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Article

Production and Harvest Quality of Tomato Fruit Cultivated Under Different Water Replacement Levels and Photoprotector Strategies

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Abstract: The tomato (*Solanum lycopersicum*) is the second most produced vegetable globally, playing a significant role in national and international economies. This crop is highly sensitive to water deficit and thermal stress, which directly affect yield and fruit quality. Foliar application of calcium carbonate ($CaCO_3$) may be a possible strategy to minimize the effects of these abiotic stresses. This research aimed to determine: (a) the effects of different water replacement levels (WRLs) and photoprotector strategies (Ps) applied to the canopy on production and harvest quality of tomato fruit, (b) thermal responses—Crop Water Stress Index (CWSI) and soil temperature and (c) crop water productivity (WP_c). The research was conducted at the University of São Paulo (USP/ESALQ), Piracicaba, State of São Paulo, Brazil. The experimental design adopted was randomized blocks, with four blocks and nine treatments, totaling 36 plots. The treatments were arranged in a 3 × 3 factorial scheme, with three WRLs (70, 100 and 130% of the required irrigation depth) and three photoprotector strategies (without photoprotector, with photoprotector and with photoprotector + adjuvant). Biometric and thermal responses, productivity, harvest quality and WP_c were determined. The highest plant height and stalk diameter values were found in the treatment with photoprotector and adjuvant, with an average of 0.98 m and 0.0130 m, respectively. For the variables soil temperature, CWSI and tomato productivity, no significant differences were observed. The general average productivity obtained was 77.9 Mg ha^{-1}. The highest WP_c values were found in the WRL 70 treatments, with an average of 23.6 kg m^{-3}. No significant differences were observed for pulp firmness. The highest average value of soluble solids was observed in the treatments with photoprotector (4.8 °Brix) and the highest average value of titratable acidity was observed in the WRL 130 treatments (0.36%). Therefore, deficit irrigation resulted in water savings without compromising tomato productivity and the application of photoprotector and adjuvant increased tomato quality.

Keywords: agricultural sunscreen; crop water productivity; deficit irrigation; *Solanum lycopersicum*

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1. Introduction

Tomatoes (*Solanum lycopersicum* L.) are among the most eaten vegetables globally because of their significant nutritional value, being rich in fiber and vitamins C and E, as well as potassium, calcium, phosphorus and phenolic acids [1]. Commercially, tomato cultivation occupies an area of more than 4.9 million hectares worldwide [2], which indicates that this crop plays an important economic role in various regions.

Within this context, Brazil is among the ten largest tomato producers in the world, with an area of 54,500 hectares and an annual output of 3.8 million megagrams, accounting for 2% of global production [2]. Brazil's average productivity is 70 Mg ha^{-1}, with the states of Goiás, São Paulo and Minas Gerais being the largest producers, with productivity of 80, 77 and 76 Mg ha^{-1}, respectively [3].

Despite productivity figures showing an increase over the decades, tomato cultivation faces challenges arising from climate change, which directly influences plant development, yield and post-harvest fruit quality, especially in tropical and subtropical climate regions, where the management of this crop has become a challenge due to the occurrence of water stress and the high incidence of solar radiation, resulting in high temperatures [4–7].

Among the stages of tomato development, fruiting is the period most sensitive to abiotic stresses, especially the effects caused by heat stress, so that an increase of 2.5 °C compared with the ideal temperature (around 24 °C) can reduce the percentage of fruiting by 40%, impacting the production and quality of the fruit [8–10]. In relation to water deficit, the effects caused by this stress are reduced fruit set [11], reduced translocation of nutrients in plants and reduced absorption of nutrients by the root system, which impairs the absorption of calcium, an immobile macronutrient that influences fruit quality since Ca deficiency in tomato plants causes apical rot [1,12].

Moreover, water and heat stress promote the formation of reactive oxygen species, including enzymes like superoxide dismutase, catalase, and glutathione peroxidase, which adversely affect the CO_2 fixation process, flower morphology and fertilization [13,14]. Heat stress, which can also be caused by solar radiation, also causes physiological disorders, such as flower rot, cracks and sun scald, which directly affect productivity [15].

In general, high radiation and temperature triggers responses in the vital mechanisms of plants, particularly those related to photosynthesis and water use, which can lead to significant yield losses. Tomato crops have a high water demand, especially during the fruiting and flowering periods, and lack of water at these stages can directly affect the crop's productivity. Furthermore, high radiation and temperature can cause physiological disorders in plants, such as the abortion of flowers and fruits, photoinhibition of photosynthesis, the formation of reactive oxygen species and photointoxication of photosystem structures and pigments [16–19].

One possible approach to reducing the negative impacts of water shortage and heat stress in tomato farming is the foliar application of calcium carbonate ($CaCO_3$), commonly referred to as foliar sunscreen or photoprotector. Calcium carbonate, when applied to the plant, limits the light spectrum to the visible spectrum only, favoring the photosynthetic process and reducing thermal and light stress and evapotranspiration and, consequently, reducing the plant's water consumption [20–22].

Agricultural crops respond favorably to foliar application of calcium carbonate, particularly under conditions of thermal stress [23–25]. However, the foliar application of calcium carbonate could also induce other effects that have been less explored, such as enhancing crop water productivity (WP_c), potentially reducing water usage without affecting yield. Concerning WP_c, it is anticipated that studies on optimizing water replacement levels (WRLs) in combination with photoprotection strategies (Ps) will result in greater tomato production per unit of water consumed.

Thus, the aim of this research was to assess the impact of water replacement levels (WRLs) and photoprotector applications on production and harvest quality of tomato fruit, as well as thermal responses (Crop Water Stress Index and soil temperature) and crop water productivity (WP_c).

2. Materials and Methods

2.1. Study Area

The study was carried out in the experimental area of the University of Sao Paulo, Piracicaba, SP, Brazil. The geographic coordinates of the experimental site are −22°42′ and −47°38′ and the elevation is 546 m. The climate of the region is humid subtropical (Cwa) according to the Köppen climate classification [26]. The soil of the study area is classified as Oxisol typic Hapludox [27]. The chemical characteristics of the soil at a depth of 0.20 m can be seen in Table 1.

Table 1. Chemical characterization of soil in the experimental area.

pH $CaCl_2$	OC	Available P	K^+	Ca^{2+}	Mg^{2+}	$H^+ + Al^{+3}$	Al^{+3}
	g dm^{-3}	mg dm^{-3}			cmolc dm^{-3}		
5.2	15.7	18.4	2.24	22.7	8.7	22.4	<0.1

Hydrogen potential (pH), organic carbon (OC).

2.2. Treatment Applications and Experimental Design

The treatments imposed were three WRLs (70, 100 and 130% of the required irrigation depth) and three photoprotective strategies (without photoprotector, with photoprotector and with photoprotector and adjuvant). The experimental design used was randomized blocks in a 3 × 3 factorial scheme, with four blocks and nine treatments.

Water replacement levels were based on the required irrigation depth to maintain the soil profile at field capacity (WRL 100—reference treatment). The other treatments were based on a fraction of 70 and 130% of the required irrigation depth in the WRL 100 treatment.

The photoprotector used was a water-soluble, nanoparticle (0.8 micron) foliar application product based on calcium carbonate ($CaCO_3$), known as liquid limestone. $CaCO_3$ was applied using a backpack pump, diluting 100 mL of the product in 5 L of water. The adjuvant was included in one of the treatments because these products modify the dynamics of the liquid with the contact surface, which can make the interaction of these substances more delicate, altering the efficiency of the photoprotector in some way.

2.3. Crop Management and Weather Monitoring

The tomatoes were transplanted on 1 March 2023, and harvested on 20 July 2023, totaling 142 days of growth cycle. The tomato hybrid cultivar Tronus RZ was used, which is a salad tomato plant, with indeterminate growth and red fruit, and recommended for planting in open fields. Planting was carried out at a depth of 0.1 m and the adopted spacing was 0.6 m between plants and 1 m between rows.

The irrigation system, using self-compensating drip emitters, was managed based on soil water potential. For this purpose, tensiometers were installed at a depth of 0.20 m in all the replications of the reference treatment (WRL 100). Matric potential was measured with a portable digital tensiometer calibrated against a mercury vacuum. Irrigation rate calculations were performed using a spreadsheet developed in Microsoft Excel®.

The soil moisture content before irrigation was estimated from the matric potential by using the van Genuchten [28] soil water retention equation, according to Equation (1):

$$\theta\ (\Psi_m) = \theta_r + \frac{(\theta_s - \theta_r)}{\left(1+(\alpha \times \Psi_m)^n\right)^m} \tag{1}$$

where $\theta\ (\Psi_m)$ is soil volumetric water content (cm^3 cm^{-3}), θ_r is the soil residual volumetric water content (cm^3 cm^{-3}), θ_s is the saturated soil volumetric water content (cm^3 cm^{-3}), m and n are the regression parameters of equation (without dimension), α is the parameter with dimension equal to the inverse of the tension (kPa^{-1}) and Ψ_m is the function of the matric potential (kPa).

The criterion established to start irrigation was the soil matric potential at −25 kPa. Meteorological data were collected using an automatic weather station.

2.4. Analyzed Variables and Harvest Quality of Tomato Fruit

Plant height assessments were carried out using a measuring tape and considered to be measured starting from the ground level to the inflection of the highest leaf. The stalk diameter was measured using a digital caliper. Assessments of plant height and stalk diameter were carried out 90 days after transplanting (DAT). Soil temperature and canopy temperature were evaluated using a FLIR T640 thermal camera (Wilsonville, OR, USA) with emissivity (ε) set at 0.95. The device has a thermal sensitivity of 0.04 °C and a pixel pitch of 25 µm. The operational temperature range is from −40 to 2000 °C. The waveband used is long wave infrared of spectral range is from 7.5 to 13 µm. The accuracy is +/−2 °C or +/−2% of reading, whichever is greater, at 25 °C nominal. Each pixel corresponded to an effective temperature reading. The images were obtained in the sunlit side of the plants at a distance of 2 m from the crop canopy around 11:00 a.m. All plants were photographed and the images analyzed using FLIR Tools software version 6.x (Figure 1A).

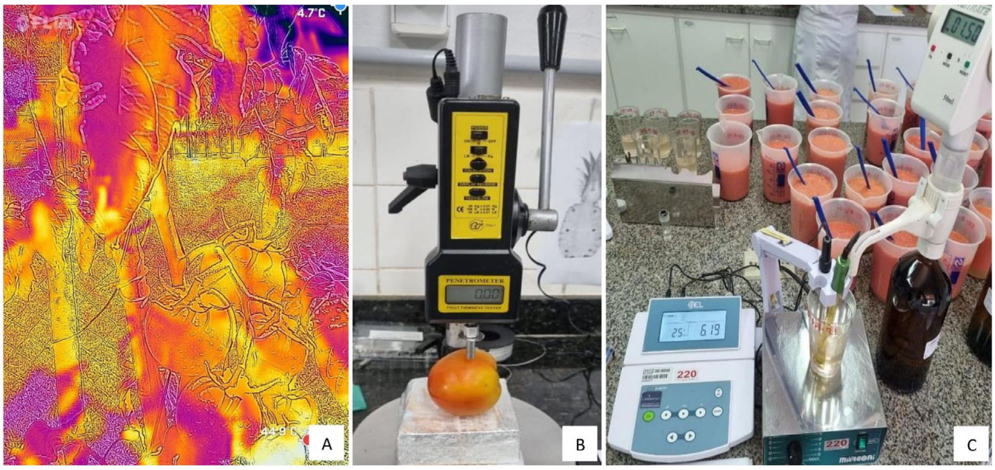

Figure 1. Photos of evaluations made during the research. Analysis of thermal images of tomato plants (**A**), analysis of pulp firmness using a digital penetrometer (**B**) and analysis of titratable acidity using potentiometric volumetry (**C**).

Analysis within the program resulted in average canopy temperature values. Canopy temperature and weather data were used to calculate the Crop Water Stress Index (CWSI), using Equation (2) [29]:

$$CWSI = \frac{(T_c - T_{air}) - T_{wet}}{T_{dry} - T_{wet}} \quad (2)$$

where T_{air} is the air temperature (°C), T_c is the canopy temperature (°C), T_{wet} is the non-water-stressed baseline (temperature of the canopy transpiring at the potential rate), and T_{dry} is the water-stressed baseline (temperature of the non-transpiring canopy). The lower and upper temperature baselines were determined by the minimum and maximum difference between T_c and T_{air}, respectively, according to Costa et al. [30].

Productivity was obtained by weighing tomato fruit. Fruit mass per plant was converted to Mg ha^{-1} considering a spacing of 1 m between rows and 0.6 m between plants. Crop water productivity (WP_c) was calculated relating productivity to the total amount of irrigation water applied (IWU), using Equation (3):

$$WPc = \frac{Y}{IWU * 10} \quad (3)$$

where WP_c is the crop water productivity (kg m^{-3}), Y is the productivity (kg ha^{-1}) and IWU is the total volume of irrigation water applied (mm).

For quality analyses at harvesting time, the tomato fruit were harvested at the point of physiological maturation, through visualization of the red color, and transported on trays to the laboratory. The pulp firmness, titratable acidity and soluble solids content were analyzed. Pulp firmness was obtained using a MCCORMICK digital penetrometer, Baltimore, MD, USA (Figure 1B), titratable acidity was obtained using potentiometric volumetry (Figure 1C) and the soluble solids content was obtained using a digital refractometer.

2.5. Data Analysis

All the statistical analyses were performed using the statistical software Sisvar, version 5.6. One-way analysis of variance (ANOVA) was performed after testing the homogeneity of variances and normality of the residuals by the Levene and Shapiro–Wilk tests, respectively. The means were compared using Tukey's test at 5% probability.

3. Results and Discussion

3.1. Weather Conditions and Water Consumption

The meteorological data obtained show that on different days of the tomato growth cycle, extreme values of meteorological variables occurred that could have resulted in losses of productivity and fruit quality and that justified the use of photoprotector strategies. The average daily temperature, for example, was above 26 °C at 3 and 26 days after transplanting (DAT). The maximum daily temperature was higher than 30 °C on 41 days of the tomato growing cycle, and the minimum daily temperature was higher than 20 °C on 5 days in the experimental period (Figure 2).

Tomato crops can withstand temperatures ranging from 10 to 34 °C without compromising their development and production. However, tomatoes are rich in lycopene, an antioxidant pigment that gives the fruit its reddish color. When temperatures exceed 30 °C, lycopene synthesis is inhibited, causing the fruit to have an uneven color. Extreme temperatures above 35 °C impair pollination, reduce nutrient utilization, reduce plant development, and cause flower drop, abortion and fruit burn [31].

The average daily values of global solar radiation were above 15 MJ m^2 day^{-1} on 79 days of the tomato growing cycle. Extreme values of solar radiation above 23 MJ m^2 day^{-1} were recorded 2, 3, 7, 8, 16 and 22 DAT. The average daily relative humidity was below 70% on 20 days of the tomato growing cycle and the daily wind speed was greater than 4 m s^{-1} on 29 days in the experimental period. High relative humidity combined with high temperatures favor the development of most fungal and bacterial diseases that attack the aerial part of tomato crops [32].

The total amount of irrigation water applied to the tomato crop in the experimental period was 337, 529 and 761 mm for treatments WRL 70, WRL 100 and WRL 130, respectively. The average daily irrigation depth applied in the WRL 70, WRL 100 and WRL 130 treatments were 2.4, 3.7 and 5.4 mm. The total amount of irrigation water required for tomato plants depends on weather conditions, the irrigation system and the cultivar, among other factors. Water consumption by tomato plants under average conditions in Brazilian producing regions varies between 250 and 950 mm during the growing cycle, as observed by Campagnol et al. [33] who also studied the impact of irrigation levels on tomato crops. Lu et al. [34] observed that severe water stress in tomato plants occurs at deficit irrigation rates of less than 50%. According to Takács et al. [35], deficit irrigation practices are positive considering the current climatic conditions if they do not lead to reduced productivity.

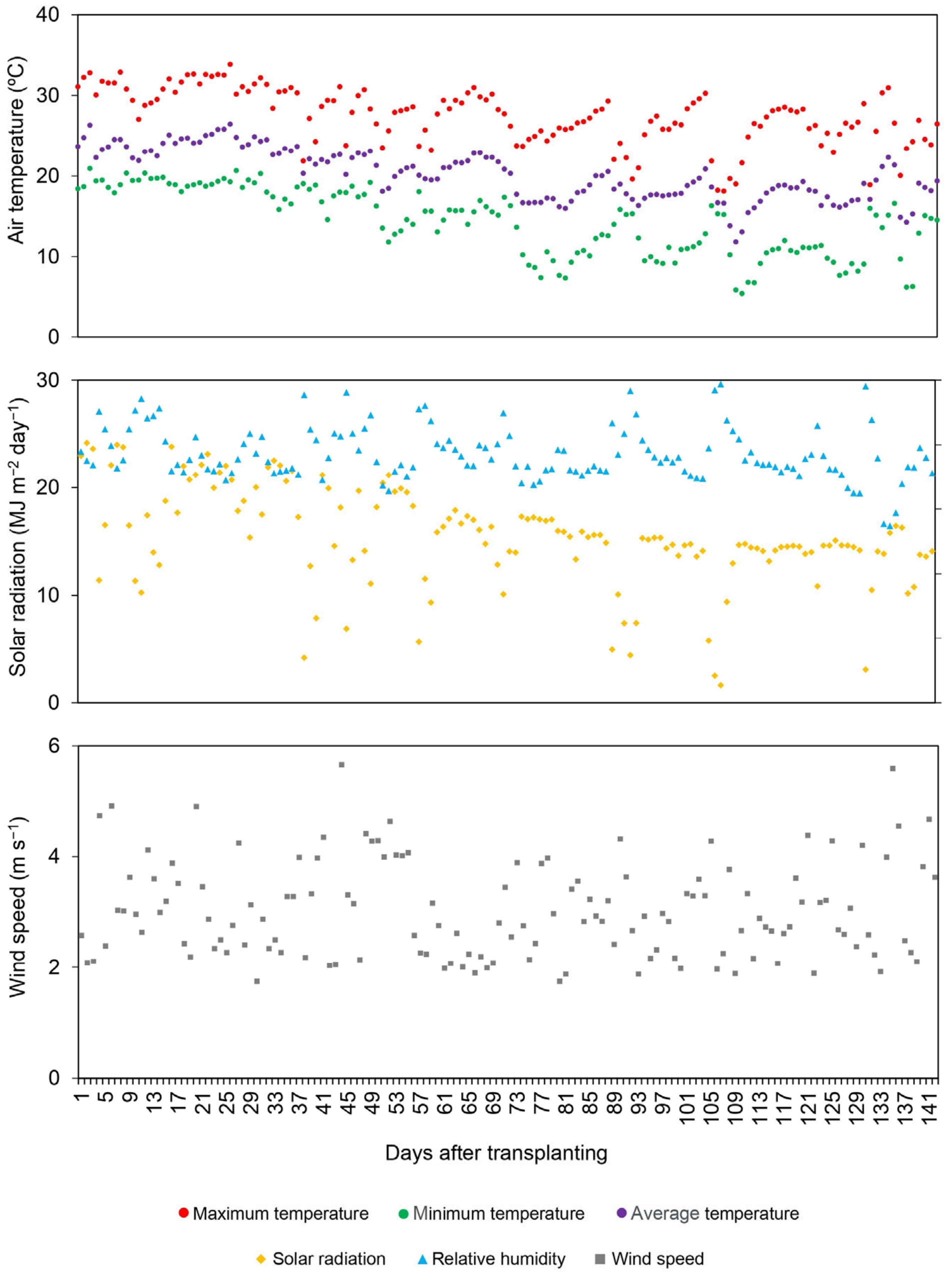

Figure 2. Maximum, minimum and average air temperature; relative humidity; solar radiation and wind speed recorded during the experiment.

3.2. Plant Height, Stalk Diameter and Productivity

No significant differences were observed in the variables of plant height and stalk diameter with the different WRL treatments and the WRL × Ps interaction. For the Ps factor, significant differences were observed using the F test ($p < 0.05$). The mean values obtained in this study for the plant height and stalk diameter were 0.93 and 0.0127 m, respectively. The highest plant height values were found in the treatment with photoprotector and adjuvant, with an average of 0.98 m. For the stalk diameter variable, it was observed that the highest average values were also found in the treatment with photoprotector and adjuvant, with an average of 0.0130 m (Table 2).

Table 2. Average values of plant height and stalk diameter of the tomato plant subjected to different water replacement levels and photoprotector strategies.

	Plant Height (m)				Stalk Diameter (m)			
	No Pp	**Pp**	**PpA**	**Mean**	**No Pp**	**Pp**	**PpA**	**Mean**
WRL 70	0.88	0.92	0.95	0.92	0.0123	0.0126	0.0125 b	0.0125
WRL 100	0.93	0.90	0.98	0.94	0.0124 B	0.0127 AB	0.0132 Aab	0.0128
WRL 130	0.89 B	0.91 B	1.00 A	0.93	0.0127 AB	0.0123 B	0.0134 Ab	0.0128
Mean	0.90 B	0.91 B	0.98 A		0.0125 B	0.0125 B	0.0130 A	
WRL				ns				ns
Ps				*				*
WRL × Ps				ns				ns

Without photoprotector (No Pp), with photoprotector (Pp), with photoprotector and adjuvant (PpA), water replacement level (WRL), photoprotector strategies (Ps). * Significant differences at 0.05 significance, ns not significant. Means followed by distinct lowercase letters within a column and distinct capital letters within a row are different by the Tukey test at 0.05 significance.

The higher values of plant height and stalk diameter obtained in the treatment with photoprotector and adjuvant were possibly due to the more homogeneous formation of the thin film formed by calcium carbonate when mixed with the adjuvant [20,36]. Tomato plants benefited from the use of photoprotector with adjuvant, which increases reflectance and allows the leaves to be more effective in photosynthetic processes, water consumption and nutrient use, suffering less from thermal stress [36].

Light radiation is a determining factor for photosynthesis, the main biochemical process that generates energy for plants. This energy is used to synthesize the compounds necessary for plant growth and development; wavelengths outside the light spectrum directly interfere with this biochemical process. Temperatures above 35 °C cause less use of nutrients, less plant development, flower drop and premature death of tomato seedlings [17,23]. The reduced use of nutrients by tomato plants is due to physiological disturbances caused by heat stress. High temperatures result in depressed water and nutrient uptake rates, which are related to reduced oxygen solubility and increased enzymatic oxidation of phenolic compounds in epidermal and root cortex tissues [37].

The thin white film formed by calcium carbonate on plant leaves and fruits increases the reflection of incoming solar radiation on the leaf and allows the plant to absorb more radiation in the visible range (400 to 700 nm), which is the ideal range for photosynthesis, changing the radiation and heat balance and reducing the risk of leaf damage from high temperatures [20]. In this sense, studies show that the use of calcium carbonate via foliar use is promising in promoting better conditions for plants to be more efficient in water use and in their biochemical processes [19,25].

No significant differences were observed for tomato productivity. The general average productivity obtained was 77.9 Mg ha^{-1}. Within the WRL treatments, the averages obtained were 82.8, 73.1 and 77.7 Mg ha^{-1} for the treatments without photoprotector, with photoprotector and with photoprotector and adjuvant, respectively. Within the photoprotector strategy treatments, the averages obtained were 79.3, 82.1 and 72.2 Mg ha^{-1} for treatments WRL 70, WRL 100 and WRL 130, respectively (Figure 3). It was found that the dispersion of productivity data was greater in the treatments with photoprotector and with photoprotector and adjuvant when compared with the treatment without photoprotector. Maximum productivity found in treatments with photoprotector in WRL 100 of 112 Mg ha^{-1}, and with photoprotector and adjuvant in WRL 70 of 103 Mg ha^{-1}, stood out.

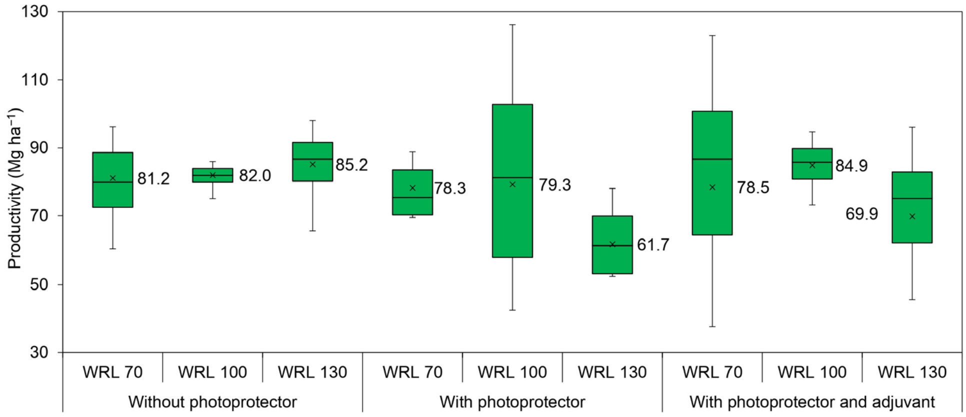

Figure 3. Productivity of the tomato plant submitted to different water replacement levels and photoprotector strategies. The box represents the interquartile range (IQR) and whiskers represent the range of data. The median is depicted by a horizontal line within the box, and the averages are illustrated by individual x symbols inside the boxes.

3.3. Soil Temperature, CWSI and Crop Water Productivity

No significant differences were observed for the soil temperature and CWSI variables, and the average values of these variables were 29 °C and 0.4, respectively. Within the WRL treatments, the average soil temperature values obtained were 30, 29 and 29 °C for the treatments without photoprotector, with photoprotector and with photoprotector and adjuvant, respectively. Within the photoprotector strategy treatments, the averages obtained were 30, 28 and 29 °C for treatments WRL 70, WRL 100 and WRL 130, respectively. Regarding CWSI, it was found that the average values obtained were in a range between 0.3 and 0.5 (Figure 4).

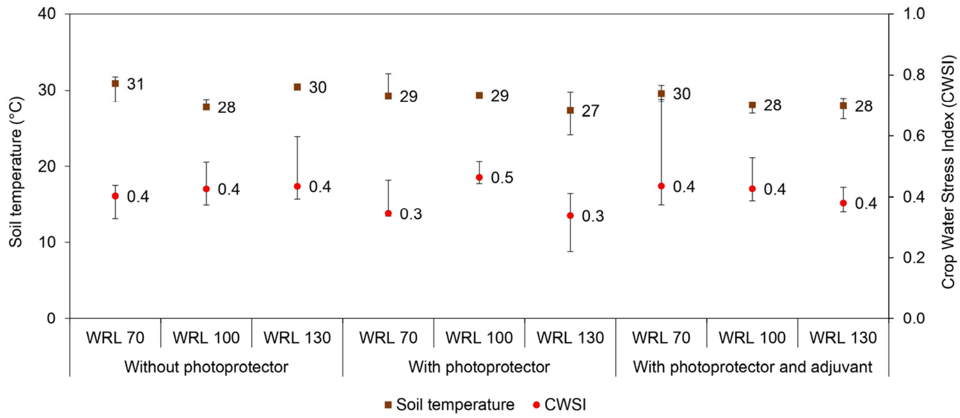

Figure 4. Soil temperature and Crop Water Stress Index (CWSI) of the tomato plant subjected to different water replacement levels and photoprotector strategies.

Regarding WP_c, significant differences were observed with the different WRLs within the photoprotector strategies. For the photoprotector strategy factors, no significant differences were observed using the *F* test ($p < 0.05$). The highest WP_c values were found in the treatment WRL 70, with an average of 24.1, 23.3 and 23.3 kg m^{-3} within the treatments without photoprotector, with photoprotector and with photoprotector and adjuvant, respectively (Figure 5). The highest WP_c values found in WRL 70 occurred due to the low amount of irrigation water applied (337 mm) in this treatment and the lack of significant impairment of tomato productivity in this deficit irrigation condition. Similar studies [38,39] on tomatoes have demonstrated that reducing WRLs increased WP_c.

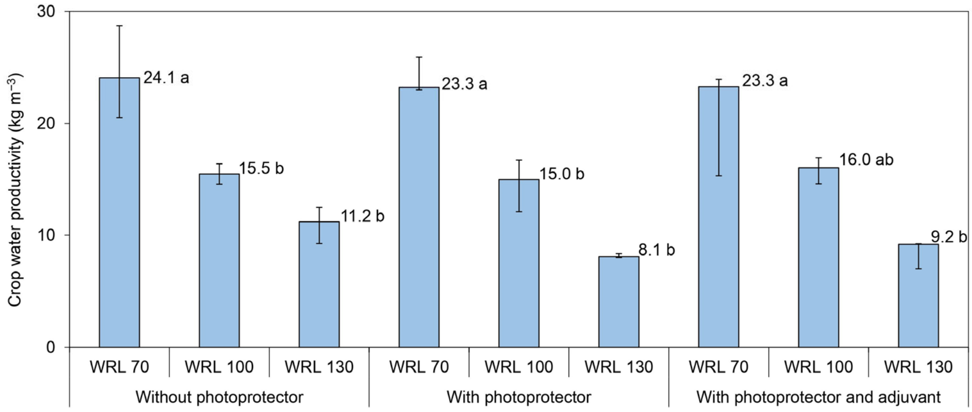

Figure 5. Crop water productivity of the tomato plant subjected to different water replacement levels and photoprotector strategies. Means followed by distinct lowercase letters are different by the Tukey test at 0.05 significance.

3.4. Quality at Harvesting Time

For the soluble solids and titratable acidity, significant differences were observed depending on the applied treatment. No significant differences were observed for pulp firmness. The treatment that produced the highest average value of soluble solids was with photoprotector (4.8 °Brix) treatment and the treatment with the lowest average value of soluble solids was the treatment without photoprotector (4.3 °Brix). The treatment WRL 130 was the one that produced the highest average value of soluble solids. The treatment that produced the highest average value of titratable acidity and soluble solids was WRL 130 (0.36%) (Table 3). This increase could have been caused by the fact that the increased total amount of irrigation water applied led to a greater dilution of the nutrients, causing an imbalance in the absorption of nutrients, which affected the physiology of the tomato plants and, consequently, caused an increase in the production of organic acids and titratable acidity.

Soluble solids were higher in treatments with photoprotector, indicating less competition between photoassimilates, since the source–sink relationships were favorable to the fruit, allowing the accumulation of more sugars than in the treatment without application of photoprotector. The accumulation of sugars and aromatic compounds in the presence of acids gives the fruit its characteristic flavor and aroma [40–42].

Solar irradiation does not have a direct effect on the fruit when evaluating ripeness, although it accelerates its development and color; the concentration of sugars in the fruit is directly related to the irradiance received by the plant during the growth period [41,43].

In our study, higher average soluble solids were observed when WRL 70 was applied compared with WRL 100 in conditions where no photoprotector was applied (control). This increase may have occurred due to the defense mechanism developed by tomato plants under conditions of water stress, resulting in a defense response that increased soluble solid content. Looking at the soluble solids and titratable acidity values of the plants exposed to WRL70, the use of the foliar photoprotector attenuated the effect of water stress. This allowed tomato plants to be grown with a lower volume of water throughout the growing cycle, without compromising productivity and fruit quality.

The limitations of this study were the initial evaluation of the response of tomato plants for only one crop cycle and the absence of physiological and biochemical analyses. However, it should be noted that in the initial studies carried out, good practices were adopted to control possible variation sources that were not the object of study in this research. In this sense, the application of these treatments in the field for more crop cycles and the performance of physiological and biochemical evaluations would provide more information to justify the defense mechanisms developed by tomato plants in response to WRLs.

Table 3. Average values of soluble solids, titratable acidity and pulp firmness of tomato fruit submitted to different water replacement levels and photoprotector strategies.

	Soluble Solids (°Brix)				Titratable Acidity (%)			
	No Pp	**Pp**	**PpA**	**Mean**	**No Pp**	**Pp**	**PpA**	**Mean**
WRL 70	4.2 ABab	4.8 A	4.1 Bb	4.4 b	0.30 b	0.31 b	0.30	0.31 c
WRL 100	3.9 Bb	4.8 A	4.8 Aa	4.5 ab	0.32 b	0.34 ab	0.34	0.33 b
WRL 130	4.8 a	4.9	4.6 ab	4.8 a	0.36 a	0.37 a	0.34	0.36 a
Mean	4.3 B	4.8 A	4.5 AB		0.33	0.34	0.33	
WRL				*				*
Ps				*				ns
WRL × Ps				*				ns

	Pulp Firmness (N)			
	No Pp	**Pp**	**PpA**	**Mean**
WRL 70	20.0	23.0	28.4	23.8
WRL 100	22.8	22.1	44.8	29.9
WRL 130	28.4	44.8	23.8	32.3
Mean	23.7	30.0	32.3	
WRL				ns
Ps				ns
WRL × Ps				ns

Without photoprotector (No Pp), with photoprotector (Pp), with photoprotector and adjuvant (PpA), water replacement level (WRL), photoprotector strategies (Ps). * Significant differences at 0.05 significance, ns not significant. Means followed by distinct lowercase letters within a column and distinct capital letters within a row are different by the Tukey test at 0.05 significance.

4. Conclusions

Photoprotector treatments resulted in discrete positive biometric responses (plant height and stalk diameter) and improved the soluble solids of tomato fruit by harvesting time, when compared with the treatment without the use of photoprotector. The results also show that the use of the photoprotector helped to improve the quality of the fruit, as the fruit had commercially acceptable values for soluble solids, titratable acidity and pulp firmness.

Water replacement levels (WRLs) influenced crop water productivity (WP_c), obtaining the best performance in the WRL 70 treatment. Therefore, deficit irrigation combined with the application of photoprotector and adjuvant resulted in water savings without compromising tomato productivity and harvest quality.

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