for reserve accumulation in the wood.

5. Conclusions

This research highlights the beneficial effects of TNT application to the cluster zone of the canopy in the white cv. 'Verdicchio' in protecting leaves and berries from the negative effects of the increasingly frequent period of high temperatures in Mediterranean viticultural areas. The TNT effectively protected the vines from photoinhibition while maintaining normal physiological activity. Covering the clusters provided significant protection against overexposure, markedly reducing the incidence of sunburn and berry dehydration, which resulted in increased yield and improved grape chemical composition without impairing reserves accumulation. The TNT shows strong potential as a practical tool for viticulturists to mitigate the effects of excessive heat and solar radiation, allowing for better management of ripening to improve final wine quality. Finally, it is also economically viable, especially if applied only on the sun-exposed side of the row during the afternoon. The cost of shading film applied does not result in increased production costs and can be considered a sustainable practice for the crop. Moreover, its cost can be easily amortized, particularly in vineyards frequently affected by heat waves and/or dedicated to the production of premium wine grapes. The conclusions presented here are based on a two-year study with ordinary meteorological conditions; however, the assessment of long-term effects remains to be addressed, as well as the possible effects on pest disease, phytosanitary treatments, and wind speed, especially in years characterized by excess of rains and winds during the time of sheet applications on the canopies.

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