agronomy

MDPI

Article

Impact of a High-PAR-Transmittance Plastic Cover on Photosynthetic Activity and Production of Cucumber (*Cucumis sativus* L.) Crops in a Mediterranean Solar Greenhouse

María Ángeles Moreno-Teruel [1], Francisco Domingo Molina-Aiz [1], Alejandro López-Martínez [1,*], Diego Luis Valera-Martínez [1,*], Araceli Peña-Fernández [1] and Fátima Baptista [2]

[1] Research Centre CIAIMBITAL, University of Almería, Ctra, de Sacramento s/n, 04120 Almería, Spain; mamorenoteruel@ual.es (M.Á.M.-T.); fmolina@ual.es (F.D.M.-A.); apfernan@ual.es (A.P.-F.)
[2] Research Centre MED, University of Évora, Pólo da Mitra Apartado 94, 7006-554 Évora, Portugal; fb@uevora.pt
* Correspondence: alexlopez@ual.es (A.L.-M.); dvalera@ual.es (D.L.V.-M.)

Abstract

The optical properties of greenhouse cover materials play a critical role in controlling the internal light environment, directly affecting photosynthetic performance and crop productivity. This study evaluates the impact of a high photosynthetically active radiation (PAR) transmittance and high-light-diffusivity polyethylene film on the microclimate, photosynthetic activity, yield, and disease incidence of cucumber (*Cucumis sativus* L.) crops grown in a Mediterranean passive solar greenhouse. Trials were conducted over two consecutive autumn–winter seasons using a multi-span greenhouse divided into two sectors: one covered with an experimental high-transmittance film and the other with a standard commercial plastic. The experimental cover increased PAR transmission by 8.7% and 11.6% at canopy level in the first and second seasons, respectively, leading to improvements in leaf-level net photosynthesis of 9.3% and 17.9%. These effects contributed to yield increases of 5.0% and 17.3% in the respective seasons. The internal air temperature rose by up to 1.3 °C without exceeding critical thresholds, and no significant differences were observed in plant morphology or fruit quality between treatments. Additionally, the experimental film reduced the incidence of major fungal diseases, particularly under higher disease pressure conditions. The use of high-PAR-transmittance films enhances radiation use efficiency and crop performance in resource-limited environments without increasing energy inputs. This approach offers a sustainable, low-cost strategy to improve yield and disease resilience in protected cropping systems under passive climate control.

Keywords: greenhouse cover plastic; PAR transmittance; diffusivity; photosynthetic activity; cucumber

Academic Editor: Daniela Romano

Received: 27 December 2025
Revised: 28 January 2026
Accepted: 28 January 2026
Published: 31 January 2026

1. Introduction

Almería (Spain) is the Mediterranean region with the highest concentration of greenhouses in Europe, covering 33,635 hectares [1]. These greenhouses are predominantly covered with plastic films, a common choice in warm climates like the Mediterranean. Greenhouse production is often associated with high operational costs, particularly during off-season cultivation and when climate control systems rely on fossil fuels. However, in the Mediterranean region, specifically in Almería, passive climate control systems are widely used. The solar greenhouses in Almería base their operation on passive cooling by natural ventilation, with the wind as the primary source of energy, and using solar radiation energy for passive heating. These systems do not require external energy inputs, thereby reducing the overall cost of crop production [2] and carbon footprint [3].

One of the main limitations of horticultural production in the solar greenhouses of the Mediterranean region is the insufficient solar radiation during the cold winter. In this period, it is necessary to use cover plastics with the maximum possible transmissivity, as increasing the cover's transmittance enhances photosynthesis and yield while reducing energy requirements during colder periods [4].

On the other hand, during the spring–summer warm period the main problem is the excess temperature in the central hours of the day. In addition to natural ventilation, whitewashing of the roof is traditionally used in the Mediterranean area to reduce solar radiation that penetrates the greenhouse and contributes to its heating [5]. In Almería, whitewashing is applied to the greenhouse cover at the end of summer, for the autumn–winter crop cycles, and at the end of the winter, for the spring–summer cycles, when new crops are transplanted in the greenhouses. When outside temperatures decrease, growers remove the whitewashing from the cover, washing it with water [6]. However, this passive cooling method is irregular [6,7] and drastically limits the PAR available inside the greenhouses [6,8], reducing the plant's photosynthesis [9,10] and crop yield [10].

Solar radiation is a key factor for agricultural crops, heating greenhouses and providing the necessary energy for photosynthesis, biochemical processes, and cell elongation [11,12]. Photosynthesis supports plant growth, biomass accumulation, germination, and flowering, among other functions that depend not only on the quantity but also on the quality of light [13]. The photosynthetic rate of leaves is determined by the amount of photosynthetic protein per unit leaf area and the stomatal conductance of CO_2 [14]. Under adequate CO_2 concentration and optimal greenhouse temperatures, photosynthetic activity is primarily driven by light intensity. Plants grown under low-light conditions are more susceptible to photo inhibition than those grown under high-light intensity [15]. To adapt to varying light environments, plants have developed numerous mechanisms, including morphological and physiological changes at the leaf level [16]. Low light levels can lead to an increase in specific leaf area and plant height, adaptations that enhance light capture and meet the photosynthetic demand [17].

Selecting the appropriate greenhouse cover material is crucial for optimising protected crop development, as the optical properties of these materials directly influence the greenhouse microclimate [18]. Plastic covers designed to improve both the quality and quantity of light reaching the crops offer a significant advantage in promoting plant growth and productivity compared to traditional covers [19]. Ideally, a cover material should allow 100% transmission of photosynthetically active radiation, which is efficiently utilised by plants in the photosynthesis process [20]. The transmittance of polyethylene (PE) plastic covers ranges between 70% and 90%, varying on cloudy and sunny days [21]. The use of energy-efficient cover materials, which alter light transmittance [22], can reduce cooling and heating needs [23,24].

Different radiometric properties of cover materials have distinct effects on the greenhouse microclimate and crop yield [25]. Recent advancements have focused on developing greenhouse cover materials that modify light properties, such as photo-selective plastics, UV-blocking films, and high-light-diffusivity covers. These innovative cover materials can not only reduce production costs and mitigate negative impacts on total yield but can minimise energy losses and improve crop yields and fruit quality without additional energy input [26–29]. Appropriate greenhouse cover materials can reduce annual cooling and heating loads by 9.8% and 6.3%, respectively [30].

Diffusive cover materials, which can transform 45–71% of direct light into diffused light, are used to increase light diffusion without reducing overall light transmission [31], creating more homogeneous light profiles and improving crop growth and yields [32–34]. Additionally, diffused light results in lower leaf and flower temperatures and reduced photo inhibition, due to less severe local peaks in light intensity [33,35,36]. Photosynthetic processes can be 10–15% more efficient under diffused light compared to direct light [37]. In addition, the properties of the plastic cover can influence the response of plants to biotic stresses such as fungal diseases [38].

Cucumber is a crop that requires a relatively high light intensity, being more sensitive to the quality of light and the amount of radiation than other greenhouse crops [39,40]. Therefore, radiation is a fundamental aspect in the cultivation of cucumbers [41], since its growth and net assimilation rate are directly correlated with light intensity [42]. The vertical distribution of light inside the cucumber canopy can also affect the structure of the plants and the efficiency of photosynthesis, impacting its yield [43].

The initial hypothesis of this study is that using an experimental plastic cover with high PAR transmittance and high light diffusivity will improve radiation conditions inside the greenhouse, thereby enhancing photosynthetic activity and cucumber crop yield. This expected enhancement of production without any additional energy costs can increase the economic and environmental sustainability of Mediterranean solar greenhouses. Therefore, the objective of this study was to investigate the impact of an experimental plastic cover with high PAR transmittance and high light diffusivity on the photosynthetic activity, plant development, yield, and fruit quality of cucumber (*Cucumis sativus* L.) during two consecutive autumn–winter seasons in a Mediterranean solar greenhouse. Additionally, the study assessed the effects of the experimental plastic cover on the main fungal diseases that commonly affect cucumber crops.

This work is a part of the RINFOC Project based on the hypothesis that the combined use of different passive climate control techniques (plastic cover, photoconversion inside double roof, natural ventilation, and reflective soil mulching) will allow for an increase in the photosynthetic activity of greenhouse crops, which will translate into a rise in production, improving the profitability and the economic and environmental sustainability of Almería's solar greenhouses. The novelty of this work is that it investigates in a multidisciplinary way (analysing the effects on the microclimate, the development of plants, the quality and quantity of production, and crop resistance to fungal diseases) the effect of increasing light in the autumn–winter cycle in a sensitive crop like cucumber.

2. Materials and Methods

2.1. Experimental Site

The present investigation was carried out during the autumn–winter seasons of 2020/21 and 2021/22 at the Centre for Innovation and Technology Transfer 'Fundación UAL-ANECOOP' (Latitude: 36°51′53.2″ N. Longitude: 2°16′58.8″ W; Altitude: 87 m). A multi-span greenhouse (1800 m^2—orientation: 118° N) was divided into two similar sectors, East and West (Table 1), by a vertical plastic sheet (Figure 1a).

An experimental plastic cover (AA Politiv (1999) Ltd., Kibbutz Einat, Israel) was installed in the West sector, while a commercial plastic cover was installed in the East sector. Both plastic covers were developed by Politiv Europe S.L. (Israel) according to the standards UNE-EN 13206:2017 [44] and ASTMD 1003-13 [45] for optical properties (Table 2).

Table 1. Characteristics of the two sectors of the experimental greenhouse. Greenhouse soil surface S_C (m^2), vent opening surface S_V (m^2), and ventilation surface/greenhouse surface ratio S_V/S_C (%).

Sector	Plastic Cover	Dimensions	S_C	Crop Season 20/21		Crop Season 21/22	
				S_V	S_V/S_C	S_V	S_V/S_C
West	Experimental	40 m × 25 m	1000	109.1	10.9	232.2	23.2
East	Commercial	40 m × 20 m	800	84.9	10.6	193.9	24.2

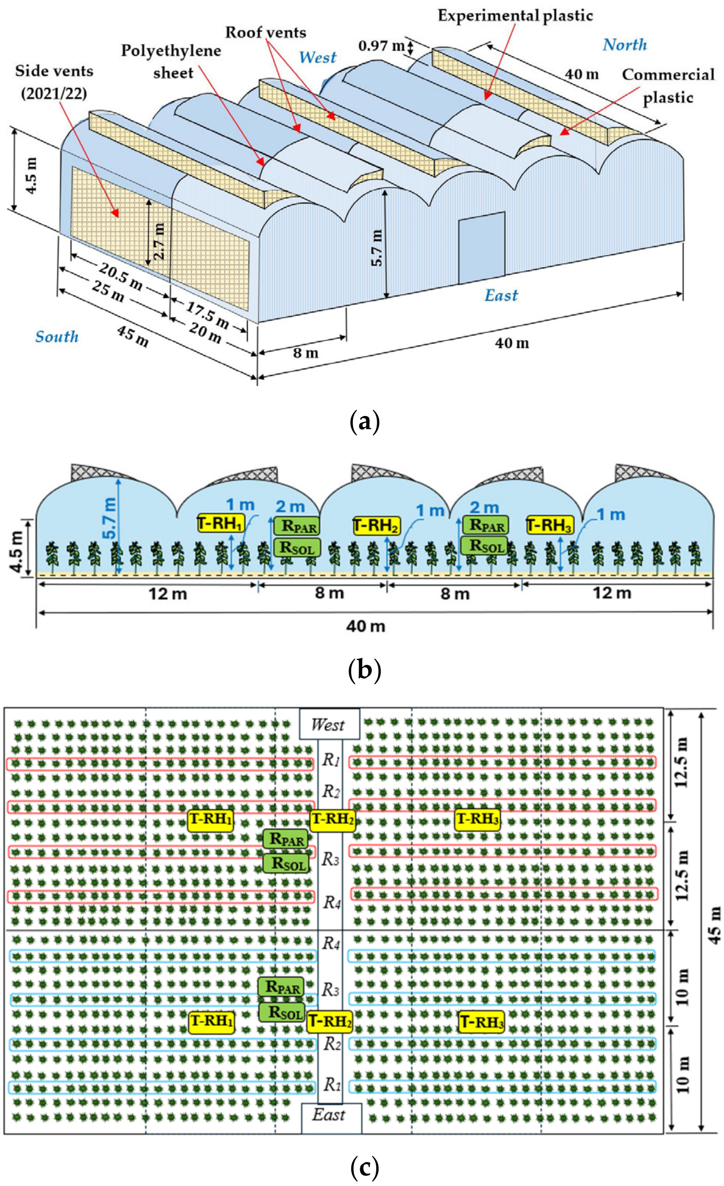

Figure 1. 3D schematic of the experimental greenhouse with dimensions of side vents installed in the season 2021/22 (**a**); vertical profile (**b**) with the position of the temperature and humidity sensors (T-RH), solar and PAR sensor (R_{PAR} and R_{SOL}); and locations of the plant rows (R1–R4) used to measure growth, production and photosynthesis parameters (**c**). Red and blue rectangles indicate the plant rows selected for measurements.

The average service life of plastic covers is estimated to be four seasons in central North Europe and two-to-three seasons in the Mediterranean regions [46,47]. Emekli et al. [47] determined an initial PAR transmittance of 80.1–83% and losses in PAR transmittance were 4.9–6.2% at the end of the service life. In our case, both cover plastics were in their second (2020/21) and third (2021/22) seasons of service life. The optical properties of the plastic cover varied from those of the first year of a spring–summer tomato cycle [48]. Cover transmissivity was similarly modified in both sectors by the application of cover whitewashing at a dose of 0.500 kg L^{-1}, which is recommended for the beginning of the autumn–winter growing season [10]. Cover whitewashing was applied before transplanting, as radiation in Almería is very high in September and plants may be affected due to their sensibility at this first phenological stage.

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

Sector	Plastic Cover	T_{PAR}	T_{UV}	D	T
West	Experimental	0.90	0.24	0.55	0.90
East	Commercial	0.85	0.24	0.60	0.85

The greenhouse had roof vents in the first crop season, while in the second crop season side vents were installed on both sides of the greenhouse (Figure 1a). As a result of the new side vents, the ventilation surface increased in the season 2021/22 in both sectors of the greenhouse (Table 1). The side ventilation surface was augmented for the second cucumber season as consequence of the high inside temperatures observed for a tomato crop developed in the season 2020/21 in the spring–summer cycle.

Ventilation was controlled by Synopta Software 5.4.2.3931422 (Ridder Growing Solutions B.V., Maasdijk, The Netherlands), a centralised climate control and data logging system with a weather station. The temperature setpoint for the control of vent opening was 20 °C.

2.2. Crop System

To determine the influence of plastic covers on cucumber crops (*Cucumis sativus* L.), two consecutive autumn–winter seasons with the commercial variety Insula (Rijk Zwaan Iberica, S.A., Almería, Spain) were carried out. The transplant was carried out on 4 September 2020 in the first crop season and on 8 September 2021 in the second. In both crop seasons, plants develop in 'arenado' sand-mulched soil, which is stratified soil that is commonly used in Almería greenhouses [2]. The plant density was 1.2 plants m^{-2}, with the cultivation lines perpendicular to the ridge of the greenhouse. Fertigation was applied uniformly in both sectors by drip irrigation and managed in both experimental sectors by the SUPRA irrigation controller (Hermisan, Alicante, Spain). Cucumber crop management tasks (cleaning, trellising, pruning, and harvesting) were carried out at the same time in both sectors. The total period in both cucumber crop seasons was 18 weeks.

2.3. Microclimate Measurement Equipment

The outside climatic parameters were measured by a meteorological station located 135 m north of the experimental greenhouse (Table 3) during the two crop seasons. To compare the effect of the two plastic covers on the greenhouse microclimate, we placed six HOBO® Pro Temp-HR U23-001 (Onset Computer Corp., Pocasset, MA, USA) with temperature and humidity sensors (Table 3) on vertical profiles of both sectors at a height of 1 m in the three central spans of the greenhouse (Figure 1b,c). The autonomous HOBO air temperature and humidity sensors were protected from solar radiation by open boxes. PAR sensors were installed in the central aisle of each experimental sector at a height of 2 m, with an additional solar radiation sensor located in the western sector.

Table 3. Characteristics of all sensors used for microclimate measurements.

Parameter	Sensor	Manufacturer	Rank	Accuracy
Outside climatic parameters measured at the weather station				
Outside global solar radiation	Kipp Solari−MII	HortiMax B.V. (Maasdijk, Holland)	±2000 W m^{-2}	±5% or ±20 W m^{-2}
Wind speed	Anemometer−MII		0–40 ms^{-1}	±5%
Wind direction	Vane Meteostation II		0–360°	±5°
Outside temperature	Pt1000 IEC 751 1/3B	Vaisala Oyj (Helsinki, Finland)	−25–75 °C	±0.2 °C
Outside humidity	HUMICAP HMT100		0–100%	±2.5%
Inside climatic parameters				
Inside air temperature nside relative humidity	HOBO® Pro Temp-HR U23-001	Onset Computer Corp. (Pocasset, MA, USA)	−4–70 °C ± 0.18 °C	0−100% ± 2.5%
Inside solar radiation	Pyranometers SP1110	Campbell Scientific Spain (Barcelona, Spain)	350–1100 nm	±5%
Inside PAR	SKP215 Quantum sensor		400–700 nm	±5%

2.4. Measurement of Photosynthesis Activity

Three plants were randomly selected in four measurement rows (R1–R4) from each experimental sector (Figure 1c). In the first crop season, measurements were carried out 77, 81, 96, 102, 103, 109 days after transplantation (DAT) and in the second growing season 62, 70, 76, and 84 DAT, resulting in n = 72 and n = 48 measurements in each sector, in 2020/21 and 2021/22, respectively. Photosynthetic activity was measured at an intermediate plant height, on a mature and fully expanded leaf [49] following the methodology used by Jiang et al. [50]. The equipment used was a portable LCi SD analyser (ADC BioScientific Limited, Hertfordshire, UK) equipped with an IRGA CO_2 and H_2O concentration sensor (infrared gas analysis; with a CO_2 measurement range of 0 to 2000 ppm, 0 to 75 mbar H_2O, with accuracy ± 2%; and PAR of 0 to 3000 m^{-2} s^{-1}). The photosynthetic rate, the evapotranspiration rate, the concentration of CO_2 in the leaf environment, the PAR reaching the leaf surface, the leaf temperature, and the stomatal conductance were measured. Photosynthesis was measured on sunny days, under natural light conditions and with the CO_2 concentration in the environment of the crop leaves. The route followed to measure data in the 8 rows of plants inside the greenhouse (Figure 1c) was randomly assigned for each day of measurement to prevent variations in climatic parameters during the measurement period from influencing the results. Furthermore, data were always recorded during the same time interval, between 12:00 and 12:30 h.

2.5. Measurement Equipment for Crop Development and Yield Analysis

To evaluate crop development, four plant rows (R1–R4, considered as statistical repetitions) with four plants per row were randomly selected in each sector (Figure 1c). The growth parameters were measured (n = 80 measurements per sector) 5 times every two weeks during the season (in the first season 20, 35, 50, 65, 80 DAT and in the second season 15, 30, 45, 60, 75 DAT) in the same selected plants. The instruments used were a tape measure and a digital gauge with a measuring range of 0 to 150 mm and an accuracy of 0.01 mm (Medid Precision, SA, Barcelona, Spain). The morphological parameters measured every 15 days (in the same plants) were as follows: distance from the apical meristem of the plant to the last node (N_T), which was measured considering the last node under the last leaf at physiological maturity; total length of the stem (L_S), calculated from N_T and the distance from the last node to the ground; length of two internodes (L_I), measured below the last leaf at physiological maturity; stem diameter (D_S) and number of nodes (N_N).

In each season, nine harvests were carried out, in which the yield of the cucumbers was measured by weighing all the marketable and non-marketable fruits of the four row plants (R1–R4) selected in each sector (Figure 1c). Harvests were carried out with a frequency of once or twice a week (40, 45, 49, 56, 61, 66, 74, 80, and 98 DAT in 2020/21 and 43, 47, 50, 55, 61, 68, 75, 82, and 96 DAT in 2021/22). Fruits were weighted with a Mettler Toledo electronic scale (Mettler-Toledo, SAE EE19.1, Barcelona, Spain) with a sensitivity of 20 g and a maximum capacity of 60 kg.

For the evaluation of the quality of the fruit, ten cucumbers were randomly selected from each sector and harvest. Weight measurements (W_F) were performed using an electronic scale PB3002-L (Delta Range®; Mettler Toledo, SA, L'Hospitalet de Llobregat, Spain, with a sensitivity of 0.1 g); the diameter of the fruit (D_F) using a 150 mm digital gauge (Medid Precision, SA, Barcelona, Spain); the length of the fruit (L_F) using a measuring tape and the content of soluble solids (T_{SS}) using a refractometer (PAL1, Atago Co. LTD., Fukuoka, Japan, with a precision of ±0.2%).

Crop growth largely depends on light availability, making radiation use efficiency (RUE) a key parameter for assessing crop development and productivity. RUE can be defined as the dry matter crop production per mole of photosynthetically active photons absorbed by green canopy components [51]. Enhancing RUE, both at the leaf and crop levels, directly contributes to the overall efficiency of the production system. Indeed, RUE has been identified as the main factor explaining the higher production rates observed in modern cultivars compared with older ones [14].

Radiation use efficiency on a fresh yield basis (RUE_F) was calculated as the ratio between fresh yield and cumulated PAR (P_i), as described by Cossu et al. [52]:

$$RUE_F = \frac{Y_t}{\sum_{i=1}^{n} P_i} (\mathrm{g\ MJ^{-1}})$$

where Pi is the PAR cumulated on the n days of the growing cycle (MJ m^{-2}) obtained from the PAR R_{PAR} (W m^{-2}) measured every minute by the sensors inside each sector. To convert the photosynthetically active radiation measured as Photosynthetic Photon Flux Density (PPFD) Q_{PAR} (μmol $s^{-1}m^{-2}$) into energy units R_{PAR} (W m^{-2}), we used the conversion factor of 4.56 μmol·J^{-1}, corresponding to the spectral distribution of scattered sunlight on Earth's surface [53].

2.6. Development of Fungal Diseases

During the two crop seasons, a parallel trial was carried out to determine the effect of the plastic cover with high PAR transmissivity and high diffusivity on the main fungal diseases that usually attack the cucumber crop [38]. For the design of the trial, the standards of the European and Mediterranean Plant Protection Organisation (EPPO) were followed. For diseases of downy mildew and powdery mildew diseases, EPPO standards PP 1/181 (conduct and reporting of efficacy evaluation trials), PP 1/152 (design and analysis of efficacy evaluation trials), PP 1/57 (powdery mildew in cucurbits), and PP 1/65 (downy mildew of lettuce and other vegetables, PSPECU) are applicable. Fifty random leaves were analysed in plants located in 4 plots (2 in the south and 2 in the north of rows R2 and R3 in Figure 1c) of each of the experimental sectors, obtaining a total of 200 samples for each disease and for each sector. For more detailed information, consult Ávalos-Sánchez et al. [38].

2.7. Statistical Analysis

The data analysed are the results obtained in two independent trials (autumn–winter 2020 and 2021 crop seasons) with 4 plant rows as replicates for each treatment at yield (harvest date). The growth and photosynthesis parameters of 12 and 16 plants, respectively, were evaluated in each experimental sector and ten cucumber fruits (in each harvest) were used to analyse the quality of the yield. The results were analysed using the multifactor

ANOVA procedure [54] with the software Statgraphics®Centurion (considered significant if the *p*-value is ≤0.05) and comparing mean values with Fisher's least significant difference method (LSD). We consider as factors the greenhouse sector (with 2 levels of variation), the row of plants (4 levels), and the harvest date (9 levels) for yield in every season (2 levels). Previously, the normality of the data was assessed using the Kolmogorov–Smirnov test. Bartlett's, Cochran's and Hartley's tests were used to determine whether the two sectors had similar parameter variances. When there was a statistically significant difference between standard deviations, parametric analysis using analysis of variance was not feasible. In this case, a nonparametric analysis was performed with the Friedman test, where each row represents a block (the measurement date) using the box and whisker plot [54].

3. Results and Discussion

3.1. Microclimate Conditions

Recorded values of outside global solar radiation indicate stable climatic conditions during the study period, within a typical annual cycle of a Mediterranean climate. Inside the greenhouse, clear differences were observed in the monthly accumulated PAR under the two plastic covers. The experimental plastic cover transmitted higher PAR levels, with mean values of approximately 3.5–4 MJ m^{-2} in September, which progressively declined toward the end of the cropping period (Figure 2). This represents a 14% increase in PAR transmission compared with the commercial plastic cover, whose values ranged from 3.0 to 3.5 MJ m^{-2} over the same period (Figure 2). These results are consistent with those reported by Deligios et al. [55] of 5 MJ·m^{-2} under a commercial plastic cover without whitewashing during the same time of year.

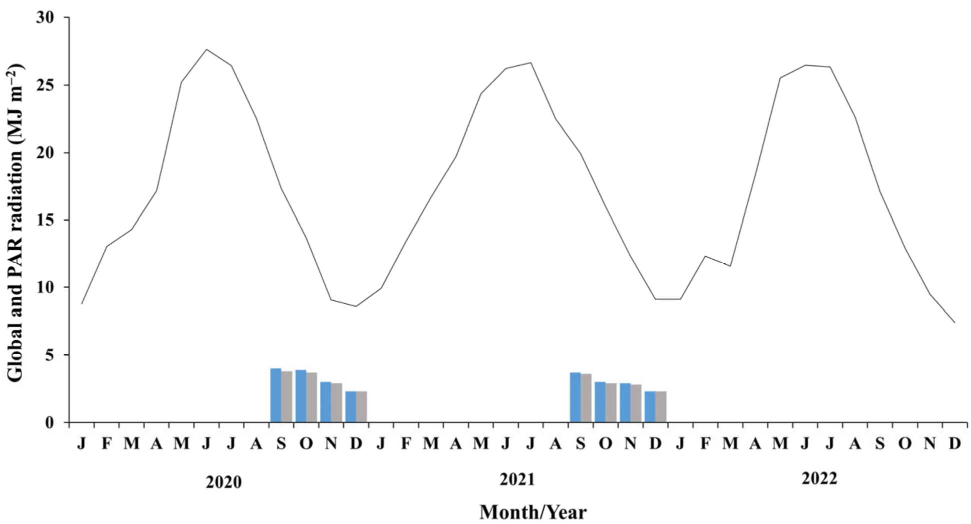

Figure 2. Monthly cumulative PAR under commercial plastic cover in the East sector (■) and the experimental plastic cover in the West sector (■) inside the greenhouse during 2020 and 2021 and comparison with the daily average and global solar radiation outside (——) the greenhouse.

The microclimatic parameters measured at 1 m height showed a slight difference between the East and West sectors of the greenhouse (Figure 3), with a progressive reduction in temperatures along the first crop season (Figure 3a).

During the second crop season, as in the first, the microclimatic parameters measured (air temperature, relative humidity and absolute humidity) behaved in a similar way (Figure 4).

https://doi.org/10.3390/agronomy16030354

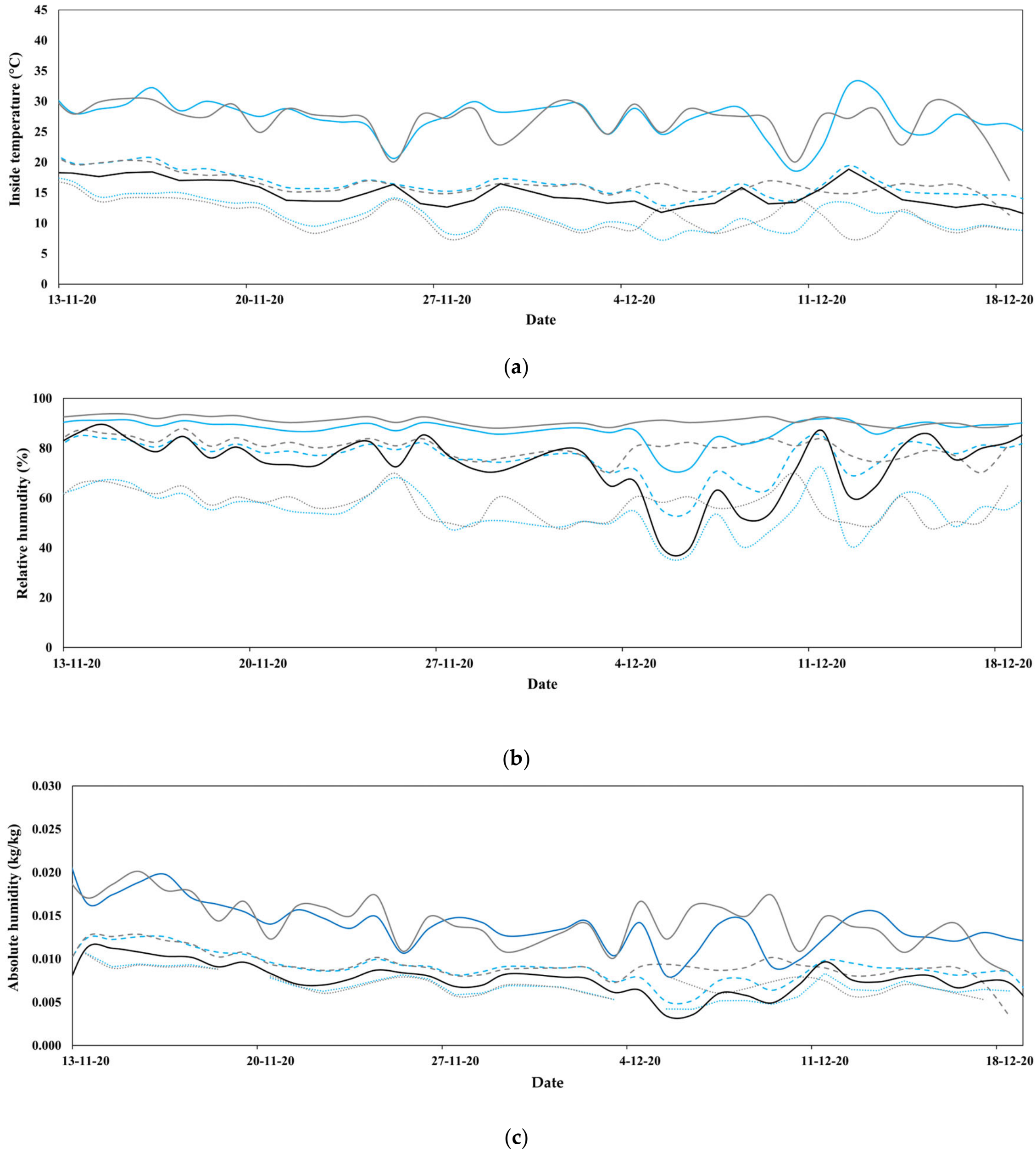

Figure 3. Evolution of values of temperature (**a**), relative humidity (**b**) and absolute humidity (**c**) outside the greenhouse (——) and average (- - -), maximum (——) and minimum (···) inside of the East sector with commercial plastic cover and average (- - -), maximum (——) and minimum (···) inside the West sector with experimental plastic cover. Crop season 2020/21.

The increase in the transmissivity of the roof in the West sector with the experimental plastic resulted in an increase in the maximum daily air temperatures (Figures 3a and 4a). These values were recorded in the central hours of the day, when the solar radiation that heats the surface of the ground was maximum. The greenhouse air in this period reaches its maximum value because of the transfer by convection of part of the heat absorbed by the soil (another important part is stored in the soil) to the air [56,57].

The installation of side windows carried out for the 2021/22 season reduced the maximum temperature values and increased the minimum values, reducing the thermal oscillation of the air in the greenhouse, despite it being a warmer season. In 2020, outdoor temperatures ranged from 24.1 to 13.4 °C (average 18.4 °C) from September to December, respectively, while in 2021 the variation was from 25.3 to 13.9 °C (average 18.9 °C).

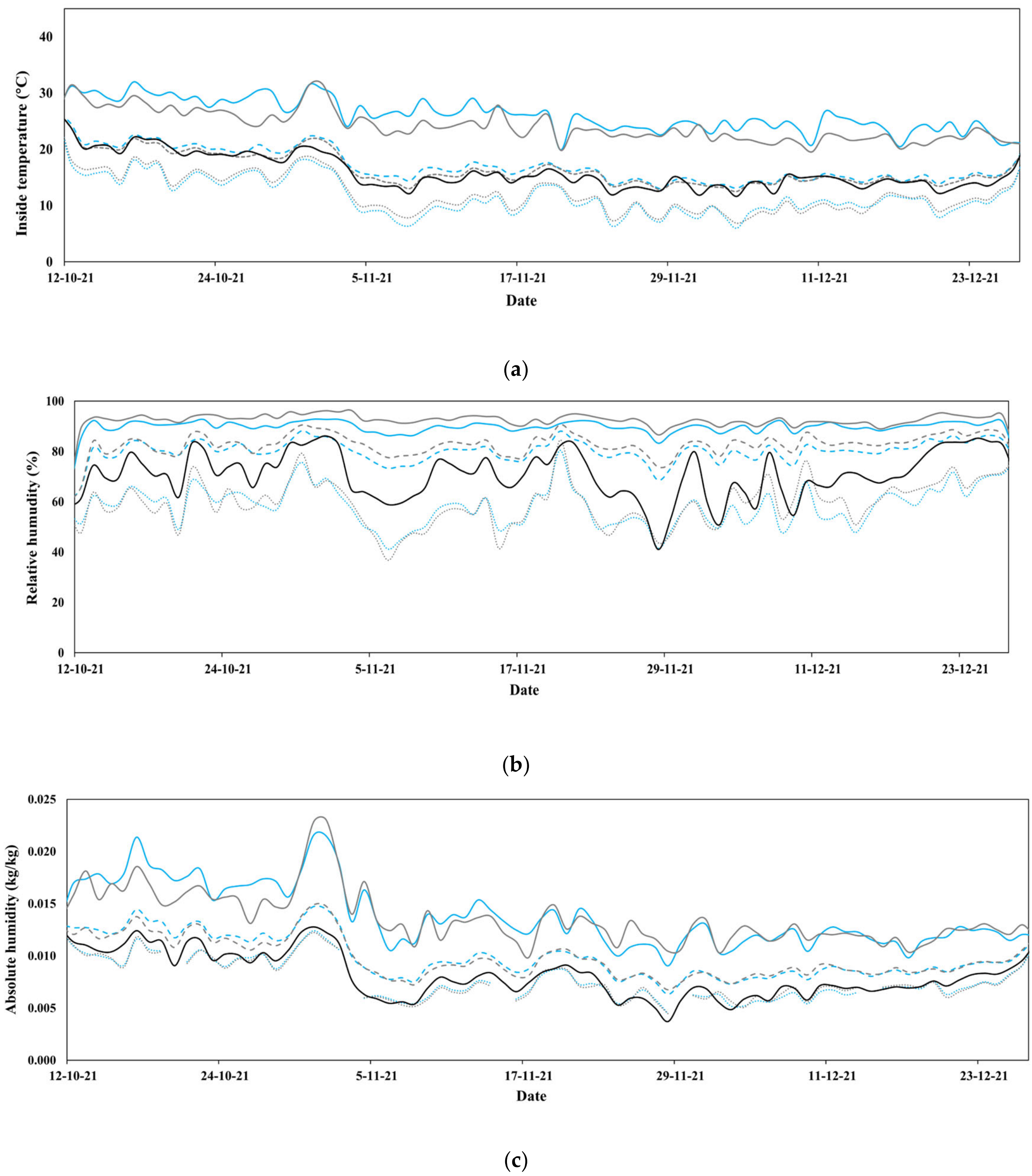

Figure 4. Evolution of values of temperature (**a**), relative humidity (**b**) and absolute humidity (**c**) outside the greenhouse (——) and average (- - -), maximum (——) and minimum (···) inside of the East sector with commercial plastic cover and average (- - -), maximum (——) and minimum (···) inside the West sector with experimental plastic cover. Crop season 2021/22.

As a result of the increase in cover transmission, the inside air temperatures (average, maximum, and minimum) were higher in the sector with the experimental plastic cover during the first crop season (Table 4). The increase in air temperature (0.2 °C) observed in the sector with the experimental plastic cover agrees with the increase in surface temperature (1.1 °C) measured in plant leaves (see Section 3.3). As in the first crop season, in the second the air temperature values were higher in the sector with the experimental plastic cover (Table 4), with an increase of 0.4 °C in the average air temperature, 1.3 °C in the maximum temperature, and 0.2 °C in the leaf surface temperature.

Table 4. Average values (±standard deviations) of mean, maximum, and minimum values of temperature T [°C], relative humidity RH [%], and absolute humidity x [kg kg^{-1}] measured at height of 1 m in the north, central and south areas of the two greenhouse sectors.

	Cucumber Crop Season 2020/21			**Cucumber Crop Season 2021/22**		
	T	**RH**	**x**	**T**	**RH**	**x**
Average values						
East—Commercial plastic	15.6 ± 1.4	76.1 ± 5.2	0.0064 ± 0.0005	17.2 ± 3.0	78.8 ± 2.8	0.0084 ± 0.0007
West—Experimental plastic	15.8 ± 1.8	76.2 ± 4.7	0.0062 ± 0.0003	16.8 ± 2.9	79.8 ± 2.3	0.0087 ± 0.0007
Average daily maximum values						
East—Commercial plastic	30.8 ± 1.4	92.2 ± 1.5	0.0173 ± 0.0030	28.2 ± 3.7	93.4 ± 1.9	0.0182 ± 0.0044
West—Experimental plastic	31.9 ± 0.8	91.9 ± 0.5	0.0191 ± 0.0044	29.5 ± 3.4	93.3 ± 1.1	0.0175 ± 0.0044
Average daily minimum values						
East—Commercial plastic	6.7 ± 3.4	38.6 ± 10.6	0.0020 ± 0.0010	8.4 ± 3.5	41.1 ± 6.1	0.0029 ± 0.0010
West—Experimental plastic	7.1 ± 3.1	39.5 ± 9.5	0.0022 ± 0.0010	8.6 ± 3.2	43.4 ± 5.1	0.0030 ± 0.0009

Humidity values were similar between both experimental sectors in both seasons (Table 4). Similarly, crop evapotranspiration, which is mainly related to absolute humidity, was very similar in both experimental sectors and in both crop seasons, with no statistically significant differences (see Section 3.3).

The main drawback of the increase in cover transmissivity is that the augmentation of heat introduced in the greenhouse by solar radiation results in a rise in inside temperature. In autumn–winter cycles during the cold period, this effect can positively affect crop production, but in warm periods during the spring–summer cycles the increase in temperature can reduce plant photosynthesis and generate fruit damage. To avoid high temperatures, growers use the whitewashing of the greenhouse cover, drastically reducing plant photosynthesis.

To avoid this great disadvantage of whitewashing, passive climatic control methods have been tested in the RINFOC project, in which the experimental plastic test presented in this work is framed. The effectiveness of the increase in the natural ventilation surface and the use of white marble gravel soil mulching as passive cooling systems has been demonstrated in solar greenhouses in Almería [3,58,59]. In this way, the combined use of three of the techniques proposed in the RINFOC project (plastics with high PAR transmissivity, large side windows, and white marble mulching) will be able to provide greater PAR at the crop level and reduce the temperature inside the greenhouse simultaneously, increasing photosynthesis and the production of horticultural crops, which was the initial objective of the RINFOC project.

3.2. Fungal Diseases

Greenhouse conditions are generally favourable for pest and pathogen development due to the warm and humid microclimate under plastic covers [60]. Modifying the spectral properties of greenhouse films can interfere with pathogen development and is therefore relevant within integrated pest management strategies [61]. Light quality influences fungal sporulation, as exposure to ultraviolet and blue light affects fungal development [62–64]. Consequently, the analysis of physiological and agronomic parameters in this study should be interpreted in relation to the infection levels of the main fungal diseases affecting cucumber crops in the study area.

The most important disease in both seasons was powdery mildew; however, for the first crop season, downy mildew reached infection rates similar to powdery mildew. In the second crop season, statistically significant differences were observed in the three fungal diseases studied. The incidence of fungal diseases studied was generally lower in the greenhouse sector with the experimental plastic cover (Table 5), due to the higher PAR transmissivity of the plastic cover. It should be noted that during the second crop season, the infection rates of the three diseases studied were higher in both sectors compared to the results obtained in the first crop season, which was subsequently reflected in the results obtained in photosynthesis and crop yield.

Table 5. Average values (±standard deviations) of percentage of infection at the end of the trial in both sectors of the experimental greenhouse (extracted from Ávalos-Sánchez et al. [38]). Number of observations per sector n = 200 (50 leaves in 4 rows as repetitions).

Sectors	Plastic Cover	Powdery Mildew *Sphaerotheca fuliginea*	Downy Mildew *Pseudoperonospora cubensis*	Gummy Stem Blight *Didymella bryoniae*
End of first crop season (24 December 2020)				
East	Commercial	$34.11^{b} \pm 30.32$	$19.05^{a} \pm 23.37$	$7.69^{a} \pm 19.30$
West	Experimental	$12.38^{a} \pm 21.18$	$15.79^{a} \pm 23.78$	$8.94^{a} \pm 20.18$
End of second crop season (18 December 2021)				
East	Commercial	$45.22^{b} \pm 34.93$	$47.14^{b} \pm 35.07$	$32.74^{b} \pm 37.58$
West	Experimental	$19.49^{a} \pm 24.17$	$37.86^{a} \pm 33.27$	$25.71^{a} \pm 33.15$

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

3.3. Photosynthetic Activity

In the first crop season, the use of the experimental plastic cover with higher transmittance increased PAR by 8.7% at leaf level (Figure 5a), from 604 µmol m^{-2} s^{-1} in plants of the East sector with the commercial plastic cover to 657.2 µmol m^{-2} s^{-1} in the West. The photosynthetic activity measured in the leaves was 9.3% higher in plants in the sector with the experimental plastic cover, with an average value of 12.9 µmol CO_2 m^{-2} s^{-1} compared to 11.8 µmol CO_2 m^{-2} s^{-1} measured with the commercial plastic. However, as a consequence of the big variability of values measured (Figure 4b) in the different leaves of selected plants along the measuring period (32 days between the first and last measurement), no statistically significant differences were observed (Table 6).

Leaf temperature was 1.1 °C higher in plants in the sector with the experimental plastic cover, as a result of the increase in radiation absorbed by plants and the increase in air temperature. The CO_2 concentration at canopy level, evapotranspiration, and stomatal conductance were practically the same in both experimental sectors (Table 6).

In the second crop season, PAR in the West sector with the experimental cover was 11.6% greater than in the East sector with the commercial plastic. Statistically significant differences were not observed because of the high variability of measured data in the season 2021/22, greater than in the first season 2020/21 (Figure 5a). The variability of the outside temperature was lower (Figure 3a) than in the second one (Figure 4a) when there were more cloudy days and low temperatures.

The photosynthetic activity was 17.9% higher in plants in the sector with the experimental plastic cover (10.5 µmol CO_2 m^{-2} s^{-1}) compared to values corresponding to the commercial plastic (8.9 µmol CO_2 m^{-2} s^{-1}). In this case, the greater difference between both sectors (Figure 5b) and the reduction in the variability of data (reducing the period between the first and last measurements to 22 days) allowed us to obtain statistically significant differences (Table 6).

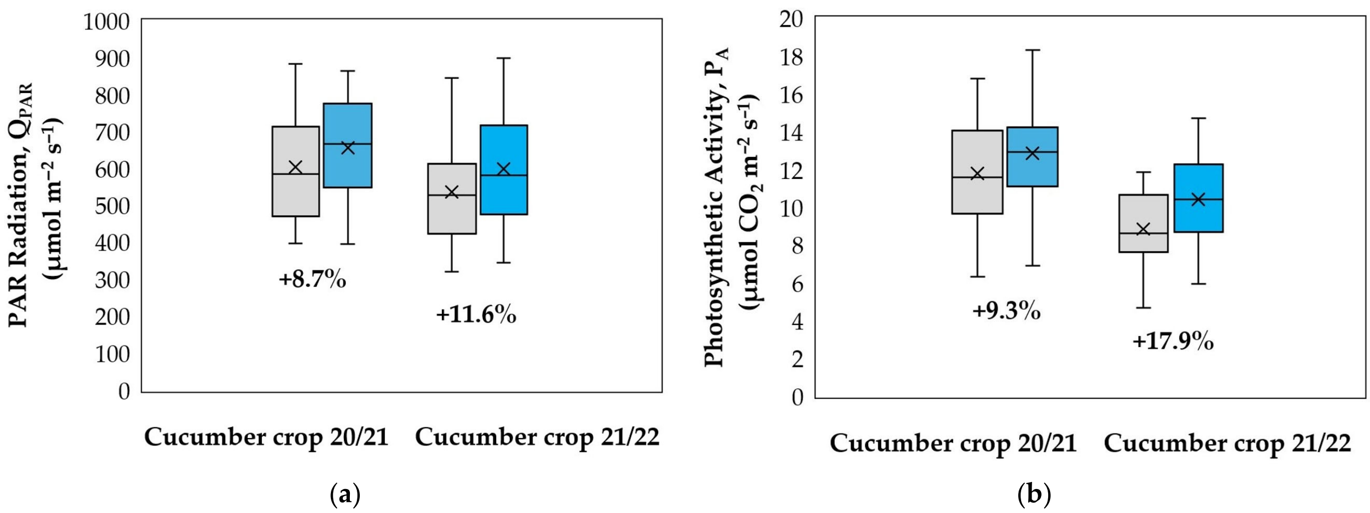

Figure 5. PAR (**a**) and photosynthetic activity (**b**) of cucumber crops with commercial plastic (■) and experimental plastic covers (■) in the 2020/21 and 2021/22 crop seasons. Mean value (×) and median (—) with the lines indicating the maximum and minimum values measured (I).

Table 6. Average values (±standard deviations) of the measurements made on the leaves of plants grown in the two greenhouse sectors with different plastic covers. Outside solar radiation R_{so} [W m^{-2}] during the period of measurements, photosynthetic activity P_A [μmol CO_2 m^{-2} s^{-1}], PAR Q_{PAR} [μmol m^{-2} s^{-1}], leaf temperature T_L [°C], CO_2 concentration C_L [ppm], evapotranspiration E_L [mmol m^{-2} s^{-1}], and stomatal conductance C_E [mol m^{-2} s^{-1}]. Number of observations per sector n = 72 in 2020/21 and n = 48 in 2021/22 (3 leaves by 6 and 4 dates, respectively, in 2020/21 and 2021/22, in 4 rows as repetitions).

Sectors	Plastic Cover	R_{so}	P_A	Q_{PAR}	T_L	C_L	E_L	C_E
Cucumber crop season 2020/21								
East	Commercial	452.1 ± 37.7	11.8 ^{a} ± 3.2	604.2 ^{a} ± 145.4	26.7 ^{a} ± 3.9	415.9 ^{a} ± 20.2	2.3 ^{a} ± 1.0	0.20 ^{a} ± 0.11
West	Experimental		12.9 ^{a} ± 2.8	657.0 ^{a} ± 138.9	27.8 ^{a} ± 3.1	418.0 ^{a} ± 37.5	2.5 ^{a} ± 0.9	0.19 ^{a} ± 0.10
Cucumber crop season 2021/22								
East	Commercial	533.7 ± 21.5	8.9 ^{a} ± 1.9	537.3 ^{a} ± 149.2	27.8 ^{a} ± 2.4	418.2 ^{a} ± 48.5	3.2 ^{a} ± 1.0	0.21 ^{a} ± 0.11
West	Experimental		10.5 ^{b} ± 2.3	600.1 ^{a} ± 172.9	28.0 ^{a} ± 2.6	404.1 ^{a} ± 25.8	3.2 ^{a} ± 0.8	0.22 ^{a} ± 0.11

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 second season 2021/22, the temperature of leaves under the experimental plastic cover was slightly higher (0.2 °C) than under the commercial plastic. As for the previous season, in 2021/22 the concentration of CO_2 in plants, the evapotranspiration, and stomatal conductance showed similar values in the plants of the two experimental sectors (Table 6).

An increase in incident radiation results in enhanced photosynthetic activity was observed, with comparable responses observed for both plastic covers (Figure 6), consistent with the light-dependent nature of the process [65]. However, in the 2020/21 cropping cycle (Figure 6a), photosynthetic rates reached values of 5–20 μmol m^{-2} s^{-1} higher than those observed in the 2021/22 cycle of 5–15 μmol m^{-2} s^{-1} (Figure 6b) for similar values of PAR between 400 and 1200 μmol m^{-2} s^{-1}. The differences may be attributed to external factors such as less favourable weather conditions or ageing of the greenhouse cover material [66].

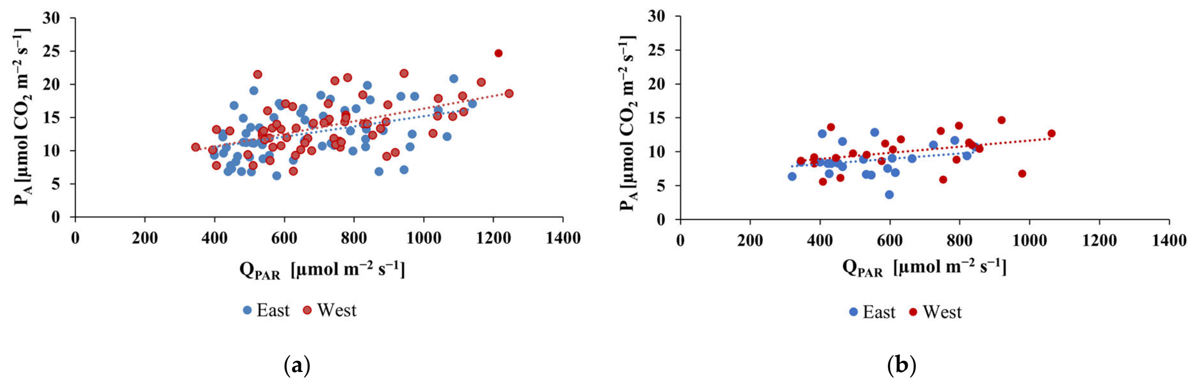

Figure 6. Simple regression line showing the relationship between photosynthetically active radiation (Q_{PAR}) and photosynthetic activity (P_A) in the East sector with commercial greenhouse plastic and in the West sector with experimental plastic during the 2020/21 cropping cycle (**a**) and the 2021/22 cropping cycle (**b**).

3.4. Plant Morphology

In general, there were no statistically significant differences between any of the morphological parameters analysed. Only the average value of the length of the internode was statistically higher in plants under the influence of the experimental plastic cover in the second crop season (Table 7).

Table 7. Average values (±standard deviations) of the morphological parameters measured in plants grown in sectors with different plastic covers. Total length of the stem L_S [cm], length of the apical meristem N_T [cm], length of the internodes L_I [cm], diameter of the stem D_S [mm], number of nodes N_N. Number of observations per sector n = 80 (4 plants at 5 dates in 4 rows as repetitions).

Sectors	Plastic Cover	L_S	N_T	L_I	D_S	N_N
			Cucumber crop season 20/21			
East	Commercial	340.9 ^{a} ± 175.4	24.9 ^{a} ± 4.8	10.5 ^{a} ± 1.8	13.6 ^{a} ± 2.0	25 ^{a} ± 9.3
West	Experimental	338.7 ^{a} ± 173.0	23.2 ^{a} ± 4.7	10.6 ^{a} ± 1.8	13.9 ^{a} ± 1.6	25 ^{a} ± 9.5
			Cucumber crop season 21/22			
East	Commercial	245.6 ^{a} ± 184.3	13.0 ^{a} ± 6.7	10.3 ^{a} ± 2.0	11.2 ^{a} ± 2.6	21 ^{a} ± 11.1
West	Experimental	249.8 ^{a} ± 184.8	13.3 ^{a} ± 6.5	11.4 ^{b} ± 2.2	11.8 ^{a} ± 3.0	20 ^{a} ± 10.4

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

3.5. Yield and Fruit Quality

Multifactor ANOVA analysis shows statistically significant effects of season and plastic cover type (but no effect of rows) on marketable and total yield (Table 8). Logically, the main effects affecting production are the seasons and the harvest date as a consequence of variation in meteorological conditions and plant development. Taking into account the two crop seasons as a whole, the increase in commercial production was 9.85% with statistical significance.

Executing the statistical analysis separately for each of the growing seasons, marketable and total yields increased statistically significantly in the 2021/22 season, but without statistical significance in 2020/21 (Table 9). In the first season 2020/21 of cucumber crops, marketable yield increased 5.0% (0.47 kg/m^2) in the greenhouse sector with the experimental plastic compared to the commercial plastic cover (Figure 7a). Furthermore, the total cumulative yield was 4.3% higher (Figure 7b) with the experimental plastic cover (12.04 kg/m^2) compared to 11.55 kg/m^2 with the commercial one. During the second season 2021/22, with a greater level of fungal infection (Table 5), marketable and total yield were much lower than in the first season 2020/21 (Figure 7). The increases in the second season of 17.3% and 18.0% (Figure 7b) in marketable and total yield, respectively, produced by the commercial plastic cover, could be the result of the combined effect of the increase in PAR and photosynthesis measured in the leaves (Table 6) and the lower infection rate of fungal diseases in plants in this West sector (Table 5).

Table 8. Influence of season, greenhouse plastic cover, harvests, and rows on marketable and total yields of cucumbers (kg m^{-2} $harvest^{-1}$) obtained from the multifactor ANOVA analysis. Number of observations per sector n = 36 (9 harvests in 4 rows as repetitions).

Yield	Marketable Y_M		Total Y_T	
Source	***F*-Ratio**	***p*-Value**	***F*-Ratio**	***p*-Value**
A: Season (2020/21–2021/22)	88.21	0.0000	61.92	0.0000
B: Harvest (1–9)	52.57	0.0000	18.66	0.0000
C: Plastic cover (W-E)	5.68	0.0186	6.01	0.0156
D: Rows (1–4)	0.69	0.5608	0.71	0.5461

Table 9. Average values (±standard deviations) of the production parameters measured for plants grown in areas with different plastic covers. Cumulated marketable yield Y_M [kg m^{-2}], total yield Y_T [kg m^{-2}], weight W_F [g], diameter D_F [mm], fruit length L_F [cm], and soluble solids content SSF [°Brix]. Number of observations per sector n = 90 (10 fruits in 9 harvests as repetitions).

Sectors	Plastic Cover	Y_M	Y_T	W_F	D_F	L_F	S_{SF}
Cucumber crop season 20/21							
East	Commercial	9.17 ^{a} ± 0.14	11.54 ^{a} ± 0.16	474.3 ^{a} ± 105.4	33.8 ^{a} ± 4.0	44.4 ^{a} ± 2.7	3.7 ^{a} ± 0.8
West	Experimental	9.94 ^{a} ± 0.22	12.04 ^{a} ± 0.34	463.0 ^{a} ± 80.9	32.8 ^{a} ± 3.1	44.7 ^{a} ± 4.3	3.4 ^{a} ± 0.5
Cucumber crop season 21/22							
East	Commercial	5.95 ^{a} ± 0.31	7.97 ^{a} ± 0.26	399.5 ^{a} ± 73.9	41.5 ^{a} ± 3.7	33.4 ^{a} ± 2.2	2.9 ^{a} ± 0.4
West	Experimental	6.98 ^{b} ± 0.27	9.40 ^{b} ± 0.34	427.7 ^{a} ± 99.6	42.5 ^{a} ± 3.8	33.9 ^{a} ± 2.8	2.8 ^{a} ± 0.4

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

It is interesting to observe how, although in the first season the differences in crop yield were much lower than those of the second season, yields of the four crop rows located under the experimental plastic were always higher than those of the four rows located in the commercial plastic sector (Figure 7c,d).

In both cucumber crop seasons, the statistical analysis of the quality parameters of the fruits did not show any statistical differences between the fruits harvested under the influence of the two plastic covers tested (Table 9). During the second season, fungal diseases reached higher infection rates, causing a reduction in the weight, length and soluble solids content of the harvested fruits, compared to the fruits harvested in the first season (Table 9). Downy mildew, caused by the fungus *Pseudoperonospora cubensis*, is one of the most dangerous diseases that attack cucumbers, causing serious crop losses [67] and reducing crop yields, which results in significant economic damage [68].

The results show a clear reduction in cucumber yield during the 2021/22 crop season compared to 2020/21, across both plastic cover types. This drop is especially evident in total yield (Y_T), which decreased from 11.54 to 7.97 kg m^{-2} under the commercial film and from 12.04 to 9.40 kg m^{-2} under the experimental one. This reduction is consistent with the lower photosynthesis values measured in the second cucumber cycle (Figure 6). During the second crop cycle of the 2021/22 season, fungal disease severity was higher than in the previous cycle (Table 5), leading to reduced cucumber yield.

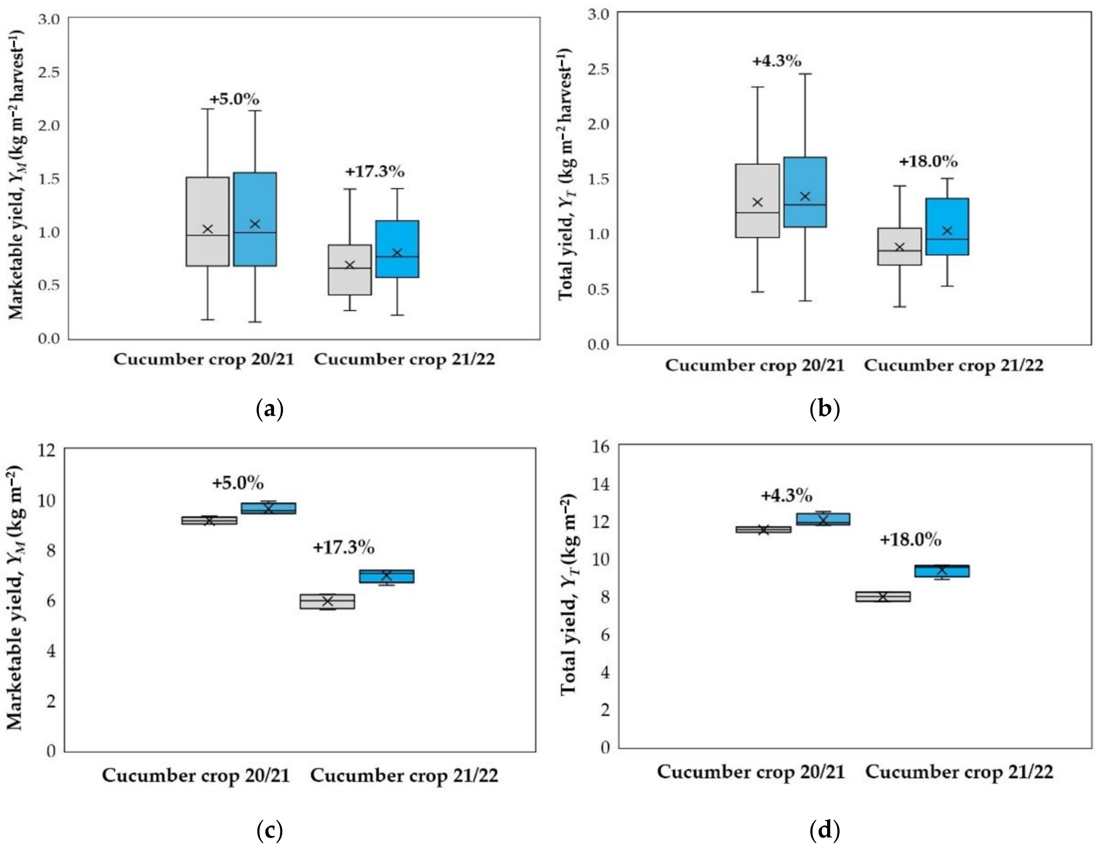

Figure 7. Marketable (**a**) and total yield (**b**) per harvest of cucumber crops with commercial (■) and experimental (■) plastic covers in 2020/21 and 2021/22 crop seasons (n = 36). Cumulated marketable (**c**) and total yield (**d**) of the four rows inside each sector. Mean value (×) and median (—) with the lines indicating the maximum and minimum values measured.

Furthermore, the decline corresponds with lower indoor temperatures during December (Figure 3a), where several days recorded average values below 15 °C and minimum temperatures were 7–8 °C.

Cucumber is a thermophilic crop, and suboptimal temperatures (<18–20 °C) during fruit development and set can reduce carbon assimilation and cell division, leading to fewer and smaller fruits [69]. In 2021/22, this thermal limitation seems to have led to lower fruit weight (W_F) and lower soluble solids content (S_{SF}), particularly under the commercial plastic (Table 9).

Nevertheless, the experimental cover partially mitigated the negative temperature effect. In 2021/22, fruits grown under the experimental film showed higher commercial yield (Y_t), fruit weight (W_F), and fruit diameter (D_F), with statistically significant differences in total yield. This suggests that the experimental film helped maintain a more favourable microclimate by improving daytime radiation transmission [20,70].

3.6. Radiation Use Efficiency for Fruit (RUE$_F$)

During the two crop cycles evaluated, the radiation use efficiency for fruit production (RUE_F) was compared under the two plastic covers. In the first crop cycle, the accumulated photosynthetically active radiation (PAR) was slightly higher under the experimental cover (341.3 MJ m^{-2}) compared with the commercial one (329.3 MJ m^{-2}). The 3.6% increase in incident light observed under the experimental plastic led to a proportional 4.2% increase in total fruit yield, which reached 12.04 kg m^{-2} compared with 11.55 kg m^{-2} under the commercial cover. As a consequence the RUE_F remained essentially unchanged, with values of 35.6 and 35.4 g MJ^{-1}, respectively.

However, during the second crop cycle, a 4% increase in cumulative radiation (304.1 MJ m^{-2} under the experimental cover versus 291.8 MJ m^{-2} under the commercial cover), comparable to that observed in the previous cycle, resulted in a markedly larger increase in fruit yield (+17.9%), reaching 9.41 kg m^{-2} with the experimental cover compared with 7.98 kg m^{-2} with the commercial cover. This response was substantially greater than that observed in the 2020/21 season. Consequently, RUE_F values were 30.9 g MJ^{-1} under the experimental cover and 23.7 g MJ^{-1} under the commercial cover (Table 10). One factor contributing to these differences in RUE_F could be the higher incidence of fungal infections during the second cycle of 2021/22, where plants grown under the commercial plastic appeared to be more affected (Table 5), negatively impacting crop yield (Table 9).

Table 10. Radiation use efficiency for fruits (RUE_F) under commercial and experimental plastic covers during the two growing seasons. Outside temperature To and humidity RHo values during the growing cycles.

Cycles	East—Commercial Plastic	West—Experimental Plastic
Cycle 1 (*To* = 18.5 °C; *Rho* = 63.0%) in season 2020/21		
Cumulated PAR $\boldsymbol{P_i}$ (MJ m^{-2})	329.3	341.3
Total yield $\boldsymbol{Y_T}$ (g m^{-2})	11,550	12,040
$\mathbf{RUE_F}$ (g MJ^{-1})	35.1	35.3
Increase PAR (%)	-	3.6
Increase total yield (%)	-	4.2
Cycle 2 (*To* = 17.8 °C; *RHo* = 63.5%) in season 2021/22		
Cumulated PAR $\boldsymbol{P_i}$ (MJ m^{-2})	291.8	304.1
Total yield $\boldsymbol{Y_T}$ (g m^{-2})	7980	9410
$\mathbf{RUE_F}$ (g MJ^{-1})	27.3	30.9
Increase PAR (%)	-	4.2
Increase total yield (%)	-	17.9

These results indicate that the experimental cover enhanced the capture of PAR and improved the efficiency of converting this energy into fruit biomass. This behaviour is consistent with the findings of Zamani et al. [71], who reported that smart greenhouse covers can improve the spectral quality of light and optimise photosynthesis in protected crops. Similarly, studies such as that of Li [72] emphasise that improving RUE_F is essential for increasing productivity in greenhouse systems, particularly when light is the main limiting factor.

4. Conclusions

In this study, an experimental greenhouse plastic cover with higher photosynthetically active radiation (PAR) transmissivity (90%) was compared with a commercial plastic cover (85%) in a Mediterranean solar greenhouse during two consecutive autumn–winter cucumber crops. The increased transmissivity of the experimental cover resulted in a 3–4% increase in cumulative radiation and an 8.7–11.6% rise in PAR at leaf level, accompanied by only slight increases in air and leaf temperatures.

These changes were associated with higher net photosynthetic activity (9.3–17.9%) and increases in commercial cucumber yield (5.0–17.3%), particularly during the second season, when growing conditions were more restrictive. No significant effects were observed on plant morphology or fruit quality. In addition, the experimental cover showed a lower incidence of major fungal diseases.

Overall, the use of a high-PAR-transmittance plastic improved crop performance without additional energy inputs, contributing to the economic and environmental sustainability of Mediterranean solar greenhouses. This enhancement contributes to the greater economic and environmental sustainability of the greenhouse. Achieving this sustainability was the main objective of the RINFOC project, to which this trial belongs. The main drawback of increasing the transmissivity of the greenhouse cover is the potential rise in indoor solar radiation, leading to excess heat during spring–summer cycles. This issue can be mitigated by enlarging the side ventilation areas and using white marble soil mulching, as demonstrated in the tests conducted during subsequent seasons within the framework of the RINFOC project.

Author Contributions: Conceptualization, F.D.M.-A., A.L.-M., F.B., A.P.-F. and D.L.V.-M.; methodology, F.D.M.-A., A.L.-M. and M.Á.M.-T.; formal analysis, M.Á.M.-T., F.D.M.-A. and A.L.-M.; writing—original draft preparation, M.Á.M.-T.; review and editing, A.L.-M., F.D.M.-A., A.P.-F., D.L.V.-M. and F.B.; project administration, D.L.V.-M.; funding acquisition, F.D.M.-A. and D.L.V.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by POLITIV EUROPA S.L. and the Spanish Ministry of Science, Innovation and Universities by the National R+D+i Plan Project PID2019-111293RB-I00 project Improving greenhouse profitability by increasing photosynthetic activity with passive climate control techniques (RINFOC).

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author(s).

Acknowledgments: The authors would like to thank POLITIV EUROPE, the University of Almería-ANECOOP Foundation for their collaboration and assistance during the development of this study, and the CIAIMBITAL Research Centre.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. CAGPDS. *Cartography of Greenhouses in Almeria, Granada and Malaga*; Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible (CAGPDS), Junta de Andalucía. Secretaria General de Agricultura, Ganadería y Alimentación: Sevilla, Spain, 2023; p. 29. Available online: www.juntadeandalucia.es/export/drupaljda/producto_estadistica/19/06/Cartografia%20_inv_AL_G-R_MA_v201127.pdf (accessed on 30 October 2025). (In Spanish)
2. Valera, D.L.; Belmonte, L.J.; Molina-Aiz, F.D.; López, A. *Greenhouse Agriculture in Almería: A Comprehensive Techno-Economic Analysis*; Publicaciones Cajamar: Almería, Spain, 2016; p. 408. Available online: https://publicacionescajamar.es/series-tematicas/economia/greenhouse-agriculture-in-almeria-a-comprehensive-techno-economic-analysis (accessed on 15 October 2025).
3. Molina-Aiz, F.D. Deliberarle 3.2. Case Studies. Project THEGREEFA—Thermochemical Fluids in Greenhouse Farming. European Union's Horizon 2020 Research and Innovation Programme Under Grant Agreement 101000801. 2024. Available online: http://thegreefa.eu/training/ (accessed on 20 November 2025).
4. Dieleman, J.A.; Marcelis, L.F.M.; Elings, A.; Dueck, T.A.; Meinen, E. Energy saving in greenhouses: Optimal use of climate conditions and crop management. *Acta Hortic.* **2006**, *718*, 203–210. [CrossRef]
5. Baille, A.; Kittas, C.; Katsoulas, N. Influence of whitening on greenhouse microclimate and crop energy partitioning. *J. Agric. For. Meteorol.* **2001**, *107*, 293–306. [CrossRef]
6. López-Martínez, A.; Valera-Martinez, D.L.; Molina-Aiz, F.D.; Moreno-Teruel, M.D.; Peña-Fernandez, A.; Espinoza-Ramos, K.E. Analysis of the effect of concentrations of four whitening products in cover transmissivity of Mediterranean greenhouses. *Int. J. Environ. Res. Public Health* **2019**, *16*, 958. [CrossRef]
7. Ganguly, A.; Ghosh, S. A review of ventilation and cooling technologies in agricultural greenhouse applications. *J. Iran. Energy Environ.* **2011**, *2*, 32–46.
8. Kittas, C.; Baille, A.; Giaglaras, P. Influence of covering material and shading on the spectral distribution of light in greenhouses. *J. Agric. Eng. Res.* **1999**, *73*, 341–351. [CrossRef]
9. Garcia, M.L.; Medrano, E.; Sánchez-Guerrero, M.C.; Lorenzo, P. Climatic effects of two cooling systems in greenhouses in the Mediterranean area: External mobile shading and fog system. *J. Biosyst. Eng.* **2011**, *108*, 133–143. [CrossRef]

10. Moreno-Teruel, M.A.; Valera, D.L.; Molina-Aiz, F.D.; López-Martínez, A.; Peña, A.; Marín, P.; Reyes-Rosas, A. Effects of cover whitening concentrations on the microclimate and on the development and yield of tomato (*Lycopersicon esculentum* Mill.) inside mediterranean greenhouses. *Agronomy* **2020**, *10*, 237. [CrossRef]
11. Zheng, J.; Meng, S.; Zhang, X.; Zhao, H.; Ning, X.; Chen, F.; Omer-Abaker, A.A.; Ingenhoff, J.; Liu, W. Increasing the comprehensive economic benefits of farmland with Even-lighting Agrivoltaic Systems. *PLoS ONE* **2021**, *16*, e0254482. [CrossRef] [PubMed]
12. Zhang, G.; Shen, S.; Takagaki, M.; Kozai, T.; Yamori, W. Supplemental Upward Lighting from Underneath to Obtain Higher Marketable Lettuce (*Lactuca sativa*) Leaf Fresh Weight by Retarding Senescence of Outer Leaves. *Front Plant Sci.* **2015**, *14*, 1110. [CrossRef]
13. Bures, S.; Urrestarazu, M.; Kotiranta, S. LED light has been described as the most revolutionary invention in horticultural lighting in recent decades. In *Artificial Light in Agriculture*; Valencia, Spain, 2018; p. 46. Available online: https://agris.fao.org/search/en/records/6473b05396fdec8b71b5a17f (accessed on 23 October 2025).
14. Higashide, T.; Heuvelink, E. Physiological and Morphological Changes Over the Past 50 Years in Yield Components in Tomato. *J. Amer. Soc. Hort. Sci.* **2009**, *134*, 460–465. [CrossRef]
15. Long, S.P.; Humphries, S.; Falkowski, P.G. Photoinhibition of Photosynthesis in Nature. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* **1994**, *45*, 633–662. [CrossRef]
16. Zhang, S.; Ma, K.; Chen, L. Response of photosynthetic plasticity of Paeonia suffruticosa to changed light environments. *Environ. Exp. Bot.* **2003**, *49*, 121–133. [CrossRef]
17. Steinger, T.; Roy, B.A.; Stanton, M.L. Evolution in stressful environments II: Adaptive value and costs of plasticity in response to low light in Sinapis arvensis. *J. Evol. Biol.* **2003**, *16*, 313–323. [CrossRef]
18. Von Elsner, B.; Briassoulis, D.; Waaijenberg, D.; Mistriotis, A.; Von Zabeltitz, C.; Gratraud, J.; Russo, G.; Suay-Cortes, R. Review of Structural and Functional Characteristics of Greenhouses in European Union Countries: Part I, Design Requirements. *J. Agric. Eng. Res.* **2000**, *75*, 1–16. [CrossRef]
19. Wargent, J.J.; Elfadly, E.M.; Moore, J.P.; Paul, N.D. Increased exposure to UV-B radiation during early development leads to enhanced photoprotection and improved long-term performance in Lactuca sativa. *Plant Cell Environ.* **2011**, *34*, 1401–1413. [CrossRef] [PubMed]
20. Papadakis, G.; Briassoulis, D.; Scarascia-Mugnozza, G.; Vox, G.; Feuilloley, P.; Stoffers, J.A. Radiometric and thermal properties of, and testing methods for, greenhouse covering materials. *J. Agric. Eng. Res.* **2000**, *77*, 7–38. [CrossRef]
21. Farkas, I.; Weihb, P.; Biró, A.; Laube, W.; Eitzinger, J.; Wójcicki, A. Modeling of radiative PAR transfer in a tunnel greenhouse. *Math. Comput. Simul.* **2001**, *56*, 357–368. [CrossRef]
22. Gao, Y.; Dong, J.; Isabella, O.; Santbergen, R.; Tan, H.; Zeman, M.; Zhang, G. Modeling and analyses of energy performances of photovoltaic greenhouses with sun tracking functionality. *Appl. Energy* **2019**, *233*, 424–442. [CrossRef]
23. Abdel-Ghany, A.; Al-Helal, I.; Alzahrani, S.; Alsadon, A.; Ali, I.; Elleithy, R. Covering materials incorporating radiation-preventing techniques to meet greenhouse cooling challenges in arid regions: A review. *Sci. World J.* **2012**, *2012*, 906360. [CrossRef]
24. Samaranayake, P.; Liang, W.; Chen, Z.H.; Tissue, D.; Lan, Y.C. Sustainable Protected Cropping: A Case Study of Seasonal Impacts on Greenhouse Energy Consumption during Capsicum Production. *Energies* **2020**, *13*, 4468. [CrossRef]
25. Baeza, E.; Hemming, S.; Stanghellini, C. Materials with switchable radiometric properties: Could they become the perfect greenhouse cover? *Biosyst. Engin.* **2020**, *193*, 157–173. [CrossRef]
26. Kittas, C.; Tchamitchian, M.; Katsoulas, N.; Karaiskou, P.; Papaioannou, C. Effect of two UV-absorbing greenhouse-covering films on growth and yield of an eggplant soilless crop. *Sci. Hortic.* **2006**, *110*, 30–37. [CrossRef]
27. Ilic, Z.; Fallik, E. Light quality manipulation improves vegetable quality at harvest and postharvest: A review. *Environ. Exp. Bot.* **2017**, *139*, 79–90. [CrossRef]
28. Murakami, K.; Fukuoka, N.; Noto, S. Improvement of greenhouse microenvironment and sweetness of melon (*Cucumis melo* L.) fruits by greenhouse shading with a new kind of near-infrared ray-cutting net in mid-summer. *Sci. Hort.* **2017**, *218*, 1–7. [CrossRef]
29. Petropoulos, S.; Fernandes, A.; Katsoulas, N.; Barros, L.; Ferreira, I. The effect of covering material on the yield, quality and chemical composition of greenhouse-grown tomato fruit. *J. Sci. Food Agric.* **2019**, *99*, 3057–3068. [CrossRef] [PubMed]
30. Baneshi, M.; Gonome, H.; Maruyama, S. Wide-range spectral measurement of radiative properties of commercial greenhouse covering plastics and their impacts into thee energy management in a greenhouse. *Energy* **2020**, *210*, 118535. [CrossRef]
31. Hemming, S.; Dueck, T.; Janse, J.; Van Noort, F. The effect of diffuse light on crops. *Acta Hortic.* **2008**, *801*, 1293–1300. [CrossRef]
32. Li, T.; Heuvelink, E.; Dueck, T.A.; Janse, J.; Gort, G.; Marcelis, L.F.M. Enhancement of crop photosynthesis by diffuse light: Quantifying the contributing factors. *Ann. Bot.* **2014**, *114*, 145–156. [CrossRef]
33. Li, T.; Heuvelink, E.; Van Noort, F.; Kromdijk, J.; Marcelis, L. Responses of two Anthurium cultivars to high daily integrals of diffuse light. *Sci. Hortic.* **2014**, *179*, 306–313. [CrossRef]
34. Hemming, S.; Swinkels, G.L.; Van Breugel, A.J.; Mohammadkhani, V. Evaluation of diffusing properties of greenhouse covering materials. *Acta Hortic.* **2016**, *1134*, 309–316. [CrossRef]

35. Kempkes, F.; Stanghellini, C.; Victoria, N.G.; Bruins, M. Effect of diffuse glass on climate and plant environment: First results from an experiment on roses. *Acta Hortic.* **2012**, *952*, 255–262. [CrossRef]
36. Urban, O.; Klem, K.; Ač, A.; Havránková, K.; Holišová, P.; Navrátil, M.; Zitová, M.; Kozlová, K.; Pokorný, R.; Šprtová, M.; et al. Impact of clear and cloudy sky conditions on the vertical distribution of photosynthetic CO_2 uptake within a spruce canopy. *Funct. Ecol.* **2012**, *26*, 46–55. [CrossRef]
37. Brodersen, C.R.; Vogelmann, T.C.; Williams, W.E.; Gorton, H.L. A new paradigm in leaf-level photosynthesis: Direct and diffuse lights are not equal. *Plant Cell Environ.* **2008**, *31*, 159–164. [CrossRef]
38. Ávalos-Sánchez, E.; Moreno-Teruel, M.Á.; Molina-Aiz, F.D.; López-Martínez, A.; Peña-Fernández, A.; Baptista, F.; Valera-Martínez, D.L. Influence of the Diffusivity and Transmittance of a Plastic Greenhouse Cover on the Development of Fungal Diseases in a Cucumber Crop. *Agronomy* **2022**, *12*, 2743. [CrossRef]
39. Hernández, R.; Kubota, C. Growth and morphological response of cucumber seedlings to supplemental red and blue photon flux ratios under varied solar daily light integrals. *Sci. Hortic.* **2014**, *173*, 92–99. [CrossRef]
40. Trouwborst, G.; Oosterkamp, J.; Hogewoning, S.W.; Harbinson, J.; van Leperen, W. The responses of light interception, photosynthesis and fruit yield of cucumber to LED-lighting within the canopy. *Physiol. Plant.* **2010**, *138*, 289–300. [CrossRef]
41. An, S.; Hwang, H.; Chun, C.; Jang, Y.; Lee, H.J.; Wi, S.H.; Yeo, K.-H.; Yu, I.-h.; Kwack, Y. Evaluation of Air Temperature, Photoperiod and Light Intensity Conditions to Produce Cucumber Scions and Rootstocks in a Plant Factory with Artificial Lighting. *Horticulturae* **2021**, *7*, 102. [CrossRef]
42. Ahn, D.; Higashide, T.; Nakano, A.; Kawasaki, Y.; Iwasaki, Y. Influence of light intensity on growth and CO_2 assimilation rates of three genotypes of cucumber seedlings grown in chambers. *Acta Hortic.* **2014**, *1037*, 759–764. [CrossRef]
43. Särkkä, L.E.; Jokinen, K.; Ottosen, C.O.; Kaukoranta, T. Effects of HPS and LED lighting on cucumber leaf photosynthesis, light quality penetration and temperature in the canopy, plant morphology and yield. *Agric. Food Sci.* **2017**, *26*, 102–110. [CrossRef]
44. Plastics—Thermoplastic Covering Films for Use in Agriculture and Horticulture. Asociación Española de Normalización (UNE): Madrid, Spain, 2020. Available online: https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0064784 (accessed on 15 October 2025).
45. *ASTM D 1003-13*; Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics. American Society for Testing and Materials (ASTM): West Conshohocken, PA, USA; 64p. Available online: https://www.astm.org/Standards/D1003.htm (accessed on 15 October 2025).
46. Emekli, N.Y.; Buyuktas, K.; Bascetincelik, A. Changes of the light transmittance of the LDPE films during the service life for greenhouse application. *J. Build. Eng.* **2016**, *6*, 126–132. [CrossRef]
47. Dilara, P.A.; Briassoulis, D. Degradation and stabilization of low-density polyethylene films used as greenhouse covering materials. *J. Agric. Eng. Res.* **2000**, *76*, 309–321. [CrossRef]
48. Moreno-Teruel, M.Á.; Molina-Aiz, F.D.; Peña-Fernández, A.; López-Martínez, A.; Valera-Martínez, D.L. The Effect of Diffuse Film Covers on Microclimate and Growth and Production of Tomato (*Solanum lycopersicum* L.) in a Mediterranean Greenhouse. *Agronomy* **2021**, *11*, 860. [CrossRef]
49. Hogewoning, S.W.; Douwstra, P.; Trouwborst, G.; Van Ieperen, W.; Harbinson, J. An artificial solar spectrum substantially alters plant development compared with usual climate room irradiance spectra. *J. Exp. Bot.* **2010**, *61*, 1267–1276. [CrossRef]
50. Jiang, C.; Johkan, M.; Hohjo, M.; Tsukagoshi, S.; Ebihara, M.; Nakaminami, A.; Maruo, T. Photosynthesis, plant growth, and fruit production of single-truss tomato improves with supplemental lighting provided from underneath or within the inner canopy. *Sci. Hortic.* **2017**, *222*, 221–229. [CrossRef]
51. Kimball, B.A.; Kobayashi, K.; Bindi, M. Responses of agricultural crops to free-air CO_2 enrichment. *Adv. Agron.* **2002**, *77*, 293–368. [CrossRef]
52. Cossu, M.; Sirigu, A.; Deligios, P.A.; Farci, R.; Carboni, G.; Urracci, G.; Ledda, L. Yield response and physiological adaptation of green bean to photovoltaic greenhouses. *Front. Plant Sci.* **2021**, *12*, 655851. [CrossRef] [PubMed]
53. Thimijan, R.W.; Heins, R.D. Photometric, radiometric, and quantum light units of measure: A review of procedures for interconversion. *HortScience* **1983**, *18*, 818–822. [CrossRef]
54. Statgraphics. *Statgraphics® Centurion 19: User Manual*; Statgraphics Technologies: The Plains, VA, USA, 2020.
55. Deligios, P.; Farci, R.; Cossu, M.; Sirigu, A.; Pisanu, A.B.; Ledda, L. Wild asparagus domestication for food/energy cropping system set up. *Int. Agrophys.* **2023**, *37*, 415–424. [CrossRef]
56. Molina-Aiz, F.D.; Valera, D.L.; López, A. Numerical and experimental study of heat and mass transfers in an Almería-type greenhouse. *Acta Hortic.* **2017**, *1170*, 209–218. [CrossRef]
57. Reyes-Rosas, A.; Molina-Aiz, F.D.; Valera, D.L.; López, A.; Khamkure, S. Development of a single energy balance model for prediction of temperatures inside a naturally ventilated greenhouse with polypropylene soil mulch. *Comput. Electron. Agric.* **2017**, *142*, 9–28. [CrossRef]

58. Molina-Aiz, F.D.; Honoré, M.N.; Fatnassi, H.; Valera, D.L.; López-Martínez, A.; Moreno-Teruel, M.Á. Modelling the effect of a white marble gravel mulch on the energy balance inside a Mediterranean naturally ventilated greenhouse with a tomato crop. *Acta Hortic.* **2025**, *1425*, 199–206. [CrossRef]
59. Molina-Aiz, F.D.; Honoré, M.N.; Marín-Membrive, P.; Galindo-Rodríguez, C.; Valera, D.L. Use of marble gravel mulching for tomato production inside a Mediterranean naturally ventilated solar greenhouse. *Acta Hortic.* **2025**, *1426*, 89–96. [CrossRef]
60. Xu, L.L.; Li, F.; Xie, H.Y.; Liu, X.Z. A novel method for promoting conidial production by a nematophagous fungus, *Pochonia chlamydosporia* AS6.8. *World J. Microbiol. Biotechnol.* **2009**, *25*, 1989–1994. [CrossRef]
61. Su, Y.Y.; Qi, Y.L.; Cai, L. Induction of sporulation in plant pathogenic fungi. *Mycology* **2012**, *3*, 195–200. [CrossRef]
62. Fernández-Ortuño, D.; Torés, J.A.; De Vicente, A.; Pérez-García, A. Field resistance to QoI fungicides in *Podosphaera fusca* is not supported by typical mutations in the mitochondrial cytochrome b gene. *Pest Manag. Sci.* **2008**, *64*, 694–702. [CrossRef]
63. Pérez-García, A.; Romero, D.; Fernández-Ortuño, D.; López-Ruiz, F.; De Vicente, A.; Torés, J.A. The powdery mildew fungus *Podosphaera fusca* (synonym *Podosphaera xanthii*), a constant threat to cucurbits. *Mol. Plant Pathol.* **2009**, *10*, 153–160. [CrossRef]
64. Lebeda, A.; Krístková, E.; Sedláková, B.; McCreight, J.D.; Coffey, M.D. Cucurbit powdery mildews: Methodology for objective determination and denomination of races. *Eur. J. Plant Pathol.* **2016**, *144*, 399–410. [CrossRef]
65. Taiz, L.; Zeiger, E.; Moller, I.M.; Murphy, A. *Plant Physiology and Development*, 6th ed.; Sinauer Associates: Sunderland, CT, USA, 2015.
66. Papadakis, G.; Frangoudakis, A.; Kyritsis, S. Effect of greenhouse microclimate on plant photosynthesis and transpiration: Simulation and experimental validation. *Agric. For. Meteorol.* **2008**, *148*, 524–532.
67. Ojiambo, P.S.; Gent, D.H.; Quesada-Ocampo, L.M.; Hausbeck, M.K.; Holmes, G.J. Epidemiology and population biology of *Pseudoperonospora cubensis*: A model system for management of downy mildews. *Annu. Rev. Phytopathol.* **2015**, *53*, 223–246. [CrossRef]
68. Savory, E.A.; Granke, L.L.; Quesada-Ocampo, L.M.; Varbanova, M.; Hausbeck, M.K.; Day, B. The cucurbit downy mildew pathogen *Pseudoperonospora cubensis*. *Mol. Plant Pathol.* **2011**, *12*, 217–226. [CrossRef] [PubMed]
69. Heuvelink, E. *Tomatoes*; CABI Publishing: Oxfordshire, UK, 2005; 339p.
70. López-Marín, J.; González, A.; Gázquez, J.C.; Rodríguez, D. Photosynthesis, yield and fruit quality of pepper grown under different plastic films. *Sci. Hortic.* **2012**, *135*, 45–51.
71. Zamani, F.; Duri, L.G.; Mori, M.; Paradiso, R. Advances in light manipulation in greenhouse horticulture: The innovative smart covers. *Front. Plant Sci.* **2025**, *16*, 1640530. [CrossRef] [PubMed]
72. Li, T. Improving Radiation Use Efficiency in Greenhouse Production Systems. Ph.D. Thesis, Wageningen University & Research, Wageningen, The Netherlands, 2025.

https://doi.org/10.3390/agronomy16030354