agronomy

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Effect of Greenhouse Film Cover on the Development of Fungal Diseases on Tomato (*Solanum lycopersicum* L.) and Pepper (*Capsicum annuum* L.) in a Mediterranean Protected Crop

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Abstract: Greenhouses on the Mediterranean coast mainly use plastic materials as their cover. The influence of light exerted by these materials directly affects the crops by modifying the environment in which they develop. The aim of this study was to analyze the effect of the use of two plastic films in an experimental greenhouse on the development of fungal diseases in two spring–summer crop cycles: tomato (*Solanum lycopersicum* L.) from February to July 2021 and pepper (*Capsicum annuum* L.) from February to July 2022. The study was carried out in Almeria (Spain) in a multispan greenhouse divided transversely into two sectors by a polyethylene sheet. A commercial film was installed in the east sector (90% of transmissivity and 55% diffusivity) and an experimental film was installed in the west sector (85% of transmissivity and 60% diffusivity). In addition, the effect of the yield and quality of the harvested fruit was determined. In this study, two diseases were established naturally on the crop: (i) powdery mildew (*Leveillula taurica*) in both the tomato and the pepper crop cycles and (ii) early blight (*Alternaria solani*) in the tomato. The analyses of both diseases showed that the areas of the greenhouse that used the plastic cover, which presented a lower sunlight transmissivity, showed higher levels of disease than the areas that used the plastic cover that allowed greater transmissivity of light within the greenhouse, differing statistically in some phases of the crop. The marketable yield was 4.2% (for tomato) and 3.1% (for pepper) higher in the sector with the experimental film with high transmissivity. For both crops, the quality of the fruits did not show statistically significant differences.

Keywords: greenhouse; cover film; protected cultivation; fungal infection

Citation: Ávalos-Sánchez, E.; Moreno-Teruel, M.Á.; López-Martínez, A.; Molina-Aiz, F.D.; Baptista, F.; Marín-Membrive, P.; Valera-Martínez, D.L. Effect of Greenhouse Film Cover on the Development of Fungal Diseases on Tomato (*Solanum lycopersicum* L.) and Pepper (*Capsicum annuum* L.) in a Mediterranean Protected Crop. *Agronomy* **2023**, *13*, 526. https://doi.org/10.3390/agronomy13020526

Academic Editor: Mukesh Dubey

Received: 26 December 2022
Revised: 7 February 2023
Accepted: 10 February 2023
Published: 11 February 2023

1. Introduction

Almeria is the Mediterranean region with the highest concentration of greenhouses in Europe and in the world, with a greenhouse land surface of 32,827 ha in 2021 [1]. Mediterranean greenhouses are mainly composed of tensile steel cable structures supported by columns and covered with transparent plastic roofs [2]. These greenhouses protect crops from external environmental conditions using mainly passive climate systems without energy inputs [3], making them more sustainable with a lower carbon footprint [4].

Plastic covers can increase the level of diffuse radiation inside greenhouses, reaching diffuse radiation in the shaded areas and providing higher rates of photosynthetic activity in crops [5]. Under cover materials that transform direct light into diffuse light, the light profiles are more homogeneous and can increase yield [6–8] of tomato (9%) [9] and cucumber (*Cucumis sativus* L.) (11–15%) [10,11]. The increase of transmissivity to photosynthetically active radiation (PAR) of the greenhouse cover improves photosynthetic activity and consequently can enhance tomato yields [12]. These changes in the light that reaches the crops, and the effect on them, could influence the microclimate inside the greenhouse and affect the development of certain fungal diseases. The incidence of light in the canopy affects some diseases such as powdery mildew. The quality of light can affect the conidiophore development [13], which can modify the severity of powdery mildew on the crop depending on the PAR, ultraviolet or infrared radiation that reaches the plants [14]. In addition, host plants of some diseases show increased transpiration and decreased photosynthetic activity [15].

Normally, farmers apply phytosanitary products periodically throughout the crop, without regard to the severity of the disease, which leads to excessive applications of phytosanitary products [16]. It is an unsustainable agricultural practice, which causes environmental and health risks; it also contributes to the emergence of disease resistance to phytosanitary products due to their excessive use [17,18]. The European Economic Community has reduced in the last years the active materials allowed for use in the fight against diseases and agricultural pests. In the current regulatory framework, any knowledge or technique allowing reductions of damage to crops generated by agricultural pests acquires significant interest. The reduction of pests by the use of new plastic films does not increase the work of the producers and generates an environmental benefit by reducing the use of pesticides, making the farms more sustainable.

The main fungal disease in tomato and pepper crops developed in the spring–summer cycles in Almería greenhouses is powdery mildew. This endemic disease in the southwest of Spain is one of the biggest concerns for greenhouse growers. It is one of the diseases with the highest expenditure on phytosanitary products at the European level [19] and one of the most widespread worldwide [20]. The climate of the area, characterized by warm temperatures with high humidity (due to the proximity of the sea) and dew at the beginning of the day, favors the development of powdery mildew [21–23]. Additionally, the characteristic winds of the Almería region that reduce the ambient humidity can facilitate the dispersion of the spores [21]. In addition, Mediterranean greenhouses (mostly naturally ventilated without forced ventilation to reduce excess humidity [24]) also benefit the presence of powdery mildew.

Powdery mildew is one of the fungal diseases that most affects the production of tomato and pepper in greenhouses [19] and could cause losses in the final production of the crop between 2–4 kg m^{-2} [25]. This disease is the main cause of the increase in the use of pesticides in Europe due to the important damages that are produced in agricultural production [19,26]. *Leveillula Taurica* is the pathogen that causes powdery mildew in tomato and pepper, which in turn is one of the most important fungal diseases in these crops. Powdery mildew in most cases is an epiphytic disease, generating main damages to the outer parts of the leaf. *L. taurica* is an endophytic fungus that penetrates the internal tissues of the leaf (the mesophile), causing internal damage to the leaf and defoliation, which generates production losses in crops [19].

Alternaria solani is also one of the most common pathogens in solanaceous crops, causing early blight on all tomato varieties worldwide that can reduce production [27]. The symptoms of early blight are the appearance of necrotic spots in concentric rings with a yellow chlorotic halo on the leaves, causing the reduction of the photosynthetic area of the plant [28–31]. After colonization, the damage is visible 2–3 days after infection and spores occur between 3 and 5 days later. The pathogen can remain in the greenhouse between different crop cycles, with mycelia on hosts or conidia in the soil, in crop residues and in seeds [32]. This pathogen attacks at all stages of growth and in all plant structures of the tomato, including fruits, leading to crop losses that can reach up to 79% of the yield [33,34].

Tropical climates with elevated temperatures and rainfall favor the development of the pathogen; this requires the use of specific fungicides to control crop damage [35]. Frequent rains, high humidity and high temperatures (24–29 °C) help the development of early blight, but also semi-arid climates with wet nights causing frequent and prolonged night dew favor the proliferation on crops [29].

It is known that there are differences in the development of fungal diseases in different crops, depending on the quality and quantity of light received by the plants [13,14,36–39].

The light in the canopy could be related to the development of diseases that a priori would be more influenced by environmental humidity, as would be the case of early blight. In a previous cucumber crop developed in the same experimental greenhouse, we observed that powdery mildew infection decreased by 30% under the influence of a plastic cover with high transmissivity [11].

The aim of this study was to evaluate the effect of an experimental cover film with high transmittance and high light diffusivity on the development of fungal diseases and yield and fruit quality in tomato and pepper crops developed in the spring–summer cycles in a Mediterranean greenhouse.

2. Materials and Methods

2.1. Characteristics of Experimental Greenhouse

The trials were carried out in a multispan greenhouse located at the UAL-ANECOOP Experimental Station "*Catedrático Eduardo Fernández*" of the University of Almeria (36°51′ N, 2°16′ W and 87 m.a.s.l.). The greenhouse had two isolated sectors separated by a polyethylene sheet (Table 1). The greenhouse had roof and side vent openings (Table 1) protected with insect-proof screens (10 × 20 threads cm^{-2}).

Table 1. Characteristics of the two sectors of the experimental greenhouse. S_C—crop surface; S_V—vent opening surface; S_V/S_C—ventilation surface percentage.

Sector	Plastic Cover	Dimensions	S_C (m^2)	S_V (m^2)	S_V/S_C (%)
West	E_F	40 m × 25 m	1000	232.2	23.2
East	C_F	40 m × 20 m	800	193.9	24.2

An experimental diffuse film with high transmissivity (E_F) was installed in the cover of the west sector of the greenhouse, while a commercial diffuse film (C_F) covered the east sector (control sector). Both plastic films were developed by Politiv Europa S.L. (Israel) and their optical properties (Table 2) were determined following the UNE-EN 13206: 2017 + A1 [40] and ASTM D 1003-13 [41] standards.

Table 2. Optical properties of the cover films. 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
E_F	0.90	0.24	55	90
C_F	0.85	0.24	60	85

In this trial, the cover was whitewashed in both sectors of the greenhouse. This technique is traditionally used by most Almeria growers to reduce temperatures inside the greenhouse, decreasing crop stress and irrigation needs in the months with the highest incidence of radiation (spring–summer). This technique reflects part of the direct radiation reaching the greenhouses, thus influencing the radiation transmitted through the plastic covers [42]. A whitewashing concentration of 0.25 kg L^{-1} of calcium carbonate was applied in May 2021 for the tomato crop and 0.5 kg L^{-1} was applied for the pepper crop in March 2022. The whitewashing of the greenhouse covers degraded over time, detaching from the plastic covers due to weather or climatic conditions [42].

2.2. Crop System

The study was carried out in two spring–summer crop cycles: (i) a tomato crop was transplanted on 7 February 2021 with the commercial variety Ramyle RZ F1 (Rijk Zwaan Ibérica, S.A., Almeria, Spain); (ii) a pepper crop was transplanted on 20 February 2022 with the commercial variety Bemol RZ F1 (Rijk Zwaan Ibérica, S.A., Almeria, Spain).

The plants grew in "arenado", which is an artificial sand mulched soil, typically used in Almeria greenhouses [43]. The plant density used in the trial was 1.2 plants m^{-2} for tomato and 2 plants m^{-2} for pepper. Fertigation was applied uniformly in both sectors by drip irrigation. Tomato and pepper crop management tasks (such as cleaning, trellising, pruning and harvesting) were carried out at the same time in both sectors.

2.3. Measurement of the Infection Level in Plants

For each experimental sector (west-E_F and east-C_F), four evaluation plots were established: two in the northern zone and two in the southern (with an area of 10 m^2 each in both crops). The plots chosen were away from the edges of the greenhouse to avoid the edge effect (Figure 1).

(**a**) (**b**) (**c**)

Figure 1. Detail of tomato (**a**), pepper (**b**) and distribution of the evaluation plots in each experimental sector (**c**).

The methodology used to determine the infection rate for each disease was the same that was used by Ávalos et al. [11]. Twelve plants were randomly selected in each evaluation plot for tomato and twenty plants for pepper. The percentage of affected leaf area on the upper and lower side of four leaves of similar characteristics was evaluated for each selected plant. The identification of the pathogens (*L. taurica* and *A. solani*) that cause the diseases was carried out by direct observation in the greenhouse and subsequent microscopic observation of mycelia, spores and conidia [44,45]. The choice of the evaluation plots followed the European and Mediterranean Plant Protection Organization (EPPO) standards. For powdery mildew diseases, EPPO PP 1/181 (conduct and reporting of efficacy evaluation trials), PP 1/152 (design and analysis of efficacy evaluation trials) and PP 1/57 (powdery mildew on cucurbits and other vegetables) are applicable, as well as EPPO PP 1/263 (*Alternaria solani* and *Alternaria alternata* on potato and tomato), PP 1/135 (phytotoxicity assessment) and pp 1/121 (leaf spot on vegetables, ALTESO). Disease level assessment (powdery mildew and early blight) was carried out weekly from the observation of the first symptoms in both crop cycles.

2.4. Yield and Fruit Quality Measurements

To determine the influence of different plastic films on tomato and pepper yield, four crop lines were selected in each sector (considered as statistical replicates). Marketable yield was weighed at each harvest with a Mettler Toledo electronic balance (Mettler Toledo, S.A.E., L'Hospitalet de Llobregat, Spain; sensitivity of 20 g and maximum capacity 160 of 60 kg).

For the evaluation of fruit quality, we used different parameters depending on the crop. In the case of tomato, ten fruits were randomly selected in each harvest to measure their weight [46] with 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. The equatorial diameter [47] was measured with a digital gauge (Medid Precision, SA, Barcelona, Spain), with a measuring range of 0–150 mm and resolution of 0.010 mm. The soluble solids' content was determined with a PAL1 refractometer (Atago Co. Ltd., Fukuoka, Japan), with a measurement range of 0–53% and an accuracy of 0.2%. The skin firmness [48] was measured with a digital texture analyzer PCE-FM 200 (PCE- Ibérica SL, Tobarra, Spain), with a range of 0–20 kg and an accuracy of 0.5 g. The dry matter content [46] was determined by drying fruits at 70 °C for 48 h in an oven (23–240 I, FD series, Binder GmbH, Tuttlingen, Germany). Visual quality of fruits [49] was estimated 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 and three for lighting control). In the case of the pepper, we selected ten random fruits of every sector in each harvest. In addition to the quality parameters measured in tomato fruits, we measured the length and width of pepper fruits and the length of the pedicel with a tape measure and the mesocarp thickness with a digital gauge.

2.5. Statistical Analysis

Statistical analysis of the data was carried out with Statgraphics Centurion v.18 software (Manugistics Inc., Rockville, MD, USA) using analysis of variance (considered significant if the *p*-value is ≤ 0.05), comparing mean values with Fisher's least significant difference (LSD) procedure. Bartlett's, Cochran's and Hartley's tests were used to determine whether a sector had similar variance. For parameters with different variance, a non-parametric analysis was performed with Friedman's test, where each row represents a block (the date of measurement) using the box-and-whisker plot [50].

3. Results

3.1. Tomato Crop Cycle

The most important disease during the tomato crop cycle was powdery mildew. The disease level was not very high, with an infection rate around 25 % (Figure 2). Early blight does not usually appear on the dates but appeared in our trial. The exceptional rains that fell in Almería between May and June favored the appearance of this disease, presumably due to the increased humidity. Early blight reached lower infection levels than powdery mildew but was sufficient for the farmer to carry out an antifungal treatment, mainly due to the damage caused on tomato leaves and fruit (Figure 2).

(**a**) (**b**) (**c**)

Figure 2. Leaves affected for different disease: powdery mildew in tomato (**a**), early blight in tomato (**b**) and powdery mildew and early blight in the same tomato leaf (**c**).

3.1.1. Powdery Mildew

The evaluation of infection by powdery mildew began on April 21 (appearance of the first symptoms) until July 10, which was the end date of the crop. At the end of the trial, some of the evaluated plots reached infection rates above 20% (Figure 3). Powdery mildew development was faster in the areas covered by the commercial film (C_F), with statistically significant differences even at times with very low infection levels (May 29). Between May 29 and June 19, there was a significant increase in the disease in both sectors. The statistically significant higher levels of infection in the sector with the commercial plastic film were mainly observed in the final phase of the crop, when the incidence of disease increased in the greenhouse (Figure 3).

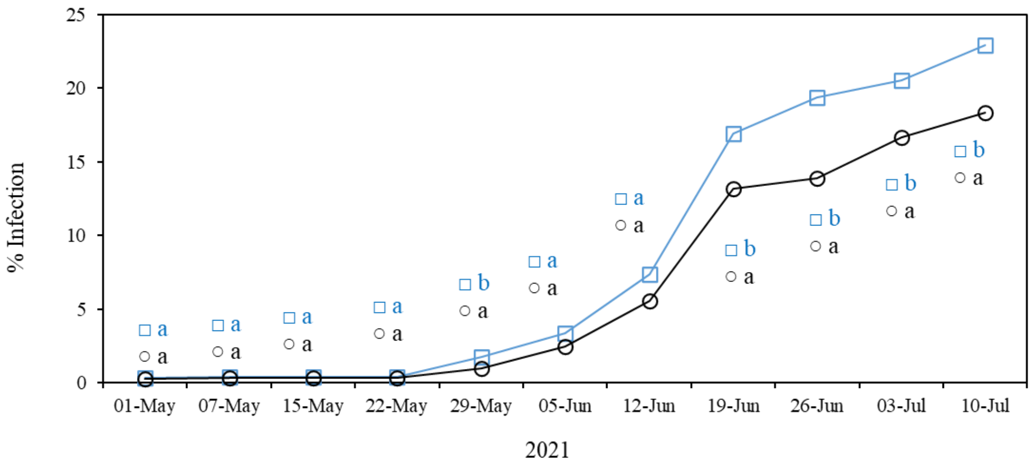

Figure 3. Development of powdery mildew in the tomato: commercial film C_F (□); experimental film E_F (○). Different letters indicate statistically significant differences (p-value $\leq$ 0.95).

The evolution of the infection rate may be influenced by the transmissivity and diffusivity of the radiation of the experimental cover plastic. The results in the tomato crop agreed with the results obtained in two previous cucumber crops developed in the autumn–winter cycles in the same experimental greenhouse [11].

To reduce excessive inside temperatures at the end of the tomato crop, a cover whitewashing was applied with a concentration of 0.25 kg L^{-1} of calcium carbonate in May 2021. Several unusual days of rain (May and June) eliminated the whitewashing of the greenhouse, which was not replaced because of the proximity of the end of the crop. After the rainy days, the disease incidence was higher in both sectors.

3.1.2. Early Blight

Early blight appeared naturally in this trial, with the first symptoms observed from 20 May onwards. A period of elevated temperatures and 8 days of rain (Figure 4), which increased the environmental humidity, favored the development of the disease. Although the trial was carried out in a protected environment (greenhouse), external environmental factors were important for the development of fungal diseases. The accumulated rainfall recorded during the trial was 50 mm, in an area where the average annual rainfall is less than 250 mm.

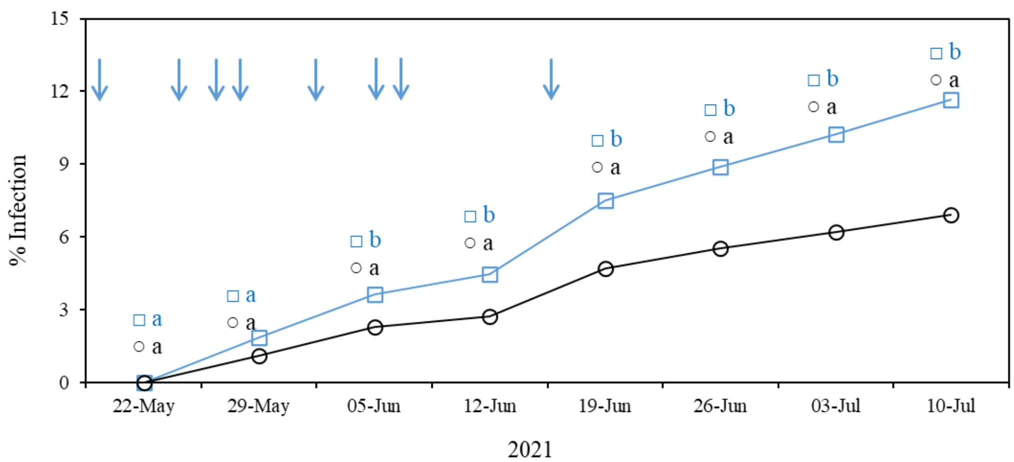

Figure 4. Development of early blight in the tomato: commercial film C_F (□); experimental film E_F (○). Different letters indicate statistically significant differences (p-value $\leq$ 0.95). Arrows indicate rainy days.

The level of disease reached was not extraordinarily high and the development was progressive and without notable periods of severity. The early blight infection rate was always higher in the areas covered with the commercial film, with statistically significant differences from the onset of the disease (Figure 4).

3.1.3. Fruit Quality

The statistical analysis of the fruit quality parameters did not show statistically significant differences between the two sectors. The greatest differences were observed in fruit weight and firmness, both greater in the sector with the commercial film (Table 3). The soluble solids' content and equatorial diameter of the fruit were slightly higher in the sector with the commercial film. The dry matter content was the same between the fruit harvested in the two sectors (Table 3).

Table 3. Average values of the production quality parameters for the tomato: weight—WF (g); equatorial diameter—DF (mm); firmness—FF (kg cm^{-2}); soluble solids content—SSC (°Brix); dry matter—DM (%).

Film	WF	DF	FF	SSC	DM
E_F	130.1 ^{a} ± 21.6	65.3 ^{a} ± 4.2	1.6 ^{a} ± 0.7	4.4 ^{a} ± 0.3	6.6 ^{a} ± 0.9
C_F	133.3 ^{a} ± 14.1	65.9 ^{a} ± 4.8	2.1 ^{a} ± 4.4	4.6 ^{a} ± 0.5	6.6 ^{a} ± 0.9

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

Fruit color did not show statistically significant differences between the commercial film and the experimental film. The luminosity (L) and the yellow/blue color component (b) were higher in the fruit harvested in the sector with the experimental film. The red/green color component (a) was slightly higher in the sector with the commercial film (Table 4).

Table 4. Average values of the color characteristics measured in tomato fruits. Colorimetric coordinates corresponding to the luminosity (L), the red/green color component (a), the yellow/blue color component (b) and the chromaticity (a/b).

Film	L	a	b	a/b
E_F	39.4 ^{a} ± 3.3	23.1 ^{a} ± 2.9	25.2 ^{a} ± 4.4	0.9 ^{a} ± 0.2
C_F	39.0 ^{a} ± 3.3	23.3 ^{a} ± 3.0	25.1 ^{a} ± 4.6	0.9 ^{a} ± 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).

Chromaticity (a/b) is a parameter proportional to fruit maturity associated with visual quality, which translates into better commercial quality. This parameter was similar between the two experimental sectors.

3.1.4. Tomato Production

The results for the tomato show an increase in marketable yield of 0.21 kg/m^2 in the sector of the greenhouse with the experimental film E_F (Figure 5), with an increase of 4.2% compared with the commercial film. Additionally, the total cumulative yield was higher with E_F (6.52 kg/m^2) in comparison with C_F (6.38 kg/m^2) (Figure 5). With E_F, the total yield was 2.2% higher than with C_F.

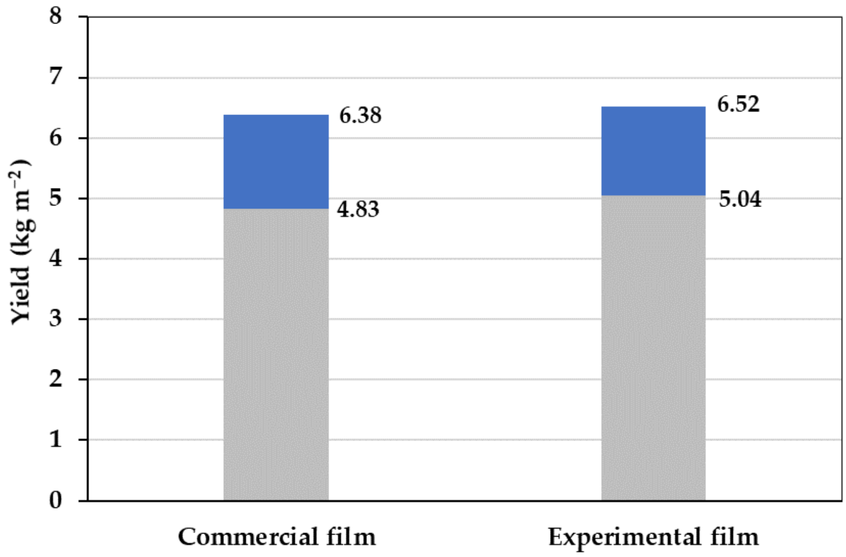

Figure 5. Marketable (■) and total yield (■) of the tomato with commercial film (C_F) and experimental film (E_F).

3.2. Pepper Crop Cycle

In the second crop cycle (February–June 2022), powdery mildew also affected the pepper. The first symptoms of the disease were observed in April 2022, with a low incidence. Therefore, the evaluations started in May when powdery mildew spots could be observed in almost all the evaluation plots. Figure 6 shows the damage caused by the high incidence of the disease in peppers and even the defoliation present in some plants.

(**a**) (**b**) (**c**)

Figure 6. Leaves affected for powdery mildew (**a**,**b**) and defoliation leaves in pepper (**c**).

3.2.1. Powdery Mildew

In the pepper, at the beginning of the crop cycle, no differences were observed between the evaluation plots. Statistically significant differences only appeared in the last three evaluations. Previously, even with infection percentage levels superior to 10 percent, no difference was observed between the evaluation plots (Figure 7).

In this case, a whitening dose of 0.5 kg L^{-1} of calcium carbonate was used in March 2022, because pepper is more sensitive to elevated temperatures at the beginning of the crop. There were no significant rains during crop development, so the whitening remained on the canopy until deterioration, as described by López-Martínez et al. [42]. At the beginning of the crop cycle, there were no clear differences in the development of the disease between the two sectors. However, with the deterioration of the whitening, we observed how the differences in the development of the disease manifested (Figure 7), as happened in the tomato.

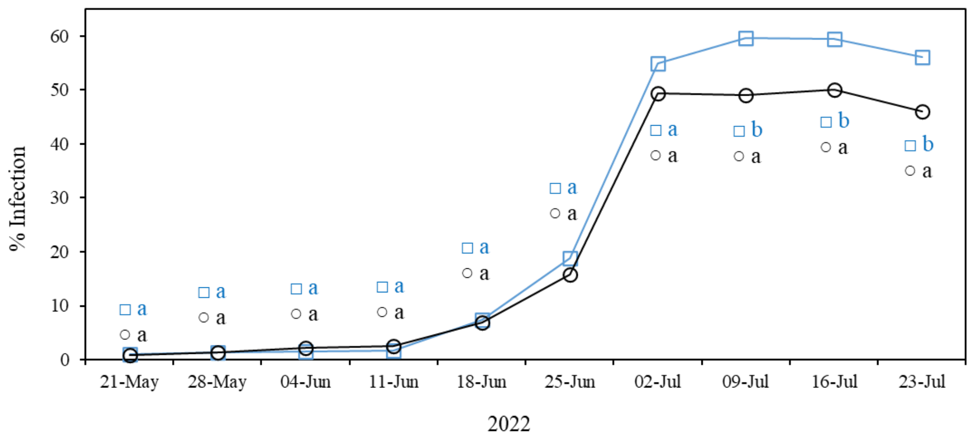

Figure 7. Development of powdery mildew in the pepper: commercial film C_F (□); experimental film E_F (○). Different letters indicate statistically significant differences (p-value $\leq$ 0.95).

The development of powdery mildew at the beginning of the pepper crop cycle was very low. In the last phase of the crop cycle (18 June–2 July 2022), an aggressive development of the disease caused severe damage to the crop that drastically reduced the yield, producing as a consequence the premature end of the crop. In this period, environmental conditions inside the greenhouse were very favorable for the development of the disease, because the leaf area of pepper affected by powdery mildew increased fivefold (Figure 7).

3.2.2. Fruit Quality

No statistically significant differences were observed for any of the pepper quality parameters studied. The size and weight of pepper fruits were higher in the sector with the experimental film. However, the pedicel length and the dry matter were higher in the sector with the commercial film (Table 5).

Table 5. Average values of the production quality parameters for the pepper: weight—WF (g); fruit length—LF (mm); fruit width—WiF (mm); mesocarp thickness—MT (mm); pedicel length—PL (mm); firmness—FF (kg cm^{-2}); soluble solids content—SSC (°Brix); dry matter—DM (%).

Film	WF	LF	WiF	MT	PL	FF	SSC	DM
E_F	259.2 ^{a} ± 46.7	87.5 ^{a} ± 10.9	93.1 ^{a} ± 5.7	7.1 ^{a} ± 1.1	46.44 ^{a} ± 12.6	2.5 ^{a} ± 0.4	7.7 ^{a} ± 0.7	9.6 ^{a} ± 1.6
C_F	252.6 ^{a} ± 44.8	87.4 ^{a} ± 12.2	91.9 ^{a} ± 6.7	7.1 ^{a} ± 1.0	50.0 ^{a} ± 14.4	2.5 ^{a} ± 0.5	7.8 ^{a} ± 0.7	9.9 ^{a} ± 1.5

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

The pepper color did not show statistically significant differences between the sectors studied. All the parameters that quantify it—luminosity (L) and the yellow/blue (b) and red/green (a) color component—were higher in the sector with the experimental film (Table 6). Chromaticity (a/b) was similar in the two sectors.

Table 6. Average values of the color characteristics measured in pepper fruits. Colorimetric coordinates corresponding to the luminosity (L), the red/green color component (a), the yellow/blue color component (b) and the chromaticity (a/b).

Film	L	a	b	a/b
E_F	35.1 ^{a} ± 1.9	27.1 ^{a} ± 3.5	15.9 ^{a} ± 2.7	1.7 ^{a} ± 0.2
C_F	35.0 ^{a} ± 2.1	26.9 ^{a} ± 4.0	15.8 ^{a} ± 2.8	1.7 ^{a} ± 0.2

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

3.2.3. Pepper Production

The marketable production of the pepper was similar in the two sectors. As with the tomato, it was slightly higher in the sector with the experimental film, in this case by 3.1% (0.06 kg/m^2) compared with the sector with the commercial film.

4. Discussion

For tomato and pepper crops developed in the spring–summer cycles, a greater development of some fungal diseases was generally observed in the greenhouse sector with the commercial film; it could be related to the higher light transmissivity of the experimental film (90%) compared with the commercial film (85%). Powdery mildew survives and grows well in shady conditions; the conidia are sensitive to direct sunlight and ultraviolet radiation [51–54]. However, the whitewashing effect results in lower temperatures and higher relative humidity due to the lower incidence of radiation, which also influences the development of pathogenic fungi.

The quantity of light reaching the plant leaves can influence the development of powdery mildew [55], as we can see in Figures 3 and 7. The areas covered with the plastic that allowed a lower total light transmission showed a higher development of the disease, which could be related to a lower incidence of ultraviolet radiation (UV-B, 280–300 nm) that inhibits the development of powdery mildew in the tomato [54]. The differences in the disease development under different plastics may be because of different light qualities under different plastic films or an indirect effect on host plant susceptibility [14,56]. Light intensity and light quality can affect the pathogen or host plant in powdery mildew infections, as has been shown with *L. taurica* on pepper [57] and powdery mildew on cucumber [58].

The cover whitewashing also influenced the light transmitted through the films tested in this work. In the tomato cycle, the whitewashing did not have a significant effect on the results because the rains removed it from the greenhouse canopy (Figure 4). In this case, we observed the different incidences of diseases from the beginning of the crop. In the pepper cycle, there was practically no rain, so the whitewashing remained on the roof of the greenhouse until it deteriorated. Therefore, even with infection rates of 20%, the two areas covered with different films did not differ in disease level. In July, with the whitewashing severely degraded, we observed statistically significant differences. The different levels of disease in both sectors clearly showed the importance of the light that reaches the crop for the development of powdery mildew.

In the tomato cycle, early blight development was also observed. In this case, there was also a lower level of disease in the greenhouse sector covered with the experimental plastic (Figure 4). Early blight development is known to be strongly affected by the need for high humidity and elevated temperatures [35]. Rainfall during the trial could benefit the development of early blight in the crop.

Different wavelengths of light affecting crops can influence the development of diseases as well as the host plant, which can make it more susceptible to these diseases [59]. Early blight needs elevated temperatures and high humidity values for its correct development [35], so the effect of light reaching the crop acts indirectly on the development of the disease [60]. Under the experimental film, there is a greater transmission of total light, which increases photosynthetic activity [12] and may retard the development of the disease. In addition, other studies show that low light in tomato plants reduces the production of antioxidants and hydrogen peroxide and increases the presence of malondialdehyde [61], reducing the plants' natural defenses against pathogens.

The analysis of the marketable yield of the tomato showed an increase of 0.25 kg m^{-2} in the western sector of the greenhouse with the experimental film (Figure 5). This 4.2% increase in marketable yield could be due to the higher radiation transmissivity of the experimental film. For cucumber crops, the yield increased by 14% [11], 10% [9] and 4.8% [7] with diffuse film covers. Similarly, Dueck et al. [10] found an increase in tomato yield of 4.8%. Fruit quality showed no statistically significant differences (Tables 4 and 5) in any of the parameters analyzed. In the tomato crops, sugar contents associated with fruit flavor and pigments associated with fruit maturity can be influenced by the cover materials [62,63]. Plastic covers increase the level of diffuse radiation inside greenhouses, providing higher rates of photosynthetic activity in crops since this diffuse radiation reaches areas that are shaded in outdoor crops [5].

The increase of 0.06 kg/m^2 in the yield of marketable fruits obtained in the sector with the experimental film with respect to the commercial film for the pepper crop (Figure 8) could be also attributed to the higher light transmissivity of the cover. Hee et al. [64] obtained a higher productivity of peppers in a greenhouse with a plastic cover with a high light diffusion rate with respect to a polyethylene plastic cover. The production increased by 3.1%, values similar to those studied by Hemming et al. [65], which were found to increase by 5–6% during the summer months due to the use of a diffuse cover film. There were no statistically significant differences in any of the cases studied (Tables 5 and 6) in the quality parameters of the pepper fruit studied, although they were higher in the sector with the experimental film. Other authors did detect differences in dry matter content, with higher values in the sectors with the higher diffuse radiation film [64].

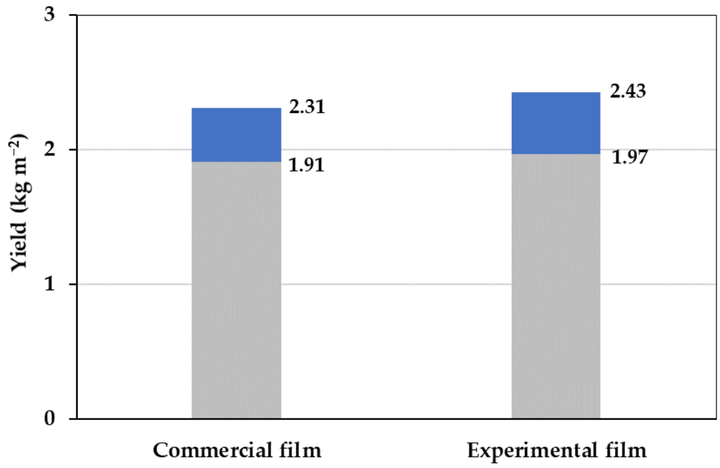

Figure 8. Marketable (■) and total yield (■) of the pepper with commercial film (C_F) and experimental film (E_F).

5. Conclusions

From the results obtained in this work, in which a commercial film (C_F) was compared with an experimental film (E_F), the following conclusions can be drawn:

- In comparison with the commercial film, the experimental film (E_F)—with a 5% higher light transmissivity—reduced the incidence of powdery mildew in the tomato and the pepper mainly in the final phase of both crop cycles, with statistically significant differences.
- In comparison with the commercial film, the experimental film (E_F) reduced the incidence of early blight in the tomato, with statistically significant differences.
- The marketable yield of the tomato and the pepper was higher with the experimental film (E_F) in comparison with the commercial film, with an increase of 4.2% for the tomato and 3.1% for the pepper. However, no statistically significant differences were observed in any of the fruit quality parameters (weight, equatorial diameter, fruit length and width, stalk length, wall thickness, firmness, soluble solids' content, dry matter and colorimetric parameters).

In the future we recommend studying the effect of the plastic cover with different optic properties combined with passive climate control systems (low energy consumption) to improve productivity and the sustainability of the greenhouses.

Author Contributions: Conceptualization, F.D.M.-A., A.L.-M., F.B. and D.L.V.-M.; methodology, F.D.M.-A., A.L.-M. and E.Á.-S.; data analysis, E.Á.-S., M.Á.M.-T., P.M.-M. and A.L.-M.; writing—original draft preparation, E.Á.-S. and M.Á.M.-T.; review and editing, A.L.-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 by the Spanish Ministry of Economy and Competitiveness by the National R+D+i Plan Project PID2019-111293RB-I00.

Data Availability Statement: Not applicable.

Acknowledgments: The authors wish to express their gratitude to Politiv Europa S.L., the Research Centre CIAIMBITAL and Ministry of Universities for the Requalification Aid granted (Margarita Salas). They would like to thank the University of Almeria—ANECOOP Foundation for their collaboration and assistance during the development of this study.

Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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