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Particle film sunscreens mitigate heat stress and improve watermelon fruit quality[1]

Filmes de partículas usados como protetores solares atenuam o estresse térmico e melhoram a qualidade dos frutos de melancia

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HIGHLIGHTS:

Sunscreens reduced peak fruit temperature by 12.8 °C and sunscald incidence from 3.62 to <1.5 severity index.
Sunscreen use increased fruit total soluble solids and improved the commercial quality of watermelon.
The sunscreens mitigated thermal and photo-oxidative stress as evidenced by preserved chlorophyll fluorescence.

ABSTRACT: Watermelon cultivation is an important component of Brazilian agribusiness, with growing relevance in emerging states such as Espírito Santo, where agricultural diversification is expanding. In the Northwest region, high solar radiation and adverse climatic conditions pose challenges to fruit quality, making the use of management strategies, such as sunscreens, a potential solution. This study aimed to evaluate the effects of different sunscreens on the yield and post-harvest quality of watermelon grown in this region. The experiment was conducted using Crimson Sweet watermelons in a randomized block design with five treatments and four replicates: T1 – no protection; T2 – paper protection; T3 – calcium carbonate (18.5%) + zinc oxide (0.5%) + adjuvants; T4 – 95% kaolin; and T5 – 97% calcium hydroxide with magnesium and 3% additives. The fruits were sprayed weekly. The variables evaluated included growth, firmness, peel thickness, total soluble solids, chlorophyll indices (a and b), normalized difference vegetation index (NDVI), fruit temperature, and scald index. It was verified that the protectants significantly reduced both temperature and sunscald damage compared to the control, with the paper treatment providing the greatest protection. The sunscreen treatments also increased total soluble solids and chlorophyll indices in the fruit. It is concluded that agricultural sunscreens are an effective strategy to improve watermelon quality under adverse climatic conditions.

Key words: *Citrullus lanatus*, sun protection, scald, post-harvest quality

RESUMO: O cultivo da melancia é uma importante atividade do agronegócio brasileiro, com crescente relevância em estados emergentes como o Espírito Santo, onde a diversificação agrícola vem aumentando. Na região Noroeste, a alta radiação solar e as condições climáticas adversas representam desafios à qualidade dos frutos, tornando o uso de estratégias de manejo, como os protetores solares, uma possível solução. Este estudo teve como objetivo avaliar o efeito da aplicação de diferentes protetores solares sobre a produtividade e a qualidade pós-colheita da melancia cultivada nessa região. O experimento foi realizado utilizando melancias do tipo Crimson Sweet, em delineamento em blocos casualizados com cinco tratamentos com quatro repetições: T1 – sem proteção; T2 – proteção com papel; T3 – carbonato de cálcio (18,5%) + óxido de zinco (0,5%) + adjuvantes; T4 – 95% de caulim; e T5 – 97% de hidróxido de cálcio com magnésio + 3% de aditivos. Os frutos foram pulverizados semanalmente. As variáveis avaliadas incluíram crescimento, firmeza, espessura da casca, sólidos solúveis totais, índices de clorofila (a e b), NDVI, temperatura dos frutos e índice de escaldadura. Verificou-se que os protetores reduziram significativamente a temperatura em relação à testemunha e os danos por escaldadura, com destaque para a proteção com papel. Os tratamentos também aumentaram os teores de SST e os índices de clorofila no fruto. Conclui-se que os protetores solares são uma estratégia eficaz para melhorar a qualidade da melancia em condições climáticas adversas.

Palavras-chave: *Citrullus lanatus*, proteção solar, escaldadura, qualidade pós-colheita

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INTRODUCTION

Watermelon [*Citrullus lanatus* (Thunb). Matsum. & Nakai] is a vegetable that belongs to the Cucurbitaceae family (Paris, 2015). It was domesticated in the Central African region, where this crop has been cultivated and harvested for more than five millennia (Nascimento et al., 2011). This crop plays a significant role in the socioeconomic aspects of Brazilian agribusiness, contributing to increased economic revenues. This activity generates high employment in the rural sector, boosting regional development (Souza et al., 2024). In 2023, Brazil consolidated its position as one of the world's largest watermelon producers, with national output exceeding 2.3 million tons. In the same year, the state of Espírito Santo significantly increased its contribution, reaching approximately 9.4 thousand tons (IBGE, 2023).

The Northwestern region of Espírito Santo state is characterized by high temperatures and intense solar radiation, with well-defined seasonal patterns. These environmental factors are essential for plant development, but when in excess, they can induce thermal and light stress, particularly in C3 plants such as watermelon (Weng et al., 2022). To mitigate the damage caused by these adverse climatic conditions, it is essential to adopt management strategies that alleviate the effects of extreme heat and direct solar radiation (Walters, 2021). One such strategy is the application of agricultural sunscreens, which have proven effective in reducing leaf temperature, preventing sunburn, and maintaining photosynthetic efficiency in crops sensitive to thermal and oxidative stress (Domingues Neto et al., 2024).

The use of brown paper on watermelons acts as a physical barrier that protects against direct radiation and sunburn, preserving the integrity and coloration of the rind. The brown color of the material is essential because it reduces light transmission, contributing to thermal stability and the maintenance of the fruit's external quality. However, this practice has limitations, including low durability in rain, the risk of moisture accumulation, and changes in the fruit's microclimate (Buthelezi et al., 2021). As an alternative, chemical antitranspirants, such as reflective particle films, have been developed to reduce thermal and water stress, thereby increasing water-use efficiency and crop yield (Ahmed, 2014).

Thermal stress significantly compromises the physiology, morphology, and productive quality of watermelon. Physiologically, it induces stomatal closure, reduces photosynthetic rate, and promotes oxidative damage to cells, as excessive heat destabilizes cellular membranes and proteins, impairing essential metabolic functions (Hasanuzzaman et al., 2013). These alterations are directly reflected in fruit development, where excessive heat can cause surface scalding, deformities, and reduced size. Internal quality is affected by a decrease in total soluble solids (sugars) and pulp firmness, compromising the crop's commercial yield (Glenn, 2016).

Applying particle films based on kaolin and calcium carbonate has been shown to reduce damage from excess solar radiation, lower leaf temperature, and prevent photoinhibition in several crops, including *Vitis* sp. (Dinis et al., 2016a; Conde et al., 2018; Cao et al., 2023), *Solanum lycopersicum* (Silva et al., 2019a), *Mangifera indica* (Hamdy et al., 2022), and *Coffea arabica* (Soela et al., 2023). When fruit surface temperature exceeds air temperature by more than 5 °C, radiative heat load surpasses the fruit's transpirational cooling capacity, and surface temperatures can rise above ~40 °C, causing cellular damage, sunscald, and other heat-related injuries that impair quality and marketability (Müller et al., 2023).

In this context, it was asked if applying agricultural sunscreens to watermelon could mitigate high temperature and incident radiation, thereby reducing surface heating and sunscald and improving fruit quality and commercial performance. Sunscreens of different compositions were evaluated for their effects on yield and quality, under the hypothesis that these protective films would reduce solar and thermal stress and, consequently, promote better physiological status, higher fruit quality, and greater marketable yield compared with unprotected fruits and those covered with traditional paper.

MATERIAL AND METHODS

The experiment was conducted in the Experimental Field Area of the Instituto Federal do Espírito Santo, Itapina Campus, from February to May 2024, in the district of Itapina, in Colatina, Espírito Santo, Brazil. Geographic coordinates are 19° 32" 22' South latitude; 40° 37" 50' West longitude, and altitude of 71 m above sea level. According to the Köppen-Geiger climate classification, the climate is AW (Alvares et al., 2013), characterized by an average annual temperature of 25 °C, a well-defined rainy season from October to January, and an average annual precipitation of 1,029.9 mm (Sales et al., 2018). The soil in the experimental area is classified as a dystrophic Red-Yellow Latosol (Santos et al., 2018), which corresponds to an Oxisol (Soil Survey Staff, 2022).

During the evaluation period, between February 9 and May 11, 2024 (Figure 1), hot and dry weather conditions were predominantly recorded, with maximum temperatures reaching 38.6 °C (on 03/18) and daily averages frequently above 28 °C, especially in March, which stood out as the hottest month of the period. Minimum temperatures ranged between 20.5 and 24.5 °C, with a slight downward trend throughout April. Cucurbits, including watermelon, adapt well to regions with hot and semiarid climates, high luminosity, and temperatures between 18 and 30 °C. Rainfall totaled 180.8 mm, concentrated mainly in February, with the highest volumes recorded on the 22nd (43.2 mm) and 16th (40.6 mm). Most days were dry, marking a transition from the end of the rainy season to the beginning of a drier period, typical of autumn in tropical regions.

In line with this pattern, the vapor pressure deficit (VPD) remained relatively high throughout the experiment, with monthly mean values around 11.9–13.7 hPa and only a slight decrease in April, indicating strong atmospheric evaporative demand and reinforcing the characterization of a hot and dry environment during fruit development.

The experiment was conducted in randomized blocks, with five treatments and four replicates: T1 - without protection, T2 - protected with brown paper, T3 - protected with calcium carbonate compound (18.5%), zinc oxide (0.5%) and adjuvants not described by the manufacturer (300 mL per 20 L), T4 - protected with 95% w/w Kaolin in 5% concentration, T5 - protected with compound of 97% calcium hydroxide and magnesium micro + 3% additives in 5% concentration.

Each experimental unit consisted of 30 plants spaced 3 × 1 m apart. Only the 10 central plants (20 fruits) were evaluated, using 20 border plants to minimize edge effects. To study the effect of applying the different products, the fruits were sprayed weekly using a 20 L manual backpack sprayer with a 40-degree atomized droplet ceramic spray nozzle (MGA-40), according to the dosage and application method determined by the manufacturer, when they reached a weight of three to five kg, totaling five applications.

Before the experiment was installed, soil samples were collected at depths of 0.0-0.20 m and later sent to the Soil Laboratory at the IFES Itapina Campus for chemical characterization, as shown in Table 1. Based on the analysis results, soil correction was performed according to the guidelines established in the manual of liming and fertilization recommendations for the State of Espírito Santo, 5th approximation. (Prezotti et al., 2007).

The soil was prepared by plowing, harrowing, and opening holes 20 days before planting in the mulching system. The watermelon seeds were sown directly into the hole, leaving only one plant per hole. Crimson Sweet watermelon fruits were used: a Manchester hybrid developed by the company Syngenta®, with a round shape, firm texture, intense red color, and crunchy flesh, weighing 11 to 14 kg.

Throughout the watermelon crop cycle, the necessary cultural treatments were carried out to ensure full development, including pruning branches, manual weeding, and phytosanitary control in accordance with the crop's recommendations (EMBRAPA, 2014).

The irrigation system used was a micro-spray drip system, with irrigation water management performed using an irrigometer to maintain soil moisture at 65%. Each planting row was equipped with a 16 mm lateral irrigation line, and at each fixed meter, a micro-spray of 20 L per hour was installed. The Electronic Soil Moisture Meter (HidroFarm) (FALKER, Porto Alegre, Brazil) was used to determine soil moisture using the High Frequency Soil Impedance (HFSI) system.

The temperature, relative humidity, wind, rain, and solar radiation during the crop cycle were recorded by an automatic weather station installed near the experimental area. The temperature of the fruits was measured weekly, one day after the application of the different products, using the portable Digital Infrared Thermometer Mira Laser -50 to 380 °C (Shenzhen Jumaoyuan Science and Technology Co., Ltd., Shenzhen, China), positioned on top of the fruits

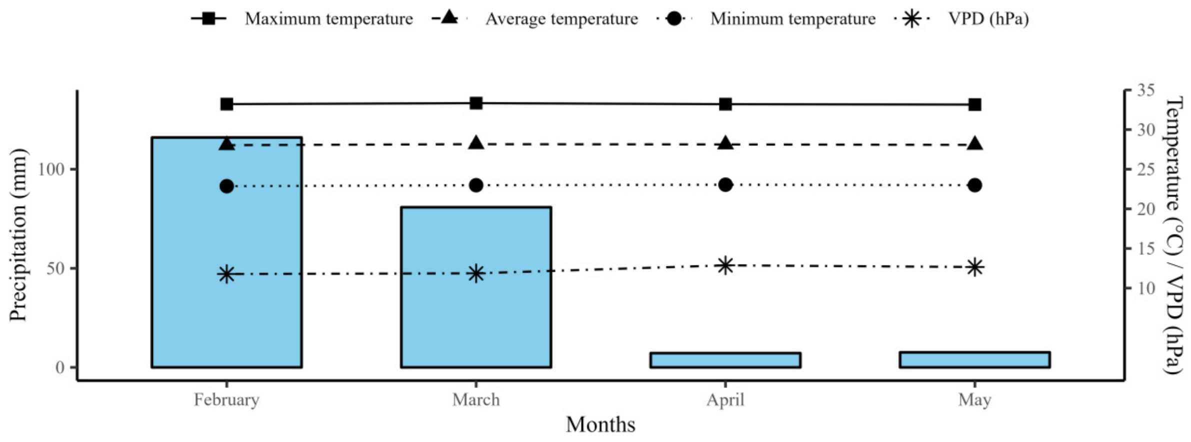


Figure 1. Values of minimum, mean, and maximum monthly air temperature, monthly precipitation, and vapor pressure deficit during the experimental period

Table 1. Chemical attributes of the soil of the experimental area

ph	M.O	P	Na^+	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^++Al^{3+}	SB	T	t	m	V
H_2O	g kg^{-1}	--- mg dm^{-3} ---			---- cmolc dm^{-3} ----			------- $cmol_c$ dm^{-3} -------				--- % ---	
6.4	0.9	87	0.39	3.07	4.2	1.1	0.0	1.6	5.6	7.2	5.6	0.0	77.9

M.O - Organic matter; P - Phosphorus; Na^+ - Sodium; K^+ - Potassium; Ca^{2+} - Calcium; Mg^{2+} - Magnesium; Al^{3+} - Aluminum; SB - Sum of Bases; T - Cation exchange capacity; t - Effective cation exchange capacity; m - Aluminum saturation; V - Base saturation. Extractors: pH in H_2O; P, K^+, and Na+ in Mehlich 1; Ca2+, Mg2+, and Al^{3+} in 1N KCl, H^++Al^{3+} in Calcium Acetate at pH 7.00, O.M. in Na Dichromate with sunscreens on clear and cloudless days. The fruits were harvested at horticultural maturity, when the spot that remained in contact with the soil changed from white to pale yellow. The tendrils closest to the fruit turned brown and dried out (Rushing et al., 1999) approximately 65 to 90 days after sowing.

After harvesting, the sunburn index (scald) was evaluated on the sun-exposed upper part of the fruits using the scale shown in Figure 2 as a reference, which comprises five scald levels.: (0) no, (1) mild, (2) moderate, (3) severe, and (4) very severe scald. The fruit weight (FW) in kg, longitudinal (DL) and transversal (DT) diameters of normal fruits in cm, longitudinal (LC) and transversal (TC) circumference in cm, peel thickness (PT) in mm, total soluble solids content (TSS, °Brix) using a portable digital refractometer (ATAGO CO LTD, Tokyo, Japan), fruit firmness (FF) (kg cm^{-2}) using a portable digital fruit penetrometer, were determined. For the chlorophyll a and b variables, the ClorofiLOG equipment, model CFL 1030 (FALKER, Porto Alegre, Brazil), was used at the median between the lightest and darkest veins of the fruit.

Reflectance spectroscopy in the visible-to-near-infrared (VNIR) range (380-2500 nm) is a fast, nondestructive, and widely used technique for evaluating the optical properties of plant surfaces, especially fruits. It is effective in determining physical, physiological, and quality attributes during ripening (Wang et al., 2015). In this study, the GreenSeeker portable analyzer (N-tech Industries, Gujarat, India) was used to measure the Normalized Difference Vegetation Index (NDVI), with measurements taken on the upper central part of the watermelon fruits. The sensor was modified with a 50 cm-diameter black viewing cone to isolate the reflectance of individual fruit.

Physiological variables, such as anthocyanins and flavonoids, were measured using a Multiplex fluorometer (Force-A, Orsay, France) equipped with multiple light excitation sources (ultraviolet, blue, green, and red). Measurements were made on the outside (peel) and inside (pulp) of the fruit, with the equipment positioned at approximately 45 degrees, pointing from top to bottom. The data were adjusted and parameterized according to the manufacturer's instructions before analysis.

The collected data were subjected to analysis of variance at $p \leq 0.05$, and the means were compared using the Tukey test at $p \leq 0.05$. Pearson's correlation analysis was performed, and the t-test was used to verify the significance of the correlation. Statistical analyses were performed using the open-source software R (R Core Team, 2025).

Results and Discussion

Table 2 shows that fruit weight did not differ significantly. The results indicate that the fruits exhibited satisfactory growth across all treatments, falling within the classification proposed by Magalhães & Souza (2020), which categorizes watermelons based on weight as large (over 12 kg), medium (between 10 and 12 kg), and small (between 7 and 10 kg). These results are consistent with those of Tegen et al. (2021), who highlighted the influence of fruit size on the quality of Crimson Sweet watermelons, noting that higher-quality fruits were observed in the medium-to-large size categories.

Regarding fruit firmness, there was no significant difference between treatments, indicating a similar ability to resist mechanical damage during transportation, which may contribute to a potential extension of the post-harvest shelf life. Contrary results were reported by Zheng et al. (2023), who found a significant difference in CaO particle concentrations between pumpkin and sweet potato plants. Calcium plays a crucial role in maintaining the structure and mechanical strength of cell walls. It facilitates the accumulation of Ca^{2} cations, which interact with pectin polymers, especially in the middle lamella, thereby increasing cell wall strength (Voxeur, 2016) and preserving fruit firmness (Chen et al., 2024).

The treatments did not influence peel thickness (Table 2). According to Wan Azman et al. (2024), this variable plays a crucial role in fruit resistance, especially in bulk production systems, where the peel must be sufficiently thick to withstand fruit handling.

All treatments with sunscreens (T2, T3, T4, and T5) increased SST, with increases ranging from 10.90 °Brix for paper to 11.47 °Brix for kaolin. Reduced fruit temperature decreased respiratory losses of sugars, while maintaining phloem assimilate import increased TSS (Table 2). The significant difference in total soluble solids content indicates that the sunscreens applied to the watermelon fruits yielded sweeter fruit, improving their quality. Such an increase can be

Source: Own work (2024)

Figure 2. Scald scale on watermelon fruits. Scald levels were evaluated based on the intensity of lesions on the fruit, ranging from no scald (0) to very severe scald (4)

Table 2. Values of fruit weight (FW), fruit firmness (FF), peel thickness (PT), and total soluble solids (TSS) under application of different sunscreens

Treatments	FW (kg)	FF (N)	PT (cm)	TSS (°Brix)
T1	9.13 a (±0.43)	103.88 a (±32.96)	10.27 a (±1.31)	8.57 b (±0.67)
T2	10.92 a (±1.07)	122.05 a (±30.10)	11.41 a (±2.30)	10.90 a (±0.92)
T3	10.53 a (±1.11)	125.58 a (±35.60)	11.95 a (±1.64)	11.07 a (±0.67)
T4	11.11 a (±2.49)	129.32 a (±26.07)	11.55 a (±2.42)	11.47 a (±1.55)
T5	9.08 a (±0.45)	112.01 a (±26.77)	10.44 a (±0.47)	11.02 a (±0.76)
CV (%)	13.57	26.67	17.22	9.71

Treatment: T1 - No protection; T2 - Paper; T3 - Composed of calcium carbonate (18.5%), zinc oxide (0.5%), and adjuvants not described by the manufacturer; T4 - 95% w/w Kaolin; T5 - Composed of 97% Calcium and magnesium hydroxide micro + 3% additives CV - Coefficient of variation. ns: not significant at $p \leq 0.05$ by F-test. Means followed by different letters in the columns are significantly different among treatments by the Tukey test ($p \leq 0.05$). Values are expressed as mean ± standard deviation (n =20)

explained by the reduced direct exposure to solar radiation, which helped preserve fruit integrity and enhanced sugar accumulation, as observed by Hamdy et al. (2022) in mango (*Mangifera indica* L.) plants. However, Song et al. (2012) observed no effect of kaolin particle film application on total soluble solids content in studies with grapevines.

Under severe stress, the plant has difficulty transporting water and nutrients to the fruit, which may impair sugar synthesis and accumulation (Hou et al., 2020). This process directly affects the final fruit quality, as the total soluble solids content is closely related to flavor and is considered a key parameter for watermelon quality, as highlighted by Silva et al. (2024). It was observed that the TSS values in this study were satisfactory, as they exceeded the market requirement average of 9% (Rodrigues et al., 2016), except for the untreated control, which fell below this threshold.

The low soluble solids content in the control is due to a warmer microclimate around the fruit, which limits sugar accumulation in cucurbits; fruit-level thermal manipulations show that higher temperatures reduce sweetness, whereas controlled adjustments can increase it (Aydogan, 2024). In parallel, there is stomatal closure under water/heat stress and a decline in CO_2 assimilation, reducing the supply of photoassimilates to reproductive sinks (Zandalinas et al., 2018). Water and solute transport to the fruit is also compromised: water restriction first reduces xylem flow and then phloem flow, thereby affecting growth and solute concentration, altering the balance between water accumulation and solute metabolism, and directly impacting quality variables (Hou et al., 2020). Treatments with sunscreens showed significantly higher chlorophyll a values than those without protection, ranging from 53.62 to 55.77 ICF (Figure 3A). The treatment without protection showed the lowest Chla value (22.00 ICF), indicating lower photosynthetic capacity.

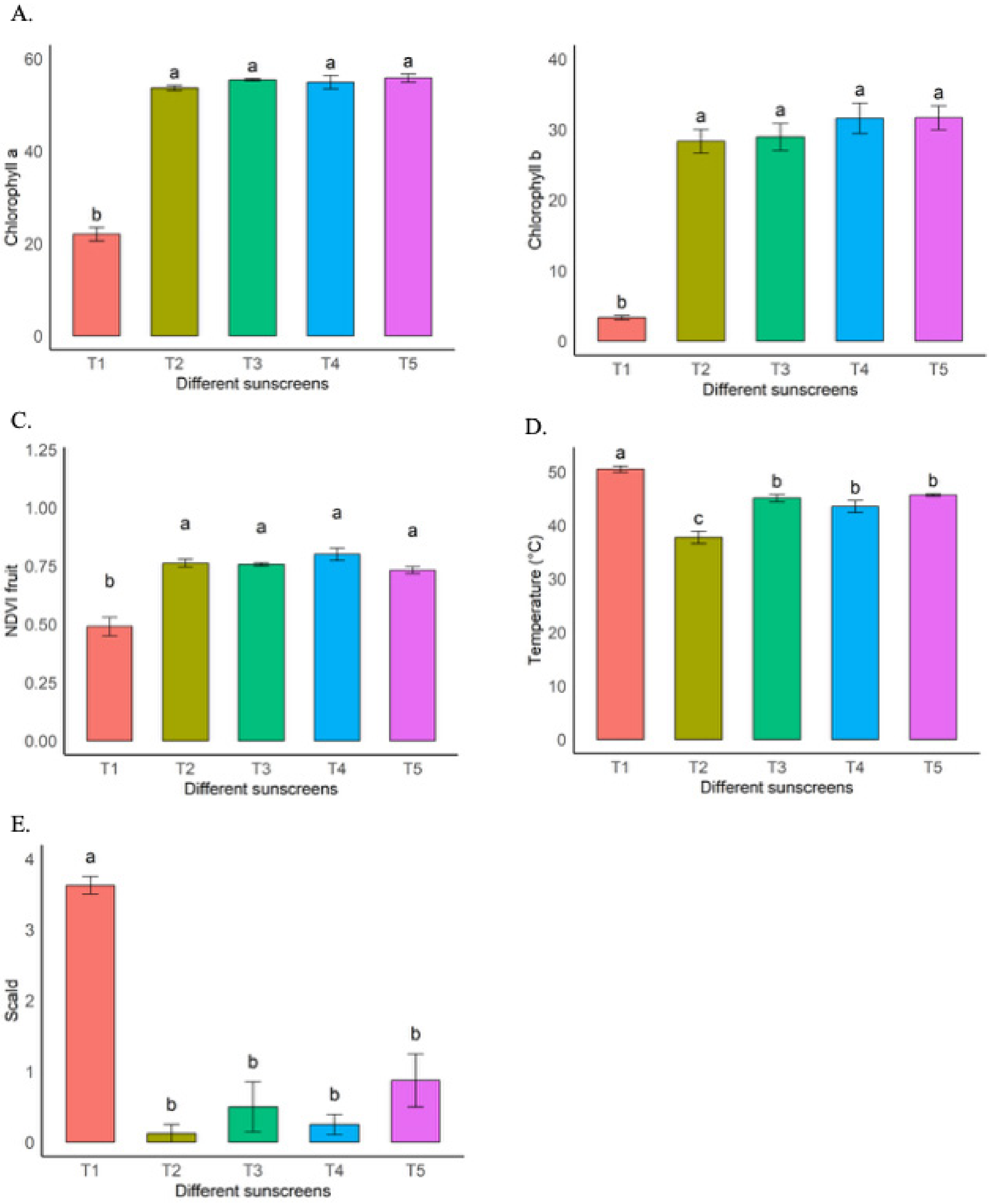
The higher chlorophyll a concentration in fruits treated with sunscreens indicates preservation of the photosynthetic apparatus, which can be attributed to protection against intense solar radiation and a reduction in oxidative stress caused by excess light (Teixeira et al., 2022). The application of certain chemical compounds, as well as the use of paper, can protect the photosynthetic system of plants against damage caused by thermal and light stresses, improving plant performance in the field (Soela et al., 2023).

Calcium carbonate compounds have been used as an effective technology to improve plant adaptation to adverse climatic conditions, thereby controlling photooxidative stress (Silva et al., 2019b). These compounds help minimize damage caused by excessive exposure to light and heat, promoting plant resistance to these unfavorable environmental factors and protecting the photosynthetic apparatus (Soela et al., 2023). Furthermore, calcium compounds provide mechanical support to plants by maintaining cell wall rigidity and strengthening their structure and resistance (Hawkesford et al., 2012; Li et al., 2012).

The application of calcium carbonate compounds has demonstrated photoprotective effects in grapevines (*Vitis vinifera* L.) (Bernardo et al., 2017) and contributed to the reduction of leaf temperature in apple (*Malus domestica*) (Glenn, 2016). In addition, the photoprotection provided by these compounds significantly increases the net rate of photosynthesis in coffee plants (Silva et al., 2019c). These benefits suggest that calcium carbonate can improve plant adaptation to adverse climatic conditions, promoting increased photosynthetic efficiency and protection against stress caused by intense light and heat, as shown in Figure 1.

Chlorophyll b followed a similar pattern to chlorophyll a, with greater increases in sunscreen treatments, with values ranging from 28.30 to 31.65 ICF. Chlorophyll b is essential for capturing light at wavelengths complementary to chlorophyll a. These results indicate that the use of sunscreens helps maintain photosynthetic efficiency in fruits (Abreu et al., 2023). The presence of chlorophylls in the early and green stages of fruits is crucial, as they play a vital role in absorbing sunlight and transferring energy for photosynthesis, the process by which plants convert light into chemical energy to produce nutrients, such as sugars and starches (Taiz et al., 2017).

The highest Normalized Difference Vegetation Index values in the fruits were observed in the treatments with sunscreens (Figure 3C). The treatments with sunscreens showed fruit NDVI values ranging from 0.73 to 0.79, while the unprotected treatment showed a value of 0.49. This indicates good physiological condition and high pigmentation in the fruits protected by sunscreens. Martins et al. (2021) evaluated NDVI for monitoring coffee ripening using aerial images and also found a significant difference.



Mean ± standard error of the mean for the different treatments. T1 - Treatment without protection; T2 - Paper; T3: Composed of calcium carbonate (18.5%), zinc oxide (0.5%) and adjuvants not described by the manufacturer, T4 - 95% w/w kaolin, T5 - Composed of 97% calcium and magnesium hydroxide micro + 3% additives Different letters (a-b) between bars indicate statistical differences between the groups by Tukey test ($p \leq 0.05$)

Figure 3. Values of chlorophyll a index – (A), chlorophyll b index – (B), NDVI of fruits (C), temperature of fruits (D), and scald of watermelon fruits (E) under application of different sunscreens

The treatment without a protector showed lower NDVI values, the fruit heated up more, and suffered photooxidative stress, thereby accelerating chlorophyll degradation (Dinis et al., 2016b). NDVI is a useful tool for detecting and monitoring the impact of extreme heat on fruit physiological quality (Soto et al., 2024). Fruits with consistently low NDVI values reflect chlorophyll degradation and reduced metabolic health, indicating the need for management strategies to minimize the effects of heat stress. According to Tsoulias et al. (2023), chlorophyll content in fruits is crucial to assess crop maturation, quality, and overall health. NDVI values can serve as an accurate indicator of this degradation, enabling timely corrective actions to improve the quality of agricultural production (Furuya et al., 2024).

Fruit temperature varied significantly between treatments. Unprotected watermelon fruits (T1) had a higher temperature of 50.49 °C, indicating greater exposure to direct solar radiation and heat stress, resulting in greater fruit heating (Figure 3D). Treatments with sunscreens significantly reduced fruit temperature, with the most significant reduction in T2, which had the lowest temperature of 37.70 °C, followed by T3, T4, and T5.

This reduction in temperature with the use of sunscreens is a crucial factor, as excessive temperatures can cause thermal damage to the fruits, such as dehydration and loss of firmness. The reduction in temperature in watermelon fruits treated with sunscreens helps maintain their physical and physiological quality and avoid thermal stress (Brito et al., 2019).

Similar thermal effects were observed in plants treated with kaolin particle films, such as grapevines (*Vitis vinifera* L.), tomatoes (*Solanum lycopersicon*), and Persian walnuts (*Cucumis sativus*) (Boari et al., 2014; Dinis et al., 2016b; Silva et al., 2019c). The decrease in leaf temperature is associated with the protective layer formed by the film and the reflective and photoprotective mechanisms, which increase the amount of reflected solar radiation (Boari et al., 2014; Silva et al., 2019a; Silva et al., 2019b; Soela et al., 2023). Plants and fruits that receive shade or are subjected to the application of products similar to sunscreens have shown a reduction in the temperature of leaves and fruits, which allows for greater stomatal opening and, consequently, an improvement in the assimilation of CO_2 (Abreu et al., 2023).

Cobra et al. (2020) observed significant differences between treatments with and without calcium carbonate when evaluating the application of calcium to Arabica coffee seedlings. The authors obtained consistent results regarding scalding, demonstrating the effectiveness of calcium carbonate application compared to treatment without protection. Karaat & Denizhan (2022) compared the effects of different applications of particle films on almond (*Prunus dulcis*) and observed that the highest leaf temperature (37.4 °C) was recorded in the treatment without protection, compared with the treatments with protection.

The scald results indicated that the absence of sun protection caused severe fruit damage, with the unprotected treatment (T1) exhibiting the highest scald index (3.62). In contrast, the use of sunscreens significantly reduced this damage, as shown in Figure 3. The high variability in the results, as indicated by a coefficient of variation of 49.33%, suggests that the effectiveness of sunscreens may depend on factors such as uniformity and application conditions, highlighting the importance of adjusting management practices to ensure more uniform protection of the fruits.

Photo-oxidative stress and an increase in reactive oxygen species (ROS) production occur in situations of environmental stress due to high irradiance and temperature, causing damage to DNA, proteins, and membranes (Devireddy et al., 2021). Protection against oxidative stress may occur through increased dissipation of energy excitation via carotenoids or by metabolism of reactive oxygen species, as well as greater antioxidant system activity (Palma et al., 2023). The use of sunscreens on plants reflects solar radiation, reduces heat accumulation and oxidative stress, reduces water loss through transpiration, and alleviates abiotic stress, thereby improving the plant's physiological, morphological, and biochemical mechanisms (Abreu et al., 2023).

Table 3 shows the means of the chlorophyll, flavonoid, anthocyanin, and nitrogen balance in the watermelon rind determined using the Multiplex® device.

The values of absorbed chlorophyll in green light and absorbed chlorophyll in red light indicate that more chlorophyll was absorbed in the rinds of watermelons treated with different sunscreens on the peel of watermelon fruits, according to Table 3. The treatments with sunscreens (T2, T3, and T4) presented the highest values for SFR_G, and T2 and T4 for SFR_R, respectively, which indicates greater green intensity compared to the witness, indicating greater photosynthetic efficiency. These results demonstrate that sunscreens in general increased the intensity of green, which is correlated with an increase in chlorophyll in the rinds, suggesting that they may protect against excessive solar radiation, thereby preserving the plant's photosynthetic capacity (Teixeira et al., 2022).

Regarding flavonoids, which are essential antioxidant compounds, treatment T1 (fruits without sunscreen) had the highest FLAV value (1.19), indicating a higher concentration of flavonoids in the watermelon rind without sunscreen application, according to Table 3. Treatments with sunscreens, on the other hand, showed lower FLAV values, with emphasis on T2 (paper) 0.50, the lowest flavonoid index, followed by T3 (0.62) and T4 (0.56). This result suggests that the protective films reduced oxidative stress in plants by attenuating the direct incidence of solar radiation. Lower light exposure, particularly to UV wavelengths, reduces the need for flavonoid synthesis, since these secondary metabolites serve as important antioxidant and photoprotective components that mitigate radiation-induced cellular damage (Shomali et al., 2022).

Plants counter excess solar radiation via integrated defense/adaptation pathways: avoidance (leaf-angle adjustment, epicuticular waxes/trichomes, UV-screening flavonoids), dissipation/ROS control (xanthophyll-cycle–mediated NPQ, antioxidant enzymes), and repair/

Table 3. Chlorophyll absorbed in green light (SFR_G), chlorophyll absorbed in red light (SFR_R), flavonoids (FLAV), anthocyanin in the red-green wavelength (ANTH_RG), anthocyanin in the red-blue wavelength (ANTH_RB), nitrogen balance in green light (NBI_G), and nitrogen balance in red light (NBI_R) as a function of different sunscreens on the peel of watermelon fruits

Treatments	SFR_G	SFR_R	FLAV	ANTH_RG	ANTH_RB	NBI_G	NBI_R
T1	1.70 c (±0.47)	1.60 c (±0.14)	1.19 a (±0.13)	0.193 a (±0.06)	-0.14 a (±0.06)	0.21 c (±0.63)	0.11 d (±0.63)
T2	3.48 a (±0.17)	3.11 a (±0.09)	0.50 c (±0.05)	0.022 b (±0.04)	-0.42 b (±0.03)	1.13 a (±0.30)	0.94 a (±0.34)
T3	3.10 a (±0.36)	2.80 b (±0.18)	0.62 c (±0.04)	0.029 b (±0.08)	-0.43 b (±0.05)	0.77 b (±1.00)	0.67 b (±0.57)
T4	3.27 a (±0.45)	2.97 a (±0.09)	0.56 c (±0.04)	0.028 b (±0.02)	-0.44 b (±0.02)	1.26 a (±0.81)	0.90 a (±0.29)
T5	2.64 b (±0.84)	2.59 b (±0.10)	0.81 b (±0.01)	0.043 b (±0.05)	-0.40 b (±1.50)	0.57 b (±1.21)	0.49 c (±0.23)
CV (%)	7.62	8.27	13.37	37.02	12.4	17.5	15.29

Treatment -T1: No protection; T2 - Paper; T3 - Composed of calcium carbonate (18.5%), zinc oxide (0.5%), and adjuvants not described by the manufacturer; T4 - 95% w/w kaolin, T5 - Composed of 97% calcium and magnesium hydroxide micro + 3% additives CV - Coefficient of variation. ns: not significant at $p \leq 0.05$ by F-test. Means followed by different letters in the columns are significantly different among treatments by the Tukey test ($p \leq 0.05$). Values are expressed as mean ± standard deviation (n = 20)

acclimation (PSII D1 turnover, heat-shock proteins, photolyases), maintaining photosynthetic function under high light. These adaptive mechanisms include an increase in flavonoid concentration (which absorbs UV-B) and the formation of an enzymatic antioxidant system composed of catalase, superoxide dismutase, glutathione reductase, and ascorbate peroxidase, which eliminates reactive oxygen species (Khan et al., 2025).

The anthocyanin indices at the red-green and red-blue wavelengths reveal that T1 (without sunscreen) obtained the highest value of ANTH_RG (0.193) and the best performance in ANTH_RB (-0.14), which indicates a greater presence of anthocyanins, according to Table 3. The treatments with sunscreens showed significantly lower values for ANTH_RG and ANTH_RB, with emphasis on T2, T3, and T4, whose values were similar.

Anthocyanins are pigments that vary in color from red, purple, and blue and act to protect the photosynthetic system of plants by intercepting solar radiation and preventing excessive light exposure (Zhu et al., 2016). As a result of this protection, the concentration of these compounds can be significantly altered during sunburn. This reduction in anthocyanin production in plants treated with sunscreens is also related to reduced solar stress, since the synthesis of these pigments is often induced by high light and UV radiation.

Nitrogen balance reflects the relationship between the amount of chlorophyll and the amount of nitrogen-rich compounds in the plant. The treatments with sunscreens, T2 and T4, presented the highest values of NBI_G (1.13 and 1.26) and NBI_R (0.94 and 0.90), indicating a good balance between the amount of nitrogen and chlorophyll production, suggesting more vigorous plants with good nutritional development. In contrast, treatment T5 had the lowest NBI values among the sunscreen treatments.

In general, the results indicate that the use of sunscreens at the doses recommended by the manufacturers and the use of paper provide a higher chlorophyll index, better nitrogen balance, and lower production of flavonoids and anthocyanins. T2 presented the best overall results, proving to be an effective strategy for protecting plants from intense solar radiation, thereby preserving photosynthetic and nutritional performance. Treatment T1 (without sunscreen application) showed greater synthesis of antioxidant compounds, such as flavonoids and anthocyanins, suggesting greater oxidative stress.

Table 4 presents the results of physiological variables measured in watermelon pulp using the Multiplex® device, which evaluated the efficacy of different sunscreens applied to the fruit surface. The variable includes the absorbed chlorophyll index in the green and red light bands, the flavonoid index, anthocyanins measured at different wavelengths, and the nitrogen balance measured in the green and red light bands.

There were significant differences among treatments in the chlorophyll index absorbed in red light, with T3 showing the highest value (0.95), followed by T4 (0.78) and T2 (0.68), while T1 had the lowest value (0.60). These results indicate that the use of sunscreens, especially T3, increased chlorophyll retention in the red range, which may be related to reduced pigment degradation in the pulp due to protection against solar radiation (Dinis et al., 2016a).

Treatment T2 showed the highest flavonoid value (-0.27), while treatments T3, T4, and T5 showed lower values, similar to those without protection (Table 4). Flavonoids are antioxidant compounds that protect plants against environmental stress (Singh et al., 2013). The results indicate that treatment with paper resulted in less degradation of flavonoids in the pulp, suggesting that this sunscreen offered greater antioxidant protection.

T3 and T4 (with sunscreen) showed significantly lower values than the unprotected treatment, indicating a lower anthocyanin concentration. Anthocyanin is produced in response to stresses, such as intense radiation, suggesting that sunscreens reduce the need for its production (Martínez-Lüscher et al., 2019). There was no significant difference between treatments, suggesting that anthocyanin production in the pulp, measured in this light range, was not significantly affected by the different sunscreens.

Table 4. The variables evaluated in watermelon pulp in the Multiplex® relating to chlorophyll index absorbed in green light (SFR_G), chlorophyll index absorbed in red light (SFR_R), flavonoids (FLAV), anthocyanin in the red-green wavelength (ANTH_RG), anthocyanin in the red-blue wavelength (ANTH_RB), nitrogen balance in green light (NBI_G), and nitrogen balance in red light (NBI_R) in watermelon pulp as a function of different sunscreens

Treatments	SFR_G	SFR_R	FLAV	ANTH_RG	ANTH_RB	NBI_G	NBI_R
T1	3.28 a (±0.43)	0.60 c (±0.39)	-0.34 b (±0.27)	-0.12 a (±0.03)	-0.65 a (±0.09)	4.91 a (±0.25)	1.24 d (±0.17)
T2	4.27 a (±0.32)	0.68 b (±0.21)	-0.27 a (±0.06)	-0.17 a (±0.01)	-0.67 a (±0.08)	5.41 a (±0.18)	1.52 c (±0.16)
T3	4.04 a (±0.09)	0.95 a (±0.06)	-0.32 b (±0.21)	-0.25 b (±0.09)	-0.71 a (±0.04)	5.50 a (±0.54)	2.01 a (±0.49)
T4	4.11 a (±0.20)	0.78 b (±0.12)	-0.36 b (±0.23)	-0.23 b (±0.06)	-0.73 a (±0.04)	5.81 a (±0.37)	1.82 ab (±0.31)
T5	3.46 a (±0.42)	0.71 b (±0.37)	-0.35 b (±0.28)	-0.16 a (±0.02)	-0.68 a (±0.05)	5.89 a (±0.55)	1.71 bc (±0.49)
CV (%)	14.37	7.96	9.66	15.28	6.86	7.78	5.48

Treatment: T1 - No protection, T2 - Paper; T3 - Composed of calcium carbonate (18.5%), zinc oxide (0.5%), and adjuvants not described by the manufacturer, T4 - 95% w/w Kaolin, T5 - Composed of 97% Calcium and magnesium hydroxide micro + 3% additives CV - Coefficient of variation. ns: not significant at $p \leq 0.05$ by F-test. Means followed by different letters in the columns are significantly different among treatments by the Tukey test ($p \leq 0.05$). Values are expressed as mean ± standard deviation (n =20)

In the nitrogen balance in green light, all treatments showed high and similar values of NBI_G, indicating that the nitrogen balance in green light was not significantly affected by sunscreens. The nutritional balance in the pulp tissue was preserved regardless of the treatment applied. On the other hand, the nitrogen balance in red light showed significant differences, with the T3 treatment presenting the highest value (2.01), followed by T4 (1.82) and T5 (1.71). In contrast, the unprotected treatment had the lowest value (1.24). This increase in NBI_R with the application of sunscreens indicates a better retention of nitrogen compounds, which may be associated with a lower degradation of chlorophyll and a more efficient metabolism in the pulp of the protected fruits (Teixeira et al., 2022).

The results demonstrate that the application of sunscreens significantly affected some physiological variables of watermelon pulp, particularly chlorophyll retention in the red-light range and nitrogen balance (Table 4). Treatment T3 was the most effective at increasing these values, suggesting that the sunscreen's protection against solar radiation reduced chlorophyll degradation and improved nitrogen balance in the pulp. T2 also stood out in its protection against flavonoids, possibly due to its role as an effective physical barrier against radiation. In contrast, anthocyanin values decreased with the use of sunscreens, indicating a reduction in the response to solar stress (Blancquaert et al., 2019). These results suggest that sunscreens can help preserve the physiological quality of watermelon, protecting it against environmental stress and improving the nutritional content of the pulp.

The correlation matrices show statistically significant relationships between the variables analyzed, particularly between scalding (ESCALD), temperature (TEMPE), anthocyanins (ANTH_RG and ANTH_RB), and the physiological indices of chlorophyll fluorescence (SFR_G and SFR_R) and nitrogen balance (NBI_G and NBI_R).

Figure 4 shows a strong negative correlation between ESCALD and the SFR_G (-0.91, $p < 0.001$) and SFR_R (-0.92, $p \leq 0.001$) indices, suggesting that fruits more affected by scalding have lower photosynthetic efficiency (Allakhverdiev et al., 2008). This effect may be related to the degradation of photosynthetic pigments and the impairment of the structural shell cell (Silva et al., 2019a). Thus, this effect may directly compromise fruit quality, affecting characteristics such as firmness and soluble solids content, which are essential for commercialization and market acceptance (Schrader, 2009).

A more significant impact on spectral indices was observed in the present study, suggesting that scald severity may be associated with additional factors, such as accumulated radiation and epidermal tissue composition (Kim et al., 2022). This finding reinforces the need for continuous monitoring of spectral variables to predict potential impacts on postharvest yield and quality. Additionally, significant negative correlations were observed between NBI_G/NBI_R and FLAV (-0.95 and -0.94, respectively; $p \leq 0.001$), indicating that flavonoid biosynthesis may be activated in response to scald-induced oxidative stress.

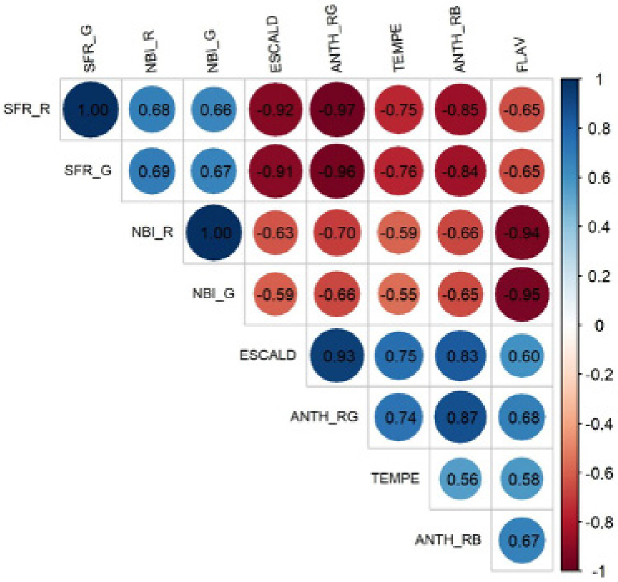


Figure 4. Pearson correlation between scald severity and chlorophyll fluorescence spectral indices

Flavonoids play an essential role in mitigating oxidative damage induced by UV radiation and high temperatures, functioning as metabolic defense compounds (Agati et al., 2021); they can limit photosynthesis and reduce productivity (Dinis et al., 2017; Celovane et al., 2018). This indicates that radiation can have positive or negative effects, depending on the intensity and time of exposure (Yadav et al., 2020).

A strong association was observed between scald severity and several physical, chemical, and physiological traits of watermelon fruits (Figure 5). Scald showed a positive correlation with fruit surface temperature (Temp) ($r = 0.75$, $p \leq 0.05$), indicating that higher temperatures on the fruit surface are closely linked to the development of scald. In contrast, scald was strongly and negatively correlated with Chl_a ($r = -0.92$), NDVI ($r = -0.91$), Chl_b ($r = -0.87$), and TSS ($r = -0.77$) ($p \leq 0.05$), suggesting that fruits with higher chlorophyll content, better spectral vegetation status and greater accumulation of soluble solids tend to be less affected by scald, probably due to a more active photosynthetic and metabolic apparatus, which is commonly associated with enhanced flavonoid biosynthesis and antioxidant protection.

Physical, chemical, and physiological variables were evaluated in watermelon fruits (Figure 5): fruit weight (FW), longitudinal circumference (LC), cross-sectional circumference (CC), longitudinal diameter (LD), cross-sectional diameter (CD), fruit firmness (FF), peel thickness (PT), total soluble solids (TSS), fruit NDVI (NDVI), chlorophyll a (Chl_a), chlorophyll b(Chl_b), temperature (Temp), and scald (Scald).

Similar patterns linking pigment status and stress tolerance were reported by Coşkun (2025), who found that drought-tolerant watermelon genotypes maintained higher chlorophyll a and SPAD values and showed smaller reductions in fresh and dry biomass under stress, while susceptible genotypes exhibited marked declines in chlorophyll and growth.

In the same study, relative water content showed a positive correlation with chlorophyll a. In contrast, oxidative stress was negatively correlated with root length, plant height, and leaf number, reinforcing the idea that preservation of the photosynthetic apparatus and water status is a key component of resilience in watermelon.

Negative correlations were also found between scald and the main size and yield attributes (LD, CC, CD, FW, LC, and PT; ranging from −0.38 to −0.64), indicating that fruits with more severe scald tend to be smaller, lighter, and with thinner peel. Taken together with the results of Coşkun (2025), who showed that genotypes with greater biomass and structural development under drought stress also presented higher chlorophyll content and better physiological performance, these patterns support the idea that warmer fruits with reduced pigment content and lower metabolic activity are more susceptible to scald. In contrast, fruits with better physiological status and structural development are less prone to this disorder.

A positive correlation was observed between ESCALD and ANTH_RG ($r = 0.74$, $p \leq 0.05$) and ANTH_RB ($r = 0.67$, $p \leq 0.05$), suggesting that anthocyanin synthesis in fruit peel may be directly related to scald severity (Figure 6). This phenomenon can be explained by the protective function of anthocyanins, which act to absorb UV radiation and attenuate the effects of thermal stress (Almeida et al., 2020). Figure 6 reinforces this relationship by showing an increase in anthocyanin levels in the fruits most affected by scald, which directly affects peel color and the commercial attractiveness of the fruits.

Therefore, it is essential to highlight the importance of monitoring spectral and biochemical variables as tools to assess fruit quality and the impact of heat stress. Furthermore, they show that choosing appropriate sunscreens can significantly help preserve the commercial quality of fruits, possibly reducing post-harvest losses. As the temperatures rise due to climate change (IPCC, 2023), strategies to mitigate heat stress, such as the use of sunscreens, become essential to preserve fruit yield and quality. Future studies should expand this approach to improve sustainable agricultural management. They will need to consider varieties and environments.

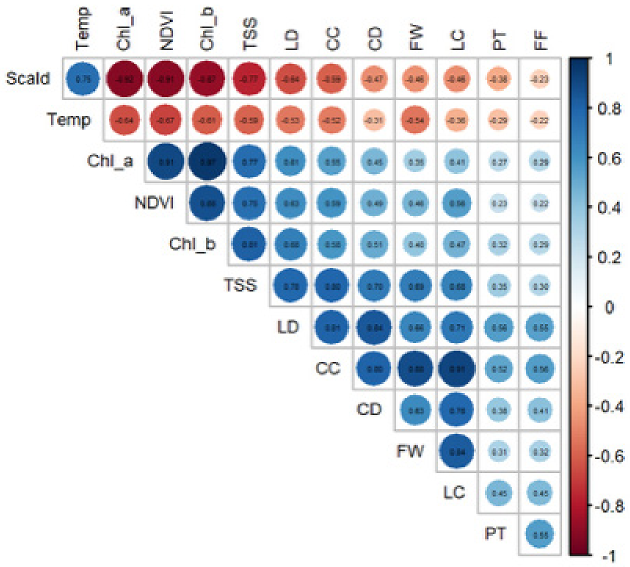


Figure 5. Pearson correlation between scald severity and flavonoid biosynthesis

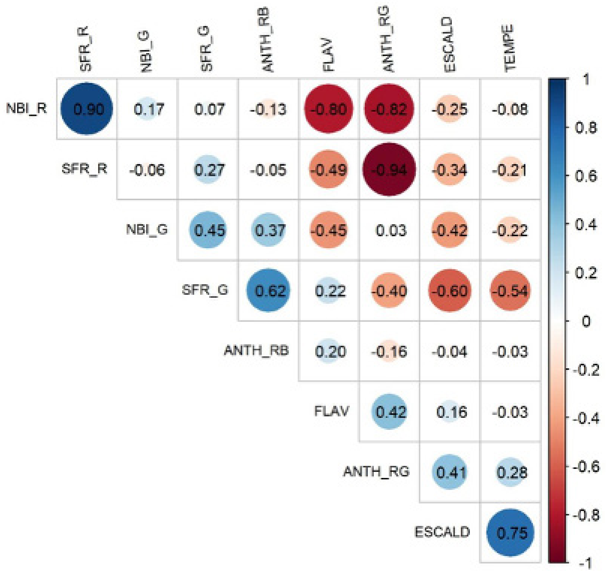


Figure 6. Pearson correlation between scald severity and anthocyanin indices

CONCLUSIONS

1. Sunscreens improved 'Crimson Sweet' watermelon fruit quality under heat stress by reducing fruit temperature and sunscald, especially with the paper-based treatment.
2. Sunscreens increased the total soluble solids of the fruits and maintained high values of chlorophyll and vegetation index.
3. The use of sunscreens is an effective strategy for cultivation under high solar radiation conditions, reducing overheating and the incidence of fruit sunburn.

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