

Dattola, A. , Gullo, G. , Accardo, A. , Zappia, R.

# Foliar application of natural reflective minerals enhances physiological performance and yield of *Vitis vinifera* L. cv. Chardonnay under Mediterranean climate stress

## Affiliation

Mediterranean University of Reggio Calabria, Department of Agriculture, Reggio Calabria, Italy.

## Correspondence

\*Antonio Dattola: antonio.dattola@unirc.it; Antonella Accardo: aaccardo566@gmail.com; Gregorio Gullo: ggullo@unirc.it; Rocco Zappia: rocco.zappia@unirc.it

## Summary

Mediterranean viticulture faces increasing challenges from severe thermal and water stress induced by climate change, which threaten both yield and grape quality. This study evaluated the effectiveness of foliar applications of three natural reflective mineral products, zeolite (TZL), basalt powder (TPB), and kaolin (TK), as sustainable adaptation strategies for *Vitis vinifera* L. 'Chardonnay' cultivated under typical Mediterranean conditions. The experimental trials demonstrated that these mineral-based reflective films are effective agronomic tools for mitigating heat and drought stress. All treatments significantly increased yield and average bunch weight compared with the untreated control, reducing losses caused by berry dehydration. Among the tested materials, zeolite (TZL) achieved the highest bunch weight and superior physiological performance. Ecophysiological assessments confirmed that reflective treatments preserved photosynthetic function by reducing photoinhibition and improving both net photosynthesis (Pn) and water-use efficiency (WUE). While zeolite provided the best overall physiological and productive response, basalt powder produced grapes of the highest quality. Overall, the use of natural reflective minerals—particularly zeolite—emerges as an innovative and environmentally sustainable approach to optimizing vine energy and water balance, thereby maintaining high-quality grape production in Mediterranean regions increasingly affected by global warming.

## Keywords

Climate resilience, mineral sunscreens, vineyard resilience, kaolin, basalt powder, zeolite.

## Introduction

Climate change is exerting increasing pressure on agroecosystems worldwide. Modelling studies consistently predict further rises in global, regional, and local temperatures, along

with more frequent and intense extreme weather events. Although projections for precipitation remain uncertain, several indices indicate a trend toward fewer but heavier rainfall events, leading to extended dry periods interrupted by intense storms (IPCC, 2021). These trends represent one of the most pressing challenges for global agriculture, a sector highly dependent on climatic stability for both productivity and quality. Rising temperatures, heat waves, and water scarcity increase production costs, reduce yield efficiency, and may ultimately lead to land abandonment and desertification in vulnerable regions (Lobell *et al.*, 2011; Moriondo *et al.*, 2015). Viticulture is particularly sensitive to thermal and radiative anomalies, as grapevine physiology is tightly regulated by the interaction between climate, soil, and topography. Temperature plays a pivotal role in determining photosynthesis, sugar accumulation, and the synthesis of secondary metabolites (Keller, 2010; van Leeuwen and Darriet, 2016). Accordingly, bioclimatic indices used to define viticultural zones—such as the Winkler and Huglin indices—are primarily temperature-based. Current warming trends threaten the suitability of many Mediterranean vineyards, where excessive heat and radiation already cause phenological shifts, sugar–acid imbalance, berry dehydration, and degradation of anthocyanins and aromatic compounds (Jones *et al.*, 2005; Fraga *et al.*, 2018). Projections suggest a northward shift of viticulture, as central and northern Europe increasingly acquire Mediterranean climatic characteristics, with warmer and drier summers and rainfall concentrated in spring and autumn. Conversely, many coastal areas of southern Europe may become unsuitable for high-quality grape production (Hannah *et al.*, 2013). Under such conditions, heat waves exceeding 40 °C can raise leaf temperature by 8–10 °C above ambient, surpassing the critical threshold for photosynthetic damage (Greer and Weedon, 2012). This induces photoinhibition, oxidative stress, and irreversible injury to photosynthetic tissues, accelerating phenological development and decoupling technological from phenolic ripeness—ultimately producing overripe and unbalanced wines. To counter these effects, viticulturists are revising traditional management



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practices and adopting adaptive strategies aimed at enhancing vineyard resilience (Santos *et al.*, 2020). Long-term strategies include rootstock–scion selection, vineyard layout optimization, and training systems, whereas short-term approaches focus on canopy management and the use of natural reflective materials. Among these, foliar applications of mineral-based sunscreens such as kaolin, basalt powder, and zeolite have gained increasing attention as cost-effective and environmentally friendly methods to reduce leaf temperature, limit water loss, and protect the photosynthetic apparatus by increasing reflectance in the visible, infrared, and ultraviolet spectra (Glenn *et al.*, 1999; Glenn, 2012; Brito *et al.*, 2018). Within this context, the present study evaluates the physiological, biochemical, and productive responses of *Vitis vinifera* L. ‘Chardonnay’ to different reflective materials treatments, aiming to assess their potential as sustainable adaptation strategies to mitigate heat and radiation stress under Mediterranean conditions.

## Material and Methods

### Experimental site

The experiment was conducted at the Brancati Farm winery, located in the municipality of Palizzi, province of Reggio Calabria, southern Italy, within the geographical production area of the Protected Geographical Indication (PGI) “Palizzi” (Ministerial Decree 27/10/1995). The study focused on *Vitis vinifera* L. ‘Chardonnay’ (code 298, registered in the National Register – Official Journal no. 323, 18/11/1978). Vegetative and productive measurements were collected over two years (2023–2024).

The vineyard, established seven years prior to the study, was trained to a unilateral spurred cordon system, with a planting density of 5,000 vines ha<sup>-1</sup> (2.5 m between rows × 0.8 m between vines). Each vine was pruned to maintain 8–10 spurs each with two buds, corresponding to a potential bud load of 40,000–50,000 buds ha<sup>-1</sup>. The rootstock used was 1103 Paulsen (*Vitis berlandieri* × *V. rupestris*; code 625, National Register – Official Journal no. 101, 23/04/1971), selected for its high tolerance to drought and salinity. Rows were oriented north–south to optimize daily solar radiation interception. According to the Calabrian Soil Map (ARSAC), the vineyard lies within Pedological Subsystem 13.6 (Pedological Province 13), characterized by medium-textured soils with good water-holding capacity and suitable rooting depth.

### Climatic and thermo-pluviometric characterization of the study area (Köppen–Geiger and Bagnouls–Gausson models)

The study area falls within the Mediterranean climatic domain, classified as Csa (temperate climate with hot, dry summers and rainfall concentrated in winter) according to the Köppen–Geiger system—typical of central and southern Mediterranean coastal regions.

Climatic data were collected using an on-farm weather station integrated with the VineSense IoT monitoring platform

(Netsens LiveData®, Calenzano, Florence, Italy). The system continuously recorded air temperature, relative humidity, solar radiation, wind speed and direction, atmospheric pressure, and rainfall. Four wireless peripheral units equipped with temperature, humidity, and leaf wetness sensors ensured accurate microclimatic monitoring within the vineyard canopy. All data were transmitted in real time to a cloud-based interface accessible via computer or mobile device, supporting precision viticulture and environmental monitoring. Data collected for the 2023–2024 period confirmed a typical Mediterranean rainfall pattern, with an average annual precipitation of approximately 300 mm. Mean monthly temperatures peaked in July (28.8 °C) and reached their minimum in February (12.1 °C), indicating severe summer drought. Both pluviometric and thermal data were provided by ARPACAL – Multi-Risk Functional Centre.

To visualize the annual hydroclimatic balance, a Bagnouls–Gausson climograph was constructed, plotting mean monthly temperature (°C) against precipitation (mm) at a 1:2 scale. In this model, months where  $P < 2T$  are defined as arid. The resulting pattern revealed a prolonged summer drought typical of Mediterranean climates, significantly influencing key phenological stages and water availability in non-irrigated vineyards (Fig. 1).

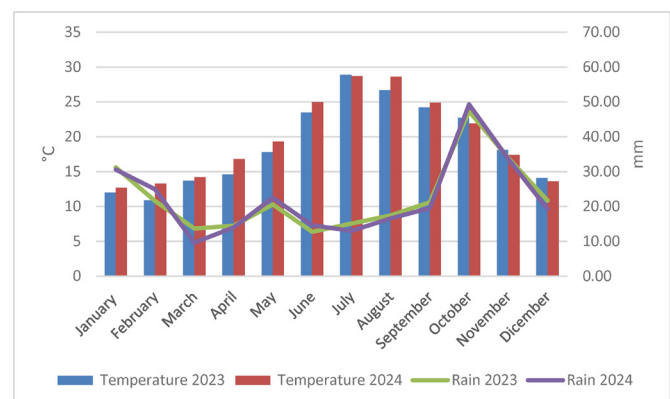


Figure 1 - Climatic characterization of the study area (Bagnouls–Gausson model), using the thermal and pluviometric data recorded in 2023 and 2024. Data source: ARPACAL – Multi-Risk Functional Centre.

### Experimental design

The experimental area was divided into randomized blocks, with a total of four blocks. Each block included three treatments with reflective materials and Untreated Control (TNT). The treatments used were three with reflective materials, Kaolin Treatment (TK), Basalt Powder (TBP), Zeolite Treatment (TZL) and Control treated with only water. Each treatment included five plants per block, for a total of 20 plants per treatment. The reflective materials were applied using a pressure sprayer at the doses recommended by the respective manufacturers, as listed below: Kaolin Surround WP (Serbios Srl, Rovigo, Italy) at a dose of 5 kg hl<sup>-1</sup>; Basalt powder (Basalti Orvieto Srl, Terni, Italy) at 3 kg hl<sup>-1</sup>; and zeolite (Hydro Fert Srl, Barletta, Italy) at 1.5 kg hl<sup>-1</sup>, ensuring uniform

coverage. The products were applied at different times: BBCH 75 – berry development, BBCH 77 – bunch closure, and BBCH 83 – veraison.

### Yield Assessment

For each treatment, yield parameters were determined. The weights of whole clusters, berries, and rachises were measured to characterize cluster composition. Quantitative and qualitative analyses were carried out on all treated samples and on the control at harvest, which occurred at the end of July.

### Refractometric determination of sugars

Total soluble solids content (TSSC) was determined using a PAL-1 Pocket Digital Refractometer (ATAGO Co., Ltd., Tokyo, Japan), which incorporates Automatic Temperature Compensation (ATC). The instrument was calibrated with deionized distilled water at 20° C prior to each set of measurements. The refractometric residue is expressed in degrees Brix (or Balling degrees): 1°Brix = 1% sugar content ~10 gL<sup>-1</sup>. This ripeness index gives the weight of the sugars in the must in grams per 100 grams of must.

### Determination of hydrogen ion concentration and total acidity

Titrateable acidity (TA) and pH were determined using a potentiometric titrator (Titralab AT1000 series, HACH, Colorado, USA). A 10 ml aliquot of must was titrated with an aqueous solution of sodium hydroxide (NaOH 0.5 N) until neutralization. Potassium phthalate (KHC<sub>8</sub>H<sub>4</sub>O<sub>4</sub>) was used as the primary standard for the standardization of the base (NaOH). Titrateable acidity (TA) was expressed as % tartaric acid. The sugar-to-acid ratio (TSSC/TA) was calculated as the ratio between total soluble solids and titrateable acidity, the latter expressed as a percentage.

### Ecophysiological investigations

Gas exchange parameters, including net photosynthesis (An, μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>), stomatal conductance (gs, mmol H<sub>2</sub>O m<sup>-2</sup> s<sup>-1</sup>), intercellular CO<sub>2</sub> concentration (Ci, ppm), transpiration rate (E, mmol H<sub>2</sub>O m<sup>-2</sup> s<sup>-1</sup>), water use efficiency (WUE, μmol CO<sub>2</sub>·mmol H<sub>2</sub>O<sup>-1</sup>); photosynthetic efficiency (An/Ci, μmol m<sup>-2</sup> s<sup>-1</sup>), were measured using an infrared gas analyzer (LI-6400XT, Li-COR Inc., Lincoln, NE, USA). Measurements were taken under saturating photosynthetic photon flux density (PPFD = 2000 μmol m<sup>-2</sup> s<sup>-1</sup>) and ambient CO<sub>2</sub> concentration (400 ppm), with an airflow of 500 μmol s<sup>-1</sup>, between 08:00 and 11:00 h under field conditions. The circular cuvette of the instrument (6 cm<sup>2</sup>) allowed isolation of a single leaf, enabling comparison between the composition of incoming and outgoing air streams to determine H<sub>2</sub>O and CO<sub>2</sub> gradients. Measurements were performed on three fully expanded leaves located in the middle portion of current-year shoots, on three vines per treatment (n = 3) across the four experimental treatments. All ecophysiological measurements were performed during the phenological window corresponding to BBCH stages 75–77. Fluorescence measurements followed

the standard protocol, including modulated light (ML), a saturating light pulse, actinic light (300 μmol m<sup>-2</sup> s<sup>-1</sup>), a second saturating pulse, and a far-red light pulse (30 μmol m<sup>-2</sup> s<sup>-1</sup>, 720–730 nm), allowing the determination of the minimum and maximum fluorescence of light-adapted leaves (F<sub>o</sub>' and F<sub>m</sub>'). During fluorescence measurements, the photosynthetically active radiation (PAR) provided by the fluorometer was set to 1500 μmol m<sup>-2</sup> s<sup>-1</sup> to ensure full light adaptation.

The maximum quantum efficiency of PSII under light-adapted conditions (Fv'/Fm') was calculated according to standard protocols, where Fv' = Fm' – F', and Fv'/Fm' expresses the efficiency of open PSII reaction centers. The photochemical quenching coefficient (qP) was determined as

$$qP = \frac{F'_m - F'}{F'_m - F'_0}$$

and reflects the redox state of plastoquinone QA, providing information on the proportion of open PSII reaction centers. The electron transport rate (ETR) was estimated using the following equation:

$$ETR = \Phi_{PSII} \times PPFD \times \alpha$$

where Φ<sub>PSII</sub> is the effective quantum yield of PSII, PPFD is the photosynthetic photon flux density at the leaf surface, and α is the product of leaf absorptance and the distribution of absorbed quanta between PSI and PSII (assumed to be 0.5). All measurements were conducted between 10:00 and 12:00 a.m. under stable environmental conditions to minimize diurnal variability. For each plant, three leaves were measured, and the mean value was used for statistical analysis. The light source in the leaf chamber consisted of LEDs emitting at 630 nm (90%) and 470 nm (10%).

### Measurement of leaf chlorophyll

Chlorophyll content was indirectly estimated by measuring the SPAD index with a portable chlorophyll meter (SPAD-502, Konica Minolta, Osaka, Japan). The instrument operates with two optical sensors at distinct wavelengths and a silicon photodiode (SPD) detector. The SPAD data are valid in detecting marked differences among treatments (Dattola *et al.*, 2026). Measurements were performed on 15 fully expanded, healthy leaves per treatment, under diffuse light conditions to minimize variability caused by illumination differences.

### Determination of Total Polyphenols and Total Antioxidant Capacity

Total polyphenols content (TP) and total antioxidant capacity (TAC) analyses were performed. The samples were homogenised using an Ultraturrax blender (20,000 rpm; T 25 Basic, IKA Werke, Germany). The TP and TAC were analysed separately using a Lambda 35 spectrophotometer (Perkin Elmer Corporation, USA). Before measuring the TPC and TAC,

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standard curves were prepared for each test. The TPC (mg gallic acid equivalents FW<sup>-1</sup>) was determined using the Folin-Ciocalteu method (Slinkard and Singleton, 1997). The TAC was determined using the modified TEAC assay and expressed as  $\mu\text{mol}$  Trolox equivalents FW<sup>-1</sup> (Pellegrini *et al.*, 1999; Re *et al.*, 1999).

### Statistical analysis

The dataset was evaluated through a two-way ANOVA, in which treatment and year were considered fixed factors, together with their interaction. Whenever the treatment effect was significant, differences among means were assessed using Tukey's post-hoc test at a significance level of  $p < 0.05$ . All values are presented as mean  $\pm$  standard error, and distinct letters denote statistically significant differences among treatments for each measured variable. Statistical analyses were performed using SPSS v.22.0 (IBM Corp., New York, USA). To further investigate the multivariate structure of the dataset and to identify patterns linking physiological, biochemical, and productive traits, a Principal Component Analysis (PCA) was carried out using XLSTAT 2014 (Addinsoft, New York, USA).

## Results

Basalt powder (TPB) and zeolite (TZL) treatments resulted in significantly higher vine yields compared with the untreated control (TNT). Unit yield per vine was 0.393 kg ( $\pm 0.17$ ) for TZL and 0.262 kg ( $\pm 0.13$ ) for TPB, both surpassing the control (0.180 kg  $\pm 0.10$ ) and the kaolin treatment (0.196 kg  $\pm 0.03$ ) (Table 1). Similarly, significant differences were recorded in the average bunch weight. The zeolite-treated vines (TZL) produced the heaviest bunches (118.43 g  $\pm 2.82$ ), followed by kaolin (TK: 97.31 g  $\pm 2.99$ ) and basalt powder (TPB: 88.45 g  $\pm 3.08$ ), all notably higher than the control (67.97 g  $\pm 3.54$ ). The relative increases were 74%, 43%, and 30% for TZL, TK, and TPB, respectively, compared with untreated vines (Table 1).

Table 1 – Productive characteristics of grape clusters, rachises, and berries of *Vitis vinifera* L. 'Chardonnay' subjected to different reflective mineral treatments (TK = kaolin; TBP = basalt powder; TZL = zeolite; TNT = untreated control) during the 2023 and 2024 growing seasons.

Treatment	Average bunch weight	Average rachis weight	Average berry weight
	g.	g.	g.
TK	97.313 $\pm$ 2.99 <sup>b</sup>	4.083 $\pm$ 0.52 <sup>c</sup>	1.010 $\pm$ 0.08 <sup>a</sup>
TNT	67.966 $\pm$ 3.54 <sup>d</sup>	3.963 $\pm$ 0.32 <sup>d</sup>	0.760 $\pm$ 0.05 <sup>c</sup>
TBP	88.446 $\pm$ 3.08 <sup>c</sup>	4.246 $\pm$ 0.23 <sup>b</sup>	0.980 $\pm$ 0.04 <sup>b</sup>
TZL	118.433 $\pm$ 2.82 <sup>a</sup>	4.720 $\pm$ 0.85 <sup>a</sup>	0.987 $\pm$ 0.02 <sup>b</sup>
T	**	**	*
Y	ns	*	ns
TxY	ns	ns	ns

Values are expressed as mean  $\pm$  standard error. Different letters indicate statistically significant differences between treatments ( $p < 0.05$ ).

T = Treatment effect; Y = Year effect; TxY = Treatment  $\times$  Year interaction; ns = not significant;  $p < 0.05 = *$ ;  $p < 0.01 = **$ .

Mean berry weight remained higher in treated groups, reaching 1.01 g ( $\pm 0.08$ ) for TK, 0.98 g ( $\pm 0.04$ ) for TPB, and 0.99 g ( $\pm 0.02$ ) for TZL, while the control exhibited significantly lower values (0.76 g  $\pm 0.05$ ). Statistically significant differences were also observed for rachis weight, exceeding 4 g in treated vines and remaining slightly lower in the control (Table 1). The year effect was generally not significant, except for rachis weight, indicating that most traits were stable across the two seasons. No significant treatment  $\times$  year interactions were detected, confirming that the response to the treatments was consistent over both growing seasons (Table 1).

At harvest, musts from all treatments showed similar titratable acidity (TA) and pH values, with no statistically significant differences compared to the control (Table 2). Average titratable acidity ranged from 0.58% to 0.61% tartaric acid, and mean pH was approximately 3.55–3.65. However, notable differences were observed in the sugar-to-acid ratio (TSSC/TA), which was significantly higher in the treated vines. The TSSC/TA ratio reached 44.55 (TBP), 43.92 (TK), and 42.34 (TZL), compared with 39.50 in the control, indicating improved ripening balance (Table 2). The year effect was generally negligible, except for pH and TSSC/TA, which showed modest seasonal variability. No significant treatment  $\times$  year interactions were detected for any variable, confirming that the treatments behaved consistently across both growing seasons. (Table 2).

Table 2 - Ripening indicators of *Vitis vinifera* L. 'Chardonnay' grape musts obtained from vines subjected to different reflective mineral treatments (TK = kaolin; TBP = basalt powder; TZL = zeolite; TNT = untreated control) during the 2023 and 2024 growing seasons.

Treatment	TSSC ( $^{\circ}$ Brix)	pH	TA (%)	TSSC/TA
TK	25.300 $\pm$ 0.32 <sup>ns</sup>	3.550 $\pm$ 0.03 <sup>ns</sup>	0.579 $\pm$ 0.02 <sup>ns</sup>	43.922 $\pm$ 2.72 <sup>a</sup>
TNT	25.667 $\pm$ 0.42	3.563 $\pm$ 0.02	0.611 $\pm$ 0.01	39.503 $\pm$ 1.57 <sup>b</sup>
TBP	25.900 $\pm$ 0.26	3.653 $\pm$ 0.08	0.591 $\pm$ 0.05	44.550 $\pm$ 4.04 <sup>a</sup>
TZL	24.467 $\pm$ 0.59	3.503 $\pm$ 0.05	0.581 $\pm$ 0.03	42.336 $\pm$ 1.86 <sup>a</sup>
T	ns	ns	ns	*
Y	ns	*	ns	*
TxY	ns	ns	ns	ns

Values are expressed as mean  $\pm$  standard error. Different letters indicate statistically significant differences between treatments ( $p < 0.05$ ).

T = Treatment effect; Y = Year effect; TxY = Treatment  $\times$  Year interaction; ns = not significant;  $p < 0.05 = *$ .

The Soil Plant Analysis Development (SPAD) index was significantly higher in all treated vines compared to the control (Table 3). However, the zeolite treatment (TZL) exhibited the highest SPAD value (39.23  $\pm 0.41$ ), followed by basalt powder (TPB: 38.02  $\pm 0.48$ ) and kaolin (TK: 37.64  $\pm 0.59$ ), representing increases of approximately 18%, 15%, and 14%, respectively,

compared with the untreated vines ( $33.07 \pm 0.33$ ). These results indicate that reflective treatments preserved chlorophyll integrity and reduced pigment degradation under high irradiance. The year effect was not significant, showing that SPAD values remained stable across the two growing seasons. Similarly, the treatment  $\times$  year interaction was not significant, meaning that the response of SPAD to the treatments was consistent over time, with no changes in treatment performance between 2023 and 2024 (Table 3). Leaf temperature showed clear differences among treatments (Table 3). The untreated control exhibited the highest values, indicating greater heat absorption in the absence of reflective materials. In contrast, kaolin, basalt powder, and zeolite all reduced leaf temperature, with TK and TBP showing the strongest cooling effect (Table 3). The treatment factor was significant, confirming that reflective particles effectively mitigated leaf heating. Conversely, neither the year nor the treatment  $\times$  year interaction influenced leaf temperature, indicating that the response to the treatments was consistent across both growing seasons (Table 3).

Table 3 - Effect of different reflective mineral treatments on the SPAD index and leaf temperature of *Vitis vinifera* L. 'Chardonnay' leaves during the 2023 and 2024 growing seasons. Treatments include kaolin (TK), basalt powder (TBP), zeolite (TZL), and the untreated control (TNT).

Treatment	SPAD Index	T Leaf °C
TK	37.643±0.59 <sup>a</sup>	32.68 <sup>b</sup>
TNT	33.065±0.33 <sup>b</sup>	34.21 <sup>a</sup>
TBP	38.021±0.48 <sup>a</sup>	32.42 <sup>b</sup>
TZL	39.230±0.41 <sup>a</sup>	33.58 <sup>b</sup>
T	**	*
Y	ns	ns
TxY	ns	ns

Values are expressed as mean  $\pm$  standard error. Different letters indicate statistically significant differences between treatments ( $p < 0.05$ ).

T = Treatment effect; Y = Year effect; TxY = Treatment  $\times$  Year interaction; ns = not significant;  $p < 0.05 = *$ ;  $p < 0.01 = **$ .

Fluorometric measurements revealed that the reflective mineral treatments significantly influenced the photochemical efficiency of PSII (Table 4). The maximum efficiency of PSII in light-adapted leaves ( $Fv'/Fm'$ ) was highest in the TZL treatment ( $0.65 \pm 0.03$ ), followed by TPB ( $0.61 \pm 0.02$ ) and TK ( $0.59 \pm 0.04$ ), whereas the control recorded a substantially lower value ( $0.46 \pm 0.01$ ). Similarly, the effective quantum yield of PSII ( $\phi_{PSII}$ ) was significantly enhanced in treated vines, reaching  $0.16 \pm 0.04$  (TZL) and  $0.15 \pm 0.03$  (TPB), compared with  $0.07 \pm 0.04$  in the control. Photochemical quenching (qP), an indicator of the redox state of PSII reaction centers, also

followed the same pattern, with the highest values in TZL ( $0.31 \pm 0.03$ ) and TPB ( $0.25 \pm 0.01$ ), intermediate in TK ( $0.23 \pm 0.02$ ), and lowest in the control ( $0.14 \pm 0.03$ ). Electron transport rate (ETR), representing photosynthetic electron flow, was markedly higher in TZL ( $115.73 \mu\text{mol electrons m}^{-2} \text{s}^{-1} \pm 2.88$ ), TPB ( $111.81 \pm 2.41$ ), and TK ( $98.65 \pm 2.15$ ) compared to the control ( $77.81 \pm 1.76$ ). These findings confirm that reflective materials mitigated photoinhibition and maintained efficient photochemical activity under high light stress. The treatment effect was significant for all chlorophyll fluorescence parameters, indicating that the reflective mineral applications consistently influenced PSII photochemical performance. The year effect was significant only for  $\phi_{PSII}$  and qP, suggesting that seasonal conditions affected these specific components of PSII activity. The treatment  $\times$  year interaction was significant solely for qP, while the remaining parameters showed stable treatment responses across both growing seasons.

Table 4 - Effect of different reflective mineral treatments on chlorophyll *a* fluorescence parameters in *Vitis vinifera* L. 'Chardonnay' during the 2023 and 2024 growing seasons. Treatments include kaolin (TK), basalt powder (TBP), zeolite (TZL), and the untreated control (TNT). Parameters measured:  $Fv'/Fm'$  = maximum efficiency of PSII in light-adapted leaves;  $\phi_{PSII}$  = effective quantum yield of photosystem II; qP = photochemical quenching coefficient; ETR = electron transport rate.

Treatment	$Fv'/Fm'$	$\phi_{PSII}$	qP	ETR $\mu\text{mol}_{\text{electrons}} \text{m}^{-2} \text{s}^{-1}$
TK	0.59±0.04 <sup>a</sup>	0.13±0.02 <sup>a</sup>	0.23±0.02 <sup>b</sup>	98.65±2.15 <sup>b</sup>
TNT	0.46±0.01 <sup>b</sup>	0.07±0.04 <sup>b</sup>	0.14±0.03 <sup>c</sup>	77.81±1.76 <sup>c</sup>
TBP	0.61±0.02 <sup>a</sup>	0.15±0.03 <sup>a</sup>	0.25±0.01 <sup>b</sup>	111.81±2.41 <sup>a</sup>
TZL	0.65±0.03 <sup>a</sup>	0.16±0.04 <sup>a</sup>	0.31±0.03 <sup>a</sup>	115.73±2.88 <sup>a</sup>
T	*	*	**	**
Y	ns	*	*	ns
TxY	ns	ns	*	ns

Values are expressed as mean  $\pm$  standard error. Different letters indicate statistically significant differences between treatments ( $p < 0.05$ ).

T = Treatment effect; Y = Year effect; TxY = Treatment  $\times$  Year interaction; ns = not significant;  $p < 0.05 = *$ ;  $p < 0.01 = **$ .

Leaf gas exchange measurements demonstrated a clear enhancement of photosynthetic activity in treated vines (Table 5). Reflective treatments significantly enhanced photosynthetic performance in the vines. Net photosynthetic rate ( $A_n$ ) increased by 29–39%, while stomatal conductance ( $g_s$ ) nearly doubled, reflecting improved  $\text{CO}_2$  diffusion and carboxylation efficiency. Intercellular  $\text{CO}_2$  concentration ( $C_i$ ) ranged from  $138 \pm 15$  to  $161 \pm 15 \mu\text{mol/mol}$  with overlapping standard errors, indicating no significant differences among treatments. Transpiration rate (E) was also elevated by up to 34%. The results demonstrate differences in water use efficiency (WUE), calculated as the ratio of  $A_n$  to E (WUE-E) and the ratio of  $A_n$  to  $g_s$  (WUE- $g_s$ ) among the various treatments.

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Table 5 - Effect of different reflective mineral treatments on leaf gas exchange parameters in *Vitis vinifera* L. 'Chardonnay' during the 2023 and 2024 growing seasons. Treatments include kaolin (TK), basalt powder (TBP), zeolite (TZL), and the untreated control (TNT). Parameters measured:  $A_n$  = net photosynthetic rate;  $g_s$  = stomatal conductance;  $C_i$  = intercellular  $CO_2$  concentration;  $E$  = transpiration rate; WUE-gs = water-use efficiency stomatal conductance-based, WUE-E = water-use efficiency transpiration-based;  $A_n/C_i$  = photosynthetic efficiency.

Treatment	$A_n$ $\mu mol CO_2 m^{-2} s^{-1}$	$g_s$ $mol H_2O m^{-2} s^{-1}$	$C_i$ ppm	$E$ $mmol H_2O m^{-2} s^{-1}$	WUE-gs $\mu mol CO_2 \cdot m^{-2} mol H_2O^{-1}$	WUE-E $\mu mol CO_2 \cdot m^{-2} mol H_2O^{-1}$	$A_n/C_i$ $mol m^{-2} s^{-1}$
TK	4.77±0.03 <sup>b</sup>	0.20±0.05 <sup>a</sup>	140.3±14.11	2.01±0.04 <sup>b</sup>	23.85±0.73 <sup>c</sup>	2.37±0.11 <sup>a</sup>	0.034±0.02 <sup>a</sup>
TNT	3.70±0.16 <sup>c</sup>	0.10±0.03 <sup>b</sup>	160.9±13.12	1.77±0.10 <sup>c</sup>	37±0.88 <sup>a</sup>	2.09±0.01 <sup>b</sup>	0.023±0.04 <sup>b</sup>
TBP	4.98±0.01 <sup>a</sup>	0.21±0.02 <sup>a</sup>	138.3±15.17	2.71±0.10 <sup>a</sup>	23.71±0.65 <sup>c</sup>	1.83±0.11 <sup>c</sup>	0.036±0.02 <sup>a</sup>
TZL	5.13±0.02 <sup>a</sup>	0.19±0.01 <sup>a</sup>	142.5±16.12	2.13±0.09 <sup>b</sup>	27±0.16 <sup>b</sup>	2.40±0.13 <sup>a</sup>	0.036±0.01 <sup>a</sup>
T	*	*	ns	*	**	**	*
Y	ns	*	ns	*	ns	ns	ns
TxY	ns	ns	ns	*	ns	ns	ns

Values are expressed as mean ± standard error. Different letters indicate statistically significant differences between treatments ( $p < 0.05$ ).

T = Treatment effect; Y = Year effect; TxY = Treatment × Year interaction;

ns = not significant;  $p < 0.05 = *$ ;  $p < 0.01 = **$ .

The results demonstrate significant differences in water use efficiency (WUE) among the various treatments and water-use efficiency (WUE-E) improved by 13–15%. In particular, TK (kaolin) exhibited a high  $A_n/g_s$  value (23.85) and an  $A_n/E$  value (2.37), suggesting efficient stomatal conductance and optimal water management. TNT (control) recorded the highest  $A_n/g_s$  value (37), but a relatively low  $A_n/E$  (2.09), indicating that, despite high stomatal conductance, more water was lost per unit of assimilated carbon. TBP (basalt powder) showed an  $A_n/g_s$  value of 23.71 and an  $A_n/E$  of 1.84, suggesting less efficient water management compared to TK and TZL, with relatively higher transpiration. Finally, TZL (zeolite) demonstrated a good  $A_n/g_s$  value (27) and an  $A_n/E$  of 2.41, indicating effective stomatal efficiency and overall favorable water management. Similarly, the ratio of net assimilation to intercellular  $CO_2$  concentration ( $A_n/C_i$ ) increased by approximately 57%, highlighting the overall enhancement of photosynthetic efficiency in treated vines. Overall, the treatments enhanced  $CO_2$  assimilation and reduced the negative impact of water stress, leading to improved photosynthetic performance and canopy cooling via optimized stomatal regulation.

The total polyphenol content (TPB) and total antioxidant capacity (TAC) of 'Chardonnay' grape samples showed comparable values across all treatments (TZL, TK, TPB, and TNT). Mean TPB values ranged from 1.79 to 1.85 mg GAE g FW<sup>-1</sup>, while TAC values were between 12.1 and 12.6  $\mu mol$  trolox g FW<sup>-1</sup> (Tab. 6). The absence of statistically significant differences indicates that the treatments did not markedly affect either the accumulation of total polyphenols or the antioxidant potential of the grapes. The overall consistency among treatments suggests that 'Chardonnay' grapes maintained a stable phenolic and antioxidant profile under the different conditions tested. The year effect (Y) was not significant for TP but was significant for TAC, suggesting that interannual

climatic variability influenced antioxidant capacity without affecting total polyphenol levels. The lack of a significant treatment × year interaction (TxY) indicates that the response of both parameters to the applied treatments was consistent across years (Table 6).

Table 6. Total Polyphenols (TP) and Total Antioxidant Capacity (TAC) in 'Chardonnay' grapes subjected to different vineyard treatments. Treatments include kaolin (TK), basalt powder (TBP), zeolite (TZL), and the untreated control (TNT).

Treatment	TP (mg GAE g FW <sup>-1</sup> )	TAC ( $\mu mol$ Trolox g FW <sup>-1</sup> )
TZL	1.82 ± 0.07	12.4 ± 0.5
TK	1.79 ± 0.06	12.1 ± 0.4
TPB	1.85 ± 0.05	12.6 ± 0.6
TNT	1.80 ± 0.08	12.3 ± 0.5
T	ns	ns
Y	ns	*
TxY	ns	ns

Values are expressed as mean ± standard error. Different letters indicate statistically significant differences between treatments ( $p < 0.05$ ).

T = Treatment effect; Y = Year effect; TxY = Treatment × Year interaction; ns = not significant;  $p < 0.05 = *$ ;

Principal Component Analysis (PCA) was performed to examine the relationships among productive, physiological, and qualitative variables. The first two principal components

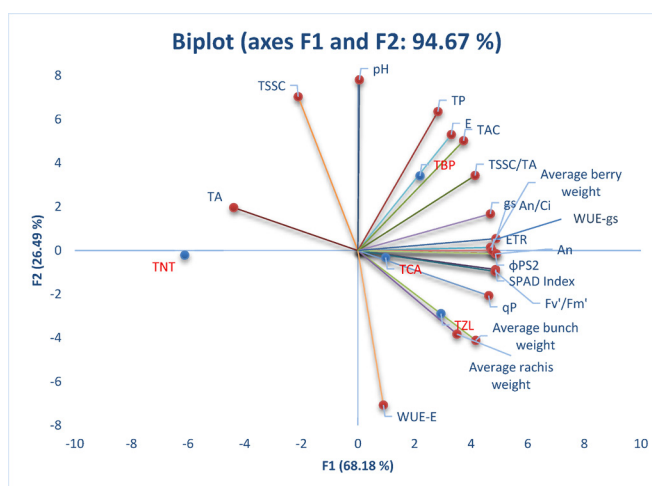
explained 94.67% of the total variance (Table 7), confirming that the reduced-dimensional representation provided a robust summary of the dataset. Variables related to productivity and ecophysiological performance (bunch weight, SPAD,  $F_v'/F_m'$ ,  $qP$ , ETR,  $A_n$ ,  $g_s$ ,  $A_n/C_i$ ) were strongly associated with the first principal component (F1), whereas variables describing must chemistry (pH, TSSC) were more closely linked to F2.

Table 7 –  $\text{Cos}^2$  values (%) of the variables contributing to the formation of the first three principal components (F1, F2, F3) of the Principal Component Analysis (PCA).

Variables	F1	F2	F3
Average bunch weight	0.7243	0.2736	0.0021
Average rachis weight	0.5114	0.2368	0.2518
Average berry weight	0.9173	0.0003	0.0824
TSSC	0.1854	0.8030	0.0115
pH	0.0001	0.9888	0.0111
TA	0.8022	0.0626	0.1352
TSSC/TA	0.7156	0.1912	0.0931
SPAD Index	0.9877	0.0122	0.0000
$F_v'/F_m'$	0.9810	0.0147	0.0043
$\phi PS2$	0.9856	0.0003	0.0141
$qP$	0.8922	0.0689	0.0389
ETR	0.9383	0.0000	0.0617
$A_n$	0.9987	0.0004	0.0010
$g_s$	0.9149	0.0456	0.0395
E	0.4552	0.4559	0.0889
WUE-E	0.0339	0.8096	0.1565
WUE-gs	0.3381	0.8031	0.1475
$A_n/C_i$	0.9939	0.0048	0.0013
TP	0.3340	0.6555	0.0105
TAC	0.5822	0.4091	0.0088

Table 8 –  $\text{Cos}^2$  values (%) of the observations contributing to the formation of the first three principal components (F1, F2, F3) of the Principal Component Analysis (PCA). Treatments include kaolin (TK), basalt powder (TPB), zeolite (TZL), and the untreated control (TNT).

Observations	F1	F2	F3
TK	0.2412	0.0252	0.7336
TPB	0.9960	0.0012	0.0028
TNT	0.2871	0.6941	0.0188
TZL	0.4888	0.4721	0.0390



Graph 1 - Biplot of the Principal Component Analysis (PCA), explaining 94.67% of the total variance, illustrating the distribution of treatments based on the main vegetative, productive, and qualitative variables of *Vitis vinifera* L. 'Chardonnay'. Treatments include kaolin (TK), basalt powder (TPB), zeolite (TZL), and the untreated control (TNT).

### Discussion

The growing seasons encompassed by this study were characterized by prolonged drought and elevated temperatures, conditions that have increasingly affected viticulture across all major grape-growing regions, particularly in the hilly and coastal zones of central and southern Italy. These climatic extremes negatively influenced vineyard management, yield potential, and the analytical and aromatic profile of musts. In recent decades, as confirmed by adverse weather patterns throughout the grapevine growth cycle, such phenomena have intensified, making vineyard management increasingly challenging and requiring timely and preventive agronomic interventions. Under these conditions, yield losses are often associated with reduced bunch weight and berry dehydration due to sunburn.

The results of this study clearly demonstrate that in *Vitis* the use of reflective mineral products can effectively mitigate the detrimental effects of drought and heat stress on vineyard performance in Mediterranean environments. Both treatments significantly improved yield, bunch structure, and berry weight while maintaining the integrity of cluster architecture, as reflected in higher rachis weights. Yield increases following the application of antitranspirant or reflective products have been reported for several fruit crops, including *Vaccinium corymbosum* (Spiers *et al.*, 2003), *Olea europaea* (Saour & Makee, 2003), *Malus domestica* (Glenn *et al.*, 2001), *Pyrus communis* (Puterka *et al.*, 2000), and *Citrus sinensis* and *Citrus clementina* (Gullo *et al.*, 2020a, b). These findings taken together support the hypothesis that reflective products are effective in reducing stress in extreme environmental conditions.

Among the treatments, TZL, followed by TPB, consistently produced the best vegetative and productive performance, increasing yield per vine and cluster weight relative to the control. Controlled modulation of the light spectrum through canopy management or reflective coatings represents a valid

agronomic approach to mitigating the harmful effects of excessive heat and radiation, particularly in semi-arid viticultural zones affected by global warming.

Light within the canopy consists of both direct and filtered components, which vary according to the optical properties of leaves, fruits, and shoots. The spectral range relevant to plant physiological processes spans from 280 to 800 nm, encompassing UV-B (280–320 nm), UV-A (300–400 nm), photosynthetically active radiation (PAR, 400–700 nm), and far-red (FR, 700–800 nm). PAR itself includes blue (400–500 nm), green (500–600 nm), and red (600–700 nm) bands, which differentially influence photosynthetic and photomorphogenic activity. The use of reflective mineral films enhances canopy reflectance in the UV and visible regions, optimizing the distribution of PAR and thus promoting balanced physiological activity.

Physiologically, the treatments preserved chlorophyll content and photosynthetic integrity.

The higher SPAD values observed in treated vines confirm that reflective films prevented pigment degradation under stress. Comparable findings were reported in *Physalis peruviana* (Segura-Monroy *et al.*, 2015) and *Carya illinoensis* (Lombardini *et al.*, 2005). Smirnoff (1993) described chlorophyll reduction as a hallmark of oxidative stress caused by pigment degradation or impaired synthesis; thus, maintaining SPAD levels reflects reduced oxidative damage in treated vines.

Fluorometric measurements ( $F_v'/F_m'$ ,  $\phi PSII$ ,  $qP$ , and ETR) indicated that reflective coatings effectively reduced photo-inhibition and enhanced electron transport efficiency. High temperatures combined with excessive radiation and limited water availability are known to impair photosystem II (PSII) functionality, causing a phenomenon termed “photoassimilative down-regulation,” which can progress to chronic photoinhibition or irreversible photosynthetic dysfunctions (Ohira *et al.*, 2005). Such stress can lead to denaturation of antenna pigments and reaction centers, culminating in proteolytic degradation of the D1 protein.

To counteract this, plants activate photoprotective mechanisms—chiefly non-photochemical quenching via the violaxanthin–antheraxanthin–zeaxanthin (VAZ) cycle—which dissipates excess energy as heat, preventing photodamage and premature leaf senescence. Thermal dissipation accounts for up to 97% of excess absorbed energy, while photorespiration and chlorophyll fluorescence contribute smaller fractions (Smirnoff, 1993). Leaf temperatures above 35 °C drastically reduce photochemical efficiency, measurable as declines in  $F_v'/F_m'$  (Björkman and Demmig, 1987). The optimal theoretical  $F_v'/F_m'$  ratio is 0.83; lower values indicate PSII stress or damage. In this study, higher  $F_v'/F_m'$  and ETR values in treated vines confirm that reflective mineral films preserved PSII efficiency and limited thermal injury. Gas exchange measurements further support these findings. Vines treated with zeolite (TZL) and basalt powder (TBP) showed higher net CO<sub>2</sub> assimilation and stomatal conductance than untreated controls. This suggests that the reflective materials effectively enhanced water-use efficiency (WUE), enabling the vines to maintain stomatal opening and photosynthetic activity under

limited water availability. By reducing leaf temperature and moderating transpiration, these treatments improved the ratio of carbon assimilation to water loss a crucial factor in sustaining productivity during drought conditions. TK (kaolin), with its high AN/g<sub>s</sub> value (23.85) and AN/E (2.37), suggests efficient stomatal conductance and optimal water management. TNT (control), on the other hand, demonstrated the highest AN/g<sub>s</sub> (37) but a relatively lower AN/E (2.09), suggesting that, despite good stomatal conductance, water loss per unit of carbon assimilation was higher. These physiological responses align with previous studies on the use of reflective materials in improving water-use efficiency in other species (Glenn and Puterka, 2005; Brito *et al.*, 2018; Dattola and Gullo, 2024; Gullo *et al.*, 2020a, b).

The results demonstrate significant differences in water use efficiency (WUE) among the treatments. TK (kaolin) showed a strong WUE-g<sub>s</sub> (AN/g<sub>s</sub>) value (23.85) and WUE-E, AN/E (2.37), suggesting efficient stomatal conductance and optimal water management. TNT (control) exhibited the highest AN/g<sub>s</sub> value (37), but a relatively lower AN/E (2.09), indicating less efficient water use. TBP (basalt powder) had an AN/g<sub>s</sub> value of 23.71 and AN/E of 1.84, suggesting moderate efficiency compared to TK and TZL, with relatively higher transpiration. Finally, TZL (zeolite) demonstrated favorable values for both AN/g<sub>s</sub> (27) and AN/E (2.41), indicating good overall water management. In addition, our results are in agreement with previous studies showing that light exposure in grapevine canopies influences the accumulation of soluble solids, organic acids, and phenolic compounds (Dokoozlian and Kliewer, 1996; Bergqvist *et al.*, 2001). Regarding grape acidity, the concentrations of malic and tartaric acids—which together account for approximately 90% of total acidity—were stable across treatments, confirming that reflective coatings did not alter must composition. *Vitis vinifera* is unique among fruit crops for its capacity to accumulate large quantities of L(+) tartaric acid, reaching 150 mM L<sup>-1</sup> at veraison and 25–75 mM L<sup>-1</sup> (3.8–11.3 g L<sup>-1</sup>) at maturity (Ribéreau-Gayon *et al.*, 2005).

Although TPB was slightly less effective than TZL in productivity, it excelled in qualitative parameters, such as pH stability and sugar/acid balance, suggesting that product choice can be tailored to specific production goals. Kaolin (TK) provided moderate improvements but was less effective overall, likely due to differences in particle size, reflectivity, and adherence affecting its persistence and coverage.

The chemical analyses of must confirmed that grape quality was not adversely affected by the treatments. Titratable acidity and pH remained within the optimal range for winemaking, demonstrating that productivity gains were not achieved at the expense of must composition. The multivariate (PCA) results reinforce these observations: zeolite (TZL) clustered with the highest loadings for photosynthetic and productive traits, while basalt powder (TPB) was associated with parameters linked to grape quality. The untreated control grouped separately, reflecting its lower physiological efficiency and greater susceptibility to thermal and radiative stress.

Overall, this study highlights the agronomic and physiological benefits of reflective mineral applications as a preventive strategy in Mediterranean viticulture. By improving photosynthetic efficiency, water-use efficiency, and canopy

light management, zeolite and basalt powder enhance vineyard resilience to the increasingly frequent heat waves and droughts predicted under future climate scenarios.

Moreover, the concentration of kaolin used in this trial was likely high. Indeed, excessively high concentrations inherently reduce the photosynthetically active radiation (PAR) reaching the leaf surface, resulting in down-regulation of photosynthetic capacity. This probably explains, at least in part, the lower plant performance observed with kaolin in this trial. Therefore, both the concentration of the suspension and the species/cultivar represent critical factors that can influence the outcomes.

The adoption of such sustainable practices can therefore contribute to maintaining both yield and grape quality, supporting climate-adaptive viticulture in regions most vulnerable to global warming.

## Conclusions

This study clearly demonstrates that the current climatic scenario, characterized by increasing heat and water stress, significantly compromises grapevine productivity and quality. The experimental trials confirmed that foliar applications of natural reflective mineral products such as kaolin, basalt powder, and zeolite represent an effective agronomic strategy for mitigating the negative impacts of high temperature and drought on *Vitis vinifera* L. 'Chardonnay'. These treatments not only enhanced yield by increasing the average bunch and berry weight but also preserved leaf photosynthetic efficiency, as evidenced by improved ecophysiological parameters (SPAD index, chlorophyll fluorescence, and gas exchange). Among the tested materials, zeolite achieved the most satisfactory results in terms of both production and physiological performance, underscoring its capacity to support vines under adverse environmental conditions. Enhanced water-use efficiency, reduced photoinhibition, and the maintenance of photosynthetic functionality during critical stress periods represent key achievements for sustainable and climate-resilient viticulture. These findings support the adoption of preventive strategies based on natural reflective coatings capable of optimizing the vine's energy and water balance without compromising must composition or yield quality. In conclusion, vineyard management under climate change requires innovative and sustainable approaches grounded in a deep understanding of grapevine physiology. The use of reflective mineral films—particularly zeolite and basalt powder—emerges as a valuable resource for maintaining productivity and fruit quality in Mediterranean wine-growing areas increasingly exposed to global warming.

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## Conflicts of interest

The authors declare that they do not have any conflicts of interest.

## Author contribution

Conceptualization: [D. A., G. G., Z. R.] Methodology: [D. A., G. G.] Investigation: [D. A., G. G.] Data curation: [D. A., G. G.] Formal analysis: [A. A., D. A.] Validation: [D. A., G. G.] Visualization: [D. A., G. G.] Software: [D. A., G. G.] Resources: [Z. R.] Funding acquisition: [Z. R.] Project administration: [Z. R.] Supervision: [G. G., Z. R.] Writing – original draft: [D. A., G. G.] Writing – review & editing: [D. A., G. G.]

The authors declare that no artificial intelligence tools were used in the preparation, analysis, or writing of this manuscript. All work was conducted by the authors in accordance with good scientific practice.

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