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# The Effect of Different Levels of Shading in a Photovoltaic Greenhouse with a North–South Orientation

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Received: 5 December 2019; Accepted: 24 January 2020; Published: 28 January 2020

**Abstract:** Photovoltaic greenhouses have been claimed to be a solution to cover the energy demand of the protected crops sector. Thus, there is a need to know what is the maximum percentage of shading produced by roof-top photovoltaic panels that does not affect crop yields. The present study analyzes the effects of increasing percentages of shading in a greenhouse tomato crop located in the southeast of Spain. For this study, photovoltaic panels have been simulated with opaque sheets located in the roof-top of a north–south oriented greenhouse. Three treatments of top roof shading percentage (15%, 30% and 50%) where studied and compared with the control treatment without shading (0%). During the study, parameters registered were radiation, temperature, pH and electric conductivity of the substrate, crop yields and fruit quality. Results of the analysis show that higher percentages of shading in the roof-top of greenhouses reduce so much available radiation for the crop causing a reduction in the yield and fruit quality, even in Mediterranean areas where radiation is not a limiting factor.

**Keywords:** photovoltaic greenhouse; tomato; shading; microclimate; yield; fruit quality

## 1. Introduction

Energy and food sustainable production is a major concern of actual society [1,2]. Several researchers have shown that photovoltaic energy production in a greenhouse could cover the energy demand of farms and get additional incomes for producers for energy selling to a general electricity network [3–10].

Therefore, the decrease in the use of fossil fuels can reduce the production of polluting gases in intensive agriculture [11–14]. In addition, photovoltaic energy production for agriculture use can be especially interesting in remote areas where connection to a general electricity network is not available or at a high-cost [15–18]. Plants growing, crop yields and the quality of fruits can be improved by controlling greenhouse climatic conditions using self-produced photovoltaic energy [19].

The main drawback of installing roof top greenhouse photovoltaic panels is the shading that these structures produces inside the greenhouse, reducing photosynthetic active radiation (PAR) radiation for crop production. In low latitude countries, such as Spain, Italy, Greece and other Mediterranean countries, solar radiation can satisfy PAR requirements of crops in greenhouses. In fact, in these countries summer period solar radiation results in being excessive, having negative effects in greenhouse crops, due to a high radiation and temperature reaching inside the greenhouse and being needed to be reduced by farmers through techniques like whitening of roof-tops or shading-screens [20–22]. However, in winter periods, this radiation is not excessive, becoming in many cases a limiting factor of greenhouse crops.

The installation of roof top greenhouse photovoltaic panels in the Southern Eastern area of Spain can be an interesting proposal for farmers, due to the high number of annual solar hours in the area [23–25]. The main drawback is that conventional photovoltaic panels are completely or partially opaque in order to maximize solar energy production. Thus, there is a reduction of the radiation that is available for the crops [2,18]. The reduction of radiation inside the greenhouse due to the photovoltaic panel installation needs to be deeply studied, because it can affect crop growth and yields, mainly in periods when solar radiation is lower [1,25,26].

During high radiation periods, shading is one of the main ways to reduce solar radiation inside the greenhouses, using materials that reflect and absorb part of the spectrum of the solar radiation [15].

Therefore, the use of photovoltaic panels during these periods can provide beneficial shadings on the crop and generate new economic incomes to the farm, or reduce costs due to electricity production. However, during low solar radiation periods, an excessive shading surface can reduce radiation inside the greenhouse too much and cause negative effects on crops [27–30].

Photovoltaic modules installed on the top of the greenhouse permanently during all the cropping season (and during several years) can produce excessive shading during low solar radiation periods. Although the shading effects in greenhouses has been widely studied [31]. It is very interesting to know which is the maximum level of shading produced by opaque roof-top greenhouse photovoltaic panels without affecting crop production.

In South-European greenhouses, structures are usually oriented East–West, being this structure orientation used for most of researchers in studies about photovoltaic energy production [18,24,25,32,33].

Yano et al. [34] studied electric energy generated by roof-top greenhouse photovoltaic panels in a North–South oriented greenhouse located in Japan. However, this study did not evaluate the effects of shading in the crop. Therefore, it can be very interesting to study effects on crop production of roof-top greenhouse photovoltaic panels in a North–South oriented greenhouse.

Recently, several studies on crop effects of shading caused by roof-top photovoltaic panels have arisen [24,25,35,36]. However, neither of these studies has evaluated simultaneity different shading levels in crops. In addition, these studies have been developed in East–West axis oriented greenhouses. For this purpose, this paper intends to describe the study of tomato crop effects due to different levels of shading produced by opaque sheets, simulating roof top photovoltaic panels in a North–South axis oriented greenhouse.

## 2. Materials and Methods

### 2.1. Experimental Design

The study was conducted in a 2.415 m$^2$ (57.5 m length and 42.0 m width) Venlo greenhouse structure located in South–East Spain, in the experimental center of Tecnova located in Paraje Cerro Gordo s/n Viator, Almería, Spain (36º53′44.23′′ N, 2º22′31.35′′ W, 185 m above sea level).

The greenhouse structure was formed by galvanized steel tubes. The greenhouse roof structure was a two-span metal frame with 6 modules of 7 m of width (Figure 1). The ridge height in the roof was 6.63 m and gutter height was 5 m. The cover material of the greenhouse was plastic in lateral and frontal walls, while several materials (plastic, photovoltaic panels, opaque sheets of polyethylene and transparent sheets of corrugated polycarbonate) were located in the rooftop, as Figure 1 shows.

Opaque sheets of polyethylene were installed on the greenhouse rooftop to simulate the effect of shading that would produce opaque photovoltaic panels. Figure 2 shows the location of opaque sheets of polyethylene on a greenhouse rooftop, in 50% of the shade treatment. The plastic cover of the greenhouse was thermic polyethylene (LDPE) three-layers, coextruded manufactured. These three layers give different properties to the plastic cover, depending on their composition: the external layer of the plastic is very resistant, with non-stick properties and protection additives against UV-radiation. The intermediate layer is high in copolymers of ethylene and vinyl acetate (EVA) content, giving thermicity to the plastic. Finally, the internal layer (inside the greenhouse side) increases light diffusion and is stable against chemical agents like phytosanitaries. The plastic cover had a 200 µm thickness, a transparent white color, 3 years of shell life and a visible light transmission rate of 84%.

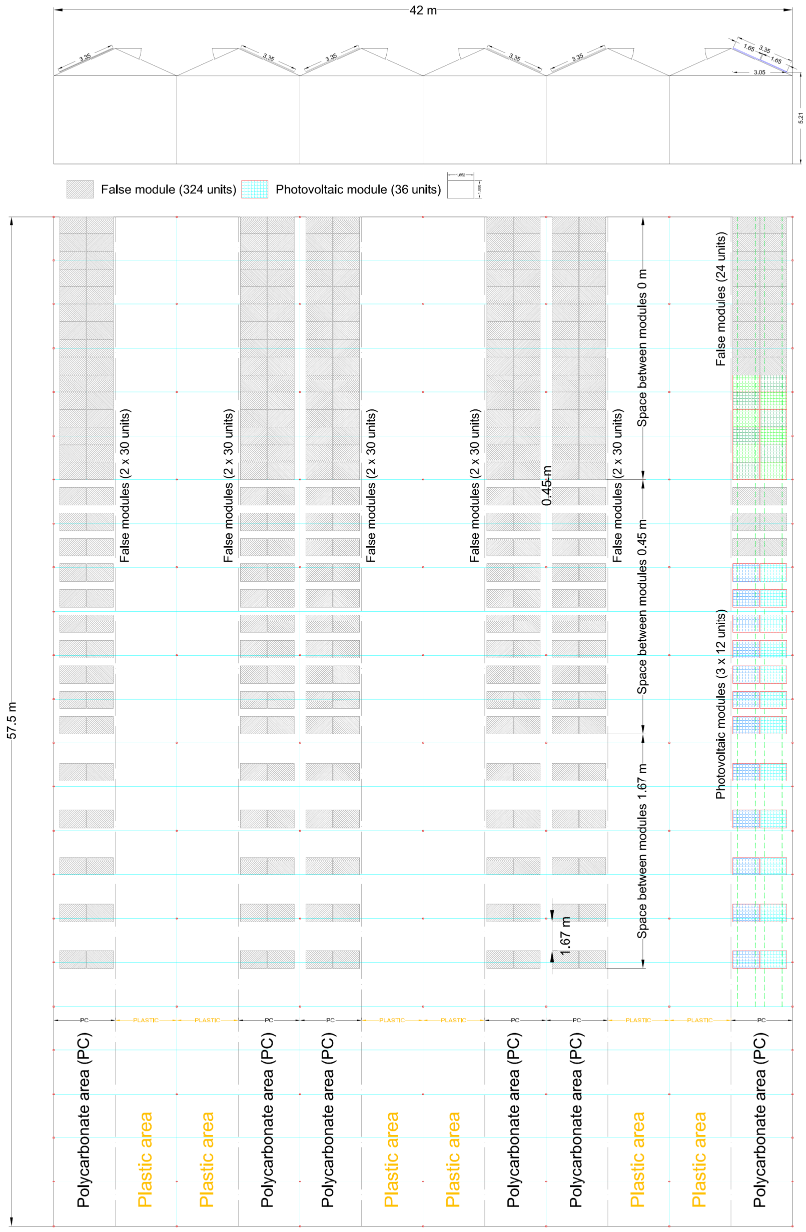


**Figure 1.** The photovoltaic panels and opaque polyethylene sheets location in the greenhouse rooftop.

**Figure 2.** (**Left**) Roof-top installation of opaque polyethylene sheets in the greenhouse outside face in the 50% shade treatment. (**Right**) The inside view of the 30% shade treatment in the greenhouse.

The greenhouse has passive ventilation, through lateral openings of 2.5 m height located around the perimeter of the structure and 5 zenithal openings of 50 m of length and 1 m width. The opening and closing of these openings are automatically controlled depending on climate conditions inside the greenhouse (temperature and relative humidity). The total ventilation area in the greenhouse was 20.7% of total floor area. Each opening was protected by insect-proof nets of 20 × 10 threads $cm^{-2}$ (50 mesh).

Thirty six photovoltaic panels, with a 1.65 m length and 1.00 m width of area by panel, were installed in the roof-top of the greenhouse. Modules were installed in 2-units groups. Besides, to simulate the shading effect that would produce roof-top photovoltaic panels in different treatments of shading, opaque polyethylene sheets were used. The size and radiation transmission of these polyethylene sheets were identical to the effect of real photovoltaic panels. Figure 1 shows the location of both materials on the roof-top greenhouse.

In order to evaluate the effect of different shading levels that would produce the installation of photovoltaic panels in the rooftop greenhouse, an experimental design was planned with 3 shadow treatments of 15%, 30%, and 50%. The three treatments were compared with a control treatment with 0% shading. Shaded treatments were 630 $m^2$ of the surface and the control treatment, 0% shade, of 525 $m^2$ (Figure 3). Each treatment was evaluated and climatic control, yield and quality parameters registered.

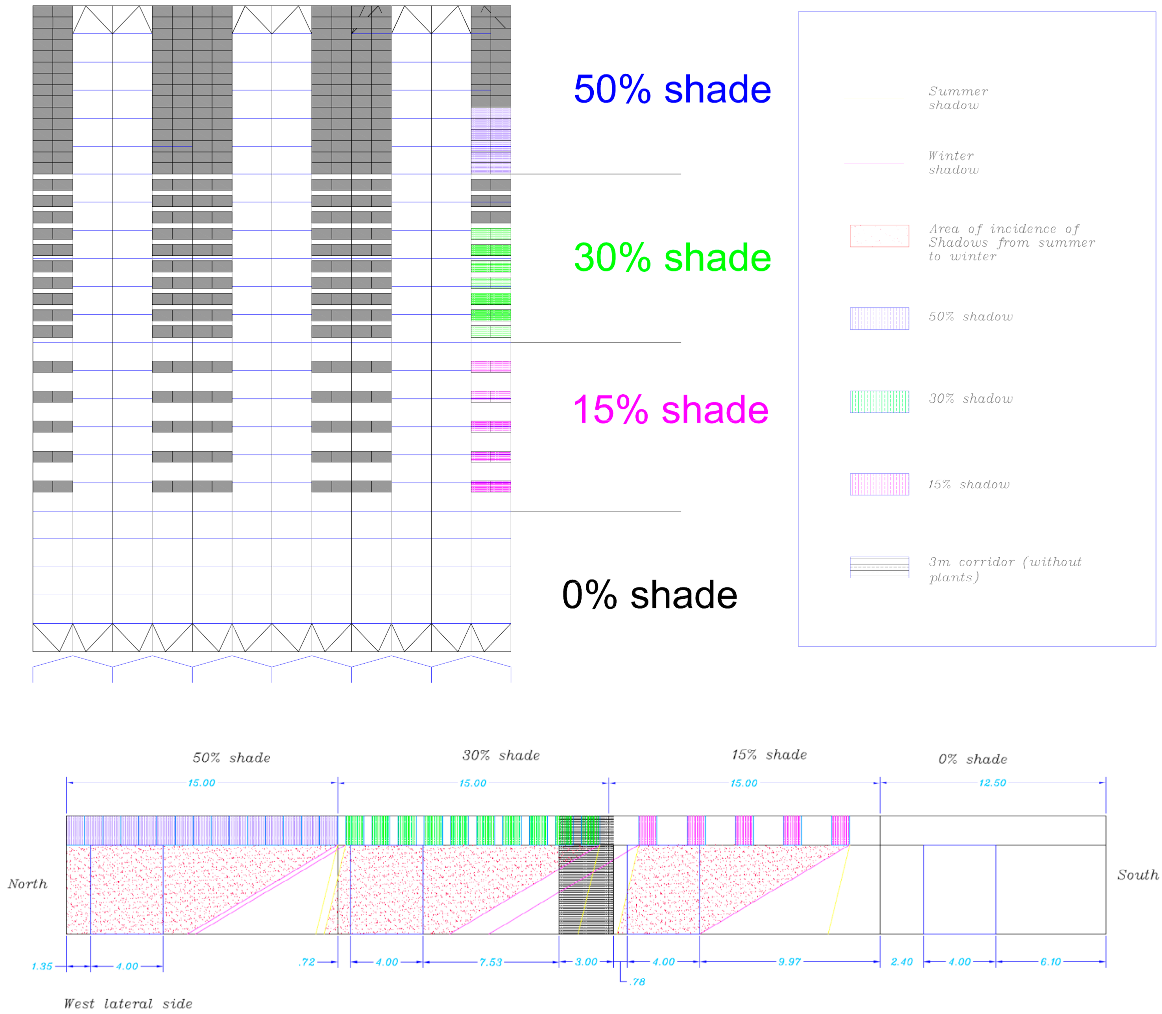


**Figure 3.** Location of photovoltaic modules and polyethylene sheets in the roof-top greenhouse (**up**). Projected shades inside the greenhouse of different shading treatments (**down**).

## 2.2. Crop Conditions

Research was conducted during the season of 2014–2015 in a tomato crop (*Solanum lycopersycum* L.) cv. Pitenza (indeterminate growing), grafted over Maxyfort rootstock. Plants were transplanted on 17th September 2014, with 35 days after germination in a commercial seedbed.

One stem pruning and formation system was used, eliminating the terminal bud, 65 days before the last harvest and end of the crop, dated on 14 May 2015. Terminal bud elimination at the end of the tomato crop is a common cultural operation in indeterminate growing varieties, with the formation of one or two stems. This technique consists of eliminating the terminal bud to avoid the development of new stems, leaves, flowers and fruits; this operation allows plants to reduce energy and resources they consume, as it does not dedicate energy to produce new vegetative parts with noncommercial fruits. Besides, it gets easier with the development of present fruits at the end of the cropping season, which will be harvested and marketed.

Plants were grown in coco fiber artificial substrate, located in 1 m high platforms (Figure 4). This hydroponic cropping system is usual in the South–East Spanish greenhouse production area. Plant density was 1.72 plants·m$^{-2}$. Water and nutrients were applied with fertigation techniques through an irrigation pipes layout over the substrate. Drippers of 2 L·hour$^{-1}$ were located with a distance of 0.5 m in each line of crop. Cultural cropping techniques like pruning, defoliation, guiding and fertigation were applied as usual in a tomato hydroponic cropping system in the area of study [25,37].

**Figure 4.** Detail of tomatoes planted on Coco fiber artificial substrate.

## *2.3. Climatic Parameters Register*

Outside radiation was registered with one sensor that took radiation data continuously during the study in W·m$^{-2}$, in the spectrum from 440 to 970 nm. A radiation sensor was located in an outside station. Inside the greenhouse, two sensors per treatment (0%, 15%, 30% and 50%) of the shading rate registered photosynthetic active radiation (PAR, 400–700 nm). The PAR radiation sensor model was a LI-1500 Light Sensor Logger (Figure 5). Each sensor was installed in a fixed leveled support, with a telescopic arm, to change the height of the sensor. The height of the sensor was modified depending on crop development, to be sure that it was located over the crop (Figure 6).

Outside and inside greenhouse temperatures were registered continuously during the study. The outside sensor was located in the outside weather station. Inside the greenhouse, 8 temperature sensors (2 by treatment) were located hanging from the truss of the structure at the same high (1.5 m from the floor). Figure 6 shows the detail of the installation of temperature sensors, Scort Log Model, EI-HS-D-32-L, with a temperature range of −40 to +70.5 °C (Cryopak Verification Technologies, USA).

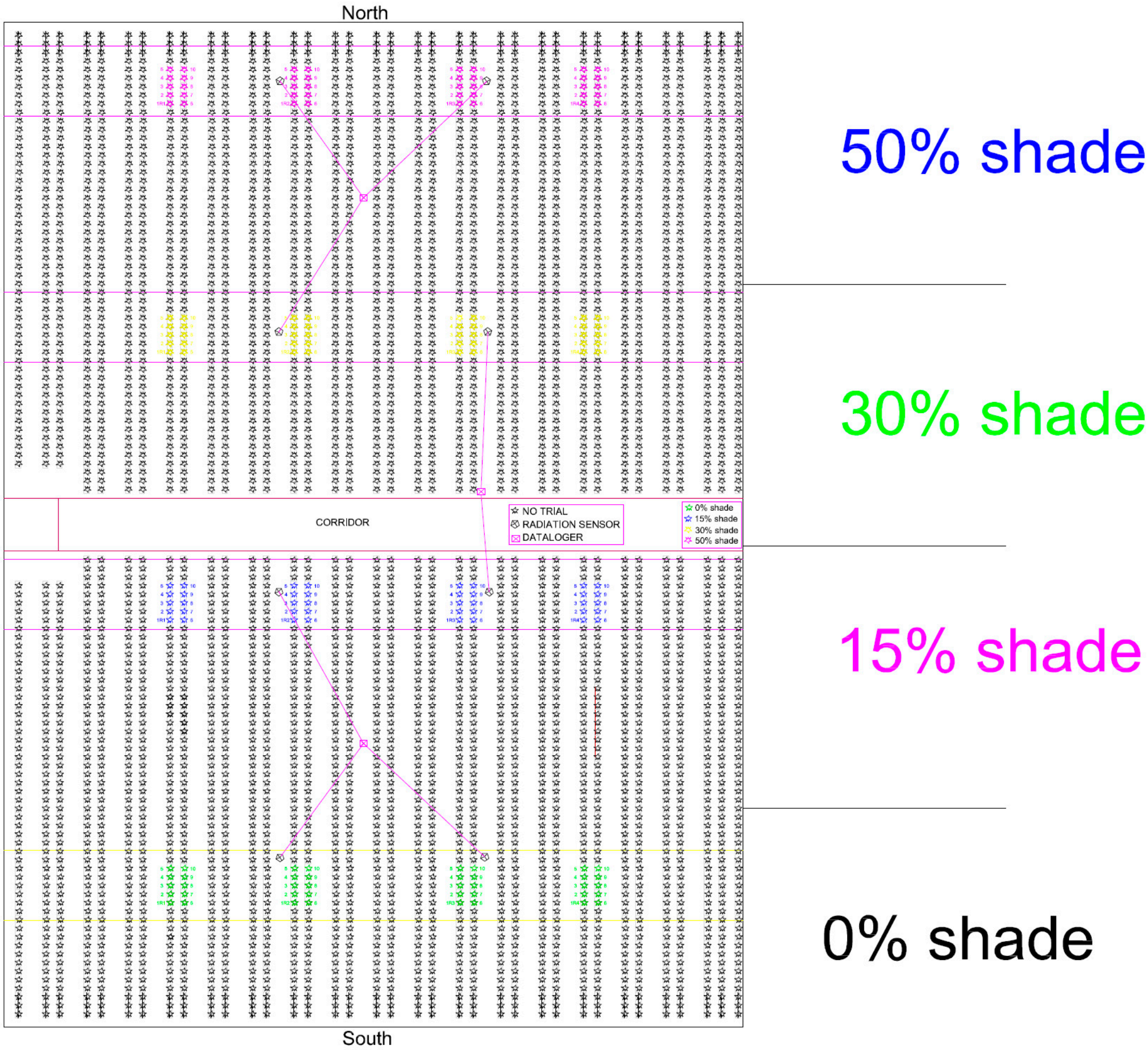


**Figure 5.** Plants distribution by repetition and treatment inside the greenhouse. Location of the radiation sensors.

**Figure 6.** Detail of installation of radiation (**left**) and temperature (**right**) sensors.

### 2.4. Agronomic Parameters Register

The pH and Electric Conductivity (EC) in the substrate solution was measured weakly during the whole cropping season. The first measure was made 23 days after transplant (d.a.t). The nutritive solution was extracted with a syringe from the drainage system of substrate bags, to be analyzed later in laboratory facilities in the Experimental Center Tecnova. An Elmeco pH and EC meter (Leidschendam, the Netherlands) was the equipment used, with a resolution of 0.01 values for pH and 0.03 mS (20 °C) for EC.

Crop yields and fruits quality was registered during the whole cropping season. Total yield and total marketable yield was calculated using four repetitions of 10 plants per shadow treatment (0%, 15%, 30% and 50%). Plants in each repetition were distributed in 2 crop rows of 5 plants in the central area of each treatment studied (Figure 5). Plants location was selected to get the maximum shade incidence taking into consideration the movement of sunrays over the cropping season (Figure 3). Plants were identified to increase the traceability of the treatments and repetitions.

Weight and diameter of fruits were registered in all harvesting operations during the cropping season. Eight harvesting operations were made 113, 131, 141, 161, 181, 209, 222 and 239 days after transplant (d.a.t.). In the last harvesting operation (239 d.a.t), all the fruits (green and mature) were harvested. Fruits from all harvesting operations were marketed with the exception of those considered non-commercial because of size, damages in fruit or color. In the case of the last harvesting operation, some of the green fruits were maturated in conservation chambers.

Harvested fruits from each repetition per treatment (10 plants per repetition and 40 plants per treatment) were stored for measurements and weight in codified plastic bags to assure the traceability of each treatment and repetition. Yields and the number of harvested fruits by repetition were determined in laboratory facilities in experimental center Tecnova, distinguishing among marketable and non-marketable fruits. The Radwag WLC30/F1/R (Radwag, Radom, Poland) scale model with 30 kg of maximum capacity and a 0.5 g precision was used for weight measurements. A sample of 18 fruits per repetition (72 fruits per treatment) was selected from marketable fruits to measure the fruit diameter with a Mitutoyo digital caliper (Mitutoyo Corporation, Japan).

Quality fruit parameters were measured in a sample of marketable fruits (18 fruits per repetition) in some of the harvesting periods (113, 131, 161, 181, 209, 222 and d.a.t.). Evaluated parameters in each fruit were firmness, color, Total Soluble Solids (TSS) and pH of the fruit. These measurements were made in laboratory facilities in the headquarters of CT TECNOVA.

Fruit firmness was measured with a Brookfield CT3 texture analyzer (Brookfield Engineering Laboratories, INC. Middleboro, Massachusetts, USA). Each fruit was compressed with a 4.5 mm probe, at a speed of 2 $mm \cdot s^{-1}$, and the maximum force expressed in Newtons (N) was recorded.

Total Soluble Solids (TSS) and pH of the fruit were measured taking the sample from the extracted juice of each fruit. TSS (°Brix) measurement was made with an ATAGO PAL-1 digital refractometer (ATAGO CO., LTD, Tokyo, Japan) with a 0.2° Brix resolution. The refractometer was periodically calibrated with 10% sucrose solution (Merck KGaA * 64,271 Darmstadt * Germany). The pH measurements were made with CRISON GLP22 pH equipment (CRISON INSTRUMENTS S.A., Alella, Barcelona, Spain).

Color determination was made with a CIELAB system using Minolta CR-400 Chroma Meter (Konica Minolta Sensing Inc. Osaka, Japan) equipment. CIELAB system methodology allows us to represent any color with three coordinates L *, a * and b*. Luminosity (L*) goes from 0 (black) to 100 (white); the red-green axis is represented by a*, and the yellow-blue axis is represented by b*. The Arana equation was used to identify color intensity [38].

### 2.5. Data Analysis

Total yields, marketable yields, number and quality of the fruits data were treated with an analysis of variance (ANOVA). The study was conducted in a randomized complete block design, and statistical analysis according to an additive linear model $Yij = \mu + \alpha i + \beta j + \varepsilon ij$, where Yij is the ij-th observation, equal to each registered data, μ is the global average of the registered data, αi is the effect of the i-th shadow treatment (0%, 15%, 30% and 50%), βj is the j-th of each repetition and εij is the experimental error. The *p*-value is obtained from the relation between αi and εij [39–41]. All the analyses were verified to be in line with the normality and homogeneity of variances hypothesis.

Average results per treatment were compared using a multiple range test with minimum significant differences with the Bonferroni correction [42]. Bonferroni correction was calculated according to the Armstrong [43] description. For the 4 treatments studied (0%, 15%, 30% and 50%), 6 independent tests and control hypotheses (no significant variation) were made and valid for all the comparisons (6). Therefore, the probability of at least one of the six tests being significant (mistake I or alpha type) is $\alpha = 0.265$, instead $\alpha = 0.05$. Thus, the Bonferroni correction value considered in the analysis was 0.0085 (99.15).

## 3. Results

### *3.1. Effects of Shading Treatments over Temperature and PAR Radiation*

Outside solar radiation was progressively decreasing in maximum radiation intensity and the number of solar hours, from crop transplanting (17th September) to December. From December onward, outside radiation increased progressively until the end of the cropping season in May (Figure 7).

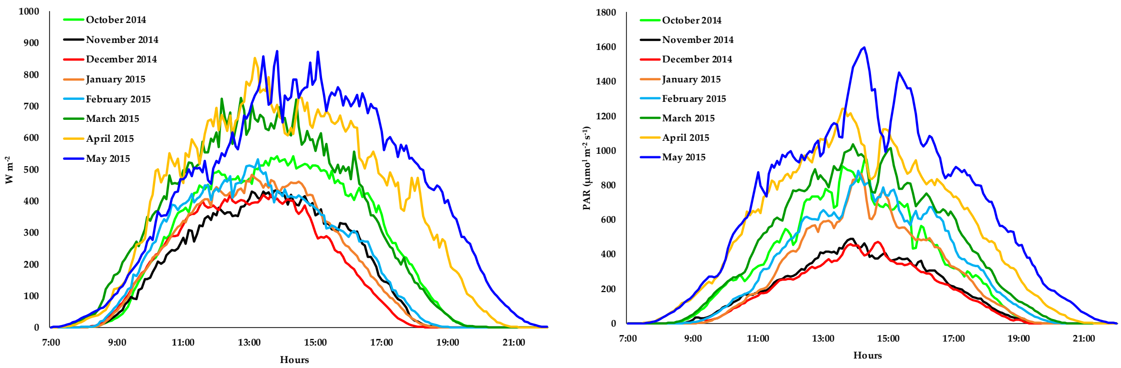


**Figure 7.** Outside average monthly radiation (W $m^{-2}$) evolution for the studied period (**left**). Average monthly photosynthetic active radiation (PAR) in the control treatment (0% shade) for the studied period (**right**).

The photosynthetic active radiation (PAR) inside the greenhouse was also studied. Figure 7 shows PAR radiation for the control treatment (0% shade). The variation of maximum radiation intensity and the number of exposition hours to PAR radiation showed similar behavior to the outside radiation description, with the lowest radiation in December and maximum in May.

Figure 8 shows, for the studied period, the average daily evolution of the monthly reduction of PAR radiation produced by shading treatments (15%, 30% and 50%) in regards to the control treatment (0% shade). We could observe that generally, every month, PAR radiation reduction was proportionally higher than the shading surface in the roof-top. Specifically, the shading treatments of 15%, 30% and 50% of the shadowed surface in the roof-top resulted in a reduction in real PAR radiation for the crop of 28.8%, 46.6% and 66.3% respectively (Figure 9).

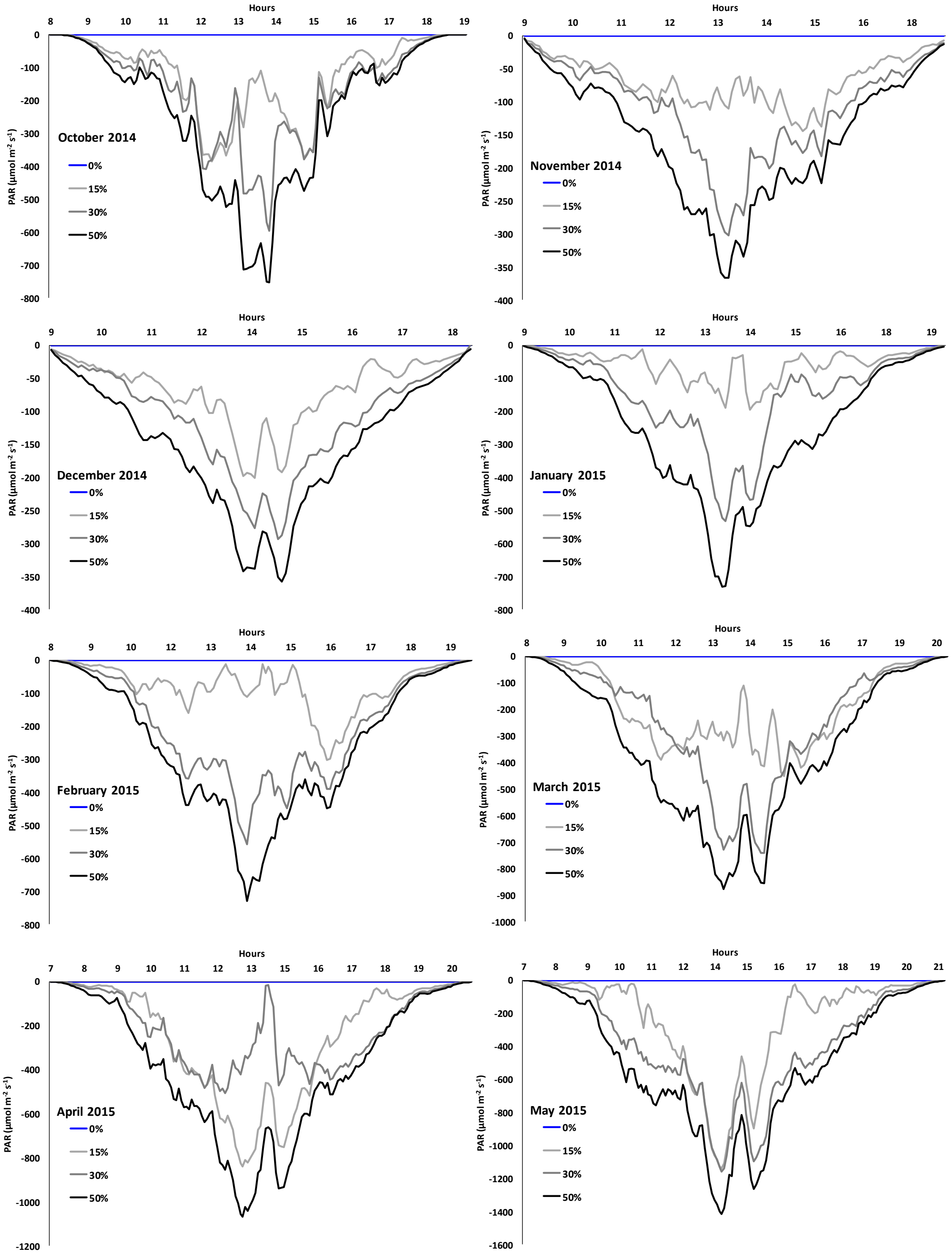


**Figure 8.** Average daily evolution of the monthly reduction of PAR radiation produced by shading treatments (15%, 30% and 50%) in regards to the control treatment (0%) shade for the studied period.

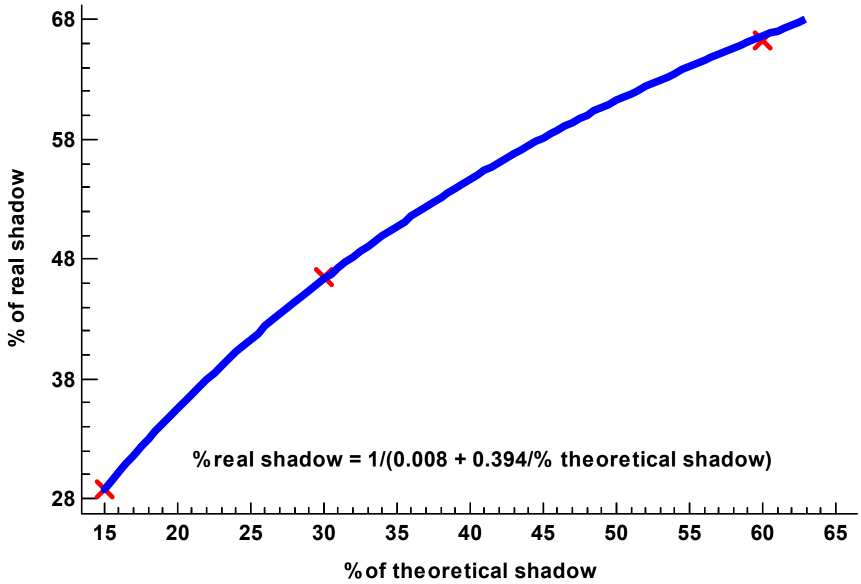


**Figure 9.** Reduction in PAR radiation produced by shading treatments of 15%, 30% and 50% in regards to the control treatment (0%). Figure shows the average values from October to May.

The variation of the average monthly temperature between shadow treatments is shown in Figure 10. Results show that the highest average monthly temperature inside the greenhouse was registered in the control treatment (0% shade) for all the months studied, with an exception in January, where the maximum temperature was registered in the 50% shadow treatment. The highest temperature in the studied period was registered in May in the control treatment (0% shade) with 34.5 °C.

The lowest inside greenhouse temperatures were registered before sunrise. In the studied treatments, the lowest temperature was registered in the 50% shade treatment for all the months of the period, with the exception of February, that were registered in the control treatment (0% shade) and in the 30% shade treatment. This February temperature (9.2 °C) was the lowest registered in the whole studied period.

### *3.2. Electric Conductivity and pH in the Substrate Solution.*

Electric Conductivity (EC) and pH in the substrate solution was statistically higher in the control treatment (0% shade) and 15% of the shade treatment than in the rest of treatments with a higher shadow percentage (Figure 11). The analysis of the average data in the period shows that the highest pH and EC values were registered in the control treatment (0% shade) with pH = 6.28 and EC = 3.09 dS·m$^{-1}$. In treatments with the highest shadow percentages (30% and 50%), results were similar, registering the 50% treatment as the lowest values (6.01 of pH and 2. 81 dS·m-1). The evolution in time of both of the parameters in the substrate solution was similar for all the studied treatments (Figure 11). EC showed a slight increase tendency during the cropping season, instead, pH, after an increase at the beginning (37 d.a.t), showed a decrease tendency until the end of the cropping season.

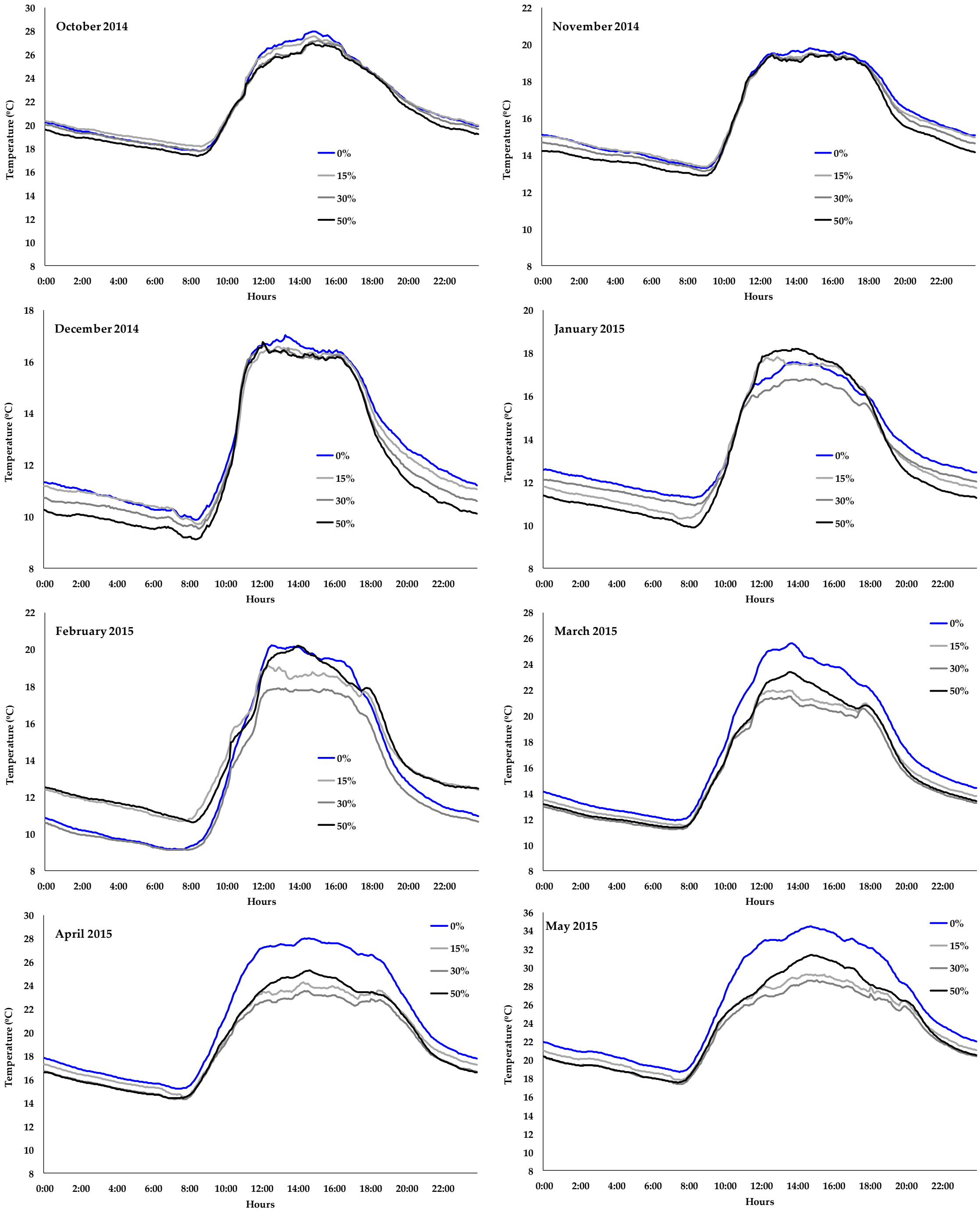


**Figure 10.** Average daily evolution of temperature in shadow treatments (0%, 15%, 30% and 50%) for the studied months.

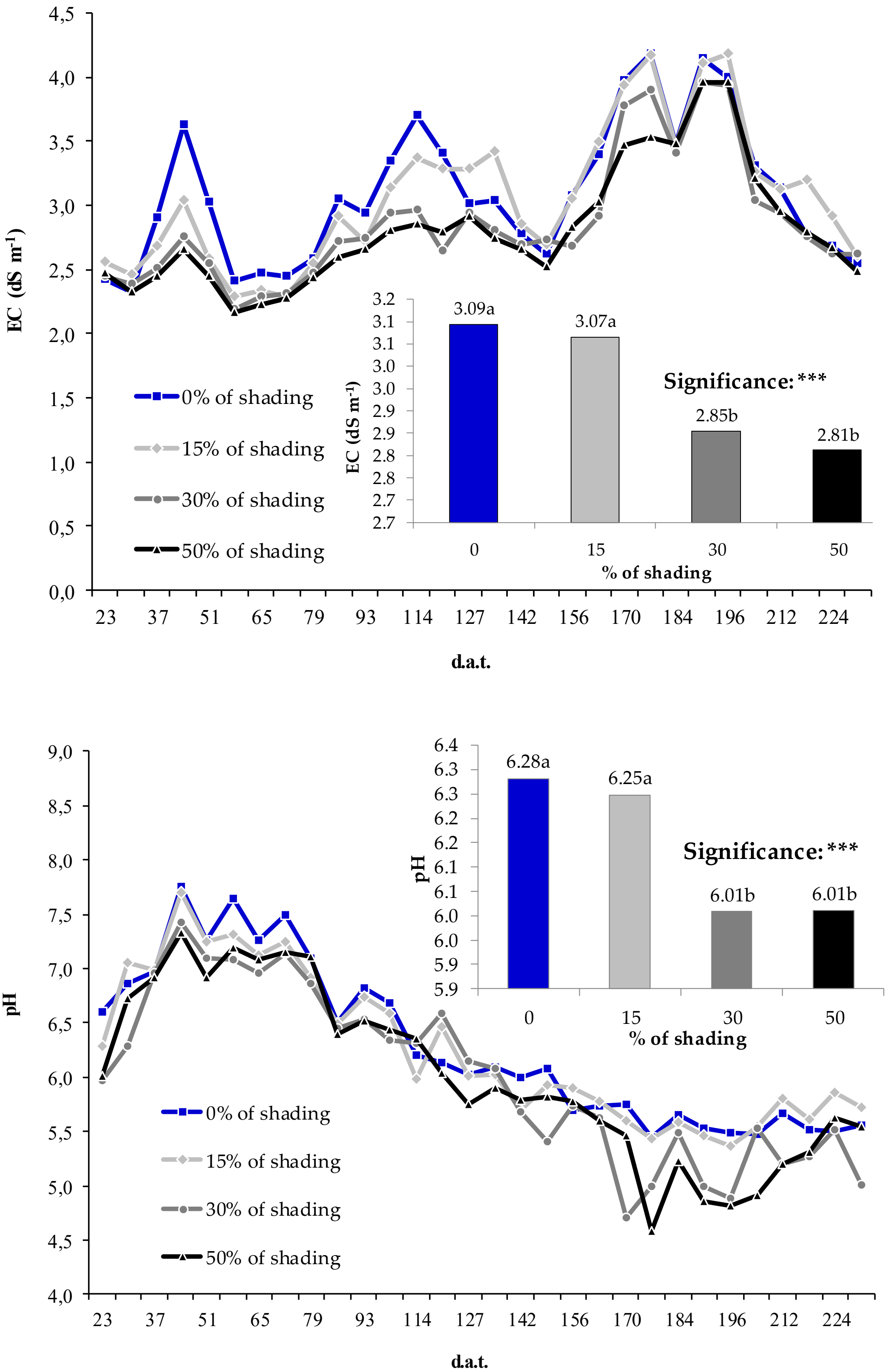


**Figure 11.** The pH and Electric Conductivity (EC) average evolution during the studied period in the substrate solution. In the period average, the analysis of the variance is performed according to the Yij model = μ + αi + βj + εij. The nomenclature n.s., *, ** and *** indicates not significant or significant for $p \leq 0.05$, 0.01 and 0.001, respectively. Numerical values for each column followed by different letters denote statistical significance for $p < 0.05$ according to the corrected minimum significant differences (LSD) test.

### 3.3. Shading Effects on Crop Yields

The different shading treatments studied affected the crop yields significantly. Both total yields (Table 1) and accumulated marketable yields (Figure 12) were significantly higher in the control treatment (0% of shadow) compared with the shadowed treatments (15%, 30% and 50%) for the whole studied period. Regarding the different shadow treatments the total yield and total marketable yield was significantly higher in the 15% shadow treatment than in the 30% and 50% shadow treatments (with an exception in the marketable yield in 141 d.a.t). Differences between 30% and 50% shadow treatments were only remarkable on data collected 131 and 239 d.a.t in regards to the total production and 131 and 161 d.a.t in regards to the marketable production. Besides, the shadow percentage was proportionally inverse to the yields obtained, meaning, the shadow percentage increase produced a linear reduction of yields.

**Table 1.** Effects of shadow treatments in the total accumulated yield (kg·m$^{-2}$) in a tomato crop.

| % Shading | Days after Transplant | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 113 | 131 | 141 | 161 | 181 | 209 | 222 | 239 |
| 0% | 1.02a | 3.5a | 5.3a | 8.5a | 12.9a | 15.7a | 17.3a | 18.8[a] |
| 15% | 0.60b | 2.1b | 3.2b | 5.5b | 9.4b | 11.9b | 14.1b | 16.9b |
| 30% | 0.19c | 1.4c | 2.3c | 4.1c | 7.4c | 9.1c | 10.5c | 13.4c |
| 50% | 0.01c | 0.7d | 1.5c | 3.3c | 6.3c | 7.8c | 9.0c | 11.5d |
| Significance | *** | *** | *** | *** | *** | *** | *** | *** |

Analysis of the variance is performed according to the Yij model = μ + αi + βj + εij. The nomenclature n.s., *** indicates not significant or significant for $p \leq 0.001$. Numerical values for each column followed by different letters denote statistical significance for $p < 0.05$ according to the corrected minimum significant differences (LSD) test.

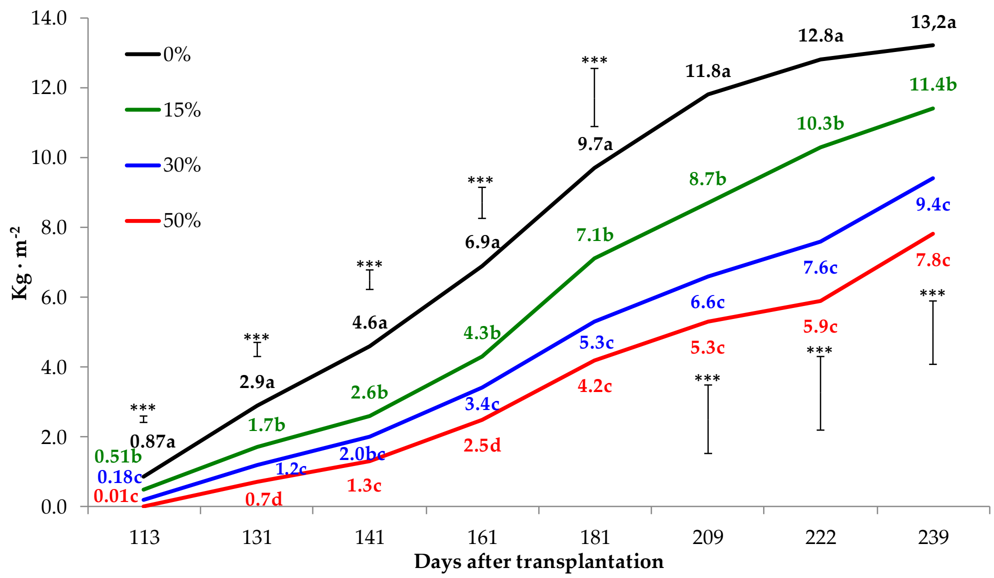


**Figure 12.** Shading effects on the temporal evolution of accumulated marketable yield (kg·m$^{-2}$). Results comes from the analysis of the variance that is performed according to the Yij model = μ + αi + βj + εij. The nomenclature n.s., *, ** and *** indicates not significant or significant for $p \leq 0.05$, 0.01 and 0.001, respectively. Numerical values for each column followed by different letters denote statistical significance for $p < 0.05$ according to the corrected minimum significant differences (LSD) test. The error bars correspond to the values of minimum significant differences according to the corrected LSD test. The nomenclature n.s., *, ** and *** indicates not significant or significant for $p \leq 0.05$, 0.01 and 0.001, respectively.

The studied levels of shadowing also produced a reduction of early production in 113 and 131 d.a.t data collection. The control treatment (0% shade) had a significantly higher early production rate compared with shadowed treatments (Table 1 and Figure 12). During the first harvesting season (113 d.a.t), plants in the 15% shadow treatment had a decrease of a total yield of 41% and 43% in marketable yield, in regards to values obtained in the control treatment (0% shade). In plants with the 30% shadow treatment, this reduction was 81% and 60% respectively. Finally, in the 50% shadow treatment, a low and insignificant production was recorded.

Finally, shadow treatments caused a delay in the production at the end of the cropping season (239 d.a.t). In 174 d.a.t data collection, a cultural technique of terminal bud elimination was applied, to avoid new vegetative material development and to foster fruits development in the last tomato clusters. In shadowed treatments a higher production of green fruits in the last harvesting season was observed (Figure 13). The control treatment (0% of shadow) showed a significantly lower production of green fruits (0.36 kg·m$^{-2}$) in regards to the shadow treatments (15%, 30% and 50%) where green fruits were 0.91, 1.52 and 1.32 kg·m$^{-2}$ respectively.

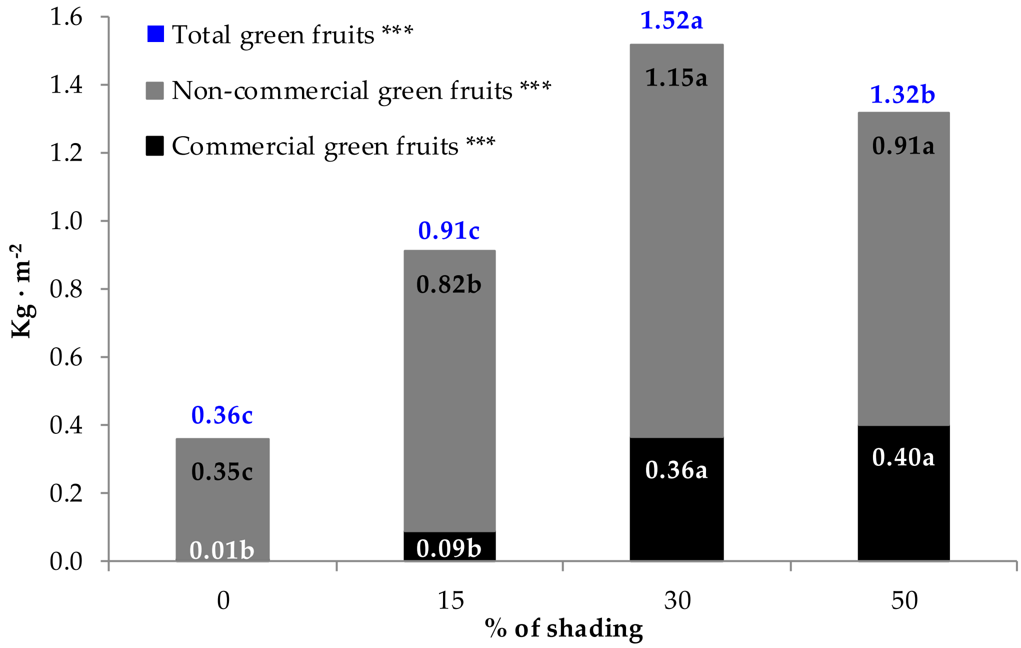


**Figure 13.** Shadow effects on the green fruits yield (kg·m$^{-2}$; total, commercial and non-commercial) harvested in the last harvesting period (239 d.a.t). Results comes from the analysis of the variance that is performed according to the Yij model = μ + αi + βj + εij. The nomenclature n.s., *, ** and *** indicates not significant or significant for $p \leq 0.05$, 0.01 and 0.001, respectively. Numerical values for each column followed by different letters denote statistical significance for $p < 0.05$ according to the corrected minimum significant differences (LSD) test.

The excessive shading percentage in the 50% shadow treatment produced a significant reduction in the number of produced fruits by plants in regards to the control treatment, (0%) and the 15% shadow treatment. The number of commercial fruits did not show significant differences between the control treatment (0%) and 15% and 30% treatments. However, a reduction of the number of fruits associated to the shadow percentage could be observed (Figure 14). Higher yields of commercial fruits were produced in the control treatment (0% shade) with 128 fruits·m$^{-2}$, followed by the 15% shadow treatment (119 fruits·m$^{-2}$), and the 30% shadow treatment (103 fruits·m$^{-2}$). In the 50% shadow treatment the number of fruits (86 fruits·m$^{-2}$) were the lowest, however no significant differences with 15% and 30% treatments were found.

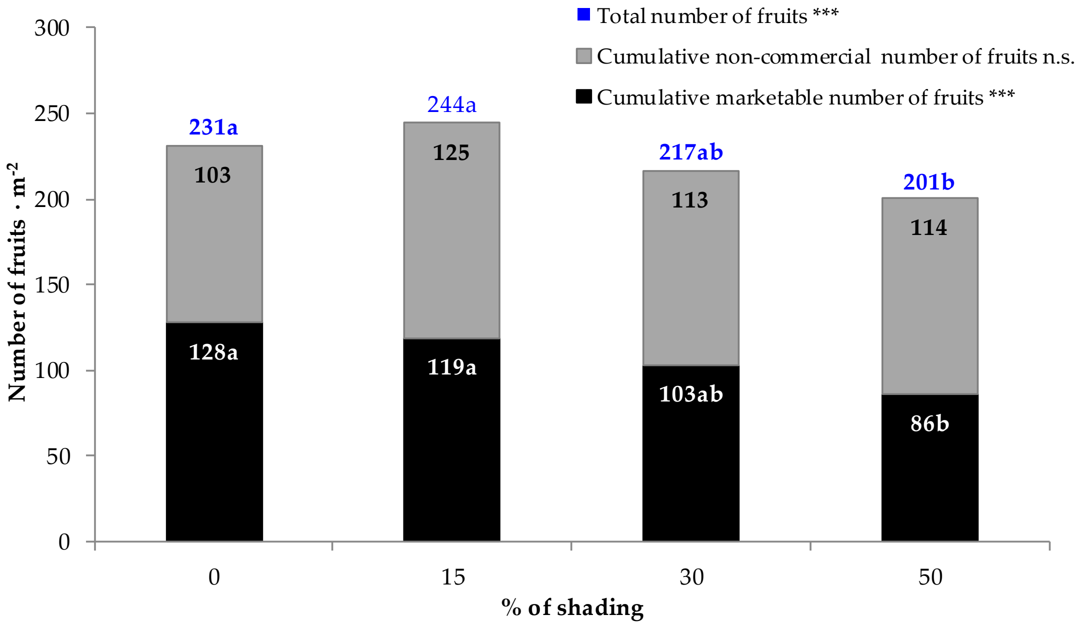


**Figure 14.** Shading effect on the number of fruits (total, commercial and non-commercial) by $m^{-2}$, harvested in the last harvesting period (239 d.a.t). Results comes from the analysis of the variance that is performed according to the Yij model = μ + αi + βj + εij. The nomenclature n.s., *, ** and *** indicates not significant or significant for $p \leq 0.05$, 0.01 and 0.001, respectively. Numerical values for each column followed by different letters denote statistical significance for $p < 0.05$ according to the corrected minimum significant differences (LSD) test.

### 3.4. Shading Effect on the Fruit Quality

Among the fruit quality parameters studied only the firmness, TSS and Croma of the fruits were significantly different between treatments (Table 2). Fruit weight registers show a decrease in the values when increasing shadow percentage area. However no statistically significant differences were found. The highest values of TSS were founded in 0% and 15% treatments, with values of 4.49 and 4.60 °Brix respectively. Among this, these treatments showed significant differences with 30% and 50% shadow treatments, where values registered were 4.43 and 4.40 °Brix. The pH of the fruit was very similar in the different treatments. However, the firmness of the fruit increased significantly with increasing shading treatments. Firmness of the fruit was significantly lower in the control treatment (0% shade) with a 4.3 N value, among 30% and 50% shadow treatments, which showed 4.7 and 4.8 N respectively.

**Table 2.** Shading effects on the fruit quality.

| % Shade | AFW (g) | Croma | Firmness (N) | TSS (°Brix) | pH |
|---|---|---|---|---|---|
| 0% | 101.6 | 30.15[a] | 4.3c | 4.49a | 4.40 |
| 15% | 97.0 | 27.92b | 4.5bc | 4.60a | 4.38 |
| 30% | 95.6 | 27.43c | 4.7ab | 4.43b | 4.40 |
| 50% | 94.9 | 27.40c | 4.8a | 4.40b | 4.45 |
| Significance | n.s. | *** | *** | *** | n.s. |

AFW: Average Fruit Weight. TSS: Total Solids Solubles. Analysis of the variance is performed according to the Yij model = μ + αi + βj + εij. The nomenclature n.s., *** indicates not significant or significant for $p \leq 0.001$. Numerical values for each column followed by different letters denote statistical significance for $p < 0.05$ according to the corrected minimum significant differences (LSD) test.

Fruit color showed significant differences between shadow treatments. The intensity of the fruit color, represented by the croma, increased when shadow percentage was reduced (Table 2). The control treatment showed the highest color intensity, with a 30.15 croma value, besides this asseveration, it could be seen with the highest values of a* and b* (Figure 15).

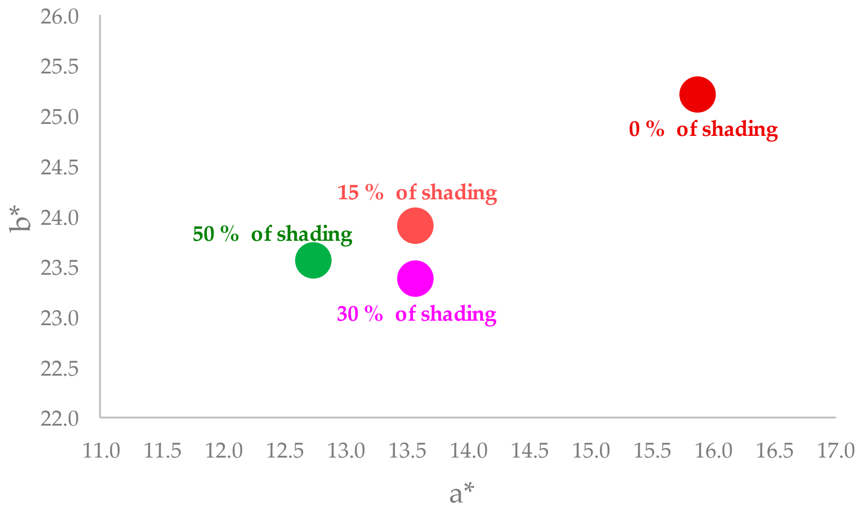


**Figure 15.** Shading effects of fruit color.

## 4. Discussion

The highest outside and inside radiation were registered in May, while the lowest radiation happened from November to January. This behavior pattern is usual in South–eastern Spain, as described by other authors whose work was also developed in the area [24,25]. The use of photovoltaic panels reduces the solar radiation inside the greenhouse, increasing while the number and opacity of these panels increase. In the present study, photosynthetic active radiation (PAR) in the control treatment was higher, and PAR radiation reduction was proportionally higher than the shading surface increase in the different treatments studied (15%, 30% and 50%). This effect was also described by Bulgari et al. [44]. According to this, Cossu et al. [26] claim that the annual global radiation decreases by 0.8% for each additional 1.0% of photovoltaic panels located in a roof-top greenhouse. In this study, 1.0% of an additional shadowed area in the roof-top (as an average value for 15%, 30% and 50% treatments) caused a 1.6% decrease of PAR radiation.

The reduction of light striking on tomato plants decrease photosynthesis and yields [45]. Excessive shading that would produce photovoltaic panels located in the roof-top in the greenhouse in the present study reduced the total and commercial yields in the crop. The main reason for yield loss is the gap in the energy balance that occurs inside the greenhouse. This affirmation is according to other authors, which asseverates that a high shading level reduces tomato yields in greenhouse crops, because of a radiation reduction [27,28,31,44,45].

Besides, the increasing % of shadow caused proportional reduction in crop yields, as described by Callejón-Ferre et al. [30], the high shadow rate studied caused, in addition, a reduction on the early yields, delaying production at the end of the crop, as described by Cockshull et al. [27]. Due to this, shading % higher than 30% produced a higher number of green non-commercial fruits at the last harvesting season. Results of this study shows that covering a roof-top greenhouse with a high number of photovoltaic modules excessively reduces the inside radiation to levels that affect crop yields, even in low-latitude Mediterranean countries, where radiation is not usually a limiting factor for crop development.

Previous studies show that shading the whole roof-top area of the greenhouse reduces the number of produced fruits and these are the tiniest [27,46,47]. Other studies show that shading is moderated, fruit size is lowest and no yield effects are shown [24,25]. Both affirmations are a coincidence with the present study, where excessive shading decreased the number of harvested fruits, and they were also tinier. In addition, the reduction on fruit weight was highest as shading percentage increased.

In Mediterranean countries, where solar radiation satisfied the plant's needs enough, roof-top greenhouse moderate shading with photovoltaic panels does not affect the production and quality parameters in a tomato crop like TSS, color, firmness and pH [24,25]. However, excessive shading can affect fruit quality [1,26]. Previous studies in the south–eastern Spanish greenhouse production area [30] showed that shading over 40% increases the firmness of the fruits and decreases the Total Solids Soluble.

In the present study, shading levels over 30% decreased the TSS and increased firmness in regards to the control treatment. In the study of the intensity of the red color of the fruit, there was a reduction in regards to the treatment control of the shaded treatments. Fruit pH was not affected by shading treatments. This was also described by other authors applying moderate [24,25] and/or high [30] shading rates. Dorais et al. [48] asseverate that tomato fruit quality was highly affected by the environment (radiation intensity and duration, temperature, irrigation, fertilization, etc.). Tomato plants cultivated under high radiation conditions produce fruits with a high concentration of sugars [49], thus, sugar concentration of tomato crops in photovoltaic greenhouses is connected to solar radiation availability. This fact, justifies, in the present study, the reduction of TSS in shading treatments over 30%.

## 5. Conclusions

The installation of a high number of photovoltaic modules in a roof-top North–South oriented greenhouse reduces excessively inside radiation in the greenhouse, affecting crop yields, even in Mediterranean countries, where radiation is not usually a limiting factor for crop development. Total and commercial yields are proportionally inverse to the increase of the shading percentage. Besides, excessive shading reduces the number and size of fruits produced.

High shading percentages studied reduced as well as early yields and delayed the production at the end of the cropping season. This reduced the production of green non-commercial fruits in the last harvesting season for shading treatments over 30%.

Moderate shading did not affect the quality of fruits, with a color exception, which was negatively affected for shading percentages over 15%. Shading treatments over 30% decreased fruit quality. TSS was reduced in high shading treatments in regards to the control treatment. The pH of the fruit was not affected by the shading treatments.

Results of this study provide evidence of effects of shading percentages over 15% in a roof-top greenhouse with photovoltaic panels. The inside radiation reduction damages the yield and quality of a tomato crop. Considering the conclusions obtained in the present study, the authors thought that further research needs to be developed on the matter, to study the effects on other commercial crops and greenhouse structures, and to determine which are the constraining factors for crop production along the year, depending on the radiation, temperature and shading percentages.

**Author Contributions:** Conceptualization, G.L.-D. and A.C.-O.; methodology, M.D.-P.; software, M.D.-P.; validation, G.L.-D., H.F. and C.P.; formal analysis, M.D.-P and A.C.-O.; investigation, G.L.-D; resources, G.L.-D.; data curation, M.D.-P; writing—original draft preparation, M.D.-P. and A.C.-O.; writing—review and editing, A.C.-O., H.F. and C.P.; visualization, G.L.-D.; supervision, A.C.-O.; project administration, G.L.-D.; funding acquisition, G.L.-D. All authors contributed equally to the manuscript, and have approved the final manuscript. All authors have read and agreed to the published version of the manuscript.

**Funding:** SOLNOVA Project (TECNOVA), University Research Contract Numbers 401428, 401431, 401453 and 401461.

**Conflicts of Interest:** The authors declare no conflict of interest.

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