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Comparative Effectiveness of Kaolinite, Basalt Powder, and Zeolite in Mitigating Heat Stress and Increasing Yield of Almond Trees (*Prunus dulcis*) Under Mediterranean Climate

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Abstract

Heat and high-irradiance stress increasingly threaten almond production in Mediterranean environments, where rising temperatures and prolonged summer droughts impair photosynthetic performance and yield. This study evaluated the effectiveness of three mineral-based shielding materials: kaolin, basalt powder, and zeolite. We hypothesized that the foliar application of reflective mineral materials would reduce leaf temperature, enhance photosynthetic efficiency, and improve yield without altering nut nutraceutical quality. A two-year field experiment (2024–2025) was conducted using a randomized block design with four materials (untreated control, kaolin, basalt powder, and zeolite). Physiological traits (gas exchange, chlorophyll fluorescence, leaf temperature, and SPAD index), morpho-biometric and biochemical parameters, and yield components were assessed. Kaolin and basalt powder significantly lowered leaf temperature (−1.6 to −1.8 °C), increased stomatal conductance and net photosynthesis, and improved photochemical efficiency (Fv'/Fm') and electron transport rates. These treatments also enhanced drupe weight, kernel dry matter, and productive yield (up to +32% compared with the control). Zeolite produced positive but less prominent effects. No significant differences were detected in fatty acid profile, total polyphenols, or antioxidant capacity, indicating that the materials did not affect almond nutraceutical quality. Principal component analysis confirmed the strong association between kaolin and basalt powder and improved eco-physiological performance. Overall, mineral shielding materials, particularly kaolin and basalt powder, represent a promising, sustainable strategy for enhancing almond orchard resilience under Mediterranean climate change scenarios.

Keywords: *Prunus dulcis*; Mediterranean agriculture; reflective materials; photo-inhibition

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1. Introduction

The almond tree (*Prunus dulcis* [Miller] D.A. Webb) is one of the oldest domesticated fruit species of the Old World, with origins traced to the arid and mountainous regions of Central and Southwest Asia. Its long history of cultivation is well-documented through archaeological findings and classical agronomic literature, which describe both its ecological requirements and its symbolic relevance across Mediterranean civilizations [1–5]. Known to the Romans as *nux Graeca*, the almond tree appears frequently in the works of Pliny the Elder, Columella, Virgil, and Horace, who highlighted its preference for warm, dry, and stony environments and celebrated its early spring flowering [5]. Modern molecular studies support the hypothesis of a single domestication event, followed by a progressive

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westward diffusion facilitated by human migration and trade routes [5]. Taxonomically, the species belongs to the subgenus *Amygdalus* within the genus *Prunus* in the subfamily *Amygdaloideae* of the *Rosaceae* family [6]. Today, almonds are widely appreciated for their high nutritional value, being rich in unsaturated fatty acids, proteins, vitamins, and minerals. Numerous studies have demonstrated their antioxidant properties and potential benefits for human health, including cognitive function [7–9]. Global demand has grown steadily, driven by consumer interest in healthy and sustainable diets. In 2023, world production remained highly concentrated, with the United States, Spain, and Australia accounting for nearly 78% of the total output [10]. Italy contributes a smaller share, approximately 2.6%, yet almond cultivation retains strong cultural and economic significance, particularly in southern regions. Recent reports indicate that Italian almond production in 2023 was negatively affected by heatwave events, highlighting the need for mitigation strategies in climatically vulnerable regions [11]. Despite this heritage, the sector faces structural challenges, such as fragmented landholdings, limited mechanization, competition from more productive cultivars, and increasing climatic instability. Although almond trees are often described as drought-tolerant due to their ability to regulate water loss through stomatal closure [12,13], prolonged exposure to water deficits and high temperatures can severely reduce carbon assimilation and overall productivity. A multi-year study demonstrated that increasing water stress negatively affects vegetative growth and yield [14]. Climate change has intensified these pressures, exposing orchards to extreme thermal conditions, episodes of high solar irradiance, irregular temperature patterns, and prolonged summer droughts. Under such conditions, excessive irradiance and heat can induce photoinhibition, reducing the efficiency of photosystem II, and, in more severe cases, trigger photo-oxidative processes driven by reactive oxygen species (ROS), ultimately damaging cellular structures and reducing yield potential [15]. These challenges underscore the need for sustainable and readily applicable mitigation strategies capable of reducing heat and radiation stress during the summer vegetative cycle. Among the approaches proposed in recent years, the foliar application of mineral-based shielding materials, such as kaolin, basalt powder, and zeolite, has attracted growing interest. Recent reviews highlight the expanding application of particle film-forming materials, showing that increased foliar reflectance can mitigate abiotic stress (heat and excessive irradiance) and enhance physiological performance across diverse crops (e.g., olive, grapevine, tree fruits), with kaolin and related particles inducing bio-stimulant-like effects and improved stress tolerance under field conditions [16–18]. However, comparative studies evaluating the combined effects of multiple mineral materials under Mediterranean conditions remain scarce. These materials can increase leaf reflectance, lower canopy temperature, and improve photosynthetic performance. However, despite their potential, no published research has comprehensively evaluated the effects of kaolin, basalt powder, and zeolite on almond trees within the same experimental framework. This gap in knowledge provides the rationale for the present study. While kaolin has been widely tested in various fruit crops, this study will be the first to simultaneously evaluate kaolin, basalt powder, and zeolite on almond trees. In particular, no published research has assessed their effects on physiological performance, morpho-biometric traits, biochemical composition, and yield under the same experimental conditions. Based on these considerations, the aim of this study is to evaluate the effectiveness of the foliar application of mineral-based shielding materials on almond trees, with the goal of reducing leaf temperature by increasing surface reflectance, enhancing photosynthetic efficiency and photochemical activity, and ultimately improving yield without compromising the nutraceutical quality of the almonds. To achieve this aim, this study sets out four main objectives: (i) to evaluate the physiological response of almond trees to kaolin, basalt powder, and zeolite; (ii) to assess their effects on the morpho-biometric and biochemical characteristics of the fruits; (iii) to quantify their influence on yield components; and (iv) to explore multivariate relationships among treatments through principal component analysis (PCA).

2. Materials and Methods

2.1. Experimental Site and Plant Material

Our research was conducted over two years, 2024–2025, in an almond orchard [*Prunus dulcis* (Miller) D.A. Webb] covering approximately one hectare, located in the municipality of Bianco (38°05′14.8″ N, 16°08′24.5″ E), Reggio Calabria, Italy (UE). The orchard, established in 1998 at Catanzariti farm, consists of plants of the self-fertile cultivar "Tuono", grafted onto GF677 rootstock (*Prunus persica* × *Prunus amygdalus*), with a planting density of 4 × 3 m^2, corresponding to a density of 833 plants ha^{-1}. According to the Soil Map of the Calabria Region, the area falls within Pedological Province 6, pedological subsystem 6.3 [19]. The physical–chemical characteristics of the topsoil are reported in Table 1.

Table 1. Physico-chemical properties of the topsoil (0–30 cm) at the experimental site.

Parameter	Value (Mean ± SE)	Unit
Clay	31.16 ± 0.65	%
Total sand	34.76 ± 1.35	%
pH	7.80 ± 0.05	–
Organic matter	1.62 ± 0.08	%
Electrical conductivity	0.30 ± 0.03	mS cm^{-1}
Cation exchange capacity (CEC)	20.02 ± 1.68	meq 100 g^{-1}
Bulk density	1.23 ± 0.03	g cm^{-3}

The climate of the area is Mediterranean (Csa according to the Köppen–Geiger classification), a variant of the temperate climate, characterized by hot, dry summers and rainfall concentrated in the winter months. During the growing season, the average monthly temperature reaches its maximum in July (28.0 °C) and its minimum in January (11.8 °C) [20]. Rainfall is mainly concentrated in the winter months. A thermo-pluviometric analysis of the area was carried out using the Bagnouls and Gaussen diagram, which is useful for an immediate visual representation of the monthly thermo-pluviometric regime. The months in which the rainfall diagram falls below the temperature diagram are considered arid; otherwise, they are considered humid (Figure 1).

2.2. Experimental Design

The experimental area was divided into randomized blocks, with a total of four blocks (replicates). Each block included four treatments: TNT—untreated control; TCL—kaolin treatment; TPB—basalt powder treatment; TZL—zeolite treatment. Each treatment included 5 plants per block, for a total of 20 plants per treatment. The shielding materials were applied using a pressure sprayer at the doses recommended by the respective manufacturers, ensuring uniform coverage: Kaolin Surround WP (Serbios Srl, Rovigo, Italy) at a dose of 5 kg hL^{-1}; basalt powder (Basalti Orvieto Srl, Terni, Italy) at 3 kg hL^{-1}; and zeolite (Hydro Fert Srl, Barletta, Italy) at 1.5 kg hL^{-1}. The zeolite applied in this study was a natural clinoptilolite-based mineral product (0–25 μm), with a measured cation exchange capacity of 161 cmol(+) kg^{-1}. Zeolite is a naturally occurring aluminosilicate that is widely employed in agriculture due to its high cation-exchange capacity and porous structure, which enhance soil water retention and nutrient availability. It is considered a safe and inert material, with no evidence of phytotoxic or ecotoxic effects when applied at recommended

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agronomic rates. Its safety has been confirmed by regulatory authorities [21], and is well-documented in the scientific literature, which describes natural zeolites as environmentally benign materials with a long history of agricultural use [22,23]. Applications were carried out at the following phenological stages: BBCH 69, 71, and 73–75.

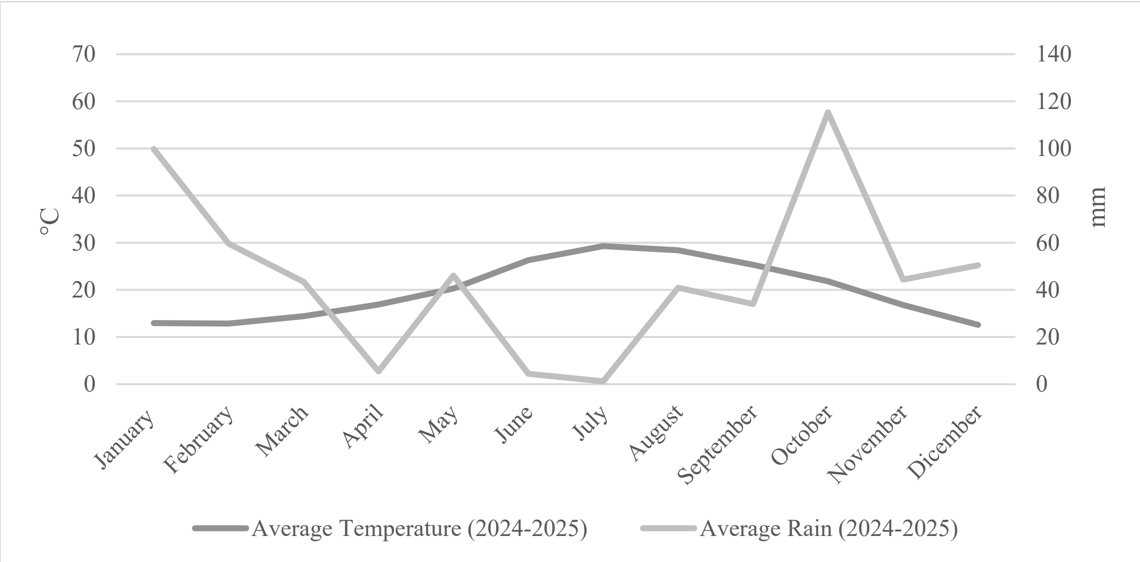

Figure 1. Bagnouls–Gaussen climograph of the almond orchard located in Bianco (Southern Italy) based on temperature and precipitation data recorded during the 2024–2025 growing season [20].

2.3. Physiological Measurements

2.3.1. Gas Exchange and Fluorimetric Measurements

Physiological measurements were taken every 30 days starting from the first application of the shielding treatments. For each experimental treatment, 3 mature leaves per plant were selected, for a total of 15 leaves per treatment per block. Fully expanded, sun-exposed leaves located in the median portion of current-year shoots were chosen to ensure physiological status uniformity. Gas exchange, leaf temperature, and chlorophyll fluorescence were measured using a portable open-flow gas exchange system (LI-COR 6400XT, Lincoln, NE, USA) equipped with a standard leaf chamber and an integrated fluorometer (Leaf Chamber Fluorometer 6400-40, Lincoln, NE, USA). The reference CO_2 concentration in the chamber was maintained at 400 ppm, with an airflow rate of 500 µmol s^{-1} and a photosynthetically active radiation (PAR) of 1500 µmol m^{-2} s^{-1} supplied by the integrated red–blue LED source. Fluorescence measurements followed the standard protocol, including modulated light (ML), a saturating light pulse, actinic light (300 µmol m^{-2} s^{-1}), a second saturating pulse, and a far-red light pulse (30 µmol m^{-2} s^{-1}, 720–730 nm), allowing the determination of the minimum and maximum fluorescence of light-adapted leaves (F_0' and F_m'). During fluorescence measurements, the photosynthetically active radiation (PAR) provided by the fluorometer was set to 1500 µmol m^{-2} s^{-1} 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

$$\mathrm{qP} = \frac{F_m' - F'}{F_m' - F_0'}$$

and reflects the redox state of plastoquinone QA, providing information on the proportion of open PSII reaction centers. The non-photochemical quenching index (NPQ) was calculated as

$$NPQ = \frac{F_m - F'_m}{F'_m}$$

and represents the dissipation of excess excitation energy as heat. The electron transport rate (ETR) was estimated using the following equation:

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

where ΦPSII 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%).

2.3.2. SPAD Index

The chlorophyll content of the leaves was estimated indirectly by measuring the SPAD index using a SPAD-502 Chlorophyll Meter (Konica Minolta, Osaka, Japan). SPAD measurements were taken on the same fully expanded, sun-exposed leaves used for gas exchange and fluorometric analyses immediately after photosynthetic measurements in order to ensure consistency in leaf physiological status and environmental conditions.

2.3.3. Determination of Chlorophyll and Carotenoid Content in Leaves

Pigment determinations were performed on 3 fully expanded leaves per plant, for a total of 15 leaves per treatment per block (n = 60 leaves per treatment). Each sample was analyzed in triplicate at each sampling date corresponding to the physiological measurements. Pigment analyses were carried out on the same fully expanded, sun-exposed leaves on which SPAD readings, gas-exchange measurements, and chlorophyll fluorescence assessments had been conducted, ensuring consistency across all physiological and biochemical evaluations. The chlorophyll and carotenoid contents were determined according to the method [24]. A 0.5 g sample of fresh leaf tissue was homogenized with 10 mL of 80% (v/v) acetone and filtered through Whatman filter paper. The final volume of the extract was adjusted to 15 mL. The absorbance of the solution was measured at 470, 646.8, and 663.2 nm using a UV–VIS spectrophotometer (Lambda 35, Perkin Elmer, Shelton, CT, USA). The contents of chlorophyll a (Chl a), chlorophyll b (Chl b), total chlorophyll (TChl), and carotenoids (Car) were calculated using the following equations:

$$\text{Chl a} = 12.25 \times A663.2 - 2.79 \times A646.8$$

$$\text{Chl b} = 21.50 \times A646.8 - 5.10 \times A663.2$$

$$\text{TChl} = \text{Chl a} + \text{Chl b}$$

$$\text{Car} = (1000 \times A470 - 1.82 \times \text{Chl a} - 85.02 \times \text{Chl b})/198$$

The results were expressed in mg g^{-1} of fresh weight.

2.4. Determination of Morphometric and Qualitative Parameters of Fruits

Morphometric and qualitative determinations were performed on 15 fruits per treatment per block (n = 60 fruits per treatment). Each fruit was measured individually, and all analyses were conducted in triplicate at the harvest date.

2.4.1. Determination of Fresh Weight of Fruits

Fresh weight (FW) was determined using an electronic balance (Mettler-Toledo GmbH, Greifensee, Switzerland), and the husk, epicarp, and seed were weighed separately. Kernel yield was calculated as the ratio between kernel weight and whole fruit weight and expressed as a percentage.

2.4.2. Determination of Dry Matter Content of Fruits

The dry matter content was determined by placing samples of the various treatments (approximately 10 g) in an oven (Binder EED240, Tuttlingen, Germany) at a constant temperature of 70 °C until a constant weight was achieved. The dry matter content was expressed as a percentage, and it was calculated using the following ratio:

$$\% \text{ ss} = (\text{Dry weight})/(\text{Fresh weight}) \times 100$$

2.4.3. Extraction of the Fatty Substances of Fruits

Fat content in the kernel was determined using a Soxhlet extractor (Model E-812/816, BUCHI Corporation, Flawil, Switzerland) with petroleum ether as the extraction solvent. Approximately 10 g of ground kernel was subjected to 6 extraction cycles (1 h), followed by a washing phase of 15 min and a drying phase of 5 min. The recovered oil was quantified gravimetrically and expressed as a percentage of dry kernel weight.

2.4.4. Analysis of Fatty Acid Methyl Esters of Fruits

The methyl esters of fatty acids were determined on oil samples extracted according to the procedure described in Section 2.4.3 [25]. Briefly, an aliquot of the extracted oil was subjected to alkaline transesterification using a methanolic potassium hydroxide solution. After phase separation, the upper hexane layer containing fatty acid methyl esters (FAMEs) was collected, dried, and transferred into vials for subsequent gas chromatographic analysis.

2.4.5. Total Polyphenol Content of Fruits

Nutraceutical determinations (TPC) were carried out on 15 fruits per treatment per block (n = 60 fruits per treatment). Fruits were homogenized to obtain a composite sample for each replicate, and all analyses were performed in triplicate at the harvest date. Samples were homogenized using an Ultraturrax blender (20,000 rpm; T 25 Basic, IKA Werke, Staufen, Germany). Prior to measurement, a standard calibration curve was prepared. TPC was determined using the Folin–Ciocalteu method [26] and expressed as milligrams of gallic acid equivalents per gram of fresh weight (mg GAE g^{-1} FW). Spectrophotometric readings were conducted using a Lambda 35 spectrophotometer (Perkin Elmer Corporation, Waltham, MA, USA).

2.4.6. Total Antioxidant Capacity of Fruits

The total antioxidant capacity (TAC) was assessed on the same fruit samples used for TPC analysis. After homogenization, TAC was measured using the modified Trolox Equivalent Antioxidant Capacity (TEAC) assay [27,28]. The results were expressed as micromoles of Trolox equivalents per gram of fresh weight (μmol TE g^{-1} FW). The TEAC assay accounted for both hydrophilic and lipophilic antioxidant contributions [29]. Measurements were performed using a Lambda 35 spectrophotometer (Perkin Elmer Corporation, USA),

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with standard curves prepared for each assay. A Trolox calibration curve was prepared for each analytical run by serially diluting a Trolox stock solution to obtain standards spanning the 0–1000 μM range. Each standard was reacted with the ABTS•$^+$ reagent, and absorbance was recorded at 734 nm to generate a linear calibration curve, which was subsequently used to interpolate sample values.

2.5. Statistical Analysis

All data were analyzed using two-way analysis of variance (ANOVA) to assess the effects of treatment (untreated control, kaolin, basalt powder, and zeolite), year (2024 and 2025), and their interaction (Treatment × Year). When significant effects were detected ($p \leq 0.05$), mean separation was performed using Tukey's honest significant difference (HSD) test. Statistical analyses were conducted using SPSS v.22.0 (IBM Corp., Armonk, NY, USA). Principal component analysis (PCA) was performed to explore multivariate relationships among treatments and to identify the variables contributing most to treatment differentiation. The analysis was based on the correlation matrix of standardized variables (z-scores). Components with eigenvalues > 1 were retained, and variables with loadings $\geq |0.60|$ were considered influential. Treatment distribution and variable contributions were interpreted using score and loading plots. PCA was carried out using XLSTAT 2014 (Addinsoft, New York, NY, USA).

3. Results

3.1. Chlorophyll Fluorescence

The maximum quantum efficiency, expressed as the ratio Fv'/Fm', was highest in the experimental group treated with basalt powder and kaolin (0.648 ± 0.02 and 0.647 ± 0.01, respectively), while plants treated with zeolite showed values close to 0.578 ± 0.01, and untreated plants exhibited the lowest values (0.491 ± 0.02) (Table 2). For this fluorometric index, the differences were also statistically significant, with the control treatment showing the lowest values (0.145 ± 0.13) (Table 2). The experimental group treated with shielding materials showed the best performance, with values of 0.161 ± 0.15 (TCL), 0.162 ± 0.14 (TPB), and 0.158 ± 0.09 (TZL) (Table 2). The TPB treatment showed the highest qP values (0.267 ± 0.01), while untreated plants showed the lowest values (0.231 ± 0.02). Less prominent values were recorded for the TCL (0.253 ± 0.01) and TZL (0.261 ± 0.02) treatments (Table 2); in the test conducted, this index did not show statistically significant differences between the different experimental groups (Table 2). The ETR values obtained showed statistically significant differences between the experimental groups. In fact, the plants of the Tuono variety, shielded with kaolin (153.441 μmol $_{electrons}$ m^{-2} s^{-1} ± 3.78), as well as basalt flour (156,705 μmol $_{electrons}$ m^{-2} s^{-1} ± 2.17) and zeolite, showed significantly higher values than the control treatment (99,567 μmol $_{electrons}$ m^{-2} s^{-1} ± 2.54) (Table 2).

3.2. Physiological Measurements and Leaf Functional Traits

During physiological measurements, all treatments exhibited higher *An* values than the control. The highest values were recorded for TCL (Table 3), which were 25% higher than TCN; however, no significant differences were observed for this parameter between TCL and the other treatments. A similar trend was observed for another important physiological parameter measured: stomatal conductance (gs). Indeed, the gs was about two times higher in treatment trees compared to TCN; in particular, the values range from the highest value of approximately 0.100 μmol H_2O m^{-2} s^{-1} ± 0.01 (TCL) to the lowest value of approximately 0.082 μmol H_2O m^{-2} s^{-1} ± 0.01 (TPB) (Table 3), but they were significantly higher compared to the control, which exhibited a value of approximately 0.060 μmol H_2O m^{-2} s^{-1} (Table 3). The application of reflective products had a clear influence on the leaf temperature of almond trees. The untreated leaves (control) showed the highest temperature, reaching 34.31 °C, indicating greater absorption of solar radiation and a lower reflectance capacity. In contrast, the treatments with kaolin and basalt powder resulted in a significant reduction in leaf temperature (Table 3). The zeolite treatment also produced a slight decrease in leaf temperature (33.78 °C), although the effect was less pronounced than that observed with kaolin and basalt powder (Table 3), suggesting a lower reflective efficiency. The above-mentioned parameters were affected by the year of the experiment, resulting in lower values, with no significant differences observed only for *Ci*. No year × treatment interaction was detected. The SPAD index showed higher values in treated plants compared with untreated ones. Moreover, no effect of year was observed (Table 3).

Table 2. Effects of foliar treatments with mineral-based shielding materials on fluorescence indices of *Prunus dulcis*. Fv'/Fm' = Maximum efficiency of PSII in light-adapted state; qP = photochemical quenching; PhiPS2 = effective quantum yield of PSII; NPQ = non-photochemical quenching; ETR = electron transport rate.

Treatment	Fv'/Fm'	qP	PhiPS2	NPQ	ETR (µmol m^{-2} s^{-1})
TNT	0.49 ^{c}	0.23 ^{c}	0.14 ^{b}	2.37 $^{n.s.}$	99.57 ^{b}
TCL	0.65 ^{a}	0.25 ^{b}	0.16 ^{a}	2.31	153.44 ^{a}
TPB	0.65 ^{a}	0.27 ^{a}	0.16 ^{a}	2.30	156.70 ^{a}
TZL	0.58 ^{b}	0.26 ^{b}	0.16 ^{a}	2.20	150.89 ^{a}
Mean ± SD	0.59 ± 0.07	0.25 ± 0.02	0.15 ± 0.01	2.30 ± 0.07	140.15 ± 24.03
T	***	**	**	n.s.	***
Y	n.s.	n.s.	n.s.	n.s.	n.s.
T × Y	n.s.	n.s.	n.s.	n.s.	n.s.

Different lowercase letters within a column indicate significant differences among treatments (Tukey's test, $p \leq 0.05$). "n.s." = Non-significant. T = Treatment effect; Y = year effect; T × Y = interaction effect. Significance levels: ** $p \leq 0.01$; *** $p \leq 0.001$.

Table 3. Effects of foliar treatments with mineral-based shielding materials on gas exchange parameters of *Prunus dulcis*. An = Net assimilation rate (µmol CO_2 m^{-2} s^{-1}); gs = stomatal conductance (µmol H_2O m^{-2} s^{-1}); Ci = intercellular CO_2 concentration (ppm); E = transpiration rate (mmol H_2O m^{-2} s^{-1}); LT = leaf temperature (°C); SPAD = chlorophyll index.

Treatment	An (µmol CO_2 m^{-2} s^{-1})	gs (µmol H_2O m^{-2} s^{-1})	Ci (ppm)	E (mmol H_2O m^{-2} s^{-1})	LT (°C)	SPAD
TNT	8.00 ^{b}	0.05 ^{b}	190.17 $^{n.s.}$	0.88 ^{b}	34.31 ^{a}	47.76 ^{b}
TCL	10.00 ^{a}	0.10 ^{a}	192.73	1.99 ^{a}	32.70 ^{b}	48.78 ^{a}
TPB	9.87 ^{a}	0.08 ^{a}	189.34	1.98 ^{a}	32.52 ^{b}	49.67 ^{a}
TZL	9.65 ^{a}	0.09 ^{a}	188.34	1.88 ^{a}	33.78 ^{b}	48.54 ^{a}
Mean ± SD	9.38 ± 0.82	0.08 ± 0.02	190.15 ± 1.83	1.43 ± 0.55	33.33 ± 0.82	48.69 ± 0.79
T	*	*	n.s.	*	*	*
Y	*	*	n.s.	*	*	n.s.
T × Y	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Different lowercase letters within a column indicate significant differences among treatments (Tukey's test, $p \leq 0.05$). "n.s." = Non-significant. T = Treatment effect; Y = year effect; T × Y = interaction effect. Significance levels: * $p \leq 0.05$.

The data presented in Table 4 highlight the effect of different shielding materials on the foliar content of photosynthetic pigments, including chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids. The untreated control (TNT) consistently exhibited the lowest values for all parameters, confirming the protective role of shielding materials against photo-oxidative stress induced by excessive solar radiation. Treatments with kaolin (TCL) and basalt powder (TPB) were particularly effective in preserving the integrity of the photosynthetic apparatus. Both treatments resulted in significantly higher chlorophyll a (7.919 ± 0.13 and 8.011 ± 0.29 mg g^{-1} FW, respectively) and chlorophyll b (8.111 ± 0.09 and 7.993 ± 0.11 mg g^{-1} FW) contents, approximately 25% higher than the control. The zeolite treatment (TZL) was significantly less effective than TCL and TPB, although it still increased chlorophyll a and b contents by 7% and 14%, respectively, relative to the control (Table 4). Total chlorophyll content reached similar maximum values in TCL and TPB (16.131 ± 0.14 and 16.124 ± 0.88 mg g^{-1} FW, respectively), confirming an overall beneficial effect on the photosynthetic system. The total carotenoid content followed a pattern consistent with that of chlorophylls, with significantly higher values in TCL (2.223 ± 0.21 mg g^{-1} FW) and TPB (2.172 ± 0.23 mg g^{-1} FW), representing a 24% increase compared to TNT. Zeolite also showed lower values than TCL and TPB, but it was still 11% higher than the control (Table 4).

Table 4. Effects of foliar treatments with mineral-based shielding materials on pigment composition of almond (*Prunus dulcis*) leaves. Chl a = Chlorophyll a; Chl b = chlorophyll b; TChl = total chlorophyll; Car = total carotenoids. All values are expressed in mg g^{-1} FW.

Treatment	Chlorophyll a (mg g^{-1} FW)	Chlorophyll b (mg g^{-1} FW)	Total Chlorophyll (mg g^{-1} FW)	Total Carotenoids (mg g^{-1} FW)
TNT	6.53 ^{c}	6.13 ^{c}	12.47 ^{c}	1.79 ^{c}
TCL	7.92 ^{a}	8.11 ^{a}	16.13 ^{a}	2.22 ^{a}
TPB	8.01 ^{a}	7.99 ^{a}	16.12 ^{a}	2.17 ^{a}
TZL	7.13 ^{b}	6.97 ^{b}	14.1 ^{b}	1.99 ^{b}
Mean ± SD	7.40 ± 0.67	7.30 ± 0.86	14.71 ± 1.63	2.04 ± 0.18
T	*	*	*	*
Y	n.s.	n.s.	n.s.	n.s.
T × Y	n.s.	n.s.	n.s.	n.s.

Different lowercase letters within a column indicate significant differences among treatments (Tukey's test, $p \leq 0.05$). "n.s." = Non-significant. T = Treatment effect; Y = year effect; T × Y = interaction effect. Significance levels: * $p \leq 0.05$.

3.3. Morphometric and Qualitative Parameters

The results presented in Table 5 demonstrate the significant influence of kaolin-, basalt-powder-, and zeolite-based shielding treatments on the main morphometric and qualitative parameters of *Prunus dulcis* drupes compared to the untreated control. Treatments with kaolin and basalt powder resulted in a similar and statistically significant increase of approximately 30% in drupe weight compared to the control.

Zeolite also induced a positive—although comparatively modest—effect, resulting in a 12% increase in fresh weight relative to the control. The analysis of the three fruit fractions, hull, shell, and kernel, allowed us to identify which component responded most to the treatments. Regarding seed fresh weight, a general upward trend was observed in the treated fruits, with statistically significant differences compared to the control. Treatments with kaolin and basalt powder, which showed statistically similar values, resulted in a 21–22% increase in average seed fresh weight compared to the control. Zeolite also produced a significant increase in seed fresh weight, although lower than the other two treatments, with a 12% increase over the control (Table 5). A similar trend was observed for the shell.

Both kaolin and basalt powder increased the shell weight similarly, with a 14% increase over the control. Zeolite treatment resulted in a statistically lower increase compared to the other two treatments, but it was still 5% higher than the control (Table 5). Finally, a clear differentiation was observed for the hull. Kaolin and basalt powder treatments showed statistically similar weight increases, with kaolin resulting in a 14% increase and basalt powder resulting in a 12% increase over the control. Zeolite treatment resulted in a more modest increase of approximately 7% (Table 5).

Table 5. Effects of foliar treatments with mineral-based shielding materials on the main morpho-biometric traits of *Prunus dulcis* fruits. ADW = Average fresh drupe weight; AHW = average fresh hull weight; ASW = average fresh shell weight; AKW = average fresh kernel weight; KY = kernel yield; DM = dry matter; OY = oil yield; PY = productive yield.

Treatment	ADW (g)	AHW (g)	ASW (g)	AKW (g)	KY (%)	DM (%)	OY (%)	PY (Kg)
TNT	17.74 ^{c}	10.39 ^{c}	8.33 ^{c}	2.58 ^{c}	30.97 ^{b}	54.66 ^{b}	42.53 ^{b}	7.13 ^{c}
TCL	23.40 ^{a}	13.59 ^{a}	9.49 ^{a}	3.15 ^{a}	33.17 ^{a}	59.71 ^{a}	44.78 ^{a}	9.45 ^{a}
TPB	22.14 ^{a}	13.05 ^{a}	9.17 ^{a}	3.00 ^{a}	32.74 ^{a}	57.68 ^{a}	45.88 ^{a}	9.11 ^{a}
TZL	19.96 ^{b}	12.16 ^{b}	8.83 ^{b}	2.88 ^{b}	32.64 ^{a}	56.28 ^{a}	43.99 ^{a}	8.33 ^{b}
Mean ± SD	20.81 ± 2.42	12.30 ± 1.32	8.96 ± 0.49	2.90 ± 0.24	32.38 ± 0.94	57.08 ± 2.14	44.30 ± 1.43	8.51 ± 0.97
T	***	***	***	***	n.s.	**	**	*
Y	*	n.s.	*	n.s.	n.s.	*	*	*
T × Y	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Different lowercase letters within a column indicate significant differences among treatments (Tukey's test, $p \leq 0.05$). "n.s." = Non-significant. T = Treatment effect; Y = year effect; T × Y = interaction effect. Significance levels: * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$.

A key indicator for evaluating productive quality is the kernel yield, which showed a statistically significant improvement in all treatments compared to the control. The maximum value was recorded with the kaolin treatment (33.175%), statistically similar to that obtained with basalt powder, although the latter showed a slightly lower average value. The zeolite treatment recorded the lowest kernel yield among the treatments, although it was still significantly higher than the control. Particularly noteworthy are the results obtained for dry matter content and oil yield in the kernel, two crucial parameters for industrial processing. Dry matter content in the kernel was significantly higher in treated fruits, with an increase of up to approximately 5 percentage points over the control. The kaolin treatment recorded the highest value (59.71%), followed by basalt powder, which showed a slightly lower but statistically similar value. Zeolite also led to an increase in dry matter percentage over the control; although the value obtained was significantly lower than the other two treatments, it was still statistically higher than the control (Table 5). A similar trend was observed for oil yield, with the highest values in the treatment with kaolin, followed by basalt powder and zeolite, all showing statistically higher values than the control, though without significant differences among treatments (Table 5).

The analysis of production data highlights significant differences among the various treatments applied to almond trees. The untreated control (TNT) recorded the lowest yield, equal to 7.132 kg tree^{-1}, representing the reference level for evaluating the effectiveness of the mineral materials used. All treatments based on mineral powders showed an increase in yield compared to the control, with varying intensity depending on the type of material applied (Table 5). The kaolin treatment (TCL) achieved the highest yield, 9.451 kg tree^{-1}, proving to be the most effective in improving production. A similar trend was observed with basalt powder (TPB), which reached a yield of 9.332 kg tree^{-1}, very close to that of

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kaolin. The zeolite treatment (TZL) produced a less prominent yield of 8.332 kg tree^{-1}, higher than the control but lower than kaolin and basalt (Table 5). Overall, the results indicate that mineral treatments led to a yield increase compared to the control, ranging from approximately 17 to 32%. However, no significant interaction (Y $\times$ T) was recorded for any parameter (Table 5).

3.4. Nutraceutical Parameters

The analysis of the data presented in Table 5 allowed us to evaluate the effect of different shielding products on the total polyphenol content (TPC) and total antioxidant capacity (TAC) of almonds. The results relating to the total polyphenol content showed very similar values for all treatments, with fluctuations ranging from 83,444 $\pm$ 0.11 mg GAE 100 g^{-1} (TZL) to 85,901 $\pm$ 0.38 mg GAE 100 g^{-1} (TPB) (Table 6). Statistical analyses showed no significant differences between the groups. This suggests that the shielding products tested did not induce appreciable changes in the accumulation of total polyphenols within almond seeds under these specific experimental conditions. Similarly, the examination of the total antioxidant capacity revealed similar behaviors. The values recorded ranged from 3998 $\pm$ 0.91 µmol Trolox g FW (TPB) to 4745 $\pm$ 0.88 µmol Trolox g FW (TCL). For both TAC and TPC, lower values were observed during the first year; however, no year $\times$ treatment interaction was detected (Table 6).

Table 6. Effects of foliar treatments with mineral-based shielding materials on total polyphenol content (TPC) and total antioxidant capacity (TAC) in almond (*Prunus dulcis*) seeds. TPC = Total polyphenol content (mg GAE 100 g^{-1} FW); TAC = total antioxidant capacity (µmol Trolox g^{-1} FW).

Treatment	TPC (mg GAE 100 g^{-1})	TAC (µmol Trolox g FW)
TNT	84.33 $^{n.s.}$	4.22 $^{n.s.}$
TCL	85.23	4.74
TPB	85.90	3.99
TZL	83.44	4.56
Mean $\pm$ SD	84.73 $\pm$ 1.03	4.38 $\pm$ 0.32
T	n.s.	n.s.
Y	n.s.	n.s.
T $\times$ Y	n.s.	n.s.

"n.s." = Non-significant. T = Treatment effect; Y = year effect; T $\times$ Y = interaction effect.

3.5. Fatty Acid Composition Analysis

The analysis reveals an extremely uniform lipid profile across all examined samples. The dominant feature of this oil is the very high concentration of unsaturated fatty acids, particularly oleic acid and linoleic acid (Table 7). Oleic acid stands as the main component, accounting for over two-thirds of the total composition. The percentages are remarkably stable, oscillating between 71.28% (TCL) and 71.32% (TPB) (Table 7). Immediately following oleic acid in terms of concentration is linoleic acid, a polyunsaturated fatty acid. Its concentration remains consistently around 19%, varying from 19.24% (TZL) to 19.34% (TNT) (Table 7). Among the other unsaturated fatty acids, palmitoleic acid is noteworthy, contributing percentages ranging from 0.54% to 0.58%. Heptadecenoic acid and eicosenoic acid are present in traces at around 0.08–0.09% and 0.07–0.08%, respectively. Saturated fatty acids occupy a minor, yet significant, portion of the total profile. The most abundant is palmitic acid, with values settling around 6%, ranging from 6.00 (TNT) to 6.15% (TZL) (Table 7). This is followed by stearic acid, which shows a precise and stable percentage, oscillating between 2.42% (TZL) and 2.46% (TNT). Several fatty acids are present in very low concentrations, often below 0.10%. These include myristic acid, which is consistently present in all samples at 0.02%. Heptadecanoic acid is stably measured at 0.05%. Arachidic acid ranges between 0.02 and 0.04%. Gamma-linolenic acid is found between 0.07% and 0.10%. Finally, long-chain acids such as behenic acid and lignoceric acid are present in minimal quantities at 0.01% and between 0.02% and 0.03%, respectively (Table 7).

Table 7. Fatty acid profile, expressed as the percentage composition of the methyl esters of fatty acids, for four different almond oil samples (TCL, TZL, TPB, and TNT).

Methyl Esters of Fatty Acids (%)	Treatment			
	TCL	TZL	TPB	TNT
C14:0—Miristic acid	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01
C16:0—Palmitic acid	6.04 ± 0.48	6.15 ± 0.48	6.05 ± 0.48	6.00 ± 0.48
C16:1—Palmitoleic acid	0.55 ± 0.07	0.58 ± 0.07	0.54 ± 0.07	0.54 ± 0.07
C17:0—Heptadecanoic acid	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01	0.05 ± 0.01
C17:1—Heptadecenoic acid	0.09 ± 0.02	0.08 ± 0.02	0.09 ± 0.02	0.08 ± 0.02
C18:0—Stearic acid	2.43 ± 0.12	2.42 ± 0.12	2.43 ± 0.12	2.46 ± 0.12
C18:1—Oleic acid 71	71.28 ± 0.98	71.24 ± 0.98	71.32 ± 0.98	71.29 ± 0.98
C18:2—Linoleic acid omega 6	19.31 ± 0.24	19.24 ± 0.24	19.27 ± 0.24	19.34 ± 0.24
C20:0—Arachidic acid	0.02 ± 0.06	0.04 ± 0.06	0.04 ± 0.06	0.04 ± 0.06
C18:3—Gamma-linoleic acid	0.10 ± 0.06	0.07 ± 0.06	0.07 ± 0.06	0.07 ± 0.06
C20:1—Eicosenoic acid	0.08 ± 0.06	0.07 ± 0.06	0.08 ± 0.06	0.07 ± 0.06
C22:0—Behenic acid	0.01 ± 0.03	0.01 ± 0.03	0.01 ± 0.03	0.01 ± 0.03
C22:1—Erucic acid	<0.01	<0.01	<0.01	<0.01
C24:0—Lignoceric acid	0.02 ± 0.04	0.03 ± 0.04	0.02 ± 0.04	0.03 ± 0.04
C18:1T—Total trans-oleic isomers	<0.01	<0.01	<0.01	<0.01
C18:2T+C18:3T—Total trans-linoleic + trans-linolenic isomers	<0.01	<0.01	<0.01	<0.01

Statistical analysis revealed no significant differences for the main effects of treatment (T) and year (Y) or for their interaction (T × Y) across all fatty acid compositions. This indicates that the observed variations among the four treatments, or between the two years of analysis, are minor and not statistically meaningful.

3.6. Multivariate Analysis: Principal Component Analysis

The data were subjected to principal component analysis (PCA), with the aim of studying the relationships between the original variables in order to find a new, smaller set that expressed the commonalities between the original items. The eigenvalue distribution shown in Figure 2 provides additional support for the robustness of the PCA structure. The steep decline observed between the first and second components, followed by a clear inflection point, indicates that only the first two principal components carry substantial explanatory power, while the remaining components contribute marginally to total variance. This pattern is consistent with a well-structured dataset in which the major sources of variability are concentrated in a limited number of orthogonal dimensions. The fact that PC1 and PC2 together account for a large proportion of the variance confirms that the multivariate response of almond trees to mineral treatments is dominated by coordinated changes in photosynthetic efficiency, thermal regulation, and yield-related traits. The $\cos^2$ values reported in Table 8 further clarify the contribution and reliability of each variable within the PCA space. High $\cos^2$ values for Fv'/Fm', PhiPS2, ETR, stomatal conductance, and leaf temperature indicate that these variables are strongly correlated with the principal components and are, therefore, well represented in the reduced dimensionality of the PCA. This confirms that photosynthetic and thermal parameters are the primary drivers of treatment separation. Conversely, variables with lower $\cos^2$ values contribute less to the definition of the PCA axes, suggesting that their variability is either more diffuse or less directly influenced by the mineral treatments. The strong representation of both physiological and productive traits in the first two components reinforces the interpretation that the effects of kaolin and basalt powder are multidimensional and coherent across functional domains. The $\cos^2$ values reported in Table 9 provide important information on the quality of representation of each treatment within the PCA space. High $\cos^2$ values indicate that the position of a treatment on a given principal component is reliable and strongly associated with the underlying structure of the data. In our analysis, TCL and TPB showed the highest $\cos^2$ values on PC1 and PC2, confirming that these treatments are well explained by the main sources of variance and are strongly associated with the physiological and morphobiometric improvements captured by the first two components. This is consistent with their superior performance in photosynthetic efficiency, leaf temperature reduction, and yield traits. TZL exhibited intermediate $\cos^2$ values, suggesting that its multivariate profile is only partially aligned with the dominant variance structure. This reflects its moderate but positive influence across several variables, without the strong, coordinated response observed for kaolin and basalt powder. Conversely, the untreated control (TNT) showed lower $\cos^2$ values on the first components, indicating a weaker association with the main physiological and productive gradients identified by PCA. This pattern is expected, as the control lacks the reflective or thermoregulatory effects induced by mineral treatments and, therefore, occupies a more peripheral position in the multivariate space.

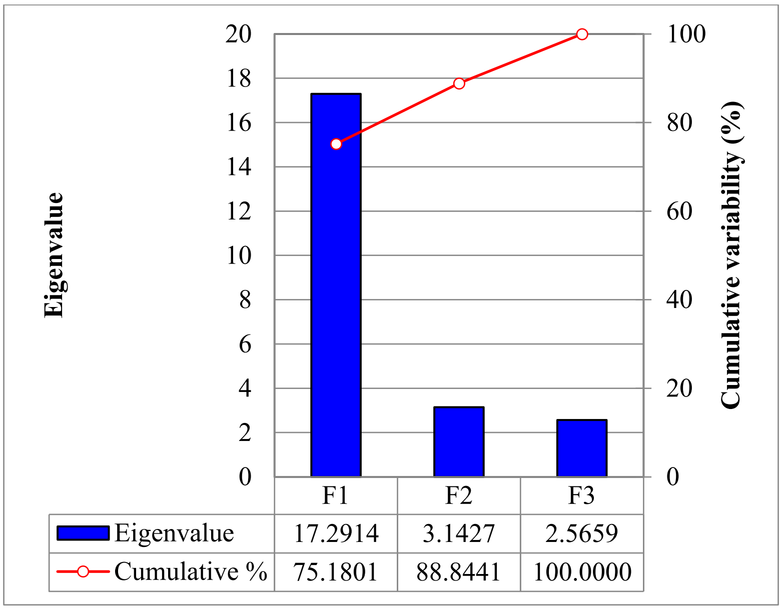

Figure 2. Eigenvalues and percentage of variance explained by the principal components derived from physiological, morphometric, and biochemical variables in almond trees under mineral shielding treatments.

Multivariate PCA provided an integrated view of the relationships among physiological, morphobiometric, and biochemical variables, allowing a clearer interpretation of treatment effects beyond univariate comparisons. In our study, the first two principal components explained a substantial proportion of total variance, indicating that the dataset was strongly structured and that the treatments generated consistent multivariate patterns. PC1 was primarily associated with variables linked to photosynthetic performance and thermal regulation, such as Fv'/Fm', PhiPS2, ETR, stomatal conductance, and leaf temperature, highlighting the strong contribution of kaolin and basalt powder to improved photochemical efficiency and reduced canopy heat load. PC2 was mainly driven by morpho-biometric traits, including drupe weight, kernel dry matter, and productive yield, further separating the high-performing treatments (kaolin and basalt powder) from the control. Zeolite occupied an intermediate position in the PCA space, reflecting its moderate but positive influence on both physiological and productive parameters. The clear clustering of treatments and the strong loadings of key variables confirm that mineral-based materials exert coordinated effects on plant physiology and yield formation, supporting the interpretation that their benefits are systemic rather than limited to isolated traits. These findings align with previous studies reporting that PCA is particularly effective in distinguishing treatment-induced physiological responses under abiotic stress conditions. Overall, the PCA results reinforce the conclusion that kaolin and basalt powder provide the most consistent improvements across multiple functional dimensions of almond performance under Mediterranean heat stress (Figure 3).

Table 8. Cos^2 values of physiological, morphometric, and biochemical variables for the first three principal components (F1, F2, and F3) obtained from the PCA performed on almond trees subjected to mineral shielding treatments.

Variables	F1	F2	F3
AN	0.9472	0.0356	0.0172
gs	0.7817	0.1864	0.0319
Ci	0.0863	0.0254	0.8882
E	0.8930	0.0571	0.0499
SPAD	0.1628	0.6973	0.1398
Fv'/Fm'	0.9876	0.0118	0.0006
qP	0.6825	0.0084	0.3091
PhiPS2	0.9577	0.0056	0.0367
NPQ	0.1624	0.5304	0.3072
ETR	0.8963	0.0370	0.0667
ADW	0.9583	0.0050	0.0367
AHW	0.9920	0.0003	0.0077
ASW	0.9424	0.0000	0.0576
AKW	0.9668	0.0060	0.0272
KY	0.9419	0.0579	0.0003
DM	0.8509	0.0002	0.1488
Oil yield	0.8389	0.0879	0.0732
Chl a	0.9672	0.0320	0.0009
Chl b	0.9597	0.0325	0.0078
Tot Chl	0.9608	0.0378	0.0015
Tot Car	0.9798	0.0100	0.0103
TPC	0.3063	0.6689	0.0249
TAC	0.0689	0.6092	0.3219

Table 9. Cos^2 values of the treatments (TNT, TCL, TPB, and TZL) for the first three principal components obtained from the PCA performed on physiological, morphometric, and biochemical variables of almond trees subjected to mineral shielding treatments.

Treatment	F1	F2	F3
TNT	0.0158	0.9735	0.0106
TCL	0.7355	0.0092	0.2553
TPB	0.5626	0.2930	0.1444
TZL	0.0080	0.7575	0.2345

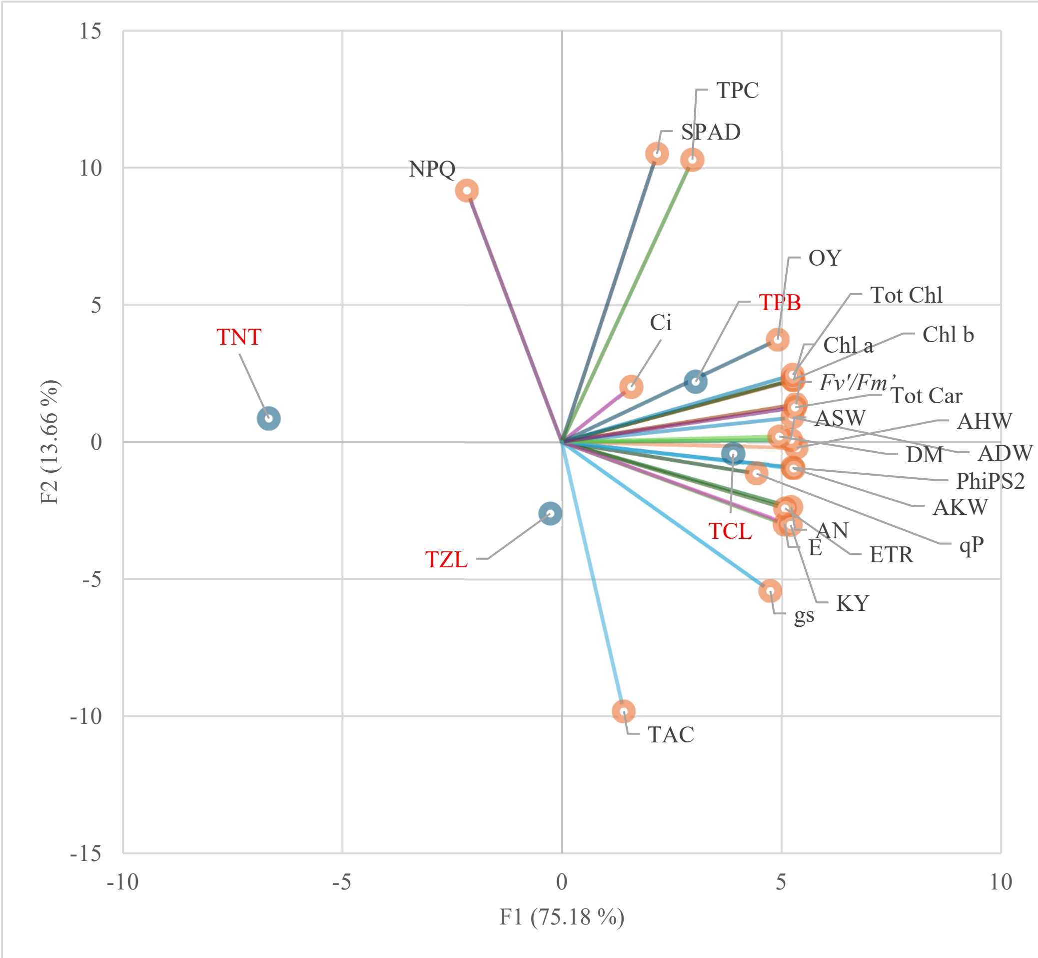

Figure 3. Principal component analysis (PCA) of physiological, morphometric, and biochemical variables in almond trees subjected to mineral shielding treatments.

4. Discussion

The application of shielding materials such as kaolin, basalt powder, and zeolite significantly influenced the physiological and productive performance of *Prunus dulcis* under Mediterranean climatic conditions. These findings are consistent with a growing body of evidence showing that reflective particle films mitigate the adverse effects of excessive heat and solar irradiance on plant metabolism, thereby improving water relations and photosynthetic efficiency [30–32]. Similar positive responses to kaolin application have been reported under Mediterranean-type climates, including studies conducted in Portugal [33] and California [34], where kaolin-treated almond trees exhibited increased cumulative kernel yields (316–545 kg ha^{-1}) and reduced bud failure compared with untreated controls. In the present study, kaolin treatment resulted in a 30% yield increase relative to the control, slightly higher than that reported in California, likely reflecting differences in local climatic conditions and stress intensity.

The reduction in leaf temperature was observed in plants treated with kaolin and basalt powder (up to −1.8 °C compared with the control), indicating decreased absorption of solar radiation due to enhanced reflectance in the visible and near-infrared (NIR) regions [35]. This thermoregulatory effect is consistent with previous findings reported for grapevine (*Vitis vinifera* L.), olive (*Olea europaea* L.), apple (*Malus domestica* L.), and citrus species [15,36–41]. By reducing the thermal energy load on leaf tissues, reflective materials contribute to maintaining optimal enzymatic activity and delaying the onset of heat-induced photoinhibition [42].

Moreover, kaolin and basalt powder applications promoted higher net photosynthetic rates (A_n) and stomatal conductance (g_s), suggesting an enhanced gas exchange capacity under stress conditions. These responses support the hypothesis that reflective coatings improve stomatal regulation and CO_2 assimilation when plants are exposed to high light intensity and elevated temperatures [43]. Improvements in PSII efficiency (Fv′/Fm′) and electron transport rate (ETR) further indicate the maintenance of photochemical stability, reinforcing the protective role of shielding materials against photooxidative stress. The higher concentrations of photosynthetic pigments (chlorophyll a, chlorophyll b, and carotenoids) detected in kaolin- and basalt-treated plants further confirm the preservation of the photosynthetic apparatus. The maintenance of chlorophyll content under intense solar radiation suggests that these coatings effectively reduce pigment degradation caused by reactive oxygen species (ROS), as previously observed in olive and grapevine [44,45]. Moreover, carotenoids likely played a key role in photoprotection by dissipating excess excitation energy through non-photochemical quenching (NPQ), thereby preventing light-induced photodamage [46,47].

These physiological benefits translated into increased productivity, with significant increases in fruit fresh weight, kernel yield, and oil content observed under kaolin and basalt treatments, highlighting their effectiveness in sustaining productivity under environmental stress. The improved yield performance, reaching up to +32% compared with the control, can be attributed to the stabilization of photosynthetic processes and a more efficient allocation of assimilates, in agreement with previous studies conducted on olive [44] and grapevine [48,49].

Differences among shielding materials can be partially explained by their optical and structural properties. Kaolin exhibits high reflectance in the visible and NIR spectral regions due to its light color, low iron oxide content, and fine particle size, characteristics that are widely documented for kaolinite-based particle films [50]. In contrast, natural zeolites generally display lower reflectance efficiency [51], mainly because of their microporous crystal structure and absorption features associated with structural water and iron-bearing impurities [52]. Basalt powder, despite its inherently lower albedo related to its mafic, iron-rich composition, is characterized by a stable and diffuse scattering behavior, as reported for basaltic surfaces [53], which may still provide partial radiation shielding when applied as a surface coating. These differences likely explain why the beneficial effects of zeolite observed in this study were comparatively milder than those obtained with kaolin and basalt powder.

Interestingly, no significant variations were detected in the biochemical composition of almond kernels, including total polyphenols, antioxidant capacity, and fatty acid profile. This indicates that, while shielding treatments enhance vegetative growth and physiological performance, they do not alter the intrinsic nutraceutical quality of the fruits. Comparable results have been reported for mango [54] and olive [44], where reflective films improved leaf functionality without affecting the chemical composition of harvested products.

Beyond physiological and productive responses, practical considerations are essential when evaluating the suitability of shielding materials for orchard management. Kaolin is among the most widely used mineral materials in fruit crops due to its broad commercial availability, ease of application, relatively low cost, and well-documented safety profile. Its effectiveness in reducing canopy heat load and improving microclimatic conditions has been demonstrated in numerous agronomic studies [30,36,37]. Basalt powder, which is increasingly used as a rock-dust amendment, is generally accessible in regions with active quarrying industries and is considered cost-effective, although its availability and price may vary geographically. In addition, its environmental footprint is minimal, as it derives from natural silicate rocks and contributes to soil remineralization processes [55]. Zeolite, while environmentally benign and characterized by high cation exchange capacity, is typically more expensive per unit mass and may require more energy-intensive micronization, which can limit its large-scale application [21,22].

Finally, multivariate PCA provided an integrated overview of the relationships among ecophysiological and productive variables. Treatments with kaolin and basalt powder were closely associated with parameters indicative of high photosynthetic efficiency (Fv'/Fm', ETR, A_n) and productivity (kernel yield and oil yield). The clear separation of these treatments from the control in the PCA biplot supports the conclusion that reflective materials enhance the resilience of almond trees to combined heat and high irradiance stress by maintaining a functional balance between light interception, heat dissipation, and carbon assimilation.

A preliminary economic appraisal indicates that the use of mineral shielding materials may represent a viable management option for almond orchards under Mediterranean conditions. Based on the application rates adopted in this study and the observed yield increase of approximately 30% compared with untreated trees, the estimated costs were about EUR 80–90 ha^{-1} for kaolin and EUR 100–120 ha^{-1} for basalt powder, including both material and application expenses. Under these assumptions, the additional revenue associated with yield enhancement would allow the investment to be recovered within a single growing season. Nevertheless, these estimates derive from a pilot-scale experiment conducted under southern Mediterranean conditions, and their long-term economic reliability should be validated across multiple seasons. Future studies should also evaluate the effectiveness of these materials under extreme drought scenarios and assess the technical and economic feasibility of a large-scale, mechanized spraying system.

5. Conclusions

This study demonstrates that kaolin and basalt powder are the most effective mineral-based materials with low environmental impact for mitigating heat and radiation stress in almond orchards under Mediterranean conditions. Both treatments consistently improved photosynthetic efficiency, reduced leaf temperature, and enhanced drupe and kernel development, ultimately resulting in the highest increases in productive yield. Zeolite also exerted positive effects, although to a lesser extent, confirming its potential but highlighting its comparatively low efficacy.

The novelty of this work lies in the first integrated, two-year comparative assessment of kaolin, basalt powder, and zeolite applied to almond trees, combining physiological, morphobiometric, biochemical, and multivariate analyses within a single experimental framework. By demonstrating that shielding materials can enhance orchard resilience without altering the nutraceutical quality of the kernels, this study provides new evidence supporting the use of sustainable, low-impact materials to counteract climate-induced stress in Mediterranean nut production systems. From a practical perspective, kaolin should be preferred in areas with clayey soils, whereas basalt powder is recommended for sandy soils.

By demonstrating that shielding materials can enhance orchard resilience without altering the nutraceutical quality of the kernels, this study provides new evidence supporting the use of sustainable, low-impact materials to counteract climate-induced stress in Mediterranean nut production systems. From a practical perspective, kaolin should be preferred in areas with clayey soils, whereas basalt powder is recommended for sandy soils. These materials should be applied before the onset of the rainy season to maximize effectiveness under moderate heat stress conditions. These findings contribute to current knowledge by clarifying the relative performance of different mineral materials and by identifying kaolin and basalt powder as the most promising tools for improving almond productivity under increasingly challenging environmental conditions.

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