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The Effect of Diffuse Film Covers on Microclimate and Growth and Production of Tomato (*Solanum lycopersicum* L.) in a Mediterranean Greenhouse

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Abstract: The efficient use of light is one of the most important factors for the development of greenhouse crops. It is increasingly necessary to use film covers that enhance transmittance and the proportion of diffuse light to generate a more homogeneous light distribution. The objective of this study was to evaluate the effect that an experimental film cover with high transmittance and high light diffusivity produces on the microclimate and the growth and yield of tomato crops (*Solanum lycopersicum* L.), compared with a commercial thermal film cover. The trial was developed during a spring–summer growing cycle in a multispan greenhouse divided into two compartments (sectors) separated by a vertical polyethylene sheet. In the East sector, a commercial film was installed (transmittance of 85% and diffusivity of 60%) and in the West sector, an experimental film was used (transmittance of 90% and diffusivity of 55%). The results show an increase in the marketable yield of 0.25 kg·m^{-2} in the sector with the experimental film, which represents 3.2% growth with respect to the commercial film. The photosynthetic activity measured in tomato leaves was 21.5% higher in plants growing in the sector with the experimental film, with had the highest transmittance. The increase in radiation transmittance of 14% produced greater photosynthetic activity without generating a higher inside air temperature at the crop level (at the height of 2 m above the floor). However, the mean temperature of the soil surface was statistically higher on the side with the diffuse experimental cover film, as a logical consequence of the higher level of intercepted solar radiation.

Keywords: greenhouse; tomato crop; diffuse film; yield; photosynthetic activity

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1. Introduction

Sunlight distribution is a fundamental factor in the development of crops affecting the light use efficiency in the greenhouse and significantly influence the growth and yield of crops [1–3]. When light energy is excessive, it can cause discoloration of the leaves or even necrosis in extreme cases [4]. Light damage primarily occurs as a result of prolonged exposure to excessive light intensity peaks [5–7]. Inside greenhouses, the distribution of light on the different leaves of a plant shows great variation depending on the solar angle, shadow-producing points, and areas of direct sunlight. Damage caused by light can occur particularly at these points of direct sunlight [8], whereas diffuse light is more uniformly distributed over crops than direct light [9–12].

Greenhouse crops require a lot of light in winter and can use a high proportion of diffuse light in summer [13]. Excessive radiation coupled with high temperatures can lead to a persistent decrease in the efficiency of converting solar energy into photosynthesis, a process known as photoinhibition [14–17]. Tomato photoinhibition can occur at 30–40 °C and high radiation levels (1500–1800 µmol·m^{-2}·s^{-1}) [18,19].

Diffused light causes less photoinhibition, due to less severe local peaks in light intensity, and allows the temperature of leaves or flowers to decrease [11,20,21]. Generally, solar radiation inside a greenhouse is not distributed homogeneously. Leaves in the canopy bottom may suffer from an energy deficit, causing a drastic decrease in photosynthetic activity [22,23], while the excessive light energy at the top canopy can produce photoinhibition and a reduction in photosynthesis [24,25].

Plants use diffuse light more efficiently than direct light as a consequence of its better penetration into the canopy and due to the non-linear response to the light flux density of the photosynthetic rate of individual leaves [26]. Several climate change models have estimated increases in diffuse light due to atmospheric water vapor as a result of increased cloud cover [27–29]. Photosynthesis in leaves can be 10–15% higher under direct sunlight exposure compared to irradiance with an equivalent amount of diffuse light [23]. This suggests that direct and diffuse light affect photosynthetic processes differently [30], depending on the adaptation of the leaves to sun exposure or shady conditions [23].

To take advantage of diffuse light in the greenhouse, covering materials are used to increase light diffusion without reducing transmission [31]. Under diffuse covering materials (capable of transforming 45% to 71% of direct light into diffuse light), the light profiles are more homogeneous, increasing yield and growth of crops [11,31,32]. Diffuse light distributes photosynthetically active radiation more uniformly to all leaves in a canopy, increasing the overall rate of photosynthesis [33]. Therefore, diffuse covers can rise the amount of integral daily light without causing damage. The increase in the total amount of daily light improves growth and development of the plants [34,35]. Fausey et al. [36] observed a linear relationship between the amount of light and dry mass of shoots in several perennial herbaceous species grown in greenhouses. Hemming et al. [31] recommended the use of cover materials with a minimum diffusivity of 50% and a transmittance of 90%.

Lawlor [37] suggested that plant growth and production are determined by several processes at the chloroplast, leaf, and canopy levels. The total net dry matter production (root and shoot) from germination to harvest is determined by the total amount of photosynthetically active radiation (PAR) intercepted by plants and the efficiency to convert energy to dry matter [37].

The interception of radiation by crops depends on the architecture of the canopy and the area and angle of inclination of leaves [37]. The light interception and radiation use efficiency (RUE) are essential components of plant performance [38]. These components vary by species and environment [39–43], leading to differences in crop production. The use of light scattering greenhouse covers increased cucumber and tomato production by 9% [44] and 11% [13], respectively. Choice of greenhouse covering plastics by growers depends on many factors as available solar radiation, crop value, cost of the films and its duration [45]. The covering material is a basic factor influencing the energy consumption, the yield and the general economics of the greenhouse [46]. It is widely accepted that a good material must have maximum transmittance in the PAR spectrum and minimal transmittance in the long waveband [47]. Therefore, choosing the material to cover a greenhouse is an extremely important factor in maintaining crop development, as it can alter the transmission of solar radiation in the greenhouse, benefiting plants according to their demands [48]. The selection of a suitable film cover could reduce the cooling load by 10% [46]. When selecting a film cover it is also necessary to take into account the flow density of photosynthetic photons, since there may be a decrease in the photosynthetic rate and therefore a reduction in the production of crops under greenhouse [49].

Some works studied the effects of different greenhouse covers, on plant growth and productivity. Aubergine production under UV stabilised polyethylene, IR absorbers polyethylene and double and single layers of polyethylene was investigated in eight greenhouses of 27 m^2 [50]. In the same way, the effect on cucumber productivity of new greenhouse covers with modified light regime was evaluated under eight high polytunnels (72 m^2), in comparison with several commercial covers as controls [51]. The effect of diffuser and blue-colored plastic cover films on the production of tomato crops was evaluated in two arch-detached type greenhouses of 225 m^2 [52]. The effect of two different covering materials, tempered glass and white polyethylene mesh, on solar irradiance was compared to open field (control) under real farming conditions. Both covering materials reduced the photosynthesis rate due to decrease of the photosynthetic photon flux density (PPFD) at pepper plant leaves [49].

Several works also investigate the degradation of the radiative properties of plastic films that was exposed for 12–13 months to Mediterranean [53] and arid climates [52,54]. These tests were carried up under greenhouse models of reduced sizes (2, 1 and 20 m^2, respectively). Greenhouse covers deteriorate rapidly and their optical performance decreases. Exposure of conventional film cover to arid climate agents for one year reduced spectral properties, increasing total radiation reflected and reducing transmittance to global solar radiation and PAR [52,54–56].

Greenhouses shelter the crop from unfavorable environmental conditions and the covering largely contributes to creating beneficial growing conditions inside [57]. The typical greenhouse in the sub-tropical/Mediterranean climate is low technology, relying on solar radiation capture for passive increase of temperature in winter, and whitewash to limit it in spring/early autumn [57]. This type of greenhouse has usually (too) small ventilation, is controlled manually and has typically no summer production. The increase of side ventilation surface (from 9.6–16.8% to 15.3–33.8%) can allow augmentations of 4.3–8.3% of tomato yield in Mediterranean greenhouses [58].

The productivity of horticultural crops in Mediterranean greenhouses with passive climate control is well below the values obtained in greenhouses in other climate areas with less favored conditions for agricultural production. Thus, the average productivity of plastic greenhouse tomato production in Almería (Spain) was 9.3 kg/m^2 in 2019 [59], well below the 50.5 kg/m^2 reached in the Netherlands in glasshouses with heating systems [60]. The main limiting factor of greenhouse crop production faced by growers of the Mediterranean sub-tropical region is the reduction of photosynthesis, affected by the light deficiency in winter and excess temperature in summer [57]. During the winter period, exterior solar radiation is below the optimum to horticultural crops. In the Mediterranean region, as in other climatic regions, an increase in the transmissivity of the cover allows to increase the photosynthetic activity of the crops and their productivity. In the spring-summer period, the transmissivity of the cover is artificially limited using cover whitewash [61]. Cover whitewashing is used as a method to decrease indoor air temperature, reducing the energy supply by solar radiation. However, cover whitewashing has the disadvantage of drastically reducing photosynthetic activity far below the optimum of plants [62]. One way to increase photosynthesis is reduce cover whitewashing and improve the natural ventilation of greenhouses [58].

With the goal of increasing photosynthetically active radiation within the greenhouses of Almeria, the project "Improving profitability in greenhouses by increasing photosynthetic activity with passive climate control techniques (GREENPHOC)" is being developed from 2020 to 2024. In particular, one of the research lines of the project is the increase of the transmissivity and diffusivity of greenhouse covers to improve the PAR radiation intercepted by the crop. Other research lines within the project include the use of interior double roof with spectrum conversion films, the use of reflective soil mulch and the increase in ventilation surface. The combination of these different passive methods can help to reduce or eliminate the need of cover whitewashing, allowing the improvement of crop photosynthesis and productivity.

The aim of this study was to investigate the behavior of an experimental high transmittance diffuse film cover compared to that of a commercial diffuse film cover over a tomato crop (*Solanum lycopersicum* L.). For this objective, the effect on the microclimate inside the greenhouse, the photosynthetic activity, the growth of the crop, and the yield and quality of the fruits in a spring-summer cycle were analyzed.

2. Materials and Methods

2.1. Description of the Experimental Greenhouse

The experimental trial was carried out at a multispan greenhouse, located in the Experimental Station "*Catedrático Eduardo Fernández*" of the Center for Innovation and Technology Transfer "Fundación UAL-ANECOOP" (Latitude: 36°51′53.2″ N Longitude: 2°16′58.8″ W; Altitude: 87 m). The greenhouse is 1800 m^2, and its main axis is parallel to the northeast/southwest direction (118° in relation to the North direction).

The greenhouse has roof vent openings on the ridges of its five spans (Figure 1), which are protected with insect-proof screens with 10 cm × 20 cm threads. Ventilation is controlled by Synopta software (HortiMax B.V., Maasdiijk, The Netherlands) and a centralized climate control and data logging system (HortiMax B.V., Maasdiijk, The Netherlands) with a weather station.

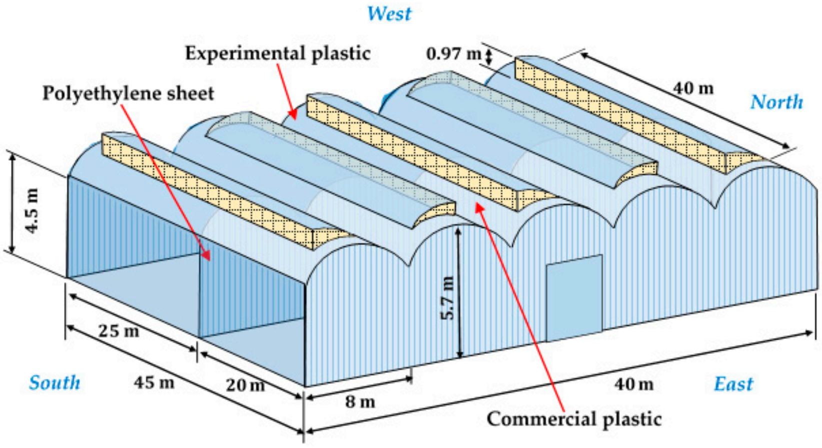


Figure 1. Greenhouse with diffuse commercial film in the East sector and greenhouse with diffuse experimental film in the West.

The greenhouse was divided into two compartments or sectors, separated by a vertical plastic sheet, with the same characteristics as those used in the roof of the greenhouse in the West sector (Table 1).

Table 1. Characteristics of the two greenhouse sectors: Length L_G [m] and width W_G [m], ground surface S_C [m^2], vent opening surface S_V [m^2], and ventilation surface percentage [S_V/S_C].

Sector	Plastic Cover	$L_G \times W_G$	S_C	S_V	S_V/S_C
East	Diffuse commercial film	40 × 20	800	84.9	10.6
West	Diffuse experimental film	40 × 25	1000	109.1	10.9

In the West sector, where the temperature, humidity and radiation sensors used by the climate controller for ventilation management are installed, a new experimental diffuse film was fitted in the greenhouse cover, and in the East sector, a commercial diffuse film cover (AA Politiv (1999) Ltd., Kibbutz Einat, Israel) was placed. The optical properties of the two types of film were determined in the laboratory following the UNE-EN 13206: 2017 + A1 [63] and ASTM D 1003-13 standards [64] (Table 2).

Table 2. Optical properties of the diffuse cover films supplied by the manufacturer that were used in the trial. Transmission of photosynthetically active radiation T_{PAR} [400–700 nm], transmission of ultraviolet light T_{UV} [300–380 nm], diffusion of light D, and thermal efficiency T.

Plastic Cover	T_{PAR}	T_{UV}	D [%]	T [%]
Diffuse commercial film	0.85	0.24	60	85
Diffuse experimental film	0.90	0.24	55	90

2.2. Microclimate Measurement Equipment

To compare the effect of the two diffuse light plastic films on the microclimate, twelve autonomous HOBO® Pro Temp-HR U23-001 (Onset Computer Corp., Pocasset, MA, USA) dataloggers with temperature and humidity sensors were located in the mean vertical profiles of both sectors at heights of 1, 2 and 4.5 m in the two central spans of the greenhouse.

On 31 March 2020, these dataloggers were replaced by twelve sensors CS215 (Campbell Scientific Spain, Barcelona, Spain) to collet inside air temperature and humidity measurements (Table S1). These new sensors were connected to two autonomous CR3000 Microloggers (Campbell Scientific Spain, Barcelona, Spain). Other sensors were also connected to these microloggers to measure solar and PAR radiation, temperature of tomato leaves, soil surface temperature, and soil heat flux (Table S1). The outside climatic parameters were measured by a meteorological station located 135 m north of the experimental greenhouse.

The autonomous HOBO air temperature and humidity sensors were protected from solar radiation by open boxes, and the CS215s connected to the CR3000 measurement boxes were placed inside 41303-5a solar protectors (Campbell Scientific Spain, Barcelona, Spain). The thermistors used to measure the temperature of tomato leaves were wrapped inside with the upper part of the sensor in contact with the leaf underside and the lower part covered by a WicuEco flexible polyethylene thermal insulator (KME Germany AG and Co, Osnabrück, Germany) to avoid direct contact with air.

2.3. Crop System

On 23 December 2019, a tomato crop (*Solanum lycopersicum* L.) of HM's HMC44698 F1 variety Clause Iberica S.A. (La Mojonera, Spain) was transplanted into the greenhouse. Plants were grown in "arenado" sand mulched soil [61] with a density of 1.5 plants/m^2 (0.5 m × 1.5 m), with the crop lines perpendicular to the greenhouse ridges.

2.4. Measurement Equipment for Crop Development and Yield Analysis

To determine the influences of different films on tomato yield, three lines of plants were selected in each sector (considered statistical replications). Marketable and non-marketable yield was weighed weekly with a Mettler Toledo electronic balance (Mettler-Toledo, S.A.E., Spain) with a sensitivity of 20 g and a maximum capacity of 60 kg.

To determine growth, 16 randomly selected plants were evaluated in each sector. The data were collected every 15 days, and the instruments used were a measuring tape and a digital gauge with a measuring range of 0–150 mm and an accuracy of 0.01 mm (Medid Precision, SA, Spain). The morphological parameters were [65]: total plant length, $\boldsymbol{L_T}$ (cm); apical meristem length, $\boldsymbol{N_T}$ (cm); internode length, $\boldsymbol{L_I}$ (cm); stem diameter, $\boldsymbol{D_S}$ (mm); number of nodes, $\boldsymbol{N_N}$; and length of the last developed leaf, $\boldsymbol{L_L}$ (cm).

For the evaluation of the fruit quality, ten tomatoes (every harvest date) were randomly selected from each sector. We characterized tomato fruits by measuring their weight [66] and diameters [67], soluble solids content [65,66], core firmness [66], and dry matter content [65,66]. The instruments used were an electronic balance PB3002-L Delta Range® (Mettler Toledo, SA, L'Hospitalet de Llobregat, Spain) with a measuring range of 0–600 kg and an accuracy of 0.1 g for weight measurement ($\boldsymbol{W_F}$) and a digital gauge (Medid Precision, SA, Barcelona, Spain) with a measuring range of 0–150 mm and resolution of 0.010 mm for measuring the fruit equatorial diameter ($\boldsymbol{D_F}$). To determine the total soluble solids content ($\boldsymbol{T_{SS}}$), a few drops of tomato juice were placed on a PAL1 refractometer (Atago Co. LTD., Fukuoka, Japan) with a measurement range of 0–53% and an accuracy of 0.2%. Firmness ($\boldsymbol{F_F}$) was measured with a digital texture analyzer PCE-FM 200 (PCE- Ibérica SL, Tobarra, Spain) with a measuring range of 0–20 kg and an accuracy of 0.5 g. To determine the dry matter ($\boldsymbol{D_M}$) content, fruits were first dried at 70 °C for 48 h in an oven (23–240 I, FD series, Binder GmbH, Tuttlingen, Germany).

To estimate the fruit visual quality, three color parameters were measured with a CR-400 portable colorimeter (Konica Minolta, Morristown, NJ, USA) with an area of 8 mm for reflected color measurement and six silicon photodiode detectors (three for the measuring beam, three for lighting control). There are many different color space, when it comes to food the most used is CIE L* a* b* color space, due to its uniform color distribution and its perception of color is closer to the human eye [68]. The colorimeter was used to measure the three color-defining parameters on a sphere: ***L**** (white to black), ***a**** (green to red), and ***b**** (blue to yellow). The relationship between parameters ***a**** and ***b**** (chromaticity) was calculated.

2.5. Measurement of Photosynthetic Activity

To compare the effect of cover film used in the greenhouse on the photosynthetically active radiation (PAR) and photosynthetic activity of tomato plants, measurements were carried out with a photosynthesis analyzer following the methodology used by Jiang et al. [67]. LCI SD equipment (ADC BioScientific Limited, Hertfordshire, UK) consists of a portable console with blade clamping chamber equipped with a CO_2 and H_2O IRGA concentration sensor (infrared gas analysis) with a CO_2 measurement range of 0–2000 ppm, 0–75 mbar H_2O (accurately $\pm$ 2%), and 0–3000 m^{-2} s^{-1} PAR radiation. CO_2 and water vapor concentrations were measured from the known airflow in the chamber at the entrance and exit of the chamber to calculate CO_2 assimilation (photosynthesis) and leaf transpiration rate. Data collection was done once or twice per week, depending on the daily weather conditions. The camera that measures photosynthesis needs clear and sunny days for proper operation. The process of measuring and observing the data was carried out on fully randomly chosen plants on each measurement day. Measurements were carried out on the last mature leaves of each selected plant (a total of 12 leaves per sector). The path for reading data was different on each measurement day and was executed randomly to prevent the sun's position from having a distorting effect on measurements. In addition, the data were always recorded during the same time interval, between 12:00 and 12:30 h.

2.6. Statistical Analysis

Statistical analysis of the data was performed with Statgraphics Centurion XVIII (Statgraphics.Net) software using a variance analysis (considered significant if the p-value is $\leq$0.05) and comparing the average values with the Fisher's least significant difference (LSD) method. Previously, normality of data was assessed using the Kolmogorov Smirnov test. Bartlett, Cochran, and Hartley tests were used to determine whether the two sectors had similar parameter variations. When there was a statistically significant difference between standard deviations, parametric analysis by variance analysis was not feasible. In this case, a non-parametric analysis was performed with the Friedman test, in which each row represents a block (the measurement date) using the box-and-whisker plot [69]. The growth parameters and photosynthesis of twelve plants were evaluated, and ten tomato fruits were used for the analysis of the quality of the yield.

3. Results and Discussion

3.1. Microclimatic Conditions

3.1.1. Radiation Measurements

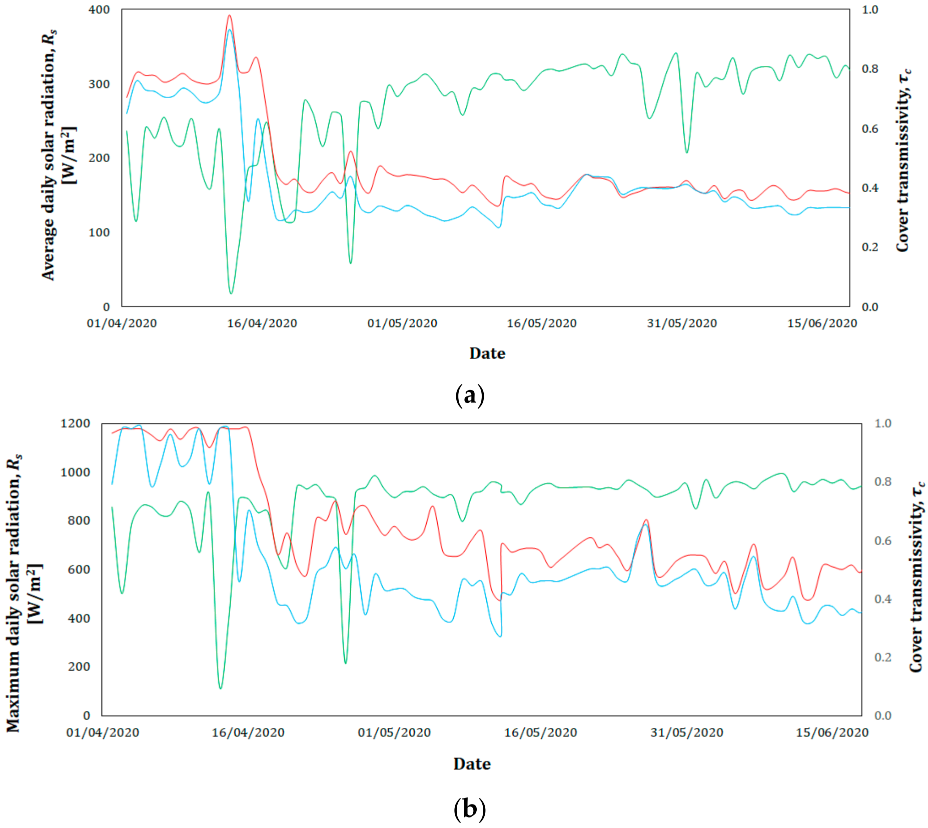
The use of the most transmissive experimental film resulted in a statistically significant increase in solar radiation of 14% (and in the transmittance of the cover) and an increase in photosynthetically active radiation (PAR) of 15% in terms of the mean values (Table 3). The differences between sectors for the daily maximum values of solar radiation and PAR were 28% and 25%, respectively (Table 3). According to Stanghellini [70], only half of the solar radiation available to the crop can be intercepted and absorbed by the leaves of canopy plants with a foliar area index (LAI) of <2 m^2 $m^{-2.}$ For high levels of solar radiation, the absorbed energy exceeds the amount of latent heat, resulting in an increase in the leaf temperature [70,71].

Table 3. Mean and maximum values of solar radiation $\boldsymbol{R_{SOL}}$, the transmittance to the solar radiation of the cover $\boldsymbol{\tau_c}$, accumulated radiation $\boldsymbol{\Sigma R_{SOL}}$, and photosynthetically active radiation $\boldsymbol{R_{PAR}}$ recorded in the two sectors of the greenhouse.

Parameters	East—Commercial Film	West—Experimental Film
	Average values from1/04/2020 to 18/06/2020	
R_{SOL} (W·m^{-2})	105.3 ^{a} ± 140.0	120.5 ^{b} ± 163.4
τ_c (mean·values)	0.43 ^{a} ± 0.16	0.49 ^{b} ± 0.16
ΣR_{sol} (MJ·m^{-2})	9.07 ^{a} ± 12.09	10.37 ^{a} ± 14.11
R_{PAR} (μmol·s^{-1}·m^{-2})	193.1 ^{a} ± 273.7	223.5 ^{a} ±303.4
	Average daily maximum values	
R_{SOL} (W·m^{-2})	442. 5 ^{a} ± 160.3	568.2 ^{b} ± 176.5
τ_c (mean·values)	0.53 ^{a} ± 0.21	0.66 ^{b} ± 0.19
R_{PAR} (μmol·s^{-1}·m^{-2})	859.0 ^{a} ± 411.8	1079.7 ^{b} ± 310.8

Values with different letters in the same column show statistically significant differences with a confidence level of 95.0% (p-value $\leq$ 0.05).

In mid-April, the cover was whitened, slightly increasing the transmittance difference between the East and West sectors in terms of the average values. Before whitening the cover, the experimental film produced an average transmittance that was 13% greater than that of the commercial film (0.79 with experimental film and 0.70 with commercial film) (Figure 2a). After whitening, the values of the greenhouse cover transmittance were reduced, changing to 0.41 with experimental film and 0.35 with commercial film (17% lower). Improvement in the transmittance of the new film observed in the field (13%) was higher than that obtained in laboratory trials (5.5%, as shown in Table 2).



(**a**)

(**b**)

Figure 2. Evolution of solar radiation outside the greenhouse (——) and cover transmittance inside the East sector with diffuse commercial film (——) and inside the West sector with diffuse experimental film (——). Average values (**a**) and maximum (**b**) daily values.

Cover whitening is a low-cost method to reduce the radiation load and modify the greenhouse environment in summer [72,73]. It is an effective method to achieve an adequate microclimate within greenhouses for plant development and to improve the quantity and quality of crops in warm and sunny regions [74].

The cover transmittance values for daily maximum values before whitening were 0.95 (14% higher) and 0.83 in the West and East sectors, respectively (Figure 2b). The value of 0.83 in the East sector with commercial film is consistent with the values measured previously on new commercial cover film of 0.80–0.87 [65]. Both field-measured values are higher than those obtained in laboratory tests (Table 2). Following the whitening of the cover, the maximum transmittance of the cover was reduced in both sectors, changing to 0.43 in the East sector with diffuse commercial film and 0.56 in the West sector with diffuse experimental film (30% higher).

Radiation variability was observed in early April as a result of cloudiness (Figures 2 and 3a). From May, less variable solar radiation curves (Figures 2 and 3b) were observed and the evolution of external radiation showed very little variability in May and June (Figures 2 and 3c,d). The increase in the transmittance difference observed after whitening is also related to the fact that, in early April, before whitening, external radiation was greatly affected by cloudiness, which increased the proportion of diffuse radiation outside the greenhouse.

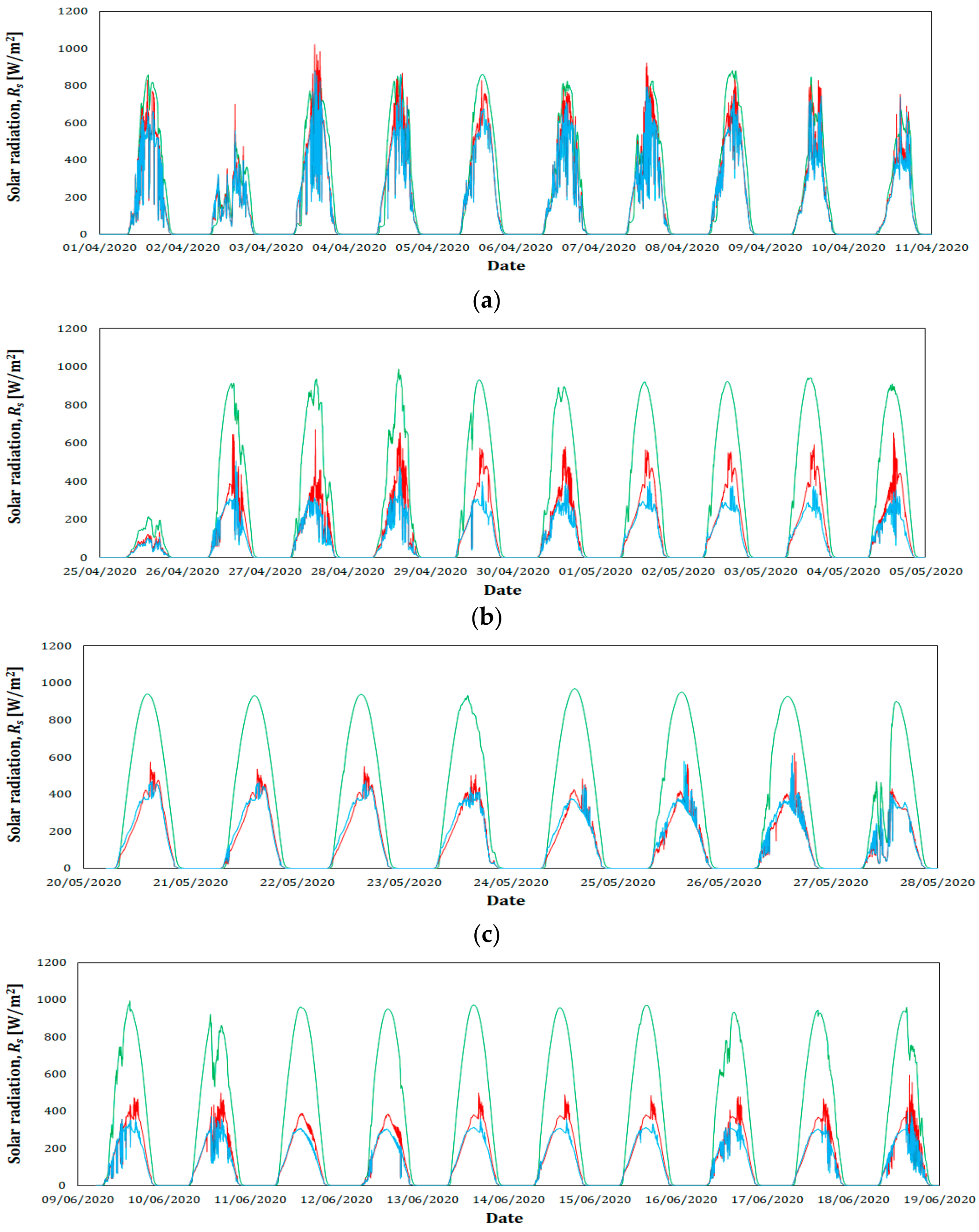
Under these circumstances, the transmittance of the cover was affected, resulting in a reduction in the radiation and transmittance difference of 13–14%. In spring–summer when cloudiness is almost non-existent in Almeria, the proportion of direct solar radiation increases considerably, and this was found to improve the effect of the experimental film, increasing transmittance in the West sector by 17–30% with respect to commercial film.

In spring–summer, when the proportion of direct solar radiation is higher and the curves measured on the outside show little variability, abrupt changes in solar radiation within both sectors are due to the shading effects of the structural materials of the greenhouse. Since the position of the sensors with respect to the geometric structure of the greenhouse was exactly the same in the two sectors, the shade on the sensors did not influence the mean difference in radiation, as evidenced by the concordance with the measurements made with the portable photosynthesis sensor (Table 9).

3.1.2. Air Temperature

The analysis of air temperatures at different measurement heights (1, 2, and 4.5 m) showed significant differences between the East sector with commercial film and the Western sector with experimental film at height of 4.5 m. At this height, the average temperature was about 0.2–0.7 °C higher in the sector with experimental film (Table 4), where solar radiation was higher (Table 3). In addition, the values were found to be higher when comparing the sensors placed in the northern and the southern parts of the greenhouse (Table 4).

However, at a height of 2 m, no statistically significant differences were observed between any of the four sensors, either between sectors or between the northern and southern parts of the greenhouse. This is certainly due to the cooling effect produced by the transpiration of the tomato canopy, which was similar in both sectors. In terms of the average values recorded at a height of 1 m, statistically significant differences were observed between the two sectors, although with different senses in the northern and southern parts. In the northern part, the temperature was higher in the Western sector with experimental film, while in the South, the highest temperatures were measured in the East sector with commercial film (Table 4).



(**a**)

(**b**)

(**c**)

(**d**)

Figure 3. Evolution of solar radiation outside the greenhouse (——) and within the East sector with diffuse commercial cover film (——) and within the West sector with diffuse experimental cover film (——). (**a**) Evolution of solar radiation from 01 April 2020 to 11 April 2020, (**b**) Evolution of solar radiation from 25 April 2020 to 05 May 2020, (**c**) Evolution of solar radiation from 20 May 2020 to 28 May 2020 and (**d**) Evolution of solar radiation from 09 June 2020 to 19 June 2020.

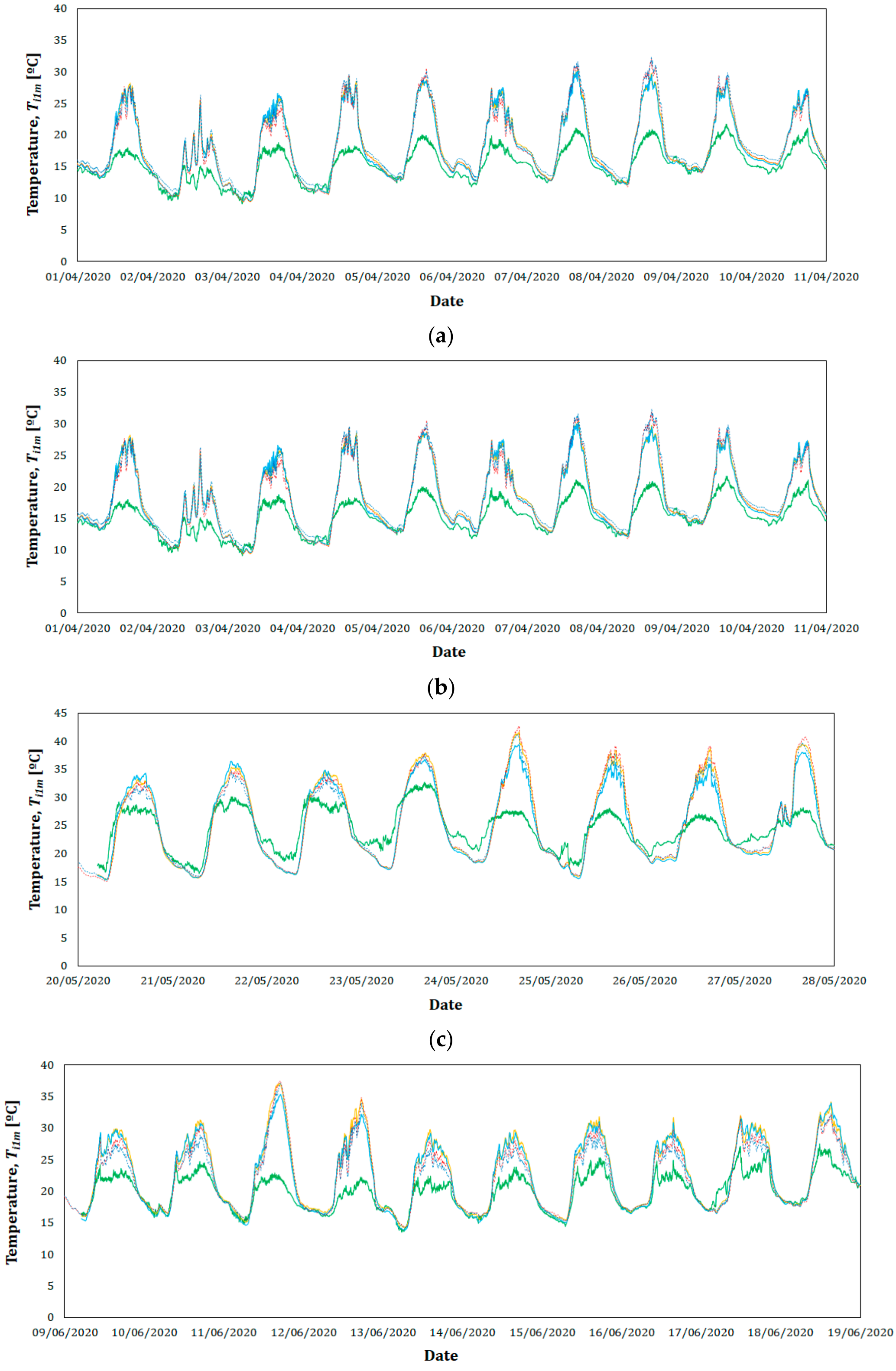
Table 4. Average, maximum, and minimum air temperature values measured at heights of 1, 2, and 4.5 m above the floor in the north and south areas of the two sectors of the greenhouse.

Parameters	East—Commercial Diffuse Film		West—Experimental Diffuse Film	
	North	South	North	South
Average values from 1/04/2020 to 18/06/2020				
$T_{1\,m}$ (°C)	$21.1^{a} \pm 6.0$	$21.4^{c} \pm 5.8$	$21.5^{d} \pm 6.2$	$21.2^{b} \pm 6.1$
$T_{2\,m}$ (°C)	$21.7^{a} \pm 6.7$	$21.3^{a} \pm 6.3$	$22.4^{a} \pm 6.9$	$21.4^{a} \pm 6.8$
$T_{4.5\,m}$ (°C)	$21.6^{a} \pm 7.2$	$21.9^{b} \pm 7.2$	$22.3^{c} \pm 7.2$	$22.1^{d} \pm 7.6$
Average daily maximum values				
$T_{1\,m}$ (°C)	$30.8^{a} \pm 4.0$	$31.2^{a} \pm 4.4$	$31.6^{a} \pm 4.4$	$31.4^{a} \pm 4.6$
$T_{2\,m}$ (°C)	$32.4^{ab} \pm 4.2$	$31.6^{a} \pm 4.4$	$33.5^{b} \pm 4.4$	$32.7^{ab} \pm 4.7$
$T_{4.5\,m}$ (°C)	$33.3^{a} \pm 4.1$	$33.5^{a} \pm 4.2$	$33.9^{a} \pm 4.2$	$34.4^{a} \pm 4.6$
Average daily minimum values				
$T_{1\,m}$ (°C)	$14.9^{a} \pm 2.0$	$15.4^{a} \pm 2.0$	$15.1^{a} \pm 2.2$	$15.0^{a} \pm 2.2$
$T_{2\,m}$ (°C)	$14.8^{ab} \pm 2.2$	$14.9^{ab} \pm 2.1$	$15.3^{b} \pm 2.3$	$14.6^{a} \pm 2.3$
$T_{4.5\,m}$ (°C)	$14.1^{a} \pm 2.1$	$14.5^{bc} \pm 2.1$	$14.7^{c} \pm 2.2$	$14.3^{ab} \pm 2.3$

Values with different letters in the same column show statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

The evolution of temperature at a height of 1 m above the floor was very similar for the four sensors throughout the measurement period (Figure 4), with a slight increase in the maximum temperature in the West sector with experimental film at the end of May (Figure 4c) and in early June (Figure 4d). At a height of 2 m, the maximum temperature was also 1 °C higher in the West sector, mainly at the end of May (Figure S1c) and in early June (Figure S1d). Similar behavior was observed for sensors located at a height of 4.5 m, where the maximum temperature value at midday was about 0.5–1 °C higher in the West sector with experimental film at the end of May (Figure S2c) and in early June (Figure S2d). Photosynthesis rapidly increases from 10 to 20 °C in many plant species, with optimal values from 20 to 30 °C [75]. The increase in photosynthesis decreased with temperature and was limited to areas with high temperatures [18]. For both sectors, PAR radiation values (Figure 5) remained below the limits for tomato photoinhibition, between 1500 and 1800 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. However, from 2 May 2020, the maximum temperatures recorded at heights of 1 and 2 m were between 30 and 40 °C, where the limit for photoinhibition of the tomato is situated [18,19].

To avoid these over-temperature problems in the future, after this trial, the experimental greenhouse was equipped with two 3 m high side roll-up vents. This change increased the ventilation surface from 10.8% at the time of the trial to 25.4%.



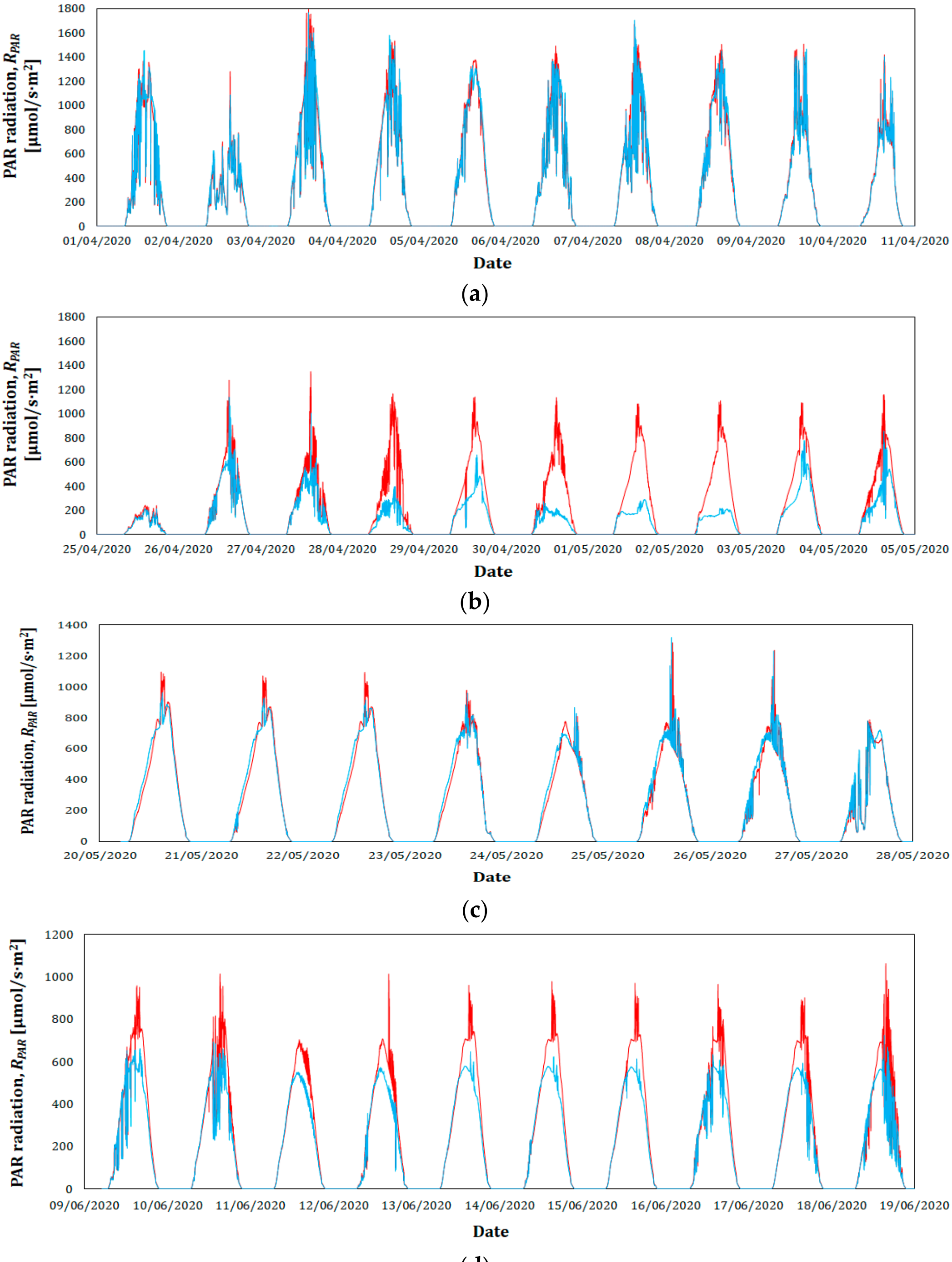
(**a**)

(**b**)

(**c**)

(**d**)

Figure 4. Evolution of air temperatures outside (——) and inside the East sector with diffuse commercial cover film on the North (——) and South (- - -) sides and inside the West sector with diffuse experimental cover film on the North (——) and South (- - -) sides at a height of 1 m above the floor. (**a**) Evolution of air temperatures from 01 April 2020 to 11 April 2020, (**b**) Evolution of air temperatures from 25 April 2020 to 05 May 2020, (**c**) Evolution of air temperatures from 20 May 2020 to 28 May 2020 and (**d**) Evolution of air temperatures from 09 June 2020 to 19 June 2020.



(**a**)

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Figure 5. Evolution of photosynthetically active radiation (PAR) within the East sector with diffuse commercial cover film (——) and the West sector with diffuse experimental cover film (——). (**a**) PAR from 01 April 2020 to 11 April 2020, (**b**) PAR from 25 April 2020 to 05 May 2020, (**c**) PAR from 20 May 2020 to 28 May 2020 and (**d**) PAR from 09 June 2020 to 19 June 2020.

3.1.3. Crop Temperature

Leaf temperature directly affects plant metabolic activities and, consequently, production and influences energy management and pest/disease control [76]. The analysis of average crop temperatures showed statistically significant differences between the northern and southern parts of both sectors but without significant differences between the two sectors. The temperature of the tomato leaves was higher for both sectors on the northern side, with exactly the same temperature values on the West and East sides (Table 5). Regarding the daily maximum temperatures, there were no statistically significant differences with an average value of 33.5 °C in the two sectors. In terms of the minimum values, something similar happened, with the same average value of 14.9 °C measured in both sectors.

Table 5. Mean, maximum, and minimum values of the temperature of the crop T_h and the temperature difference between the plants and the air $\Delta T_{h\text{-}i}$ at the height of 1 m in the north and south areas of the two sectors of the greenhouse.

Parameters	East—Commercial Diffuse Film		West—Experimental Diffuse Film	
	North	South	North	South
Average values from 1/04/2020 to 18/06/2020				
T_h (°C)	21.9 ^{b} ± 6.8	21.6 ^{a} ± 6.4	21.9 ^{b} ± 6.6	21.6 ^{a} ± 6.7
$\Delta T_{h\text{-}i}$ (°C)	0.72 ^{d} ± 1.56	0.28 ^{a} ±1.30	0.38 ^{b} ± 1.03	0.42 ^{c} ± 1.40
Average daily maximum values				
T_h (°C)	33.9 ^{a} ± 4.6	33.2 ^{a} ± 4.0	32.9 ^{a} ± 4.1	34.0 ^{a} ± 4.2
$\Delta T_{h\text{-}i}$ (°C)	4.08 ^{c} ± 1.90	3.49 ^{b} ± 1.68	2.64 ^{a} ± 1.04	3.91 ^{bc} ± 2.15
Average daily minimum values				
T_h (°C)	14.8 ^{a} ± 1.8	15.0 ^{a} ± 2.0	15.0 ^{a} ± 2.1	14.8 ^{a} ± 2.2
$\Delta T_{h\text{-}i}$ (°C)	−1.07 ^{b} ± 0.73	−1.66 ^{a} ± 0.59	−1.11 ^{b} ± 0.55	−1.23 ^{b} ± 0.55

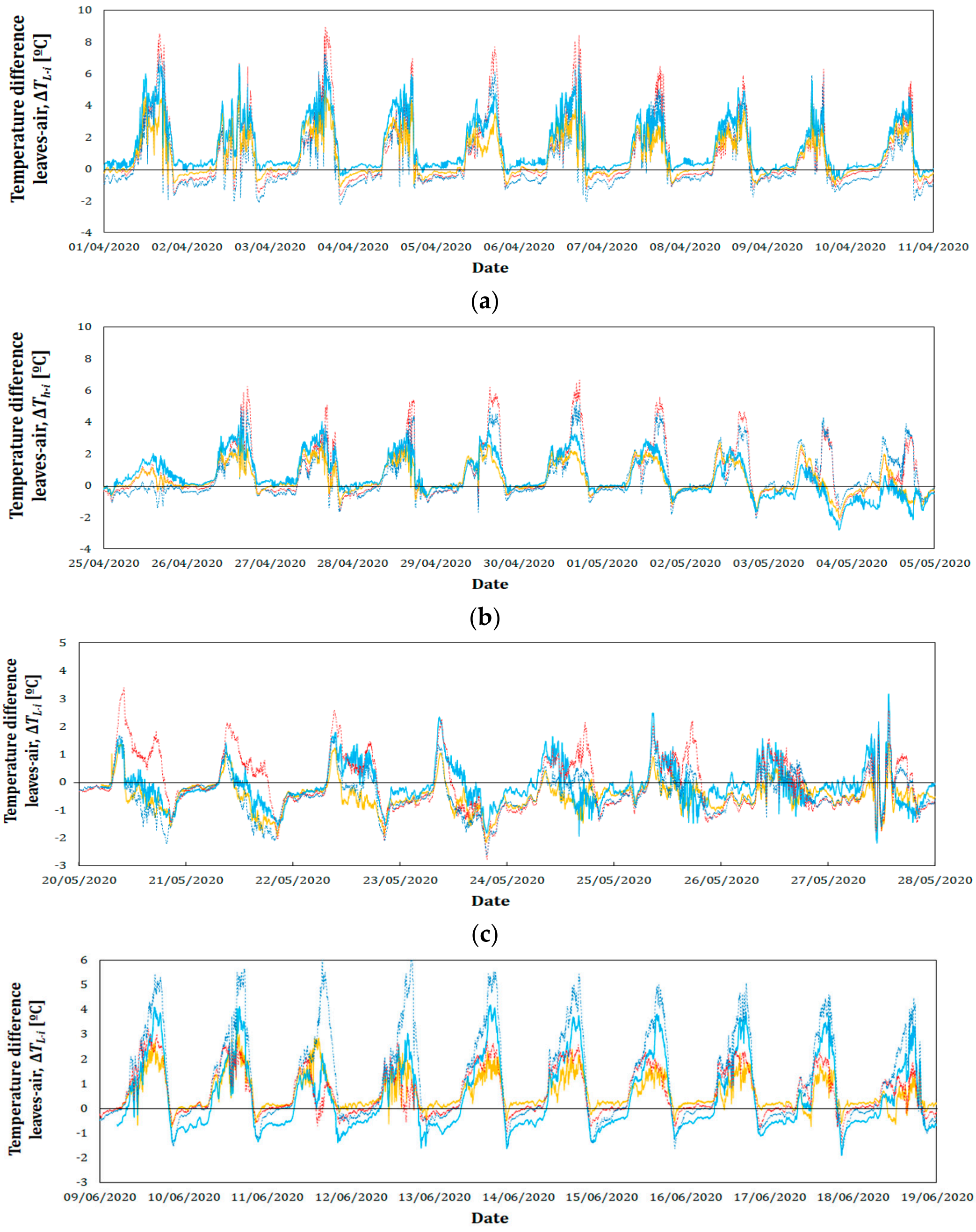
Values with different letters in the same column show statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

However, statistically significant differences in temperature gradients between the crop and air were observed at a height of 1 m. On the north side, the average difference was higher in the East sector, while on the south side, it was higher in the West sector (Table 5). The evolution of the temperature difference between the leaves and the air shows that during the central hours of the day, the temperature of the crop rises about 2–5 °C (Figure 6) above that of the air due to the excess energy provided by radiation. The measurements carried out in early May clearly showed an increase in the difference for sensors placed on the south side of both sectors (Figure 6b).

The measurements showed increases in the maximum and minimum values in the East sector in June (Figure 6d). In general, temperatures about 2 °C lower were observed in the crop than in the air at night due to radiation loss from the surfaces of the leaves (Figure 6).

3.1.4. Soil Temperature

The average soil surface temperature was statistically higher in the West sector with the experimental film (Table 6), as a logical consequence of the increased solar radiation intercepted (Table 3). The maximum and minimum values were also higher in the West sector, although without statistical differences. Some of the solar radiation absorbed by the surface of the soil is transmitted to the inside air by natural convection and another portion is transmitted to the ground by conduction (stored during the day and transferred to the air at night), and the other portion is emitted as infrared radiation [77]. The soil temperature depends on the relationship between absorbed and lost energy, which fluctuates daily, depending on variations in solar radiation [78–81].



(**a**)

(**b**)

(**c**)

(**d**)

Figure 6. Evolution of the temperature difference between the air and tomato leaves at a height of 1 m above the floor inside the East sector with diffuse commercial cover film on the North (——) and South (- - -) sides and inside the West sector with diffuse experimental cover film on the North (——) and South (- - -) sides. (**a**) Evolution of the temperature difference from 01 April 2020 to 11 April 2020, (**b**) Evolution of the temperature difference from 25 April 2020 to 05 May 2020, (**c**) Evolution of the temperature difference from 20 May 2020 to 28 May 2020 and (**d**) Evolution of the temperature difference from 09 June 2020 to 19 June 2020.

Table 6. Average, maximum, and minimum soil surface temperature values at the center of the two sectors of the greenhouse.

Parameters	East—Commercial Diffuse Film	West—Experimental Diffuse Film
	Average values from 1/04/2020 to 18/06/2020	
T_s (°C)	21.7 ^{a} ± 3.5	22.1 ^{b} ± 3.2
	Average daily maximum values	
T_s (°C)	25.8 ^{a} ± 3.2	26.8 ^{a} ± 3.1
	Average daily minimum values	
T_s (°C)	17.7 ^{a} ± 3.6	18.3 ^{a} ± 2.4

Values with different letters in the same column show statistically significant differences with a confidence level of 95.0% (p-value $\leq$ 0.05).

On most days, it was clear that temperature values were higher in the West sector (Figure S3). We also observed a gap of several hours between the evolution of the temperature in the outside air and that in the soil inside both sectors due to the great thermal inertia of the soil.

From 24 May 2020 to 28 May 2020, when the outside wind speed exceeded 8 m/s (Figure S8c), greenhouse windows were closed as a safety measure against structural damage. In the closed greenhouse, there was a sharp rise in the inside air temperature (Figure 4 and Figure S2c) that was not observed at the soil surface (Figure S3c), because of the previously mentioned soil thermal inertia.

3.1.5. Soil Heat Flux

As for solar radiation (Table 3) and soil temperature (Table 6), the average soil heat flux surface was statistically higher inside the West sector with the experimental film (Table 7). Statistically higher values in the maximum daily heat flux were also observed (Table 7), which corresponded to 10% of the maximum solar radiation recorded in both sectors (Table 3). The minimum heat flux showed no significant differences between sectors, as these values were recorded at night when the soil temperature was higher than in air (Figure S3), causing some of the heat accumulated during the daytime period to be returned. This flux is mainly determined by the characteristics of the soil, which were the same in the two sectors, and by the temperature difference between the air and the surface of the soil, also similar in both cases.

Table 7. Average, maximum, and minimum values of heat flow on the soil surface in the center of the two sectors of the greenhouse.

Parameters	East—Commercial Diffuse Film	West—Experimental Diffuse Film
	Average values from 1/04/2020 to 18/06/2020	
q_S (W·m^{-2})	3.2 ^{a} ± 21.8	5.1 ^{b} ± 27.0
	Average daily maximum values	
q_S (W00B7m^{-2})	43.0 ^{a} ± 16.8	57.1 ^{b} ± 21.3
	Average daily minimum values	
q_S (W00B7m^{-2})	–18.3 ^{a} ± 3.4	−19.8 ^{a} ± 8.3

Values with different letters in the same column show statistically significant differences with a confidence level of 95.0% (p-value $\leq$ 0.05).

At the beginning of the measurement period, the heat flux in the soil showed positive values for the day, being clearly higher in the West sector with experimental film due to the increased solar radiation intercepted by the ground. However, in the first part of the measurement period, the heat flux at night was very similar between sectors (Figure S4a,b).

On 24 May 2020, the excessive wind speed (Figure S8c) meant that the greenhouse openings had to be closed, elevating the inside air temperature (Figure 4 and Figure S2c). A rise in the soil surface temperature (Figure S3c) and an increase in negative night-time heat flux from the soil to the air were also observed on the West side (Figure S4c).

3.1.6. Air Humidity

The analysis of the absolute air humidity showed statistically significant differences in the mean values recorded in the West sector with the experimental film with respect to the East sector with commercial film at the three heights analyzed (Table 8). Furthermore, statistically significant differences were also observed between the North and South sides of both sectors. In both cases, the humidity was higher on the North side, and this was possibly affected by the configuration of the roof windows (Figure 1) and the location of the experimental greenhouse with respect to the neighboring greenhouses.

Table 8. Average, maximum, and minimum values of the absolute air humidity measured at heights of 1, 2, and 4.5 m in the north and south areas of the two sectors of the greenhouse.

Parameters	**East—Commercial Diffuse Film**		**West—Experimental Diffuse Film**	
	North	**South**	**North**	**South**
Average values from 1/04/2020 to 18/06/2020				
$x_{1\,m}$ ($kg \cdot kg^{-1}$)	$0.0119^{d} \pm 0.0031$	$0.0117^{b} \pm 0.0030$	$0.0118^{c} \pm 0.0033$	$0.0116^{a} \pm 0.0034$
$x_{2\,m}$ ($kg \cdot kg^{-1}$)	$0.0123^{d} \pm 0.0034$	$0.0118^{c} \pm 0.0032$	$0.0117^{b} \pm 0.0034$	$0.0115^{a} \pm 0.0036$
$x_{4.5\,m}$ ($kg \cdot kg^{-1}$)	$0.0120^{d} \pm 0.0034$	$0.0115^{b} \pm 0.0032$	$0.0117^{c} \pm 0.0036$	$0.0113^{a} \pm 0.0037$
Average daily maximum values				
$x_{1\,m}$ ($kg \cdot kg^{-1}$)	$0.0185^{a} \pm 0.0051$	0.0182 a ± 0.0052	$0.0186^{a} \pm 0.0058$	$0.0186^{a} \pm 0.0060$
$x_{2\,m}$ ($kg \cdot kg^{-1}$)	$0.0196^{a} \pm 0.0053$	$0.0184^{a} \pm 0.0052$	$0.0188^{a} \pm 0.0059$	$0.0190^{a} \pm 0.0063$
$x_{4.5\,m}$ ($kg \cdot kg^{-1}$)	$0.0195^{a} \pm 0.0050$	$0.0182^{a} \pm 0.0052$	$0.0188^{a} \pm 0.0058$	$0.0186^{a} \pm 0.0064$
Average daily minimum values				
$x_{1\,m}$ ($kg \cdot kg^{-1}$)	$0.0092^{b} \pm 0.0012$	$0.0091^{ab} \pm 0.0013$	$0.0089^{ab} \pm 0.0012$	$0.0087^{a} \pm 0.0014$
$x_{2\,m}$ ($kg \cdot kg^{-1}$)	$0.0092^{c} \pm 0.0013$	$0.0089^{bc} \pm 0.0014$	$0.0086^{ab} \pm 0.0014$	$0.0084^{a} \pm 0.0016$
$x_{4.5\,m}$ ($kg \cdot kg^{-1}$)	$0.0086^{a} \pm 0.0015$	$0.0086^{a} \pm 0.0015$	$0.0085^{a} \pm 0.0017$	$0.0081^{a} \pm 0.0017$

Values with different letters in the same column show statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

As a consequence of crop transpiration, the absolute humidity was higher than the external humidity at all times (Figures S5–S7). During the first part of the measurement period, there was a higher absolute humidity in the western sector on both the north and south sides (Figures S5–S7a,b). As of mid-May, when the crop was already well developed, the humidity values were approximated in both sectors (Figures S5–S7c,d). In general, the evolution of the humidity was very similar at the three heights analyzed (Figures S5–S7).

As with the inside temperatures, on 24 and 25 May and 12 and 13 June, when wind the speed forced the closing of the greenhouse windows (Figure S8c,d), there was a large increase in the inside humidity as a result of a lack of ventilation (Figures S5–S7c,d). This is common in multitunnel-type greenhouses with limited wind resistance. This is their main disadvantage with respect to Almeria-type greenhouses that can have their windows open at higher wind speeds, avoiding the problems of a rising temperature and inside absolute humidity. The use of anti-insect meshes in windows also results in a decrease in air velocity and a proportional increase in temperature [82].

3.2. Photosynthetic Activity

The statistical analysis showed significantly greater photosynthetic activity in the tomato leaves of plants in the West sector with the experimental film (with a mean value of 13 μmol CO_2 $m^{-2} \cdot s^{-1}$) than in the East sector with the commercial film (10.7 μmol CO_2 $m^{-2} \cdot s^{-1}$). This represents an increase in photosynthetic activity of 21.5%. The use of highly diffusive cover materials has been shown to be effective for increasing photosynthesis in tomato and cucumber crops [83–85]. Diffuse light distributes photosynthetically active radiation more uniformly to all leaves in a canopy, increasing the overall rate of photosynthesis [33]. PAR radiation values also were statistically significantly higher in the West sector with the experimental plastic, which has greater transmittance. These values agree with those measured above the plant canopy with the fixed sensors (Table 3).

Another parameter that also showed statistically significant differences was the stomatal conductance measured in the leaves. As for the two previously described parameters, the stomatal conductance was higher in the West sector with the experimental film (Table 9). Finally, the temperature of the leaf surface was statistically significantly higher in the East sector with the commercial film. The increase in radiation intercepted by the crop with the experimental film did not translate into an increase in temperature (Table 9). This may be because more than half of the additional radiation reaches the plants in the form of diffuse radiation. Several investigations have shown that diffuse light causes a lower leaf or flower temperature [11,20,21].

Table 9. Average values of the measurements made on the leaves of plants grown in the two greenhouse sectors with different cover films. Photosynthetic activity $\boldsymbol{P_A}$ [µmol CO$_2$ m^{-2}·s^{-1}], radiation $\boldsymbol{Q_{PAR}}$ [µmol m^{-2} s^{-1}], leaf temperature $\boldsymbol{T_L}$ [°C], concentration of CO$_2$ $\boldsymbol{C_O}$ [ppm], transpiration $\boldsymbol{E_L}$ [mmol m^{-2}·s^{-1}], and stomatal conductivity $\boldsymbol{C_E}$ [mol m^{-2}·s^{-1}].

Greenhouse Sectors	P_A	Q_{PAR}	T_L	C_O	E_L	C_E
East—Commercial diffuse film	$10.7^{a} \pm 3.4$	$432.8^{a} \pm 178.5$	$31.1^{b} \pm 2.7$	$421.6^{a} \pm 27.8$	$2.3^{a} \pm 0.7$	$0.1^{a} \pm 0.06$
West—Experimental diffuse film	$13.0^{b} \pm 3.9$	$489.9^{b} \pm 174.4$	$29.0^{a} \pm 3.0$	$438.9^{a} \pm 47.9$	$2.3^{a} \pm 0.8$	$0.2^{b} \pm 0.08$

Values with different letters in the same column show statistically significant differences with a confidence level of 95.0% (p-value $\leq$ 0.05).

3.3. Plant Morphology

All the morphological parameters analyzed show a high degree of homogeneity, with mean values without statistically significant differences. In the West sector, higher values were observed for the total length of the plants, the number of nodes, and the diameter of the stem. However, in the East sector, the plants showed greater internode lengths and greater leaf lengths. The reduction in the length of the internodes observed in the West sector with the experimental film and the corresponding increase in the number of nodes are positive growth factors, since they promote an increase in the number of fruits per plant (Table 10). Several authors have recognized the positive effects of diffuse light on plant growth, mainly in natural communities [86–88]. More recent studies have shown that the use of diffuse covers improves the yield and growth of greenhouse crops [13,31,32,89]. In our case, it was seen that the plants developed in the sector with experimental cover film generally showed greater growth and development of the crop.

Table 10. Average values of the morphological parameters measured in plants grown in sectors with different plastic covers. Total length of the stem $\boldsymbol{L_P}$ [cm], length of the apical meristem $\boldsymbol{N_T}$ [cm], length of internodes $\boldsymbol{L_I}$ [cm], diameter of the stem $\boldsymbol{D_S}$ [mm], number of nodes $\boldsymbol{N_N}$, number of fruits per plant $\boldsymbol{N_F}$, and length of the last mature leaf $\boldsymbol{L_L}$ [cm].

Greenhouse Sectors	L_P	N_T	L_I	D_S	N_N	N_F	L_L
East—Commercial diffuse film	$186.9^{a} \pm 111.9$	$20.4^{a} \pm 5.4$	$10.5^{a} \pm 2.9$	$9.1^{a} \pm 4.2$	$14.0^{a} \pm 5.0$	$19.6^{a} \pm 6.3$	$33.6^{a} \pm 4.4$
West—Experimental diffuse film	$201.2^{a} \pm 126.6$	$23.2^{a} \pm 19.1$	$9.7^{a} \pm 2.7$	$9.9^{a} \pm 3.7$	$15.0^{a} \pm 5.6$	$19.9^{a} \pm 5.6$	$33.1^{a} \pm 4.0$

Values with different letters in the same column show statistically significant differences with a confidence level of 95.0% (p-value $\leq$ 0.05).

3.4. Fruit Quality

The statistical analysis of the fruit quality parameters did not show significant differences between the two sectors for any of the parameters measured. The greatest differences were observed in the parameter weights and equatorial diameters, with both being higher in the West sector under the influence of the experimental film but without statistical significance (Table 11). The 5.3 g increase in the mean weight of tomato fruits caused by the increase in transmittance of the experimental cover is of the same order of magnitude as that observed by Dueck et al. [13] when comparing a high diffusivity cover with a standard one (5–8 g).

Table 11. Average values of the production quality parameters measured for plants grown in areas with different plastic covers. Weight W_F [g], equatorial diameter D_F [mm], firmness F_F [kg cm], soluble solids content T_{SS} [° Brix] and dry matter D_M [%].

Greenhouse Sectors	W_F	D_F	F_F	T_{SS}	D_M
East—Commercial diffuse film	$266.6^{a} \pm 86.8$	$80.1^{a} \pm 11.4$	$0.8^{a} \pm 0.3$	$5.4^{a} \pm 0.4$	$6.1^{a} \pm 1.3$
West—Experimental diffuse film	$271.9^{a} \pm 76.6$	$81.4^{a} \pm 11.5$	$0.8^{a} \pm 0.3$	$4.8^{a} \pm 5.2$	$5.9^{a} \pm 1.3$

Values with different letters in the same column show statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

In the case of the contents of soluble solids and dry matter, both were slightly higher in the fruits developed in the sector with the commercial cover film, although without statistically significant differences (Table 11). Van der Ploeg et al. [90] observed that the increase in the yield of modern tomato cultivars was due to an increase in total dry matter production resulting from greater efficiency in the use of light. Increasing the average weight of the fruits observed in the sector with the experimental film was not matched by an increase in dry matter (in m) (Table 11). Regarding firmness, no trend was seen in favor of either of the two experimental sectors, since the mean data for this parameter were exactly the same (Table 11).

The color of the fruits showed statistically significant differences in the coordinate corresponding to the luminosity, being greater in the fruits harvested in the East sector of the greenhouse with the commercial film (Table 12).

Table 12. Average values of the color characteristics measured in tomato fruits harvested in areas with different plastic covers. Colorimetric coordinates corresponding to the luminosity L^*, the red/green color component a^*, the yellow/blue color component b^*, and the chromaticity a^*/b^*.

Greenhouse Sectors	L^*	a^*	b^*	a^*/b^*
East—Commercial diffuse film	$43.1^{b} \pm 2.2$	$21.1^{a} \pm 4.2$	$18.8^{a} \pm 2.3$	$1.13^{a} \pm 0.2$
West—Experimental diffuse film	$42.4^{a} \pm 2.1$	$21.8^{a} \pm 3.8$	$19.1^{a} \pm 2.8$	$1.17^{a} \pm 0.2$

Values with different letters in the same column show statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

The other two colorimetric coordinates analyzed did not show statistically significant differences, although they had slightly higher values in the West sector with diffuse experimental film (Table 12). The chromaticity (a*/b*), which is proportional to the maturity of the fruits [91], was also higher in the West sector with the experimental plastic cover (Table 12).

3.5. Tomato Production

The analysis of the marketable production of the tomato crop showed an increase of 0.25 kg$\cdot$m^{-2} in the West sector of the greenhouse with the experimental cover film (Figure 7a). This 3.2% augmentation of the marketable yield was due to increases in both the number of fruits per plant (Table 11) and the average weight of the fruits (Table 11). This production improvement generated by the increase in transmittance of the experimental cover would have added to the increase in production associated with the use of diffuse covers. Dueck et al. [13,44] observed increases in production of 10% in tomato and cucumber crops with the use of diffusive covers. Similarly, Hemming et al. [31] found a rise in the production of a cucumber crop of 4.8% under the influence of a diffuse cover.

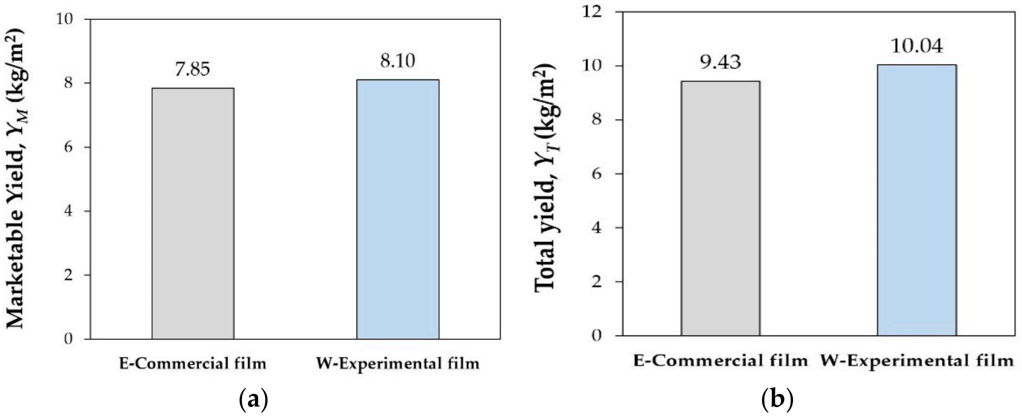


Figure 7. Marketable yield (**a**) and total yield (**b**) of tomato crops in the East sector with diffuse commercial cover film (■) and in the West sector with diffuse experimental cover film (■).

Similarly, the total accumulated production was higher in the West sector of the greenhouse with the experimental film, with a value of 10.0 kg·m^{-2}, whereas the yield was 9.4 kg·m^{-2} in the East sector with the commercial film (Figure 7b). The total yield was 0.6 kg·m^{-2} (6.4%) greater than in the sector with the commercial film. Tomato growth and production are strongly related to the amount of light. The amount of light that the plant requires for the production of 1 kg of tomatoes is the sum of the light that the plant absorbs from flowering to harvest [92]. The increase in production observed in the western sector with the experimental plastic cover (Figure 7) agrees with the increases observed in PAR radiation (Table 3) and photosynthesis activity at the leaf level (Table 9).

For most of the duration of the trial, non-marketable production was practically non-existent. Only in the last three dates have non-marketable fruits been harvested due to disorders caused by the pest *Tuta absoluta* (Meyrick). This pest, native to South America, was first detected in Eastern Spain towards the end of 2006, where it has become a serious threat to tomato production [93]. Some research suggests that plants grown under the influence of diffuse light are less sensitive to the infection of some diseases such as *Botrytis cinerea* [13].

4. Conclusions

This work is part of a research project whose objective is to increase the productivity of Mediterranean greenhouses by increasing the photosynthesis of crops. To increase photosynthetically active radiation in the winter period, plastics with greater transmissivity to PAR radiation, larger diffuse capacity and with spectrum transformer effect are tested. To allow the use of these plastics in the warm periods, it will be necessary to improve the cooling capacity of greenhouses by increasing the natural ventilation capacity and increasing radiation reflection at ground level. Improving cooling capacity, the whitewashing technique that drastically reduces the photosynthetic activity of greenhouse crops could be eliminated partial of completely.

Most previous studies have focused on measurements of the spectral radiative properties of polyethylene films in laboratories or under experimental greenhouses of reduced size. In this work has been analyzed the effect of an experimental greenhouse covers (tested in comparison with a commercial cover as control) with high PAR transmittance (90%), elevated diffusivity (55%) and high UV blocking (76%) on inside microclimate, on tomato plant photosynthesis and production in a large greenhouse (800–1000 m^2). The efficiency of tomato plants in capturing solar irradiance to photosynthesis was evaluated in leaves under the experimental and commercial films.

From the results obtained by comparing the diffuse experimental plastic cover with high transmittance (95%) with a diffuse commercial plastic cover (85% transmittance), the following conclusions can be drawn:

- Experimental plastic produced a 14–15% increase in the average cover transmittance for solar radiation and photosynthetically active radiation (PAR).
- The average photosynthetic activity measured in the leaves of tomato crop was 21.5% higher with experimental plastic as a result of a 13% increase in PAR radiation.
- As a result of increased photosynthetic activity, the marketable yield of tomato crop was 3.2% higher with the experimental plastic with higher transmittance (6.5% increase in total production).
- The production improvement was due to both an increase in the average weight of the fruits and the number of fruits per plant, although statistical differences were not observed for either of these two parameters.
- No statistically significant differences were observed in any of the plant growth parameters (length and thickness of the stem, number of nodes and length of internodes).
- The rise in solar radiation produced by the increased transmittance of commercial plastic generated a higher temperature on the soil surface, but there were no statistically significant differences in the air temperature at the height of the crop (2 m).

In the future we will study the effect of the plastic cover with high transmissivity in spring/summer period combined with the use of larger side vent openings. Effect of aging on plastic degradation and on the variation of the cover transmissivity over three seasons will also be analysed. The main aim of our research is to reduce or eliminate whitewashing of the cover that reduces PAR radiation intercepted by the crop, and as a result diminishes their productivity in Mediterranean greenhouses.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11050860/s1.

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