UNIVERSIDAD DE ALMERÍA

CONTRIBUCIÓN AL CONOCIMIENTO DE LA ACTIVIDAD FOTOSINTÉTICA PROVOCADA POR DIVERSOS SISTEMAS DE CONTROL CLIMÁTICO EN INVERNADEROS MEDITERRÁNEOS

CONTRIBUTION TO KNOWLEDGE OF PHOTOSYNTHETIC ACTIVITY CAUSED BY DIFFERENT CLIMATE CONTROL SYSTEMS IN MEDITERRANEAN GREENHOUSES

TESIS DOCTORAL

AUTORA: María de los Ángeles Moreno Teruel

DIRECTORES: Dr. Diego Luis Valera Martínez
Dra. Ana Araceli Peña Fernández

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Tesis por compendio de publicaciones para obtener el título de Doctor. 8909-Programa de Doctorado en Tecnología de Invernaderos e Ingeniería Industrial y Ambiental.

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TESIS POR COMPENDIO DE PUBLICACIONES

La presente Tesis Doctoral se presenta en la modalidad de *compendio de publicaciones*. Consta de 3 artículos de impacto científico constatable, previamente publicados de acuerdo con la normativa de Estudios Oficiales de Doctorado para esta modalidad, aprobada en Consejo de Gobierno de la Universidad de Almería de 24 de febrero de 2017.

Se permitirá presentar la tesis por la modalidad de compendio de publicaciones cuando se acrediten un mínimo de 3 contribuciones que cumplan las siguientes condiciones mínimas: (a) que dos contribuciones se incluyan en la categoría A de la escala de valoración de los resultados de investigación contenida en el Plan Propio de Investigación y Transferencia de la Universidad de Almería aprobado en el correspondiente año y (b) que una tercera contribución, distinta de las anteriores y que no consista en comunicación a Congreso, se incluya en la categoría B de la escala de valoración mencionada con anterioridad.

En esta tesis se presentan 3 artículos publicados en revistas indexadas (base de datos JCR-SCI), dos de ellos pertenecientes al primer cuartil y uno perteneciente al segundo cuartil. Las contribuciones deberán haber sido publicadas o aceptadas para su publicación como máximo un año antes de la primera matriculación en el correspondiente programa de doctorado, incluyéndose el anterior extinto, en caso de adaptación. En el caso de esta Tesis Doctoral todas las publicaciones han sido posteriores a la fecha de primera matriculación en el Programa de Doctorado de Tecnología de Invernaderos e Ingeniería Industrial y Ambiental, cumpliendo con la normativa vigente.

El cuerpo de esta Tesis Doctoral lo compone una copia de cada una de las publicaciones, además de un pequeño resumen previo.

A continuación, se detalla el nombre y afiliación de cada uno de los autores, la referencia completa de la revista o editorial y el DOI de cada una de las publicaciones:

I. **Autores (P.O. de Firma):** Alejandro López-Martínez [1], Diego Luis Valera-Martínez [1], Francisco Domingo Molina-Aiz [1], **María de los Ángeles Moreno-Teruel** [1], Araceli Peña-Fernández [1] and Karlos Emmanuel Espinoza-Ramos [2].

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

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En cumplimiento de la normativa vigente (Artículo 24) para Estudios Oficiales de Doctorado de la Universidad de Almería, la estructura de Tesis Doctoral por compendio de publicaciones debe ajustarse a una estructura concreta. Por ello la estructura del presente trabajo será la siguiente: (a) un resumen en español e inglés, (b) una introducción relacionada con la temática de la Tesis Doctoral, (c) la hipótesis de partida y los objetivos generales y específicos, (d) una copia original de cada una de las publicaciones y (e) las conclusiones generales especificando a que publicación corresponden.

RESUMEN

El futuro de la agricultura intensiva en invernadero en Almería pasa por hacerla más sostenible mediante el principio de producir más con menos. Es ahí donde los sistemas pasivos de control climático adquieren especial relevancia, puesto que su consumo energético es mínimo. Con la optimización de estas técnicas de ahorro energético podemos mejorar la radiación fotosintéticamente activa que llega hasta nuestros cultivos y, por lo tanto, incrementar la actividad fotosintética y por consiguiente la productividad.

En esta tesis doctoral se pretende afrontar el reto de optimizar el uso de técnicas de ahorro energético tanto tradicionales como de última generación. Como primer paso se determinó el efecto de una técnica tradicional como es el blanqueo de la cubierta de los invernaderos, sobre la transmisividad de la cubierta y sobre la temperatura en el interior de los invernaderos sin cultivo. Evaluándose para ello diferentes dosis de aplicación de cuatro productos de blanqueo comerciales. El segundo paso en este trabajo fue determinar los efectos de diferentes dosis de blanqueo y diferentes estrategias de aplicación del producto más usado en la cuenca mediterránea (Blanco España) sobre un cultivo de tomate (*Solanum Lycopersicum* L.). Para ello se evaluó el microclima en el interior de los invernaderos, la producción, la actividad fotosintética, la morfología de las plantas y la calidad de los frutos cosechados en dos ciclos de cultivo consecutivos.

Finalmente, se evaluó el efecto de otra técnica de ahorro energético más novedosa, como es el uso de cubiertas plásticas con alta difusividad lumínica. Para ello se analizó el comportamiento de una cubierta de plástico difuso experimental de alta transmisividad frente al uso de una cubierta plástica difusa comercial sobre un cultivo de tomate (*Solanum Lycopersicum* L.). Para ello se analizó su efecto sobre el microclima dentro del invernadero, la actividad fotosintética, el crecimiento del cultivo, el rendimiento y la calidad de los frutos en un ciclo de primavera-verano.

Los resultados obtenidos muestran que es necesario recomendar a los agricultores diferentes dosis de blanqueo en función de la época del año y de la reducción deseada de la transmisividad de la cubierta del invernadero. Los niveles más bajos de actividad fotosintética causados por una dosis de blanqueo elevada en el ciclo otoño-invierno, mostraron pérdidas significativas de producción, alrededor del 0,8%-1% por cada reducción del 1% en la transmisividad. Por lo que es recomendable lavar la cubierta a mediados de septiembre cuando la temperatura máxima interior sea inferior a 35 °C. En el ciclo de

primavera-verano el uso de una estrategia con dosis variable no fue eficaz contra el uso de una estrategia de dosis constante (0,250 kg L^{-1}), porque el efecto negativo de la reducción de la fotosíntesis causada por el uso de la dosis más alta (0,500 kg L^{-1}) al final del ciclo fue mayor que el efecto positivo producido al inicio del ciclo con una dosis más baja (0,125 kg L^{-1}). Por lo que es recomendable una dosis de 15 g m^{-2} (0,125 kg L^{-1}) al final de la primavera cuando la temperatura interior supere los 35 °C.

Los resultados del último ensayo de investigación que compone esta Tesis Doctoral muestran que, el plástico experimental produjo un aumento del 14 al 15% en la transmisión media de la cubierta para la radiación solar y la radiación fotosintéticamente activa (PAR) respectivamente. La actividad fotosintética promedio medida en las hojas de cultivo de tomate fue un 21,5% mayor con plástico experimental como resultado de un aumento del 13% en la radiación PAR. Como resultado de este aumento, el rendimiento comercial de la cosecha de tomate fue un 3,2% mayor con el plástico experimental con mayor transmitancia (aumento del 6,5% en la producción total).

ABSTRACT

The future of greenhouse-intensive agriculture in Almería is to make it more sustainable by the principle of producing more with less. This is where passive climate control systems become particularly relevant, as their energy consumption is minimal. By optimizing these energy-saving techniques we can improve the photosynthetically active radiation that reaches our crops and therefore increase photosynthetic activity and therefore productivity.

This doctoral thesis aims to face the challenge of optimizing the use of both traditional and next generation energy saving techniques. As a first step, the effect of a traditional technique such as whitening of the greenhouse cover, on the transmissivity of the cover and on the temperature inside the greenhouses was determined. Different doses of application of four commercial whitening products are evaluated for this purpose. The second step in this work was to determine the effects of different whitening doses and different strategies of application of the most used product in the Mediterranean area (Blanco España) on a tomato crop *(Solanum Lycopersicum* L.). To this end, microclimate was evaluated inside greenhouses, production, photosynthetic activity, plant morphology and the quality of the fruits harvested in two consecutive growing cycles.

Finally, the effect of another newer energy-saving technique was evaluated, such as the use of film covers with high light diffusivity. To this end, the behavior of a high transmissive experimental diffuse film cover was analyzed against the use of a commercial diffuse film cover on a tomato crop *(Solanum Lycopersicum* L.). To this end, its effect on microclimate within the greenhouse, photosynthetic activity, crop growth, yield and fruit quality was analyzed in a spring-summer cycle.

The results show that it is necessary to recommend to farmers different doses of bleaching depending on the time of year and the desired reduction of the transmissivity of the greenhouse cover. The lower levels of photosynthetic activity caused by a high bleaching dose in the autumn-winter cycle, showed significant production losses, around 0.8% -1% for each 1% reduction in transmissivity. It is therefore advisable to wash the cover in mid-September when the maximum indoor temperature is less than 35 °C. In the spring-summer cycle the use of a variable dose strategy was not effective against the use of a constant dose strategy (0,250 kg L^{-1}), because the negative effect of the reduction of photosynthesis caused using the highest dose (0.500 kg L^{-1}) at the end of the cycle was greater than the positive effect

produced at the beginning of the cycle at a lower dose (0.125 kgL^{-1}). So, it is advisable to dose 15 g m^{-2} (0.125 kg L^{-1}) at the end of spring when the indoor temperature exceeds 35 °C.

The results of the latest research trial that makes up this doctoral thesis show that, the experimental plastic produced an increase of 14 to 15%in the average transmission of the cover for solar radiation and photosynthetically active radiation (PAR) respectively. The average photosynthetic activity measured in tomato crop leaves was 21.5% higher with experimental film because of a 13% increase in PAR radiation. As a result of this increase, the commercial yield of the tomato crop was 3.2% higher with the most transmitted experimental film (6.5% increase in total production).

INTRODUCCIÓN

INTRODUCCIÓN

Almería es una de las principales áreas de producción hortícola bajo invernadero a nivel mundial, con un área de 31,614 ha [1] que se ha incrementado en alrededor de 1500 ha en los últimos dos años. El crecimiento en el área de invernaderos en los últimos años es probablemente el principal factor mitigante del cambio climático en la provincia, debido a un aumento en el albedo de las cubiertas plásticas altamente reflectantes [2], así como por su gran efecto como sumidero de CO_2. Actualmente, el sector hortícola se enfrenta a una situación económica difícil, en la que la estabilidad en los precios de venta de los productos ante el aumento gradual de los costes de producción de los cultivos de invernadero pone en riesgo la rentabilidad económica de la mayoría de las explotaciones agrícolas. Así, en los invernaderos de Almería, el beneficio neto de explotación (considerando costes variables, costes fijos, depreciación y costes de inversión) adquirió cifras negativas para la mayoría de los cultivos en las últimas temporadas de 2015 a 2017 [3,4]. El futuro de los invernaderos de Almería pasa por afrontar los grandes retos de la agricultura global y la pérdida de rentabilidad del sector a nivel local. Para ello, se encuentran disponibles varias herramientas, como la optimización de la actividad fotosintética [5].

Importancia de la calidad de la radiación solar en los cultivos en invernadero

La eficiencia en el uso de la luz puede verse afectada por su distribución e influye significativamente en el crecimiento y rendimiento de los cultivos [6-8]. Una mejora en la interceptación de luz por parte de las estructuras de los invernaderos y el uso de plásticos foto-selectivos y difusos puede aumentar la radiación que llega hasta los cultivos. En el interior de los invernaderos la distribución de la luz sobre las diferentes hojas de una planta muestra grandes variaciones en función del ángulo solar, lo que da lugar a puntos de sombra y manchas de luz. Los daños causados por la luz pueden ocurrir particularmente en esos puntos de luz [9], manifestándose en forma de decoloraciones en las hojas o incluso necrosis en casos extremos [10]. Los daños causados por la luz se producen principalmente como resultado de una exposición prolongada a picos excesivos de intensidad luminosa [11-13].

La radiación solar y la actividad fotosintética

Las plantas utilizan la energía solar para producir compuestos orgánicos que utilizan para su desarrollo y crecimiento mediante la fotosíntesis [14]. La fotosíntesis es, por lo tanto, un proceso fisicoquímico mediante el cual las plantas utilizan la energía luminosa para sintetizar compuestos orgánicos [15]. Así pues, la energía solar es, una herramienta indispensable para las plantas y su reproducción. Las plantas son capaces de reaccionar a la intensidad luminosa mediante sus fotorreceptores (fitocromos, criptocromos y fototropinas) que se activan con longitudes de onda específicos [16-18]. La fotosíntesis además de ayudar al crecimiento vegetal y a la generación de biomasa, también ayuda a la germinación y a la floración, entre otras funciones, que también dependen de la luz, no tanto en su cantidad sino en la calidad [19].

La tasa fotosintética de las hojas está determinada por la cantidad de proteína fotosintética por área foliar y la conductividad de CO_2 en lo estomas [20]. Además, un aumento en la transmisividad de la cubierta permite no solo aumentar la fotosíntesis y la producción, sino también reducir el aporte de energía en períodos fríos [21]. Bajo condiciones normales de concentración de CO_2 y con temperaturas adecuadas en el interior de los invernaderos, la actividad fotosintética es principalmente afectada por la intensidad de la luz [22].

Los niveles de radiación insuficientes producen un estrés abiótico significativo que limita el crecimiento de las plantas y el rendimiento de los cultivos en invernadero [23]. Con poca luz incidente, las hojas del dosel vegetal muestran una tasa fotosintética neta extremadamente baja y una senescencia prematura, que produce la reducción del crecimiento y el rendimiento de las plantas [24,25]. Generalmente, una disminución de luz diaria acumulada del 1% conduce a una pérdida de rendimiento del 0,8% al 1% para la mayoría de los cultivos de invernadero [26,27].

Por otra parte, una radiación excesiva junto con elevadas temperaturas puede producir una disminución persistente en la eficiencia de la conversión de energía solar en fotosíntesis, lo que se conoce como fotoinhibición [28-31]. La fotoinhibición de tomate puede ocurrir a 30-40 °C y altos niveles de radiación (1500–1800 $\mu mol\ m^2\ s^{-1}$) [32-33]. Generalmente, la radiación solar en el interior de los invernaderos no se distribuye de manera homogénea, la parte superior del cultivo intercepta luz más directa y en la zona inferior aumenta la proporción de luz difusa. Algunas de las hojas superiores expuestas a la luz directa pueden incluso experimentar un exceso de luz, que puede conducir eventualmente a la fotoinhibición, mientras que las hojas inferiores podrían sufrir un déficit energético, que provoca una dramática disminución de la actividad fotosintética [34].

Si todos los factores para mejorar la eficiencia del uso de la radiación y la eficiencia en la interceptación de la luz del cultivo se optimizan simultáneamente, la productividad de los cultivos se puede mejorar entre un 36% y un 64% [35].

Técnicas de ahorro energético que modifican la radiación en el interior de los invernaderos

La producción en invernadero puede estar asociada con altos costes, especialmente en el caso de producir fuera de temporada, y con sistemas de control climático donde se utilizan combustibles fósiles. Son diversos los sistemas de control climático que podemos encontrar en la actualidad en el campo de la agricultura, pero son las técnicas de ahorro energético las que más interés generan debido a que con una inversión mínima es posible modificar las condiciones interiores de los invernaderos para adaptarlas a las necesidades óptimas de los cultivos.

Lograr un ambiente adecuado en invernaderos en regiones cálidas y soleadas se ha convertido en un gran desafío, debido a la gran cantidad de radiación solar transmitida al invernadero, y luego convertida en calor sensible y latente [2]. Múltiples estrategias de refrigeración se utilizan en invernaderos para proporcionar un entorno adecuado para el crecimiento de las plantas y aumentar la productividad de los cultivos, tales como: (i) sistemas de refrigeración evaporativa, (ii) sistemas de ventilación forzada, y (iii) métodos de sombreado, tales como la aplicación de blanqueo o el uso de pantallas móviles de sombreado [36,37].

Blanqueo de la cubierta de los invernaderos

El sombreo de la cubierta es un método eficaz para lograr un microclima adecuado dentro de los invernaderos para el desarrollo de plantas y para mejorar la cantidad y el rendimiento de los cultivos en las regiones cálidas y soleadas [38]. Es una técnica de bajo coste para reducir la acumulación de calor y modificar el entorno de invernadero en veranos calurosos [36,39]. Este método de sombreado se realiza mezclando una cierta cantidad de óxido de calcio o carbonato de calcio con agua, para hacer una solución que se utiliza para pintar la superficie exterior del vidrio o polietileno [40-42].

La mayoría de los agricultores de Almería (99%) blanquean el techo de sus invernaderos para aumentar el coeficiente de reflexión de la radiación solar, lo que reduce la entrada de energía que calienta el invernadero en las horas pico del día [40]. El blanqueo es innecesario en invernaderos equipados con sistemas de sombreado móvil (pantallas de oscurecimiento y pantallas aluminizadas) o sistemas de refrigeración evaporativa.

La combinación de blanqueo con la ventilación natural es una técnica ampliamente utilizada en los invernaderos de la cuenca mediterránea [43,44]. El blanqueo de la cubierta no interfiere con la ventilación del invernadero, lo que representa una ventaja importante con respecto a los otros sistemas de sombreado que afectan negativamente al rendimiento de la ventilación cenital [45].

El producto más utilizado es el carbonato de calcio micronizado, más conocido como "Blanco de España", la dosis utilizada varía dependiendo de la región y la transmisividad de la cubierta de plástico. La intensidad de blanqueo se puede regular, cambiando la concentración de carbonato de calcio entre 0,34 y 0,46 kg L^{-1} [40]. Sin embargo, el sombreado con carbonato de calcio es irregular, y la pérdida del producto puede producirse por la acción de la lluvia (lavado) [36,37].

El sombreado excesivo puede reducir significativamente la radiación solar interceptada por el cultivo, afectando así negativamente al crecimiento de las plantas [26,36]. La producción de cultivos depende de la cantidad de radiación fotosintéticamente activa (PAR) absorbida por el cultivo [46], y los niveles de sombreado superiores al 40% pueden reducir el rendimiento del tomate [47].

Sin embargo, la reducción de la radiación solar por sombreado puede producir efectos positivos, como una disminución de la temperatura del aire y el consumo de agua de riego [38,48]. Por lo tanto, el uso del blanqueo puede mejorar la eficiencia del uso del agua, reduciendo la transpiración de los cultivos [36,49]. Se debe prestar mucha atención a la fecha de aplicación, a la duración y a la dosis, con el objetivo de no reducir drásticamente los flujos fisiológicos en los estratos inferiores de las plantas [50]. Además, el carácter permanente del sistema dificulta la regulación de la intensidad del campo radiativo después de su aplicación, lo que provoca un efecto negativo en el rendimiento potencial de los cultivos [51].

Esta técnica de control climático garantiza que los invernaderos se enfríen pasivamente de una manera respetuosa con el medio ambiente, sin ningún coste de energía. Mientras que con otros métodos, se requieren de usos intensivos de energía para mantener las condiciones de cultivo ideales [52].

Uso de cubiertas plásticas con alta difusividad lumínica

La manipulación activa del entorno de crecimiento de las plantas se utiliza comúnmente para optimizar la producción y la calidad de los cultivos [53,54]. Gran parte de las técnicas en los últimos años, se centran en la producción de materiales de cubierta para invernaderos que modifican las propiedades de la luz, como plásticos foto-selectivos, plásticos que bloquean los rayos UV y plásticos de cubierta con alta difusividad lumínica, que podrían minimizar las pérdidas de energía y aumentar el rendimiento sin un aumento desproporcionado del uso de energía [55-57].

Se ha demostrado que la luz difusa se distribuye de manera más homogénea sobre el cultivo que la luz directa [58-61]. Los cultivos en invernadero requieren una gran cantidad de luz en invierno y pueden utilizar una elevada proporción de luz difusa en verano [62]. Una radiación excesiva junto con elevadas temperaturas puede producir una disminución persistente en la eficiencia de la conversión de energía solar en fotosíntesis (fotoinhibición) [28-31]. La luz difusa produce menos fotoinhibición, debido a picos locales menos severos en la intensidad de la luz y permite disminuir la temperatura de las hojas y de las flores [60,63,64].

El resultado de una distribución uniforme de la luz es que penetrará más profundamente en el cultivo aumentando el área foliar fotosintéticamente activa [65]. Una distribución homogénea de la luz disminuye las ocasiones en las que se alcanzan cantidades extremadamente altas de energía lumínica, que puedan producir reducciones en la actividad fotosintética o incluso fotoinhibición [66,67].

Las plantas utilizan la luz difusa de manera más eficiente que la luz directa, como consecuencia de una mejor penetración de la luz difusa en el dosel y la respuesta no lineal a la densidad de flujo de luz de la tasa fotosintética de las hojas individuales [68]. Varios modelos de cambio climático han estimado incrementos en la luz difusa debido al vapor de agua atmosférico como consecuencia del aumento de la nubosidad [69,71]. Estas predicciones climáticas y las estimaciones de productividad enfatizan la necesidad de comprender el comportamiento de las plantas frente a la luz difusa, ya que los efectos desde el nivel del dosel hasta el nivel de la hoja aún se desconocen. La fotosíntesis en hojas normalmente expuestas al sol puede ser un 10-15% más alta bajo la luz directa en comparación con las irradiancias con una cantidad equivalente de luz difusa [65]. Esto sugiere que la luz directa y difusa afecta a los procesos fotosintéticos de manera diferente [72], dependiendo de la adaptación de las hojas a la exposición solar o a condiciones de sombra [65].

Para aprovechar la luz difusa en los invernaderos, se usan materiales de cubierta que aumentan la difusión de la luz sin disminuir la transmisión [73]. Bajo materiales de cubierta difusos (capaces de transformar entre un 45 y 71% de la luz directa en difusa), los perfiles de luz fueron más homogéneos, aumentando el rendimiento y el crecimiento de los cultivos [60,74,75]. La luz difusa distribuye la radiación fotosintéticamente activa de manera más uniforme a todas las hojas, lo que aumenta la tasa global de fotosíntesis [76]. Por lo tanto, las cubiertas difusas pueden ayudar a aumentar la integral de luz diaria sin provocar daños. El incremento de la integral de luz diaria favorece el crecimiento y el desarrollo de las plantas [27,77]. Han sido varios los autores que han demostrado los beneficios que aportan el uso de cubiertas plásticas con alta difusividad, [73] recomendaron el uso de materiales de cubierta con una difusividad mínima del 50% y una transmisividad del 90% y [53] reportaron aumentos en la producción de pepino en un 9% y en un 11% en el caso del tomate [62].

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HIPÓTESIS Y OBJETIVOS

HIPOTESIS Y OBJETIVOS

Hipótesis

Se han planteado las siguientes hipótesis:

I. La producción de cultivos en invernadero está directamente relacionada con la actividad fotosintética de los mismos.
II. Se puede mejorar la actividad fotosintética modificando el microclima interior de los invernaderos.
III. Mediante la optimización de técnicas de ahorro energético se puede mejorar el microclima de los invernaderos, aumentando la actividad fotosintética y con ella la producción de los cultivos.

Objetivos

El objetivo general de esta Tesis Doctoral es contribuir al conocimiento de la actividad fotosintética de un cultivo de tomate sometido a diferentes sistemas de climatización obteniendo como resultado una mejora en la rentabilidad de las explotaciones derivada de los incrementos productivos asociados a mejoras en la actividad fotosintética.

Este objetivo general se puede descomponer en los siguientes objetivos específicos:

I. Puesto que en esta tesis se pretende optimizar el uso de técnicas de ahorro energético, como primer paso se determinó el efecto de una técnica tradicional como es el blanqueo de la cubierta de los invernaderos, sobre la transmisividad de la cubierta plástica y sobre la temperatura en el interior de los invernaderos. Para ello se evaluaron diferentes dosis de aplicación de cuatro productos de blanqueo comerciales, el producto tradicional "Blanco España" y otros tres productos que incorporan adhesivo que aporta mayor resistencia a la lluvia.

II. Una vez se analizó el efecto del blanqueo sobre la transmisividad de la cubierta y la temperatura interior, el segundo paso a seguir es investigar los efectos de diferentes dosis de blanqueo en un cultivo de tomate (*Solanum Lycopersicum* L.). Para ello se evaluó el microclima en el interior de los invernaderos, la producción, la actividad fotosintética, la morfología de las plantas y la calidad de los frutos cosechados en dos ciclos de cultivo consecutivos.

III. Por último, se evaluó el efecto de otra técnica de ahorro energético más novedosa, como es el uso de cubiertas plásticas con alta difusividad lumínica. Para ello se analizó el comportamiento de una cubierta de plástico difuso experimental de alta transmisividad frente al uso de una cubierta plástica difusa comercial sobre un cultivo de tomate (*Solanum Lycopersicum* L.). Para ello se analizó su efecto sobre el microclima dentro del invernadero, la actividad fotosintética, el crecimiento del cultivo, el rendimiento y la calidad de los frutos en un ciclo de primavera-verano.

PUBLICACIONES

Analysis of the effect of concentrations of four whitening products in cover transmissivity of Mediterranean greenhouses

Resumen

El presente trabajo analiza el método tradicional de aplicación de productos de blanqueo en invernaderos mediterráneos. Se compararon cuatro productos de blanqueo comerciales (Protectores Solares Agrícolas, ASP), aplicados en cuatro dosis, con una cubierta sin blanqueo. Se analizó el producto tradicional “Blanco España” con un 90% de carbonato de calcio ($CaCO_3$) y otros tres productos con el 97% de $CaCO_3$ que incorporan adhesivos. El uso de adhesivos en los ASP no influyó en el efecto de los diferentes productos sobre la temperatura interior, y a la misma dosis los cuatro productos muestran un comportamiento similar. Los hallazgos respaldan la dosis máxima recomendada por otros autores de 0,50 kg L^{-1} (50/100), por encima de la cual la transmisividad de la cubierta del invernadero disminuye en más de un 50%. El efecto del ASP en la transmisividad de la cubierta depende principalmente de la dosis aplicada, pero también de las condiciones climáticas (radiación solar, nubosidad, etc.) y de la época del año (elevación solar). El uso habitual de una dosis constante a lo largo del año no parece ser el método más adecuado. Las dosis recomendadas deben variar según la época del año y el grado deseado de reducción de la transmisividad. Se muestra que los componentes adhesivos proporcionan un alto grado de protección contra las fuertes lluvias. El estudio recomienda un método estandarizado de aplicación de ASP, estableciendo un método que permita al agricultor verificar la concentración del producto que permanecerá en la cubierta del invernadero.

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Analysis of the Effect of Concentrations of Four Whitening Products in Cover Transmissivity of Mediterranean Greenhouses

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Abstract: The present work analyses the traditional method of applying whitening products on Mediterranean greenhouses. Four commercial whitening products (agricultural solar protectors, ASPs), applied at four doses, were compared with a non-whitened cover. The traditional product "Blanco de España" with 99% calcium carbonate ($CaCO_3$) and other three products with 97% $CaCO_3$ that incorporate adhesives were tested. The use of adhesives in ASP did not influence the effect of the different products on the inside temperature, and at the same dose all four products show a similar behaviour. The findings support the maximum dose recommended by other authors of 0.50 kg L^{-1} (50/100), above which the transmissivity of the greenhouse cover decreases by over 50%. The effect of ASP on the transmissivity of the cover depends principally on the dose applied, but also on the climatic conditions (solar radiation, cloud cover, etc.) and on the time of year (solar elevation). The habitual use of a constant dose throughout the year does not seem to be the most adequate. Recommended doses should vary according to the time of year and the desired degree of transmissivity reduction. The adhesive components are shown to provide a high degree of protection against heavy rain. The study recommends a standardised method of *ASP* application, establishing a method that allows the grower to verify the concentration of the product that will remain on the greenhouse cover.

Keywords: greenhouse; agricultural solar protector; crop protection; cover transmissivity

1. Introduction

The success of the greenhouses in the province of Almería (Spain) is founded on low-cost structures and a temperate climate that permit relatively high yields. However, at certain times of the year natural ventilation does not suffice to combat the high temperatures, and consequently 99% of growers whiten the greenhouse cover [1]. To do so they apply a mixture of water and micronized calcium carbonate ("Blanco de España"). Despite the importance of this technique in the climate control of Mediterranean greenhouses, few technical or scientific works have studied this topic. Transmissivity of greenhouse cover is one of the main parameters influencing the energy balance that determine inside temperature, that can vary along a crop season between 0.44 and 0.80, depending on whitening [2].

Transmissivity of greenhouse cover with whitening is difficult to determine because it depends on the dose [3].

In hot and warm climates, shading is necessary in summer to reduce the solar radiation load in the greenhouses. Excess solar radiation can produce undesirable increases of temperature inside the greenhouse negatively affecting plants' growth and direct damage on fruits (sunburn). A theoretical investigation carried out by writing energy and mass balance equations revealed that a whitened greenhouse cover significantly reduced both inside air and plant canopy temperatures [4]. A trial performed in Southern Spain with a pepper crop demonstrated that the use of whitening increased the commercial yield and reduced the incidence of sunburn [5]. Internal shading generates however a considerable amount of thermal radiation heat load that needs to be removed via cooling systems [6]. An important advantage of whitening with respect to the use of the internal shading screens is that it does not affect the ventilation of the greenhouse [7]. Gázquez et al. [8] observed that with a fully developed crop the combination of whitening and natural ventilation was the most efficient cooling strategy. They highlighted the problem need of determining the efficiency of the different whitening products and the optimum dose [8].

Kittas et al. [9] analysed different shading systems. Whitening slightly improved the proportion of photosynthetically active radiation (PAR) inside the greenhouse, reducing the proportion of infrared radiation. However, this technique has the drawback of providing less PAR uniformity than shading mesh, and its performance depends on outside climatic conditions of rain, humidity, etc. [10]. Baille et al. [11] studied the microclimate in a Greek glasshouse with a roof vent without whitening and with whitening. The transmissivity of the greenhouse cover decreased from 0.62 without whitening to 0.31 with whitening, and a similar percentage of decrease was obtained by Abreu and Meneses [12]. Baille et al. [11] also found a decreased stress level of a rose crop after whitening and an 18% increase in crop transpiration. The authors deemed the applied dose suitable, as a reduction in transmissivity of the greenhouse cover of over 50% would be excessive.

A beneficial effect of whitening is that it increases diffuse radiation inside the greenhouse [13]. In Shanghai (China), Luo et al. [14] applied a predictive model and found that crop biomass production was maximal when whitening reduced the greenhouse cover transmissivity by 10%. In Zimbabwe, Mashonjowa et al. [15] analysed, using a climatic model, the effect of whitening and of the accumulation of dirt on the transmissivity of a greenhouse cover. They observed that this technique significantly reduces maximum inside temperature, the vapour pressure deficit, the temperature difference between the crop and the surrounding air, and the crop transpiration rate, all of which help to avoid situations of crop stress.

A wide variety of whitening products are currently marketed under different commercial names. The principal component of all of them is calcium carbonate ($CaCO_3$). Some commercial products can incorporate additives to improve its adherence to the greenhouse cover and to increase its resistance to weather conditions such as rain, while other additives can modify its optical characteristics. The main aim of the present work is to evaluate the traditional method of applying whitening products on the cover of a Mediterranean greenhouse, in comparison with different doses of application of four commercial whitening products (agricultural solar protectors, ASPs): the traditional product "Blanco de España", ASP_{BE}, and three other products which incorporate adhesives that provide greater resistance to rain. The experiments analysed the effect of these products on the transmissivity of the cover and on the temperature inside the greenhouse.

2. Materials and Methods

2.1. Characteristics of the Experimental Greenhouse

The experiments were carried out in an empty multi-span Mediterranean greenhouse (24×45 m^2) with three roof vents, located at the "Catedrático Eduardo Fernández" farm of the UAL-ANECOOP Foundation (36° 51′ N, 2° 16′ W and 87 MASL) in the province of Almería in Southern Spain.

The greenhouse is permanently divided into two sectors by an interior plastic wall (Figure 1); sectors 1 (East) and 2 (West) measuring 24 × 25 m^2 and 24 × 20 m^2, respectively. The side walls of the greenhouse consist of undulating strips of rigid polycarbonate, while the roof of the greenhouse was covered with TRIPLAST three-layer co-extrusion greenhouse film (PE-EVA-PE) of 0.2 mm thickness (Plastimer-Morero & Vallejo Industrial, Almería, Spain). The manufacturer describes the technical characteristics of the cover as diffuse colourless, 200 μm thickness, 85% transmissivity to visible light, 50% transmissivity to diffuse light and 8% transmittance to infrared light.

The greenhouse is fitted with three roof vents measuring 40 × 1 m^2 each (22.5 × 1 m^2 in sector 1 and 17.5 × 1 m^2 in sector 2), with the same orientation to the wind in each sector. The ventilation surface, i.e. surface area of the vent openings/greenhouse area, or S_V/S_A, was 11.25% for sector 1 and 10.81% for sector 2. The roof vents were fitted with insect-proof screens with a thread density of 10 × 20 threads cm^{-2} (36.0% porosity) and with the following geometric characteristics: thread density measured 9.6 × 20.3 threads cm^{-2}; weft pore length 239.9 ± 18.5 μm; warp pore length 765.4 ± 27.1 μm; thread diameter 259.6 ± 19.1 μm; diameter of the inside pore circumference 241.9 ± 19.1 μm; mean pore area 0.182 ± 0.015 mm^2; corresponding with screen 3 discussed in López et al. [16].

2.2. Measurement Equipment inside the Greenhouse

Temperature and relative air humidity were measured inside and outside the greenhouse by means of 13 CS215 sensors (Campbell Scientific Spain S.L., Barcelona, Spain) with accuracy for temperature of ±0.4 °C over 5–40 °C and for relative humidity of ±2% over 10%–90% RH. The sensors were protected from radiation inside a naturally aspirated box 41003-5 (Campbell Scientific Spain S.L., Barcelona, Spain). The data of humidity did not differ between the two sectors of the greenhouse, as experiments were conducted without crop.

Solar radiation and PAR were measured inside and outside the greenhouse with three SP1110 pyranometers (Campbell Scientific Spain S.L.; sensitivity range of 350–1100 nm; accuracy of ±5%; Barcelona, Spain) and with three quantum sensors SKP215 (Skye Instruments Ltd, Llandrindod Wells, UK; sensitive to light between 400 nm and 700 nm wavelength; measurement range of 0–5 × 10^4 μmol m^{-2} s^{-1}; accuracy ±5%). Net radiation was measured inside the greenhouse with two NR-Lite2 net radiometers (Kipp & Zonen B.V., Delft, The Netherlands; spectral response: 0 to 100 μm; measurement range of ±2000 W m^{-2}; accuracy of ±5%). The data from all sensors were stored in five CR3000 microloggers (Campbell Scientific Spain S.L.) with a frequency of 1 Hz. Outside wind speed was measured at 10 m height with a Meteostation II (Hortimax S.L., Almería, Spain) incorporating a cup anemometer (measurement range of 0 to 40 m s^{-1}; accuracy of ±5%) and a vane for wind direction (accuracy ±5°). The Meteostation II measurements were stored in an independent computer system once a minute. Figure 1 presents the location of the sensors in the experimental greenhouse.

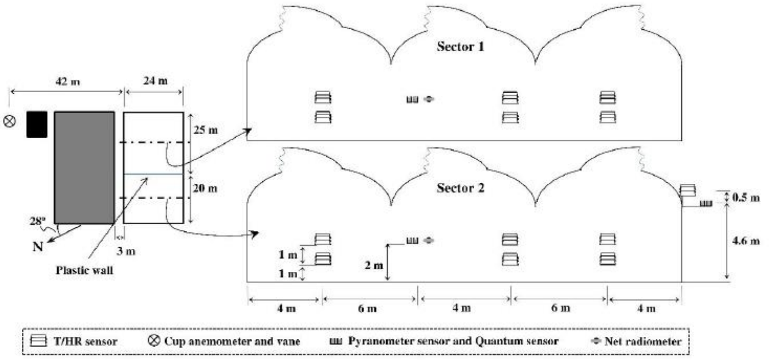

Figure 1. Position of the greenhouse at the experimental farm and location of the sensors. (Adapted of López et al. [16]).

2.3. Experimental Design

Data were taken in the months of July, August, September and October 2014 (Table 1). Sector 1 of the greenhouse without ASP was used as control. In sector 2, four *ASP* of different characteristics were applied: the traditional product "Blanco de España" (ASP_{BE}), and three products that incorporate adhesives, Flex (ASP_F), SuperFlex (ASP_{SF}) and Special Pepper (ASP_{SP}), all of which are commercial products (Indaloblanc S.L., Almería, Spain). Three concentrations of each product were tested [kg of product/l of water]: 0.125 kg L^{-1} (25/200), 0.25 kg L^{-1} (25/100), 0.50 kg L^{-1} (50/100); a fourth concentration of 0.08 kg L^{-1} (25/300) was tested for the product ASP_{BE}. The manufacturers recommend a dose of 0.25 kg L^{-1} (25/100), though a work published after the experiments were carried out found that the mean dose applied in the province of Almería is 40/100 [1], an intermediate value between 25/100 and 50/100 tested here.

Table 1. Mean daily values of outside climatic conditions on test dates: *DOY*, day of year; u_o, wind velocity [m s^{-1}]; θ, wind direction [°]; RH_o, relative air humidity [%]; T_o, air temperature [°C]; $R_{s,o}$, outside solar radiation [W m^{-2}].

ASP	[kg L^{-1}]	Date	*DOY*	u_o	θ [a]	RH_o	T_o	$R_{s,o}$
BE *"Blanco España"*	0.08	19–21/07/2014	198–200	2.9 ± 0.7	210.7 ± 65.3	63.4 ± 11.8	24.8 ± 1.8	338.6 ± 8.1
	0.125	23, 25–26/07/2014	202–205	1.6 ± 0.5	198.2 ± 6.9	62.2 ± 17.9	26.5 ± 0.7	327.8 ± 17.7
	0.25	29–31/07/2014	208–210	2.9 ± 0.5	190.2 ± 44.0	72.0 ± 9.3	26.0 ± 1.4	301.0 ± 50.6
	0.50	02–04/08/2014	212–214	1.9 ± 0.9	196.3 ± 30.8	62.4 ± 8.4	23.3 ± 0.8	326.3 ± 8.3
F *Flex*	0.125	10–12/08/2014	219–221	1.3 ± 0.5	197.5 ± 24.8	76.1 ± 3.2	25.2 ± 0.4	317.9 ± 16.4
	0.25	14–16/08/2014	223–225	4.3 ± 1.5	123.4 ± 33.6	67.1 ± 4.7	28.1 ± 1.0	274.0 ± 18.2
	0.50	20–22/08/2014	229–231	1.7 ± 0.1	187.3 ± 18.7	75.8 ± 3.8	25.1 ± 0.7	314.1 ± 7.5
SF *SuperFlex*	0.125	24–26/08/2014	233–235	2.0 ± 1.0	172 ± 61.7	70.5 ± 8.1	26.0 ± 1.4	312.3 ± 0.6
	0.25	28–30/08/2014	237–239	2.1 ± 0.9	165.2 ± 49.0	71.8 ± 8.3	27.5 ± 0.7	281.9 ± 28.2
	0.50	02–04/09/2014	241–243	1.3 ± 0.1	198.1 ± 22.3	76.6 ± 8.5	26.2 ± 0.5	292.3 ± 4.3
EP *Special pepper*	0.125	06–08/09/2014	245–247	1.6 ± 0.5	233.5 ± 33.7	75.9 ± 2.0	25.2 ± 0.3	266.2 ± 5.8
	0.25	10–12/09/2014	249–251	2.1 ± 1.0	217.3 ± 45.5	74.6 ± 2.7	24.0 ± 0.8	267.2 ± 6.0
	0.50	14–16/09/2014	253–255	1.6 ± 0.3	191.4 ± 19.8	73.1 ± 8.9	22.1 ± 0.3	214.1 ± 95.1
BE *"Blanco España"*	0.125	18–20/09/2014	257–259	1.7 ± 1.1	212.4 ± 18.5	69.5 ± 2.5	22.2 ± 0.4	185.9 ± 25.9
	0.25	24–26/09/2014	263–265	2.7 ± 1.8	144.8 ± 57.2	73.6 ± 8.2	22.0 ± 2.1	228 ± 19.1
	0.25 *	27–29/09/2014	266–268	3.0 ± 2.4	124.3 ± 49.2	76.4 ± 6.2	22.0 ± 0.5	100.3 ± 24.2
	0.50	07–09/10/2014	276–278	1.3 ± 0.3	223.0 ± 20.0	82.9 ± 2.2	20.1 ± 0.5	228.6 ± 4.2
	0.50 *	10–12/10/2014	279–281	2.7 ± 1.1	226.7 ± 76.0	76.2 ± 3.1	20.8 ± 1.0	147.9 ± 43.4

[a] Wind direction perpendicular to the roof vents is 208° for southwesterly *Poniente* winds and 28° for the northeasterly *Levante* winds. *Replications carried out on overcast days with occasional light showers.

Application of the product involves consuming approximately 0.1 l of mixture per m^2 of the greenhouse cover, which implies the following approximate quantities of product: 8.3, 12.5, 25.0 and 50.0 g m^{-2} (for the four concentrations tested). The traditional method of applying these products follows three steps: (i) the product is mixed according to the dose (kg/l) in a container of large capacity; (ii) one worker operates the hydraulic pump to apply the mixture through a hose; (iii) a second worker holding the hose (without a regulated nipple) walks over the greenhouse roof, applying the quantity of product that he considers suitable. There is no technical control of the real quantity of product applied to the greenhouse cover. Rather it all depends on the skill and knowhow of the worker.

According to the technical data supplied by the products' distributors, the traditional product "Blanco de España" ASP_{BE} consists of over 99% calcium carbonate ($CaCO_3$), whereas the other three products (ASP_F, ASP_{SF} and ASP_{SP}) have about 97% calcium carbonate ($CaCO_3$). The traditional product ASP_{BE} incorporates less than 1% of other elements, without adhesive substances. The others three products use unidentified adhesives and elements in proportions less than 3%. The manufacturer did not supply data on the precise compositions of additives, but indicate that ASP_{SF} presents a higher resistance to weather elements like rain with an approximate durability of 3 to 5 months, whereas for ASP_F and ASP_{SP} it is about 3 months.

All the products are soluble in cold water, with a mean and maximum particle diameters of 2.8 μm and 33 μm, respectively. Each dose of each product was tested over 5 days: the product was applied early in the morning on the first day and data were taken on the second, third and fourth days (used as the three repetitions for statistical analyses); on the fifth day, the cover was cleaned and the following dose was applied, commencing a new test cycle. The different concentrations of each product were tested in three consecutive days, to allow a minimum of 720 data when analysed statistically values of transmissivity in the interval 12–16 h. These three days can be considered as different replications (Figure 2) of each treatment (a product with a concentration). The climatic conditions outside the greenhouse on the days when data were recorded are presented in Table 1. For the first tests carried out with the product ASP_{BE} (from July 19 to August 4, 2014) no inside temperature data are available due to a malfunction of the sensors, and so a second set of tests was carried out with this product in late September and early October. Tests were carried out at a time of year when crops are usually transplanted, i.e. when the cooling effect of crop evapotranspiration is low. As no crop was present in the greenhouse, the effect of the products was quantified in the most extreme conditions possible, simulating the situation when a crop is transplanted.

In spring 2015, an experiment was carried out to determine the resistance to rain of the traditional adhesive-free product ASP_{BE} and of ASP_F, which includes adhesive. On March 27 2015, these products were applied in sectors 1 and 2, respectively, of the experimental greenhouse at a concentration of 0.25 kg L^{-1} (25/100). From April to July the transmissivity of the greenhouse cover was determined in both sectors at different times in order to evaluate the effect of precipitation and time on the two products. Transmissivity was determined by measuring PAR outside the greenhouse and inside each sector. An HD2302.0 photo-radiometer (Delta OHM S.R.L., Padua, Italia) was used, equipped with an LP 471 PAR probe (sensitive to light between 400 nm and 700 nm wavelength; measurement range of 0.01 to 104 μmol m^{-2} s^{-1}; accuracy <5%), to measure the photon flow in the PAR range.

2.4. Statistical Analysis

We have carried out regression analyses to compare the different variables for statistically significant relationships (p-value<0.05) using Statgraphics®Centurion 18 v 18.1 (Statgraphics Technologies, Inc., The Plains, VA, USA). The different transmissivity and inside air temperature in both compartments of the experimental greenhouse (with and without whitening) were examined using an analysis of variance (p-value < 0.05), comparing mean values using Fisher's least significant difference (LSD) approach. When there was a difference statistically significant between the standard deviations, the parametric analysis was not viable by means of an analysis of variance. For parameters with different variance, we made a non-parametric analysis with the Friedman test, appropriate when each row represents a block (the date of measurement), using box-and-whisker plot [17].

3. Results and Discussion

The aim of this work was to know about the effect on transmissivity of using products composed mainly of $CaCO_3$ at different concentration for whitening Mediterranean greenhouse roofs. The results obtained were statistically analyzed to verify the influence of different products on reduction of cover transmissivity and to compare different dose of each product. For a better understanding the results were divided and presented under four subsections. In Section 3.1 (Transmissivity of the cover with Agricultural Solar Protector without adhesives) we analyse differences in behavior of the use of traditional product for whitening Mediterranean greenhouse roofs ASP_{BE} on two test periods, July-August and September-October. Transmissivity data for ASP_{BE} are compared to the other products, ASP_F, ASP_{SF} and ASP_{SP} incorporating adhesives in Section 3.2 (Transmissivity of the cover with Agricultural Solar Protector with adhesives). Section 3.3. (Effect of climatic conditions on the transmissivity of the cover with Agricultural Solar Protectors) show the effect of rain on the transmissivity of the whitened greenhouse cover, comparing the products ASP_{BE} (without adhesive) and ASP_F (with adhesive). Finally, a global analysis of the four products on the temperature inside the greenhouse is presented in Section 3.4 (Greenhouse temperature influenced by the cover with Agricultural Solar Protector).

3.1. Transmissivity of the Cover with Traditional Agricultural Solar Protector without Adhesives

Figure 2a shows the level of solar radiation outside and inside the greenhouse for the experiment carried out with ASP_{BE} at a concentration of 0.50 kg L^{-1} on August 2–4, 2014. Irrespective of the dose applied, the use of this product has been seen to reduce fluctuations in the intensity of solar (Figure 2a) and PAR radiation inside the greenhouse, confirming the findings of Baille et al. [11]. This is beneficial for the crop, since the radiation levels received will remain stable throughout the day. The results of Baille et al. [11] showed that application of the product on the greenhouse cover reduced both the difference in temperature between crop leaves and the surrounding air and "the canopy-to-air vapour pressure deficit", while increasing the crop transpiration rate, which mitigated the previously observed fluctuations in this parameter the day after application.

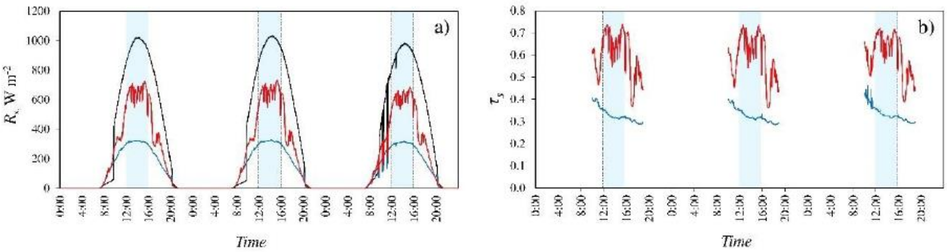

Figure 2. Levels of solar radiation (**a**) and values of transmissivity of the cover to solar radiation (**b**) on 02–04/08/2014. —, exterior; —, sector 1 (without ASP_{BE}); —, sector 2 (with ASP_{BE} at a concentration of 0.50 kg L^{-1}). Interval of 4 hours around the time when the sun is shining vertically (■).

The values of transmissivity of the greenhouse cover fluctuate less when ASP_{BE} is applied (Figure 2b). The combined effects of reduction of fluctuation of the mean inside radiation and of the calculated transmissivity are likely due to the increase in the proportion of diffuse radiation when ASP is used [13], as diffuse radiation is less sensitive to the presence of obstacles including the greenhouse structure itself and any greenhouse equipment [11]. Indeed, Baille et al. [11] found less fluctuation in the values of mean inside radiation and of transmissivity of the cover with ASP than without it (mean values of 0.31 and 0.62, respectively, from 9:00 to 19:00). Figure 2b illustrates the sharp fall in the transmissivity of the greenhouse cover in sector 1 in periods when the withdrawn shading mesh affected the radiation sensors (between 11:00 and 11:30, and 17:00 and 17:30, approximately).

Table 2 presents the values of transmissivity of the greenhouse cover to solar radiation, τ_s ($R_{s,i}/R_{s,o}$), and PAR, τ_{PAR} ($R_{PAR,i}/R_{PAR,o}$), for each dose of product applied. Transmissivity was analysded between 12:00 and 16:00 h, obtaining the average value at the interval of 4 hours around the time when the sun is shining vertically (local time 14:30 h). For the climatic conditions of the experiments, the transmissivity of the cover to total radiation and PAR can be obtained from a power regression equation based on the dose applied (Figure 3a,b).

The power regression equations presented in Figure 3 are only valid for concentrations of ASP_{BE} between 0.08 and 0.50 kg L^{-1}; for concentrations close to 0 these fits are not valid, as the values obtained would tend to infinity. Figure 3c,d show the fits to obtain the ratio $\tau_{s,2}/\tau_{s,1}$ as a function of the dose of ASP_{BE} applied. The power regression equations presented in Figure 3c,d would be valid to estimate the effect on transmissivity of any type of greenhouse cover as a function of the concentration of ASP_{BE} applied under similar climatic conditions to those of these experiments.

For all doses analysed, transmissivity of the whitened cover with ASP_{BE} was statistically lower than transmissivity of the cover without whitening (Table 2). We can also observe a reduction statistically significant of transmissivity when the dose of whitening increased (Table 2). Furthermore, transmissivity of the un-whitened cover show a statistically significant variation along the year. At the end of July, transmissivity increased with the day of year (*DOY*), as we can observe in Table 2.

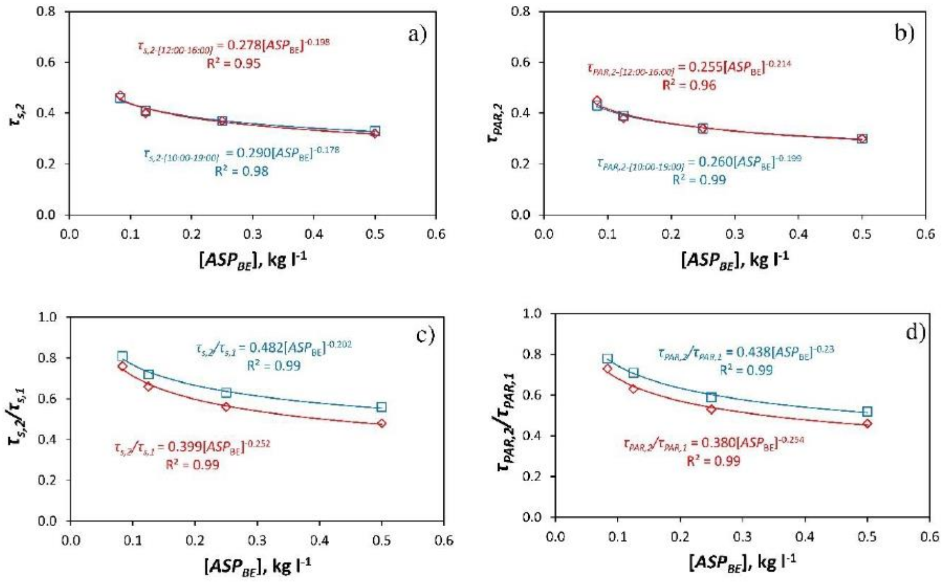

Figure 3. Mean values of transmissivity of the greenhouse cover for different concentrations of ASP_{BE}. $[ASP_{BE}]$; τ_s, transmissivity to solar radiation (**a**); τ_{PAR}, transmissivity to PAR (**b**). Mean values of the ratio $\tau_{s,2}/\tau_{s,1}$ (**c**) y $\tau_{PAR,2}/\tau_{PAR,1}$ (**d**). Subscript: *1*, sector 1 (without ASP_{BE}); *2*, sector 2 (with ASP_{BE}). □, 10:00 to 19:00; ◊, 12:00 to 16:00.

Table 2. Mean values of transmissivity of the greenhouse cover in sector 1 (without ASP_{BE}) and sector 2 (with ASP_{BE}) for the experiments carried out in summer. *DOY*, day of year at the beginning of the test; $[ASP_{BE}]$, concentration in kg L^{-1}; τ_s, transmissivity to solar/global radiation; τ_{PAR}, transmissivity to PAR; R_s, incoming solar radiation above the crop; R_{PAR}, PAR radiation; Rn, net radiation. Subscript: *1*, inside sector 1 (without ASP_{BE}); *2*, inside sector 2 (with ASP_{BE}); *o*, outside.

DOY	$[ASP_{BE}]$	$\tau_{s,1}$	$\tau_{s,2}$	$\tau_{PAR,1}$	$\tau_{PAR,2}$	$R_{n,1}/R_{s,1}$	$R_{n,2}/R_{s,2}$	$R_{PAR,o}/R_{s,o}$	$R_{PAR,1}/R_{s,1}$	$R_{PAR,2}/R_{s,2}$
					10:00–19:00					
198	0.08	0.57 ± 0.09^{f}	0.46 ± 0.03^{d}	0.55 ± 0.07^{e}	0.43 ± 0.03^{d}	0.57	0.53	0.46	0.45	0.43
202	0.125	0.57 ± 0.08^{f}	0.41 ± 0.04^{c}	0.55 ± 0.06^{e}	0.39 ± 0.03^{c}	0.56	0.50	0.45	0.45	0.43
208	0.25 *	0.59 ± 0.10^{e}	0.37 ± 0.03^{b}	0.58 ± 0.07^{f}	0.34 ± 0.03^{b}	0.57	0.49	0.46	0.45	0.42
211	0.50	0.59 ± 0.10^{e}	0.33 ± 0.03^{a}	0.58 ± 0.08^{f}	0.30 ± 0.03^{a}	0.56	0.48	0.46	0.45	0.42
					12:00–16:00					
198	0.08	0.62 ± 0.05^{e}	0.47 ± 0.01^{d}	0.62 ± 0.03^{f}	0.45 ± 0.01^{d}	0.63	0.58	0.46	0.45	0.43
202	0.125	0.61 ± 0.04^{e}	0.40 ± 0.01^{c}	0.60 ± 0.03^{e}	0.38 ± 0.01^{c}	0.61	0.56	0.45	0.45	0.43
208	0.25 *	0.66 ± 0.06^{f}	0.37 ± 0.01^{b}	0.64 ± 0.04^{g}	0.34 ± 0.01^{b}	0.63	0.56	0.46	0.45	0.43
211	0.50	0.66 ± 0.06^{f}	0.32 ± 0.01^{a}	0.65 ± 0.03^{h}	0.30 ± 0.01^{a}	0.61	0.56	0.45	0.44	0.42

* Data from the first day of experimentation, which was overcast, were omitted. [a–h] Values of transmissivity accompanied by different letters are significantly different at 95.0% confidence level (p-value < 0.05) for each time period (10:00–19:00 or 12:00–16:00).

The dose of 0.50 kg L^{-1} (50/100) could be recommended as the maximum concentration, respecting the limit of 50% reduction in transmissivity recommended by Baille et al. [11]. In the present study, with this dose, the values of transmissivity of the cover were around 0.30, which is similar to the results obtained by the cited authors with a much lower concentration of the product, 0.08 kg L^{-1} (8/100). This discrepancy may be mainly due to: (i) the traditional method of applying the product, which is imprecise and unreliable, and as a result the amount of product that is finally applied to the cover will depend on the skill of the worker to a great extent; and (ii) the use of different types of greenhouse cover, namely a three-layer co-extrusion greenhouse film (PE-EVA-PE) of 0.2 mm in the present study and a glass roof in the case of Baille et al. [11].

Baille et al. [11] found that the ratio of net to solar irradiance measured above a well-developed crop of roses was not significantly different before and after whitening, with $R_{n,i}/R_{s,i}$ values of 0.70 before application of the product and 0.73 afterwards. In the present study the greenhouse was empty, i.e. in similar conditions to a greenhouse with a recently transplanted crop, and in this case $R_{n,i}/R_{s,i}$ was slightly lower with ASP_{BE} ($R_{n,1}/R_{s,1}$) than without it ($R_{n,2}/R_{s,2}$), as Table 2 illustrates. ASP_{BE} appears to reduce the amount of direct solar radiation entering the greenhouse, but it increases the proportion of diffuse radiation inside the greenhouse, which influences the lower receiver of the net radiation sensor. Were a crop present, maybe all this radiation would be recorded by the sensor, and no difference would be observed in the $R_{n,i}/R_{s,i}$ ratios between sectors, as occurred in the above-mentioned study.

PAR is presented as μmolm^{-2}s^{-1}, and in order to compare it with the values of solar/total radiation obtained with a pyranometer (Wm^{-2}) it can be multiplied by a factor of 4.57 (in μmolm^{-2} s^{-1})/(W m^{-2}) [18] or 4.6 [19], the former of which was chosen. One drawback of using the traditional product ASP_{BE} is that it slightly reduced the proportion of PAR vs. total radiation (R_{PAR}/R_s) inside the greenhouse (Table 2), which contrasts with the findings of Kittas et al. [9], who recorded a slight increase in this proportion. This type of product is 99% calcium carbonate ($CaCO_3$), but other compounds should be sought to act selectively depending on the wavelength of the radiation.

In short, the use of ASP_{BE}, applied in the traditional fashion, led to a marked reduction in the transmissivity of the greenhouse cover. On the downside, it also appeared to reduce slightly the proportion of net radiation (though it should be noted that there was no crop in the greenhouse) and the proportion of PAR with respect to mean total radiation. The reduction in transmissivity has been seen to be statistically related to the dose applied, although the values of transmissivity of the greenhouse cover below a certain dose of product also depend on the prevalent conditions of solar radiation and elevation (see Section 3.3). It should also be remarked that the doses recommended by manufacturers are difficult to adhere to, since the product application method precludes verification of the final number of grams of product per m^2 of roof.

Due to technical problems, no inside temperature data were available for the experiments carried out in summer with ASP_{BE}, and so it was decided to repeat the experiments in early October omitting the lowest concentration of the product, 0.08 kg L^{-1}. Soriano et al. [20] carried out a laboratory study on how the angle of incidence of solar radiation affected the transmissivity of several samples of glass, finding that the transmissivity was greatest when radiation was perpendicular to the glass. Transmissivity decreased with the angle of incidence, though the decrease was not marked until the angle reached 50–60° with respect to the perpendicular; Mashonjowa et al. [15] obtained similar results. Given these findings, it might be expected that the effect of ASP_{BE} on transmissivity of the greenhouse cover would differ between the experiments carried out in summer and autumn. Furthermore, in Mediterranean greenhouses ASP_{BE} is usually only applied on the roof, not on the sides, and so the effect of the product might be expected to increase with solar elevation. In addition to the effect of the angle of incidence of the radiation, the level of diffuse radiation will affect the transmissivity values calculated, leading to differences depending on whether the sky is clear or overcast.

Table 3 presents the transmissivity data obtained for the experiments carried out in September-October, and the values in sector 1 without ASP are higher than those in summer (Table 2). Moreover, the transmissivity of the cover for the same dose of product was significantly higher than that recorded in summer (Tables 2 and 3). The transmissivity to solar radiation of the cover without

ASP_{BE} was 8% (10:00–19:00) and 10% (12:00–16:00) greater in autumn than in summer. When ASP_{BE} was applied, between 12:00 and 16:00 transmissivity to solar radiation was 18% ($[ASP_{BE}]$ = 0.125 kg L^{-1}), 19% ($[ASP_{BE}]$ = 0.25 kg L^{-1}) and 20% ($[ASP_{BE}]$ = 0.125 kg L^{-1}) greater in the autumn experiments (Tables 2 and 3). As in the first experiment, transmissivity of whitened cover decreased (with statistical significance) when the dose of ASP_{BE} increased. A statistical difference was also observed between whitened cover with ASP_{BE} and un-whitened cover (Table 3). However, in autumn transmittance of the cover without whitening reduced along the date, inversely to that observed in summer (Table 2). This difference was not statistically significant for transmissivity around the time of maximum outside solar radiation (12:00–16:00).

Table 3. Mean values of transmissivity of the greenhouse cover in sector 1 (without ASP_{BE}) and sector 2 (with ASP_{BE}) for the autumn experiments. *DOY*, day of year; $[ASP_{BE}]$, concentration in kg L^{-1}; τ_s, transmissivity to solar radiation; τ_{PAR}, transmissivity to PAR; R_s, inside solar radiation; subscript: *1*, sector 1 (without ASP_{BE}); *2*, sector 2 (with ASP_{BE}).

DOY	$[ASP_{BE}]$	$\tau_{s,1}$	$\tau_{s,2}$	$\tau_{PAR,1}$	$\tau_{PAR,2}$
			10:00–19:00		
257–259	0.125	0.68 ± 0.06 [f]	0.50 ± 0.04 [c]	0.62 ± 0.05 [e]	0.42 ± 0.04 [a]
263–265	0.25	0.62 ± 0.11 [e]	0.46 ± 0.05 [b]	0.63 ± 0.10 [d]	0.44 ± 0.07 [b]
276–278	0.50	0.59 ± 0.15 [d]	0.41 ± 0.05 [a]	0.65 ± 0.13 [c]	0.42 ± 0.10 [a]
			12:00–16:00		
257–259	0.125	0.72 ± 0.05 [d]	0.49 ± 0.04 [c]	0.64 ± 0.03 [d]	0.41 ± 0.04 [b]
263–265	0.25	0.71 ± 0.07 [d]	0.48 ± 0.04 [b]	0.70 ± 0.07 [e]	0.45 ± 0.05 [c]
276–278	0.50	0.70 ± 0.11 [d]	0.40 ± 0.04 [a]	0.74 ± 0.11 [f]	0.39 ± 0.04 [a]

[a–f] Values of transmissivity accompanied by different letters are significantly different at 95.0% confidence level (*p*-value < 0.05) for each time period (10:00–19:00 or 12:00–16:00).

This would appear to contradict the findings of other works [15,20], since solar elevation is greater in summer than in autumn, suggesting that transmissivity should also be greater. However, the mean angles of incidence of solar radiation on the greenhouse cover have been calculated (Section 3.3), and they are below 50–60°, the margin in which reduction in transmissivity becomes more marked. On the other hand, in autumn the degree of solar elevation is lower and so a greater proportion of total radiation in the greenhouse will enter through the sides, which will affect transmissivity values calculated. Finally, in autumn there is a greater probability of overcast skies, conditions in which the proportion of diffuse radiation is greater, which will contribute to higher transmissivity values calculated in autumn than in summer.

This variation in transmissivity of the greenhouse cover, an in the effect of applying ASP_{BE}, at different times of year (differences in solar elevation and the level of solar radiation) makes it difficult to compare the different *ASP* tested in the present work. It also makes it difficult for the manufacturers to suggest a recommended dose, since on the one hand the method of application would have to be standardised to ensure that the correct amount of product was applied to the greenhouse roof. On the other hand, the manufacturers' recommendations should take into account different climatic conditions (time of year, level of radiation, etc.).

3.2. Transmissivity of the Cover with Agricultural Solar Protector with Adhesives

This product was tested in the first weeks of August, with high levels of solar radiation and outside temperature. The experiments using a concentration of 0.25 kg L^{-1} (25/100) took place on overcast days, which affected the results: the transmissivity values obtained were higher than those for the concentration of 0.125 kg L^{-1} (25/200) (Table 4). This may be due to the influence of the cloudy skies (a greater proportion of diffuse radiation) and to the traditional method of application, which makes it impossible to verify the exact quantity of product retained on the cover.

Table 4. Mean values of transmissivity of the greenhouse cover in sector 1 (without *ASP*) and sector 2 (with *ASP*) for the products with adhesive. *DOY*, day of year; [*ASP*], concentration of product in kg L^{-1}; τ_s, transmissivity to solar radiation; τ_{PAR}, transmissivity to PAR; subscript: *1*, sector 1 (without *ASP*); 2, sector 2 (with *ASP*). Products: ASP_F, flex; ASP_{SF}, superflex; ASP_{SP}, special pepper.

DOY	[ASP_F]	$\tau_{s,1}$	$\tau_{s,2}$	$\tau_{PAR,1}$	$\tau_{PAR,2}$
			10:00–19:00		
219–221	0.125	0.57 ± 0.12 [d]	0.47 ± 0.03 [b]	0.56 ± 0.08 [d]	0.44 ± 0.03 [b]
223–225	0.25*	0.63 ± 0.12 [e]	0.52 ± 0.07 [c]	0.61 ± 0.09 [e]	0.48 ± 0.06 [c]
229–231	0.50	0.61 ± 0.11 [e]	0.26 ± 0.03 [a]	0.59 ± 0.08 [e]	0.24 ± 0.03 [a]
			12:00–16:00		
219–221	0.125	0.66 ± 0.09 [d]	0.48 ± 0.03 [b]	0.62 ± 0.06 [d]	0.44 ± 0.02 [b]
223–225	0.25*	0.69 ± 0.12 [f]	0.53 ± 0.09 [c]	0.66 ± 0.10 [f]	0.49 ± 0.07 [c]
229–231	0.50	0.69 ± 0.07 [e]	0.23 ± 0.01 [a]	0.65 ± 0.05 [e]	0.21 ± 0.01 [a]
DOY	[ASP_{SF}]	$\tau_{s,1}$	$\tau_{s,2}$	$\tau_{PAR,1}$	$\tau_{PAR,2}$
			10:00–19:00		
233–235	0.125	0.61 ± 0.11 [d]	0.44 ± 0.05 [c]	0.59 ± 0.08 [d]	0.42 ± 0.04 [c]
237–239	0.25*	0.62 ± 0.10 [d]	0.42 ± 0.05 [b]	0.60 ± 0.08 [d]	0.39 ± 0.07 [b]
241–243	0.50	0.62 ± 0.09 [d]	0.31 ± 0.03 [a]	0.59 ± 0.08 [d]	0.28 ± 0.03 [a]
			12:00–16:00		
233–235	0.125	0.70 ± 0.06 [e]	0.45 ± 0.06 [c]	0.65 ± 0.04 [d]	0.42 ± 0.04 [c]
237–239	0.25*	0.69 ± 0.07 [d]	0.40 ± 0.05 [b]	0.65 ± 0.06 [d]	0.36 ± 0.05 [b]
241–243	0.50	0.69 ± 0.07 [d]	0.28 ± 0.01 [a]	0.65 ± 0.05 [d]	0.25 ± 0.01 [a]
DOY	[ASP_{SP}]	$\tau_{s,1}$	$\tau_{s,2}$	$\tau_{PAR,1}$	$\tau_{PAR,2}$
			10:00–19:00		
245–247	0.125	0.66 ± 0.11 [e]	0.43 ± 0.03 [b]	0.59 ± 0.08 [c]	0.36 ± 0.03 [b]
249–251	0.25	0.65 ± 0.12 [d,e]	0.47 ± 0.05 [c]	0.60 ± 0.09 [d]	0.40 ± 0.05 [c]
253–255	0.50*	0.65 ± 0.09 [e]	0.40 ± 0.04 [a]	0.61 ± 0.07 [e]	0.34 ± 0.04 [a]
			12:00–16:00		
245–247	0.125	0.74 ± 0.10 [e]	0.43 ± 0.03 [b]	0.65 ± 0.06 [d]	0.36 ± 0.03 [c]
249–251	0.25	0.73 ± 0.08 [e]	0.48 ± 0.05 [c]	0.66 ± 0.05 [e]	0.41 ± 0.04 [b]
253–255	0.50*	0.70 ± 0.06 [d]	0.41 ± 0.04 [a]	0.66 ± 0.05 [d]	0.35 ± 0.04 [a]

* Partially overcast days. [a–f] Values of transmissivity accompanied by different letters are significantly different at 95.0% confidence level (p-value < 0.05) for each time period (10:00–19:00 or 12:00–16:00).

As for the standard product ASP_{BE} (Tables 2 and 3), the transmissivity of the cover with whitening product using adhesives in tis compositions (ASP_F, ASP_{SF} and ASP_{SP}) was statically lower that the un-whitened cover, for all the doses tested (Table 4). In general, the increase in the dose produced a reduction (statically significant) of the transmissivity (Table 4). However, differences statistically significant between the two lower doses (0.125 and 0.25 kg L^{-1}) changed in function of the date and the weather conditions (cloudy and sunny days).

The reduction of transmissivity with respect to the cover without whitening was statistically greater (lower values of the ratio $\tau_{s,2}/\tau_{s,1}$) whit the higher concentration of 0.50 kg L^{-1} (50/100) of the products ASP_F and ASP_{SF} than whit the others two doses or than whit the others products ASP_{BE} and ASP_{SP} (Table 5).

Table 5. Mean values of ratio $\tau_{s,2}/\tau_{s,1}$ of transmissivity to solar radiation of the greenhouse cover in sector 2 $\tau_{s,2}$ (with *ASP*) and sector 1 $\tau_{s,1}$ (without *ASP*) for each concentration *[ASP]* in kg L^{-1}.

[*ASP*]	ASP_{BE}	ASP_F	ASP_{SF}	ASP_{SP}	ASP_{BE}
			10:00–19:00		
0.125	0.72 [h]	0.82 [j]	0.72 [h]	0.65 [f]	0.74 [i]
0.25	0.63 [e,f]	0.83 [j]	0.68 [g]	0.72 [h]	0.74 [i]
0.50	0.56 [c]	0.43 [a]	0.50 [b]	0.62 [d]	0.69 [g,h]
			12:00–16:00		
0.125	0.66 [h]	0.73 [j]	0.64 [g]	0.58 [e]	0.68 [i]
0.25	0.56 [d,e]	0.77 [k]	0.58 [e]	0.66 [h]	0.68 [i]
0.50	0.48 [c]	0.33 [a]	0.41 [b]	0.59 [e,f]	0.57 [e]

[a–k] Values accompanied by different letters are significantly different at 95.0% confidence level (*p*-value < 0.05) for each time period (10:00–19:00 or 12:00–16:00).

With ASP_F at the dose of 0.50 kg L^{-1}, a far greater decrease in transmissivity was observed ($\tau_{s,2}/\tau_{s,1}$ = 0.33 between 12:00 and 16:00) than with ASP_{BE} ($\tau_{s,2}/\tau_{s,1}$ = 0.48 in summer and 0.57 autumn) (Table 5). However, for the concentration of 0.125 kg L^{-1} the difference between ASP_F ($\tau_{s,2}/\tau_{s,1}$ = 0.73 between 12:00 and 16:00) and ASP_{BE} ($\tau_{s,2}/\tau_{s,1}$ = 0.66 in summer and 0.68 in autumn) was to the contrary, i.e. the decrease in transmissivity was greater with ASP_{BE}. When comparing the results of these two products important factors should be taken into account: (i) the experiments were carried out on different days under similar but not identical climatic conditions; (ii) the traditional method of applying the products does not ensure that the same amount of product was applied per m^2 of greenhouse cover in each replication or test, even though the dose kg L^{-1} was the same. The results do indicate, however, that the presence of adhesives in the product (less than 3%) clearly increases the effect of the product on the transmissivity of the cover.

The ratio $\tau_{s,2}/\tau_{s,1}$ was also greater in autumn (Tables 2 and 3): $\tau_{s,2}/\tau_{s,1}$ was 3% ([ASP_{BE}] = 0.125 kg L^{-1}), 13% ([ASP_{BE}] = 0.25 kg L^{-1}) and 17% ([ASP_{BE}] = 0.125 kg L^{-1}) greater in the autumn experiments than in the summer ones (Table 5).

The difference between the products ASP_F and ASP_{SF} lies in the quantity of adhesive components they incorporate. Although the manufacturers declined to provide specific data, it is known that ASP_{SF} has the greater adhesive content. These tests were carried out using concentrations of 0.125 kg L^{-1} and 0.50 kg L^{-1} on sunny days, and of 0.25 kg L^{-1} in partly cloudy conditions. For this product, the ratio $\tau_{s,2}/\tau_{s,1}$ was similar at concentrations of 0.125 kg L^{-1} and 0.25 kg L^{-1} (Table 5), possibly due to the partially cloudy sky during the test for the latter concentration, which might explain the reduced effect of ASP_{SF} on the transmissivity of the cover. In comparison with the results obtained for the traditional product ASP_{BE}, there appear to be no statistical differences in the values of the ratio $\tau_{s,2}/\tau_{s,1}$ (Tables 2 and 4). Between 12:00 and 16:00 the ratio $\tau_{s,2}/\tau_{s,1}$ reaches similar values at a concentration of of 0.25 kg L^{-1} for ASP_{SF} (0.58) and for ASP_{BE} (0.56) in summer). Only at the highest concentration tested for ASP_{SF} (0.50 kg L^{-1}) was a greater difference observed in the ratio $\tau_{s,2}/\tau_{s,1}$ (0.48 for ASP_{BE} in summer and 0.57 for ASP_{BE} in autumn and 0.41 for ASP_{SF}). As occurs with ASP_F, with the product ASP_{SF} (which in theory contains a greater quantity of adhesives) the results provide no clear indication that the adhesive clearly increases the effect of the product on the transmissivity of the greenhouse cover.

Of the products tested, ASP_{SP} contains the largest amount of adhesives. For this product tests were carried out at concentrations of 0.125 kg L^{-1} and 0.25 kg L^{-1} on mainly sunny days, while at the concentration of 0.50 kg L^{-1} on the last two days of testing the sky was rather overcast. Comparison of the results obtained for ASP_{SP}, tested in September, with those obtained in September/October for ASP_{BE} does not highlight any great differences (Tables 3 and 4). The lowest ratio $\tau_{s,2}/\tau_{s,1}$ at concentrations of 0.125 kg L^{-1} was obtained for the ASP_{SP}, and the highest for the ASP_F with a statistical significant difference. For the higher dose of 0.50 kg L^{-1}, we can observe the inverse effect, with the ASP_{SP} producing the greatest value of the ratio $\tau_{s,2}/\tau_{s,1}$., and the ASP_F the lowest (Table 5). This result confirm the difficulty to predict the behavior of the different whitening products. At greater doses, the product with most adhesive component can allow a better adherence to the plastic cover, requiring less quantity of product to cover the roof, resulting in a greater transmissivity that product with a lower adherence. However, at low doses the effect of the different type of adhesives could affect to the greenhouse transmissivity.

3.3. Effect of Climatic Conditions on the Transmissivity of the Cover with Agricultural Solar Protectors

In short, Figure 4 illustrates that there were no notable differences between the capacity of the four products tested to reduce the transmissivity of the greenhouse cover ($\tau_{s,2}/\tau_{s,1}$) at low concentrations (0.125 kg L^{-1} and 0.25 kg L^{-1}). Bearing in mind that $CaCO_3$ constitutes 97-99% of the products, and that a maximum of 3% is composed of adhesives, we can state that the addition of this amount of adhesive does not noticeably alter the products' effect on the transmissivity of the greenhouse cover for low doses. Considering that all 4 products behave in a similar fashion at the same concentration, we can obtain a setting curve with which to estimate the ratio $\tau_{s,2}/\tau_{s,1}$ as a function of the dose applied [kg L^{-1}].

Statistical analyses have been carried out considering all the products (ASP_{BE}, ASP_F, ASP_{SF}, ASP_{SP}) as the same ASP, in order to determine which of the parameters measured bear a significant influence on the values of transmissivity of the greenhouse cover with and without ASP.

The curved roof of the experimental greenhouse means that the angle of incidence of the radiation from the cover varies from practically 0° to 90° according to the position of the sun and the part of the roof considered. Considering a mean roof angle of 23.1° (calculated as the mean value of 50 different points in the roof), the angle of incidence of solar radiation $\boldsymbol{\alpha}_c$ for the southern slope of the cover at the time of maximum solar elevation would vary between 20.3° and 37.3° (for the experiments from July 19–21 and from October 10–12, 2014, respectively), and between 23.2° and 50.7° for the northern slope of the cover for the same experimental periods. For an angle of incidence where 0° corresponds to a perpendicular incidence of solar radiation and a value of 90° corresponds to incidence parallel to the cover. These mean angles of incidence do not reach 50–60°, beyond which Soriano et al. [20] found that transmissivity decreased significantly.

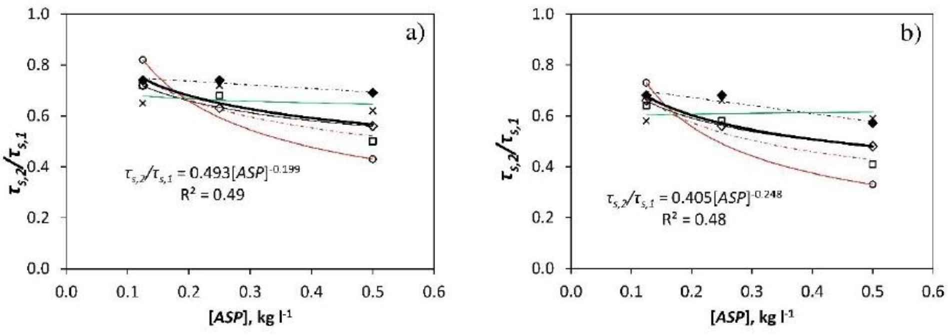

Figure 4. Mean values of the ratio $\tau_{s,2}/\tau_{s,1}$ between 10:00 and 19:00 (**a**) and between 12:00 and 16:00 (**b**) according to the dose [kg L^{-1}] of the four *ASP* tested: ◊ (—), ASP_{BE} (summer); ♦ (---), ASP_{BE} (autumn); ○ (—), ASP_F; □ (---), ASP_{SF}; × (—), ASP_{SP}. τ_s, transmissivity to solar radiation. Subscript: *1*, sector 1 (without *ASP*); *2*, sector 2 (with *ASP*). (-) setting curve considering all the products.

The angle of incidence $\alpha_{c\,(14\,h)}$ obtained for the northern slope at 14 h, around the time of maximum solar elevation, increased along the period of tests avec the *DOY*, producing a variation of transmissivity $\tau_{s,1}$ (Figure 5a). The influence of this angle in the cover transmissivity for the greenhouse without whitening (Figure 5b) can be represented by a statistically significate regression as ($R^2 = 0.85$; p-value < 0.0001):

$$\tau_{s,1} = -0.000412 \propto^2_{c(14h)} + 0.03691 \propto_{c(14h)} - 0.108279 \qquad (1)$$

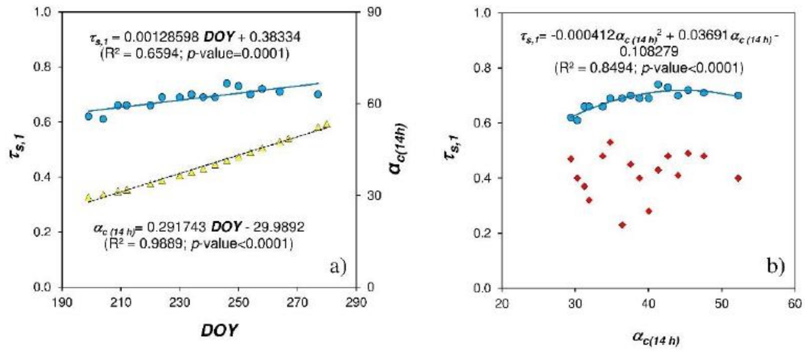

Figure 5. Evolution of the transmissivity $\tau_{s,1}$ (•) of the cover greenhouse without whitening between 12:00 and 16:00 and of the angle of incidence of solar radiation $_{c(14\,h)}$ (▲) for the northern slope at 14:00 h according to the day of the year *DOY* (**a**). Relationship between transmissivity of the cover without whitening $\tau_{s,1}$ (•) and with the different *ASP* tested $\tau_{s,2}$ (♦) in function of the angle of incidence $_{c(14\,h)}$ of solar radiation. Regression curves for cover transmissivity (—) and angle of incidence (—) (**b**).

Data analysis from all the tests carried out from July to October shows that there is a statistically significant correlation (p-value<0.01) between the transmissivity of the greenhouse cover in sector 1 (without *ASP*) ($\tau_{s,1}$), the maximum daytime solar elevation (γ_{max}) and solar radiation. Analysis of the period from 10:00 to 19:00 provides the following equation ($R^2 = 0.54$; p-value = 0.0068):

$$\tau_{s,1} = 0.83199 - 0.000526823 \cdot \gamma_{max} - 0.000369459 \cdot R_{s,o} \qquad (2)$$

Omitting solar elevation from (2), since the angles of incidence of solar radiation do not reach those beyond which Soriano et al. [20] found a sharp fall in transmissivity, provides the following equation with a lower p-value ($R^2 = 0.53$; p-value = 0.0014):

$$\tau_{s,1} = 0.822674 - 0.000418176 \cdot R_{s,o} \qquad (3)$$

The transmissivity of the cover without *ASP* increases as solar radiation decreases, which may be due to the proportion of diffuse radiation on the days in which the level of radiation is lower (overcast days and/or autumn days). Between 12:00 and 16:00 the following equation is obtained ($R^2 = 0.36$; p-value = 0.0137):

$$\tau_{s,1} = 0.830939 - 0.000172622 \cdot R_{s,o} \qquad (4)$$

Given the relationship between the transmissivity of the cover without *ASP* and the levels of outside radiation (cloud, diffuse radiation), it appears logical to suppose that the effect of applying any *ASP* product on the greenhouse cover will depend on, among other factors, solar radiation and the concentration or dose of the product [kg L^{-1}]. Between 10:00 and 19:00 the following equation is obtained ($R^2 = 0.58$; p-value = 0.0038):

$$\tau_{s,2}/\tau_{s,1} = 0.99093 - 0.000320721 \cdot R_{s,o} - 0.50184 \cdot [ASP] \qquad (5)$$

This fit improves on the value of R^2 = 0.49 obtained when only the concentration of the product is considered (Figure 6a). The same fit, for the period between 12:00 and 16:00, would be (R^2 = 0.58; p-value = 0.0037):

$$\tau_{s,2}/\tau_{s,1} = 0.939534 - 0.000199936 \cdot R_{s,o} - 0.545568 \cdot [ASP] \quad (6)$$

The effect that *ASP* has in reducing the transmissivity of the greenhouse cover ($\tau_{s,2}/\tau_{s,1}$), decreases on days with low levels of outside radiation (days that are overcast and with a higher level of diffuse radiation) and increases with the dose of product applied. The values of R^2 obtained in the different fits are low due to other factors on which this value depends but which are not included in the analysis, such as the variability in the concentration of product applied to the covering as a result of the method of application. However, the p-values below 0.05 indicate a statistically significant relationship between the variables included in the statistical analysis.

As ASP_{BE} contains no adhesive additives, on rainy days the greenhouse cover gets "washed". For the concentrations of 0.25 and 0.50 kg L^{-1} of the 6-day autumn experiments, the first three days were relatively clear, whereas the last three were cloudy with occasional precipitation and much lower levels of outside radiation (Table 1). As the days passed, the effect of the high atmospheric humidity, the morning dew and the showers led to a sharp fall in the effect of the product, with a concomitant increase in the transmissivity of the greenhouse cover. Comparison of the first three sunny days with the last three cloudy ones (Figure 6a) shows increases in transmissivity to solar radiation between 12:00 and 16:00 of 27% ($[ASP_{BE}]$ = 0.25 kg L^{-1}) and 30% ($[ASP_{BE}]$ = 0.50 kg L^{-1}), while the increases in transmissivity to PAR for the same concentrations of product were 24% and 23%, respectively. However, these increases can be attributed in part to the increase in diffuse radiation. Figure 6b illustrates that during the three cloudy days with showers the greenhouse cover is not completely washed, since the values of the ratio $\tau_{s,2}/\tau_{s,1}$ do not reach 1.

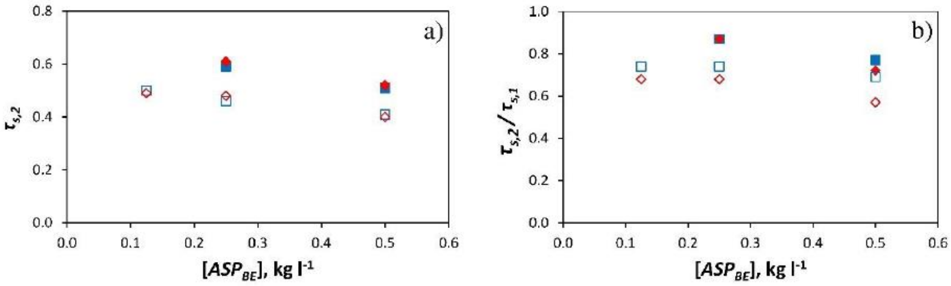

Figure 6. Mean values of solar transmissivity $\tau_{s,2}$ in sector 2 with ASP_{BE} (**a**) and of the ratio $\tau_{s,2}/\tau_{s,1}$ (**b**) for the September-October experiments. $[ASP_{BE}]$, concentration in kg L^{-1}. Sunny days: □, 10:00–19:00; ◊, 12:00–16:00. Cloudy and rainy days: ■, 10:00–19:00; ♦, 12:00–16:00. Subscript: *1*, sector 1 (without *ASP*); *2*, sector 2 (with *ASP*).

Figure 7 presents the values of transmissivity (to PAR radiation) of the greenhouse cover in sector 1 with ASP_{BE} and in sector 2 with ASP_F in spring 2015 for an initial concentration of 0.25 kg L^{-1} (25/100), together with the values of precipitation recorded at the Almería airport weather station (Almería, Spain). Transmissivity for ASP_F was 0.41 six days after application, increasing to 0.48 after 24 days, several of which were rainy. In the following months, the transmissivity remained at around the same value. For ASP_{BE}, on the other hand, transmissivity was 0.42 after six days, increasing to 0.73 after 24 days in the same meteorological conditions. This valued decreased slightly, possibly due to the accumulation of dirt on the greenhouse cover and the varied climatic conditions. The heavy rainfall at the start of the experiment washed off the ASP_{BE} almost completely. At the conclusion of the experiment the transmissivity value for sector 1 was 0.61, similar to those in sector 1 without *ASP* recorded during the experiments in 2014 (Tables 2 and 3).

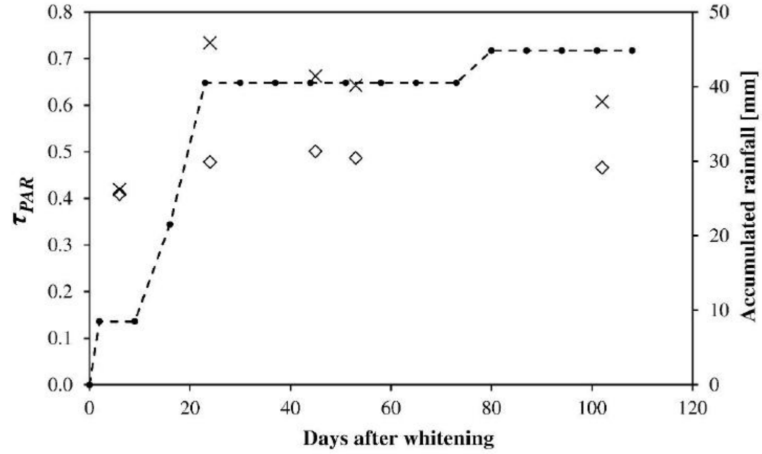

Figure 7. Transmissivity (to PAR radiation) of the greenhouse cover in sector 1 with ASP_{BE} (×) and in sector 2 with ASP_F (◊). Initial concentration of the product applied 25/100 (0.25 kg L^{-1}). Accumulated rainfall according to data from the Almería airport weather station (-•-).

3.4. Greenhouse Temperature is Influenced by the Cover with Agricultural Solar Protector

The use of whitening produced a statistically significant reduction of the temperature inside the greenhouse (Table 6) when outside mean temperature was greater than 28.5 °C (with the exception of the ASP_{SP} at 0.50 kg L^{-1}). Whitening is traditionally used in Almeria at the end of summer and at the end of the winter, when new crops are transplanted in the greenhouse. When outside temperature begin to decrease, growers remove the whitening from cover washing it with water. When outside temperature was lower than 28.5 °C, the whitening did not produce a significant effect in inside temperature (Table 6) whereas transmissivity to PAR radiation of the whitened cover was reduced (Tables 2–4).

Figure 8a illustrates that as the concentration of product applied increases there is a slight increase in temperature difference between the greenhouse sectors, although the trend is not clear due to the intrinsic variability as a result of the application method. However, it is clear that as the ratio $\tau_{s,2}/\tau_{s,1}$ decreases, the temperature difference between sectors increases (Figure 8b).

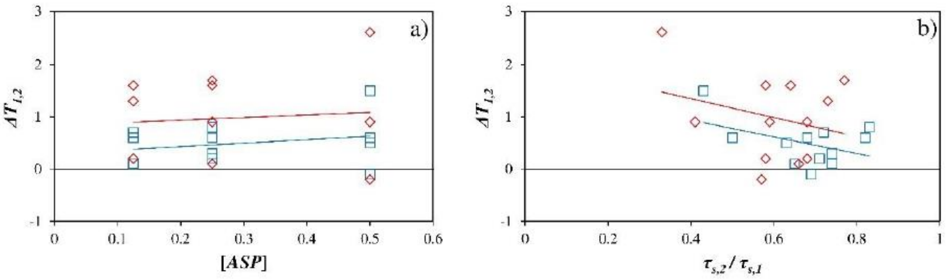

Figure 8. Mean values of temperature difference $\Delta T_{1,2}$ [°C] between sector 1 (without *ASP*) and sector 2 (with *ASP*) as a function of the concentration of product applied [*ASP*] in [Kg l^{-1}] (**a**) and the ratio $\tau_{s,2}/\tau_{s,1}$ (**b**). τ_s, transmissivity to solar radiation. Subscript: *1*, sector 1 (without *ASP*); *2*, sector 2 (with *ASP*). □, 10:00–19:00; ◊, 12:00–16:00.

A global analysis has been carried out considering all the products as one. It has been determined that there is a statistically significant relationship (p-value<0.05) between the temperature difference between the two sectors of the greenhouse on the one hand and outside solar radiation and the ratio $\tau_{s,2}/\tau_{s,1}$ on the other; the temperature difference increases with the former and decreases with the latter. For the period 12:00–16:00 the following equation is obtained ($R^2 = 0.09$; p-value<0.0001):

$$\Delta T_{1,2} = 1.01257 \ + 0.000994882 \cdot R_{s,o} - 1.40128 \cdot [\tau_{s,2}/\tau_{s,1}], \tag{7}$$

The values of temperature difference between sector 1 (without ASP) and sector 2 (with ASP) are well below the 4.4 °C reported by Baille et al. [11], whose experiments were in a greenhouse with a crop and the transpiration rate was higher in the sector with ASP. However, the maximum temperature differences recorded between the two sectors at the hottest time of day, for the concentration of product recommended by the manufacturer in this province (25/100) was 4.2 °C for ASP_{BE}, 3.9 °C for ASP_F, 5.0 °C for ASP_{SF} and 2.0 °C for ASP_{SP}. Although no great differences were observed from 12:00 to 16:00 in the mean temperature values between sectors (Table 6), with ASP the maximum temperature decreases considerably inside the greenhouse without crop. This finding may prove of interest, as the conditions are similar to those of a recently transplanted crop, when plants are more sensitive to temperature extremes.

Application of ASP does affect the heterogeneity of temperature inside the greenhouse. The difference between the mean temperatures recorded by the "warmest" and "coldest" sensors ($\Delta T_{max,1}$ and $\Delta T_{max,2}$) has been estimated for three days from 12:00 to 16:00, and it was always higher in sector 1 without ASP than in sector 2 with ASP for all four products tested (Table 6). The ratio $\sigma_{\Delta T_{i,o}}/\Delta T_{i,o}$ proposed by Kittas et al. [21] has also been estimated; the greater the value of this ratio, the greater the temperature heterogeneity inside the greenhouse. Table 6 shows that this ratio decreases in the sector where ASP is applied in 10 of the 12 experiments.

Table 6. Mean outside air temperature T_0 [°C]; mean temperatures inside sector 1 (without ASP) T_1 and sector 2 (with ASP) T_2 [°C];]; maximum difference between the mean temperatures inside sectors 1 and 2 $\Delta T_{1,2\ max}$ [°C]; temperature difference between sector 2 (with ASP) and outside $\Delta T_{2,o}$ [°C]; maximum difference between the mean temperatures recorded by the different sensors in sectors 1 and 2, $\Delta T_{max,1}$ and $\Delta T_{max,2}$ [°C]; ratio for the heterogeneity of temperature distribution inside the greenhouse $\sigma_{\Delta T_{i,o}}/\Delta T_{i,o}$,. Values for the time period 12:00–16:00.

[ASP]	T_0	T_1	T_2	$\Delta T_{1,2\ max}$	$\Delta T_{2,o}$	$\Delta T_{max,1}$	$\Delta T_{max,2}$	$\sigma_{\Delta T_{1,o}}/\Delta T_{1,o}$	$\sigma_{\Delta T_{2,o}}/\Delta T_{2,o}$
				[ASP_F]					
0.125	28.6 ± 0.9	35.5 ± 1.8 [b]	34.2 ± 1.7 [a]	3.0	5.6	3.4	2.8	0.177	0.183
0.25	32.5 ± 1.5	41.6 ± 2.7 [b]	39.9 ± 2.3 [a]	3.9	7.4	1.8	2.3	0.085	0.122
0.50	29.4 ± 2.7	37.3 ± 3.7 [b]	34.7 ± 2.9 [a]	5.5	5.3	3.8	2.5	0.182	0.179
				[ASP_{SF}]					
0.125	30.5 ± 2.6	38.5 ± 3.4 [b]	36.9 ± 2.8 [a]	4.2	6.4	3.4	2.3	0.165	0.139
0.25	31.9 ± 2.8	39.5 ± 3.8 [b]	37.9 ± 3.1 [a]	5.0	6.0	3.0	2.8	0.154	0.184
0.50	29.5 ± 0.5	36.4 ± 0.9 [b]	35.5 ± 0.9 [a]	3.6	6.0	4.1	2.1	0.208	0.136
				[ASP_{SP}]					
0.125	28.2 ± 0.6	34.1 ± 0.8 [a]	33.9 ± 0.8 [a]	2.0	5.7	3.4	2.2	0.203	0.146
0.25	27.6 ± 0.8	33.8 ± 1.3 [a]	33.9 ± 1.3 [a]	2.6	6.3	3.5	2.3	0.195	0.139
0.50	26.0 ± 1.0	31.8 ± 1.8 [b]	30.9 ± 2.0 [a]	3.0	4.9	2.9	1.7	0.166	0.135
				[ASP_{BE}] autumn					
0.125	25.4 ± 1.4	31.2 ± 2.6 [a]	31.4 ± 3.0 [a]	2.0	6.0	3.2	2.2	0.193	0.135
0.25	26.1 ± 3.7	31.9 ± 4.6 [a]	31.0 ± 3.6 [a]	4.2	4.9	2.7	1.8	0.188	0.163
0.50	23.9 ± 0.8	29.9 ± 1.2 [a]	29.7 ± 1.1 [a]	2.0	5.8	3.7	2.3	0.219	0.140

[a,b] Values of temperature accompanied by different letters are significantly different at 95.0% confidence level (p-value < 0.05) for each concentration.

4. Conclusions

As final conclusions, four agricultural solar protectors (ASPs) have been tested: "Blanco de España" (ASP_{BE}), the product traditionally used in the province of Almería, and three other commercial products that incorporate adhesives. The presence of the adhesive does not appear to influence the effect of the different products on the temperature inside the greenhouse, as all four products behave in a similar fashion at the same concentrations. The present findings support the maximum dose of product recommended by other authors: 0.50 kgL^{-1} (50/100), above which the transmissivity of the greenhouse cover produces a statistically significant decrease of over 50%. The effect of ASP on transmissivity of the greenhouse cover depends mainly on the dose applied, but also on the climatic conditions (solar radiation, cloud cover, etc.) and the time of year (solar elevation). This makes it difficult to recommend a single dose of product to growers. Different doses should be recommended depending on the time of year and the desired reduction in transmissivity. One of the products containing adhesives (ASP_F) has been shown to remain on the greenhouse cover after periods of heavy rain, while the non-adhesive product traditionally used (ASP_{BE}) is washed away. The method of application of ASP should be standardised in order to establish a means of applying a given concentration of product in gm^{-2} of cover. The traditional method of application establishes a dose (in kgL^{-1}), but the amount of product that finally remains on the cover is impossible to determine as it is applied manually.

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Effects of Cover Whitening Concentrations on the Microclimate and on the Development and Yield of Tomato (*Lycopersicon esculentum* Mill.) Inside Mediterranean Greenhouses

Resumen

Este trabajo analiza la influencia del blanqueo de la cubierta de los invernaderos en el microclima y en el rendimiento de un cultivo de tomate. En los sectores occidentales de dos invernaderos multitúnel, se utilizó como control una concentración de blanqueo de 0,250 kg L^{-1}. En un ciclo de cultivo de otoño-invierno, se utilizó una concentración inferior (0,125 kg L^{-1}) y una concentración mayor (0,500 kg L^{-1}) en los sectores orientales de invernaderos 1 y 2. En un ciclo primavera-verano, las concentraciones de blanqueo variaron dependiendo de la temperatura exterior. También se analizó el efecto del blanqueo de la cubierta sobre la actividad fotosintética, la producción, los parámetros morfológicos de las plantas y la calidad de los frutos. Para evaluar el efecto sobre el microclima, se midieron la radiación solar y fotosintéticamente activa (PAR), las temperaturas del aire y del suelo, y el flujo de calor en el suelo del invernadero 1. Los resultados muestran que el blanqueo excesivo de la cubierta conduce a reducciones de la radiación PAR interna que disminuye la fotosíntesis y el rendimiento de los cultivos. Al comienzo del ciclo de cultivo de otoño-invierno se propone una concentración de blanqueo de 0,500 kg L^{-1}, lavando la cubierta cuando la temperatura interior sea menor de 35 °C. Al final del ciclo de cultivo de primavera-verano, se recomienda una concentración de blanqueo de 0,125 kg L^{-1} cuando la temperatura interior aumenta de 35 °C.

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Effects of Cover Whitening Concentrations on the Microclimate and on the Development and Yield of Tomato (*Lycopersicon esculentum* Mill.) Inside Mediterranean Greenhouses

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Abstract: This work analyzes the influence of whitening a greenhouse roof on the microclimate and yield of a tomato crop. In the west sectors of two multi-span greenhouses, a whitening concentration of 0.250 kg L^{-1} was used as a control. In an autumn–winter cycle, a lower (0.125 kg L^{-1}) and an increased (0.500 kg L^{-1}) concentration were used in the east sectors of greenhouses 1 and 2. In a spring–summer cycle, the whitening concentrations in the east were varied depending on outside temperature. The effect of whitening on photosynthetic activity, production, plants' morphological parameters, and the quality of the fruits were also analyzed. To evaluate the effect on microclimate, solar and photosynthetically active (PAR) radiations, air and soil temperatures, and heat flux in the soil were measured in greenhouse 1. Results show that excessive whitening leads to reductions of inside PAR radiation that decreases photosynthesis and crop yield. A whitening concentration of 0.500 kg L^{-1} is proposed at the beginning of the autumn–winter crop cycle, washing the cover when inside temperature drops to 35 °C. At the end of the spring–summer cycle, a concentration of 0.125 kg L^{-1} is recommended when inside temperature increases to 35 °C.

Keywords: greenhouse; whitening; tomato crop; yield; microclimate

1. Introduction

Almería is one of the main areas of horticultural production under greenhouses worldwide, with an area of 31,614 ha [1], which has increased by about 1500 ha in the last 2 years. The growth in greenhouse area in recent years is probably the main mitigating factor of climate change in the province, due to an increase in the albedo of highly reflective plastic covers [2]. The horticultural sector is facing a difficult economic situation in recent years, in which stability in the sales prices of products in the face of the gradual rise in production costs of greenhouse crops puts at risk the economic profitability of most farms. Thus, in the greenhouses of Almería, the net profit of exploitation (considering variable costs, fixed costs, depreciation, and investment costs) became negative for most crops in the last seasons from 2015 to 2017 [3,4].

The future of Almería's greenhouses is about addressing the great challenges of global agriculture and the loss of profitability of the sector at the local level. For this purpose, various tools are available, such as optimization of photosynthesis [5]. A better light interception of the structures (higher roof slope) and the use of photo-selective and diffuse plastics can increase inside radiation. The optimization of the geometry of the crop rows could allow higher values of leaf area index and better distribution of the leaves vertically. Photosynthetic performance in greenhouse intensive production can be limited due to reduced distribution of the intercepted solar light along the canopy profile, which can reach levels of about 35% [6,7].

If all factors to improve the efficiency of radiation use and the efficiency of crop light interception were optimized simultaneously, crop productivity could be improved by 36%–64% [8]. Leaf photosynthetic rate is determined by the amount of photosynthetic protein per leaf area and CO_2 conductance in stomata [9]. In addition, a rise in the cover transmissivity allows not only to increase photosynthesis and production, but also to reduce the energy input in cold periods [10]. Under normal CO_2 concentrations and with adequate temperature conditions, photosynthetic activity is mainly affected by light intensity [11].

Insufficient radiation levels produce significant abiotic stress that limits plant growth and crop yields in intensive greenhouse production [12]. With little incident light, the leaves of the plant canopy exhibit an extremely low net photosynthetic rate and premature senescence [13–15], which produces reduction in plant growth and yield [15,16]. Generally, a cumulative daily light decrease of 1% leads to a yield loss of 0.8%–1% for most greenhouse crops [17,18].

Thus, the average level of tomato production in long cycles in greenhouses of Almería using whitening of the cover is 16.8 kg m^{-2}, although farmers with better yields reach 20.9 kg m^{-2}, both in multi-span-type greenhouses with heating by hot air generators, and in Almería-type greenhouses without heating [19]. These production levels are well below the yields of 49–55 kg m^{-2} for tomato obtained in greenhouses with hi-tech climate control systems in Northern Europe or America [20,21], or even from the values that are obtained in greenhouses of China of 20–35 kg m^{-2} [22] or Japan of 36–40 kg m^{-2}, when an integrative climate control system is used [9,23]. However, these production systems generate a much higher environmental impact with global energy requirements in the order of 50–80 MJ kg^{-1}, far larger than those generated in the Spanish unheated plastic greenhouses of 5 MJ kg^{-1} [24].

On the other hand, adverse temperatures and excessive radiation can produce a persistent decrease in the efficiency of solar energy conversion into photosynthesis, referred to as photoinhibition [25–28]. Photosynthesis limits growth at warm temperatures and decreases with temperature. Photoinhibition of tomato can occur at 30–40 °C and high levels of radiation (1500–1800 μmol m^{-2} s^{-1}) [29–31]. Furthermore, inside the greenhouses, there are stressful thermal regimes and atmospheres of high evaporative demand, which negatively affect crop growth and reduce the quantity and quality of the harvests [32]. Blossom-end rot (BER) in tomato has been generally reported as a calcium-related physiological disorder influenced by cultivar and environmental factors [33–35]. Temperature is the major climatic factor inducing blossom-end rot (BER) that impacts on fruit enlargement [33]. The cause of BER is usually an interaction between daily irradiance, air temperature, and water availability, affecting calcium uptake and distribution within the whole plant [34,36]. Shade can be used to reduce BER, as well as other physiological disorders in tomato fruit, as sun burn or sun scald [37,38] caused by temperatures exceeding 40 °C [36]. Thus, the use of 50% shade net reduces the number and weight of unmarketable tomato fruit [31].

Achieving an adequate environment in greenhouses in warm and sunny regions has become a major challenge, due to the large amount of solar radiation transmitted to the greenhouse, and then converted into sensible and latent heat [2]. Multiple cooling strategies are used in greenhouses to provide a suitable environment for plant growth and to increase crop productivity, such as: (1) Evaporative cooling systems, (2) forced ventilation systems, and (3) shading methods, such as the application of whitening or the use of mobile shading screens [32,39].

Shading is an effective method to attain a suitable microclimate inside greenhouses for plant development and to improve quantity and quality crop yield in hot and sunny regions [40]. Whitening is a low-cost method to reduce heat build-up and modify the greenhouse environment in hot summers [32,41]. This shading method is performed by mixing a certain amount of calcium oxide or calcium carbonate with water, to make a solution which is used to paint the outer surface of the glass or polyethylene [19,42,43]. Most farmers in Almería (99%) whiten the roof of their greenhouses to increase the reflection coefficient of solar radiation, which reduces the energy input that warms the greenhouse in the peak hours of the day [19]. Whitening is only needless in greenhouses equipped with mobile shading systems (as internal black-shading net and aluminized screens) or evaporative cooling systems. In the greenhouses of the Mediterranean basin, it is a technique widely used, with natural ventilation [44,45]. Cover whitening does not interfere with the greenhouse ventilation, representing an important advantage with respect to the other shading systems that affect negatively the performance of the roof ventilation [46].

The most commonly used product is micronized calcium carbonate ("Blanco de España"). The dose used varies greatly. Depending of the region and the transmissivity of the plastic cover, shading intensity of the whitening can be regulated, changing the concentration of calcium carbonate between 0.34 and 0.46 kg L^{-1} [19]. However, calcium carbonate shading is irregular, and product loss can occur with rain (washing) [32,39]. Meca et al. [47] compared the whitening of the cover (with a concentration of 0.25 kg L^{-1} of ASP "Blanco España") with the use of a low-pressure fog system and aluminized screens, obtaining greater yield of a pepper crop with the whitening of the cover. Fog system without shading reduced pepper production was 8.4%.

Excessive shading can significantly reduce the solar radiation intercepted by the crop canopy, thereby negatively affecting plant growth [17,32]. Crop production depends on the quantity of photosynthetically active radiation (PAR) absorbed by the crop [48], and levels of shading greater than 40% can reduce tomato yield [49]. However, the reduction of solar radiation by shading can produce positive effects, such as a diminution of the air temperature and the water consumption by irrigation [40,50]. Thus, the use of mobile shading can improve water use efficiency, reducing crop transpiration [32,51]. Close attention should be paid to the date of application, duration, and dose, with the aim of not drastically reducing physiological flows in the lower strata of the plant canopy [52]. Furthermore, the permanent nature of the system hinders the regulation of the intensity of the radiative field after its application, in favor of the crop, which, on certain occasions, has a negative effect on the potential yield of the crops [47]. On the other hand, this method ensures that greenhouses are passively cooled in an environmentally friendly manner, without any energy cost. With other methods, energy-intensive uses are required to maintain ideal growing conditions [53].

The objective of this work is to investigate the effects of different doses of whitening on the production of tomato crops, through analysis of the microclimate inside the greenhouse, photosynthetic activity, plant morphology, and fruit quality in two consecutive crop cycles.

2. Materials and Methods

2.1. Characteristics of the Experimental Greenhouses

This research was carried out in two multi-span Mediterranean greenhouses, located in the Experimental Station UAL-ANECOOP "Catedrático Eduardo Fernandez" of the University of Almería (36°51′ N, 2°16′ W, and 87 MASL). The greenhouses are divided transversely by a polyethylene wall, constituting two isolated sectors with similar characteristics (Table 1).

Table 1. Characteristics of sectors east (E) and west (W) of the two experimental greenhouses and different whitening concentration C_{WH} (kg L^{-1}) applied in both crop cycles. Surface area of cultivated soil S_C (m^2) and total ventilation surface area S_V/S_C (%).

Autumn–Winter Cycle								Spring–Summer Cycle	
Sector	C_{WH}	S_C	S_V/S_C	**Sector**	C_{WH}	S_C	S_V/S_C	**Sector**	C_{WH}
1E	0.125	600	18.8	2E	0.500	450	19.5	1–2E	0.125–0.250–0.500 (Variable)
1W	0.250	480	18.0	2W	0.250	360	18.7	1–2W	0.250 (Constant)

The opening and closing of the windows were managed by an environmental controller MultiMa Series II (Hortimax SL, Almería, Spain), depending on the climatic conditions. Greenhouse windows were opened at temperatures of 20 °C and closed at a wind speed of more than 8 m s^{-1}. Outside, solar radiation, temperature and relative air humidity, and wind speed and direction were measured at 10 m height with a meteorological station. Inside both greenhouses, temperature and relative air humidity were measured at a height of 2 m. Both the external and internal microclimate variables were recorded at a frequency of 1 Hz.

Additionally, the 10/12/2014 set of climate sensors was installed outside and inside sectors east and west of greenhouse 1. Temperature T_i and relative air humidity R_{Hi} were measured at 1 m and 2 m height. Solar R_S and photosynthetically active R_{PAR} radiations were measured inside and outside greenhouse 1. Soil surface temperature T_{s0} was measured beneath a polypropylene mulch covering the ground and soil temperature was measured at a depth of 0.3 m. The heat flux by conduction toward the ground q_s was measured using a soil heat flux plate placed at a depth of 0.2 m. A detailed description of all sensors used to measure microclimatic parameters is available in a previous work analyzing thermal exchanges in experimental greenhouse 1 [54].

2.2. Crop System and Experimental Design

The research was carried out in two consecutive crop cycles of tomatoes (*Lycopersicon esculentum* Mill.). First, an autumn–winter tomato cycle was conducted with the commercial variety Racymo from 19 August 2014 to 09 January 2015. A second crop in the spring–summer cycle was developed with the commercial variety Bermello (from 17 February 2015 to 2 July 2015). In both cases, the transplant was carried out 40 days after sowing, in handmade sacks of coconut fiber with a plantation density of 1 plant m^{-2}.

During this study, the effect of an agricultural solar protector (ASP) applied at different concentrations (Table 1) was evaluated. We used three concentrations recommended by the manufacturing companies of ASP [55], which were selected based on the range of whitening concentrations used by the growers of Almería [19]. A concentration of 0.250 kg L^{-1}, mainly used by growers of Almería [19], was used as control in the west sectors of both greenhouses. The option of un-whitened cover was not considered because 100% of commercial greenhouses naturally ventilated in Almería use whitening [19]. Furthermore, an un-whitened greenhouse at the beginning of the crop cycle could risk the viability of the tomato crop as a consequence of plant photoinhibition [29–31] or physiological disorders [34–38] produced by excessive radiation and extreme temperatures. Application of the different doses consisted of increasing the concentration of the mass of $CaCO_3$ (kg) diluted in a volume of water (L). The method of application was the one used by the companies in the sector. The $CaCO_3$ solution was applied with a spray nozzle while the operator moved over the surface of the greenhouse roof. Therefore, the homogeneity of the application can vary, as it is manual work and dependent on wind conditions. To determine the relationship between the concentration of dilution (kg L^{-1}) applied for the whitening of the cover and the dose of $CaCO_3$ remaining on the cover (g m^{-2}), plastic samples of 20 cm^2 were taken. The amount of $CaCO_3$ deposited on the plastic samples was weighed on an analytical lab balance QUINTIX224-1S (Sartorius Lab Instruments GmbH & Co. KG, Goettingen, Germany) with 220 g weighing capacity with readability to 0.1 mg.

In the spring–summer cycle, the concentration was varied in the east sectors of both greenhouses depending on the outside temperature conditions. The cycle started with a concentration of 0.125 kg L^{-1}, applying the most concentrated dose (0.500 kg L^{-1}) at the end of the crop. The first dose (0.125 kg L^{-1}) was applied when the maximum outside temperature reached the value of 25 °C during a three-day period. The second (0.250 kg L^{-1}) was spread when maximum outside temperature reached 27 °C and the last (0.500 kg/L) when it surpassed 30 °C. Each time a new concentration was applied, the previous application was cleaned. The concentration of control (0.250 kg L^{-1}) was renewed at the same times as the variable dose, cleaning previously the greenhouse cover. The total and spectral transmissivity of the samples of plastic cover with the different doses of $CaCO_3$ were measured as described by

Sangpradit [56]. A spectrometer MK350S (UPRTek, Jhunan, Taiwan) was used with a measurement range of 380–780 nm and accuracy of 2.5%. For each treatment, the measurements were performed at three different locations of the material.

2.3. Measurement Equipment for Crop Development and Production Analysis

To determine the influence of different ASP doses on crop yield, three lines were selected in each experimental sector (considered as statistical repetitions). Marketable and non-marketable yield were weighed with an EKS Premium electronic balance (EKS España, SA, Spain), with a measuring range of 0–40 kg and an accuracy of 10 g.

To determine growth, 12 plants were evaluated in each of the experimental sectors. Data were taken every 15 days. The morphological parameters measured were [57]: Total length of the plant, L_T (cm); length of the internodes immediately superior, H_I (cm) and immediately inferior to the internode that occupies the last true leaf, L_I (cm); diameter of the stem, D_S (mm); number of nodes below the last true leaf, N_N; Leaf Area Index L_{AI} (m^2 m^{-2}).

For the fruit quality evaluation, 20 tomatoes were taken (everyday of harvest) of each sector of experimentation. We measured tomato fruit characteristic as weight [58] and diameter [12], soluble solids content [58,59], core firmness [58], and dry matter [58,59]. The corresponding instruments used to measure these parameters were:

Weight (W_F): Electronic scale PB3002-L Delta Range® (Mettler Toledo, SA, L'Hospitalet de Llobregat, Spain), with measuring range of 0–600 kg and accuracy of ±0.1 g.

Equatorial diameter (D_F): Digital meter 150 mm (Medid Precision, SA, Barcelona, Spain) with measuring range of 0–150 mm and resolution of 0.010 mm.

Total soluble solids content (T_{SS}): A few drops of tomato juice were placed in a refractometer PAL^{-1} (Atago Co. LTD., Fukuoka, Japan) with a measuring range of 0%–53% and accuracy of ±0.2%.

Firmness (F_F): A texture digital analyzer PCE-FM 200 (PCE- Ibérica SL, Tobarra, Spain) with measuring range of 0–20 kg and accuracy of ±0.5 g.

The pH was potentiometrically determined with a multimeter MM 40 (Crison Instruments S.A., L'Hospitalet de Llobregat, Spain) with measuring range of −2.00 to 19.99 and measurement error ≤0.01.

Dry matter (D_M): Fruits were dried at 70 °C for 48 h in an oven 23–240 I, FD series (Binder GmbH, Tuttlingen, Germany).

The measurement of the photosynthetic activity of the plants [12] was carried out by means of an LCi Portable Photosynthesis System (ADC BioScientificLimited, Hertfordshire, United Kingdom). It has a measurement range of 0–2000 ppm (CO_2) and 0–75 mbar (H_2O), with an accuracy of ±2%. The system also provides measurements of leaf temperature and PAR radiation. Twelve plants per experimental sector were measured on unclouded days.

2.4. Statistical Analysis

The statistical analysis of the data was performed with the Statgraphics Centurion XVIII software, using a variance analysis (considered significant if p-value ≤ 0.05), comparing the mean values with Fisher's minimum significant difference procedure (LSD). Bartlett, Cochran, and Hartley tests were used to determine whether a sector has similar variation. When there was a statistically significant difference between the standard deviations, the parametric analysis was not viable by means of analysis of variance. For parameters with different variance, we carried out non-parametric analysis with the Friedman test, with each row representing a block (the date of measurement), using box-and-whisker plots [60]. Repetitions were 12 plants for growth parameters and photosynthesis and 20 tomatoes for analysis of production quality.

3. Results and Discussion

3.1. Effect of the Whitening Doses on the Cover Transmissivity

The spectral power distribution of sun light and light transmitted through five different samples of the plastic cover were measured over the 380–780 nm range using a spectroradiometer (Figure 1a). One sample without and four with whitening concentrations (the three used in the experimental greenhouse and an additional concentration of 1 kg L^{-1}) were analyzed. Using these spectrums, the total transmissivity of the materials was calculated (Figure 1b). Transmissivity of the plastic without whitening ranged between 0.61 and 0.91 (Figure 1b), in agreement with values measured in a new film (0.80–0.87) [55]. The transmissivity of the plastic with the control concentration of 0.250 kg L^{-1} was 0.33–0.52 (Figure 1b) for the PAR wavelengths, corresponding with the values measured in a dirty cover with 6-month-old material without cleaning [55].

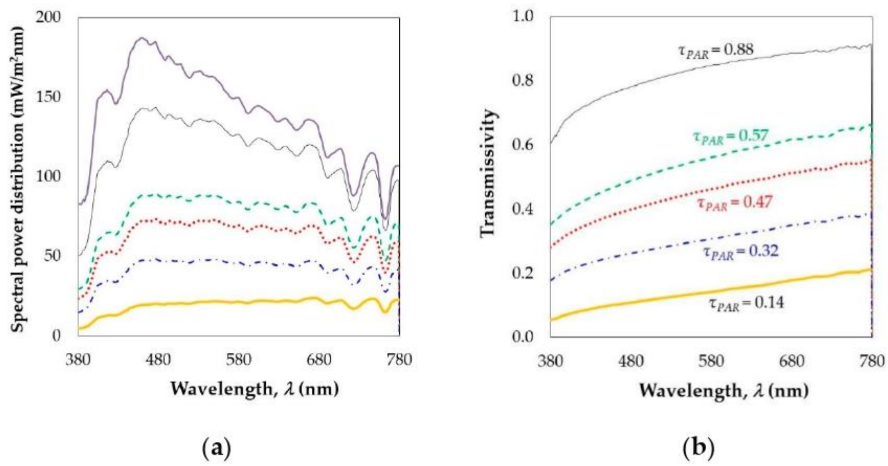
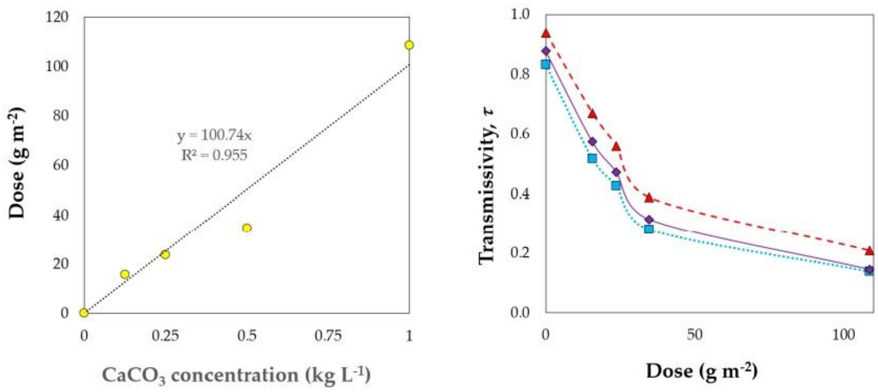


Figure 1. Spectral power distribution (**a**) and transmissivity (**b**) of sun light (—), light transmitted by a plastic cover without whitening (—) and with whitening for doses of 0.125 kg L^{-1} and 15.7 g m^{-2} (- - -), 0.250 kg L^{-1} and 23.7 g m^{-2} (·····), 0.500 kg L^{-1} and 34.6 g m^{-2} (-·-·-), 1 kg L^{-1} and 108 g m^{-2} (—).

From measurements of the quantity of the $CaCO_3$ deposited in the plastic cover (Figure 2a) and using the light transmitted spectrums (Figure 1), the total transmissivity of the materials was calculated over the PAR 400–700 nm, the 380–400 nm, and the 700–780 nm ranges (Figure 2b). The dose of $CaCO_3$ deposited in the cover after application of the whitening treatment was proportional to the concentration used, with about 0.1 kg m^{-2} for a concentration of 1 kg L^{-1}. However, the rise of the whitening dose produced an exponential decrease in PAR transmissivity of the plastic. For doses lower than 50 g m^{-2}, the transmissivity was proportionally reduced to the increase of the whitening concentration (Figure 2b), with a small reduction of transmissivity between 50 and 100 g m^{-2}.

The different levels of whitening produced a variable decrease on transmissivity of the greenhouse cover. This reduction does not seem to be proportional to the dose of calcium carbonate applied (Table 2). The causes of the irregularity in shading were the heterogeneity of the application on the cover surface and the non-uniform effect of rain washing [32,39,55]. The transmissivity of the greenhouse cover with the different doses (Table 2) differed of that measured in the plastic samples (Figure 1b), as a consequence of the effect of dirty accumulation [55], variation of sun position with time, and application heterogeneity [55].



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

Figure 2. Relationship between $CaCO_3$ concentration in the solution applied in the greenhouse cover and the dose of product remaining under the plastic (**a**). Transmissivity in function of the whitening dose (**b**) for photosynthetic active radiation corresponding to wavelengths from 400 to 700 nm (··■··), ultraviolet light 380–400 nm (-♦-) and far red radiation 700–780 nm (-▲-).

Table 2. Mean transmissivity (±standard deviation) for solar radiation τ_s and for photosynthetically active radiation τ_{PAR} measured in greenhouse 1 for the different whitening concentrations C_{WH} (kg L^{-1}) and doses D_{WH} (g m^{-2}) applied in both crop cycles.

Autumn–Winter Cycle									
Sector		**Greenhouse 1 East**				**Greenhouse 1 West**			
Period	**Dates**	C_{WH}	D_{WH}	τ_s	τ_{PAR}	C_{WH}	D_{WH}	τ_s	τ_{PAR}
1	19/8/14–1/10/2014 *	0.125	15.7	0.46 ± 0.04	0.41 ± 0.03	0.250	23.7	0.42 ± 0.04	0.39 ± 0.03
2–3	2/10/14–9/1/2015	0–Rain		0.64 ± 0.04	0.58 ± 0.03	0–Rain		0.64 ± 0.04	0.58 ± 0.03
Spring–Summer Cycle									
4	17/2/15–26/3/2015	0	0	0.61 ± 0.05	0.57 ± 0.04	0	0	0.60 ± 0.05	0.56 ± 0.04
5	27/3/15–25/5/2015	0.125	15.7	0.49 ± 0.04	0.46 ± 0.03	0.250	23.7	0.42 ± 0.04	0.39 ± 0.03
6	26/5/15–21/6/2015	0.250	23.7	0.45 ± 0.04	0.40 ± 0.03	0.250	23.7	0.42 ± 0.04	0.38 ± 0.03
7	22/6/15–2/7/2015	0.500	34.6	0.42 ± 0.03	0.37 ± 0.02	0.250	23.7	0.40 ± 0.03	0.38 ± 0.02

* Values measured in another greenhouse annex to greenhouse 1 of similar characteristics [55].

For the autumn–winter cycle, the whitening of the cover was carried out on the same day that the plants were transplanted inside the greenhouses (19 August 2014). Whitening was maintained in the cover until the rain washing it (1 October 2014 rained 12.6 mm), defining these dates as the first period. Transmissivity of the cover at this first period was measured for concentrations of 0.125 and 0.250 kg L^{-1} in a closed greenhouse (on 23–31 July and 18–26 September 2014) with the same dimension and plastic film [55]. At this first period, transmissivity of the cover was reduced considerably with the use of the lower concentration of 0.125 kg L^{-1} in the east sector (Table 2).

However, increasing by double the dose in the west sector (to the concentration of control 0.250 kg L^{-1}), the transmissivity was reduced by only 10% with respect to the lower dose. After the wash of the cover by the first rainfall, the transmissivity of both sectors rose to similar values (Table 2). At the end of the crop cycle of autumn–winter (periods 2–3), solar radiation and PAR presented a similar evolution in both sectors of greenhouse 1 (Figure 3a). These data show the similarity of microclimate in both sectors of experimental greenhouse 1 when the same whitening treatment was used in the cover. The mean solar radiation measured at the end of the autumn–winter cycle (period 3), with the cover washed by the rain, was equal in both sectors (Table 2). However, the average daily maximum values of solar radiation and PAR were statistically greater in the east sector than in the west sector (Table 3). These differences could be due to a greater persistence of the whitening after the rainfall in the cover with a greater dose of the agricultural solar protector (ASP).

The mean and maximum values of solar and PAR radiation recorded at the beginning of the spring–summer cycle (period 4), with the non-whitened cover, were statistically similar in both sectors (Table 3). This similarity in radiations guarantees that the effect of the orientations of the east and west sectors with respect to the sun's path is negligible.

When outside temperature increased, a first whitening for the spring–summer cycle was applied in the greenhouse cover (period 5), with an initial concentration of 0.125 kg L^{-1} in the east sector. Lower values of radiation were measured in the west sector with the control concentration of 0.250 kg L^{-1} (Figure 3b). These differences were statistically significant for maximum values of radiation. However, mean values were greater in the east sector, with the lower whitening concentration of 0.125 kg L^{-1}, but without statistical significance (Table 3). The average cover transmissivity measured in the west sector with the control treatment at this period was the same as the value measured in August (Table 2) [55]. However, transmissivity in the east sector with the lower concentration of whitening (0.125 kg L^{-1}) was higher than values measured in August [55]. This result put emphasis on the difficulty of making two applications with the same dose of ASP (kg m^{-2}) on the greenhouse cover.

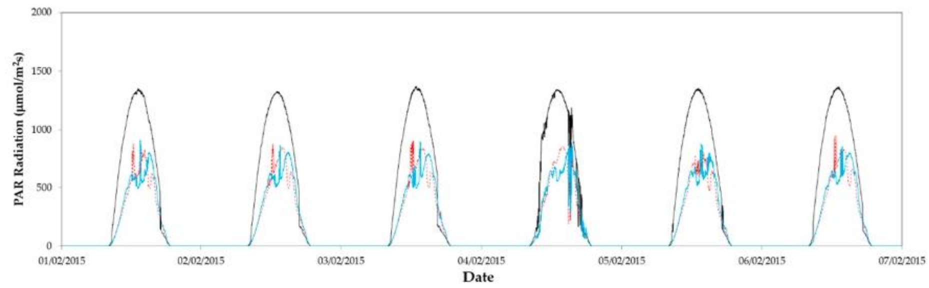
Although in period 6 the concentration of control was applied in both sectors, the amount of product remaining in the cover was different. We can observe a higher radiation in the east sector than in the west (Figure 3c), with statistical significance for the maximum values (Table 3). Finally, at the end of the production cycle (period 7), when outside temperature reached 30 °C (Figure 3d), a concentration of 0.500 kg L^{-1} was applied in the cover of the east sector, producing a reduction of the transmissivity.

Despite applying in the east sector twice the concentration of ASP than the control applied in the west sector, its transmissivity remained higher than in the west sector, and similar to that measured in September 2014 for the same concentration of 0.500 kg L^{-1} [55]. This shows that the reduction in transmissivity of the cover is not always proportional to the increase in the concentration of calcium carbonate dissolved in the application water.

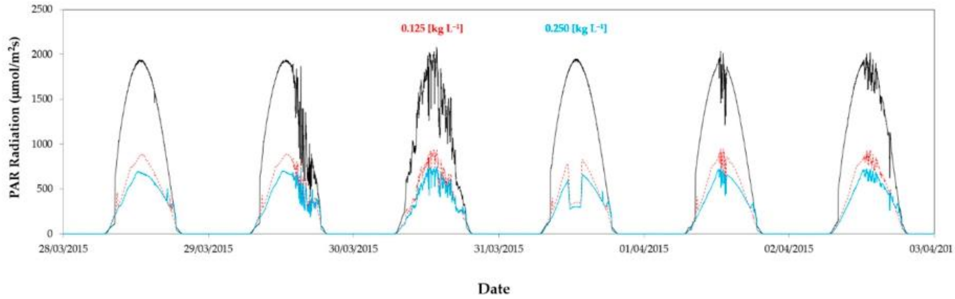
3.2. *Effect of the Whitening Doses on Temperature and Heat Flux in the Soil*

The main objective of application of whitening in the cover of Mediterranean greenhouses is to reduce solar radiation absorbed by the soil surface. One part of this energy is transmitted to the inside air by natural convection. Another part is transmitted to the ground by conduction (stocked during the daytime and released in the night to the air), and the other is emitted as infrared radiation [54]. The soil temperature depends on the ratio of the energy absorbed to that lost from the soil, fluctuating daily, affected mainly by variations in solar radiation [61–64].

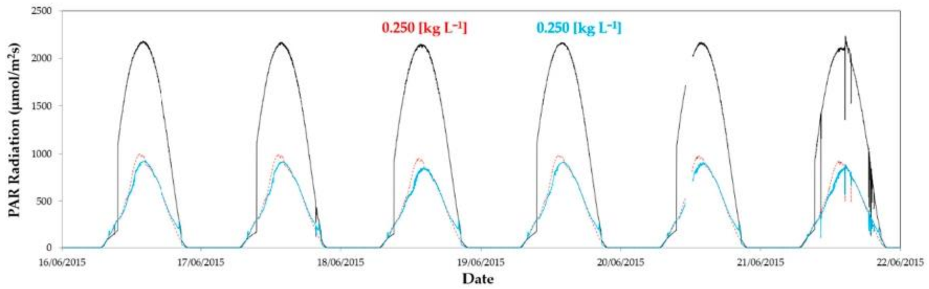
Because of whitening, air temperature, vapor pressure deficit, and canopy-to-air temperature difference can experience drastic changes while transpiration rate was not strongly affected [45]. Cover whitening can produce a positive effect decreasing air temperature (more than 4 °C). This climate control method can be considered as an efficient means for reducing the heat load during summer in warm countries [45]. However, whitening can drastically reduce the photosynthesis capacity of plants inside greenhouses [54].



(**a**)

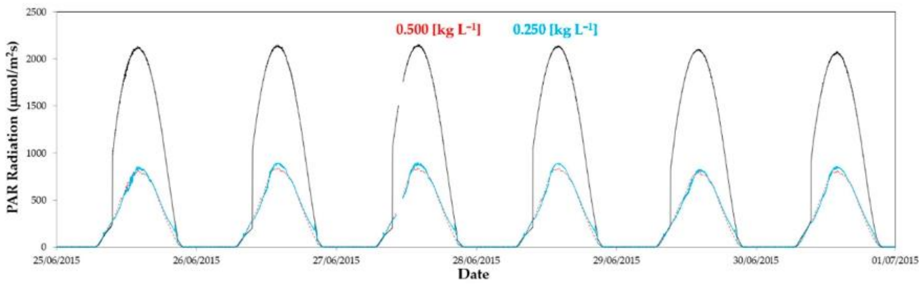


(**b**)



(**c**)

Figure 3. *Cont.*



(**d**)

Figure 3. Evolution of photosynthetically active radiation (PAR) outside (—-) and inside greenhouse 1 in the east sector (·····) and west sector (——): (**a**) From 1 to 5 February2015 without whitening in both sectors; (**b**) from 28 March 2015 to 3 April 2015 with a concentration of 0.125 kg L^{-1} in the east and 0.250 kg L^{-1} in the west; (**c**) from 16 to 22 June 2015 with a concentration of 0.250 kg L^{-1} in both sectors; (**d**) from 25 June 2015 to 1 July 2015 with a concentration of 0.500 kg L^{-1} in the east and 0.250 kg L^{-1} in the west.

Table 3. Mean and average maximum (±standard deviation) values of air temperature recorded inside the east and west sectors of the experimental greenhouse 1 at 2 m height T_{i2} (°C) for the different periods P and whitening concentrations C_{WH} (kg L^{-1}). Air temperature at 1 m height T_{i1} (°C), relative air humidity of inside air HR_i (%), soil surface temperature T_{s0} (°C), temperature of the soil at 0.3 m depth $T_{s0.3}$ (°C), inside solar radiation R_{si} (W m^{-2}), inside PAR radiation R_{PARi} (W m^{-2}), and soil heat conducted in the soil at 0.2 m q_s (W m^{-2}).

Greenhouse-Sectors		Greenhouse 1 East								Greenhouse 1 West					
							Mean Values in the Autumn–Winter Cycle								
P	Dates	C_{WH}	R_{si}	T_{i1}	T_{i2}	HR_i	T_{s0}	$T_{s0.3}$	C_{WH}	R_{si}	T_{i1}	T_{i2}	HR_i	T_{s0}	$T_{s0.3}$
1	19/8/14–1/10/14	0.125	-	-	26.4^{a} ± 2.3	-	-	-	0.250	-	-	25.7^{a} ± 2.3	-	-	
2	2/10/14–9/12/14	Rain	-	-	18.3^{a} ± 4.5	-	-	-	Rain	-	-	18.0^{a} ± 4.5	-	-	
3	10/12/14–9/1/15	0	146.1^{a} ± 15	12.9^{a} ± 1.6	13.1^{a} ± 1.7	80.7^{a} ± 3.8	15.5^{a} ± 0.7	17.6^{a} ± 0.5	0	144.2^{a} ± 15	12.6^{a} ± 1.4	12.8^{a} ± 1.5	80.8^{a} ± 3.9	15.5^{a} ± 0.6	17.6^{a} ± 0.5
							Mean Values in the Spring–Summer Cycle								
4	17/2/15–26/3/15	0	173.3^{a} ± 25	14.0^{a} ± 1.8	14.3^{a} ± 1.9	68.1^{a} ± 11.8	17.2^{a} ± 2.8	17.9^{a} ± 1.7	0	175.7^{a} ± 23	13.9^{a} ± 1.9	14.0^{a} ± 1.9	68.1^{a} ± 12.0	17.6^{a} ± 2.5	18.2^{a} ± 1.7
5	27/3/15–25/5/15	0.125	235.4^{a} ± 35	18.6^{a} ± 2.3	19.1^{a} ± 2.4	65.7^{a} ± 8.3	23.8^{a} ± 2.0	22.2^{a} ± 1.7	0.250	204.7^{a} ± 29	18.5^{a} ± 2.2	18.8^{a} ± 2.3	66.8^{a} ± 8.4	22.9^{a} ± 1.7	21.8^{a} ± 1.9
6	26/5/15–21/6/15	0.250	310.4^{a} ± 21	24.0^{a} ± 2.0	24.6^{a} ± 2.0	59.0^{a} ± 9.6	28.9^{a} ± 1.3	27.0^{a} ± 0.7	0.250	289.7^{a} ± 18	24.2^{a} ± 2.1	24.5^{a} ± 2.2	59.0^{a} ± 11.0	28.3^{a} ± 1.6	27.0^{a} ± 0.7
7	22/6/15–2/7/15	0.500	288.2^{a} ± 9	28.2^{a} ± 1.7	28.7^{a} ± 1.8	56.2^{a} ± 11.9	31.4^{a} ± 1.0	29.4^{a} ± 0.7	0.250	279.9^{a} ± 9	28.5^{a} ± 1.9	29.0^{a} ± 2.0	54.9^{a} ± 12.8	31.5^{a} ± 1.1	29.6^{a} ± 0.8
							Average Daily Maximum Values in the Autumn–Winter Cycle								
P	Dates	C_{WH}	R_{si}	R_{PARi}	q_s	T_i	T_{s0}	$T_{s0.3}$	C_{WH}	R_{si}	R_{PARi}	q_s	T_i	T_{s0}	$T_{s0.3}$
1	19/8/14–1/10/14	0.125	-	-	-	34.4^{b} ± 3.2	-	-	0.250	-	-	-	33.6^{ab} ± 3.4	-	-
2	2/10/14–9/12/14	Rain	-	-	-	27.0^{b} ± 5.1	-	-	Rain	-	-	-	26.9^{b} ± 5.2	-	-
3	10/12/14–9/1/15	0	435.5^{b} ± 57	752.5^{b} ± 102	9.3^{b} ± 3.7	21.8^{b} ± 2.1	20.1^{a} ± 1.1	17.7^{a} ± 0.5	0	403.1^{a} ± 56	693.6^{a} ± 80	5.7^{a} ± 3.2	22.1^{b} ± 2.3	20.4^{a} ± 0.9	17.8^{a} ± 0.5
							Average Daily Maximum Values in the Spring–Summer Cycle								
4	17/2/15–26/3/15	0	496.6^{a} ± 103	943.2^{a} ± 199	11.7^{a} ± 4.6	25.0^{a} ± 3.9	24.5^{a} ± 6.1	18.7^{a} ± 0.4	0	486.0^{a} ± 79	909.9^{a} ± 160	10.4^{a} ± 6.5	25.3^{a} ± 3.4	25.5^{a} ± 4.8	19.1^{a} ± 0.4
5	27/3/15–25/5/15	0.125	487.3^{b} ± 61	933.8^{b} ± 105	12.7^{b} ± 5.0	30.5^{a} ± 5.1	33.7^{b} ± 4.5	23.6^{b} ± 0.8	0.250	395.7^{a} ± 62	781.5^{a} ± 118	2.9^{a} ± 0.9	29.4^{a} ± 4.9	31.3^{a} ± 4.2	23.2^{a} ± 0.8
6	26/5/15–21/6/15	0.250	545.0^{b} ± 29	1022^{b} ± 53	15.0^{b} ± 4.9	32.9^{a} ± 3.3	38.1^{a} ± 2.3	27.8^{a} ± 0.5	0.250	483.8^{a} ± 33	942.6^{a} ± 58	9.3^{a} ± 2.6	32.5^{a} ± 3.1	36.5^{a} ± 2.6	28.0^{a} ± 0.5
7	22/6/15–2/7/15	0.500	457.2^{a} ± 46	847.4^{a} ± 84	17.0^{b} ± 3.2	37.6^{b} ± 2.7	39.9^{a} ± 1.6	30.1^{a} ± 0.8	0.250	442.0^{a} ± 30	868.8^{a} ± 67	11.7^{a} ± 1.9	37.6^{b} ± 3.0	40.2^{a} ± 2.1	30.6^{a} ± 0.9

[a,b] Values with different letters are significantly different at 95.0% confidence level (p-value ≤ 0.05).

A higher soil temperature was observed in the east sector in periods 4 and 5 (Figure 4b,c) when the transmissivity was greater that in the west sector (Table 2). Statistically significant differences were only observed for maximum soil surface temperature T_{s0} in period 4 (Table 3), when difference between cover transmissivity was maximum. In both periods (3 and 4), without whitening in the greenhouse cover, very similar values of mean and maximum soil surface temperature were observed (Table 3). At the end of the spring–summer cycle (period 6), the increase of the whitening concentration to 0.500 kg L^{-1} in the east sector produced a reduction in soil surface temperature (Figure 4d) but without statistical significance (Table 3).

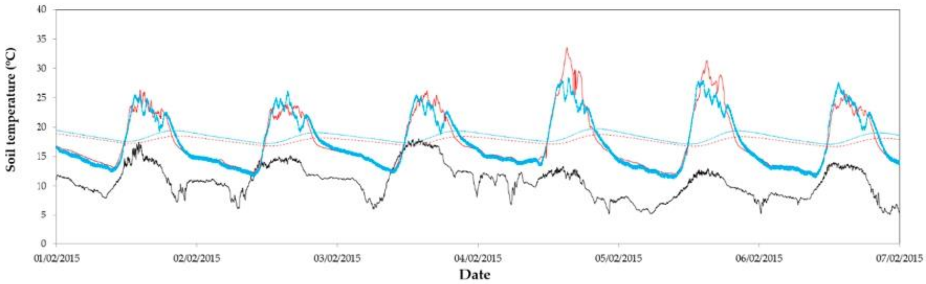
Temperatures measured at a depth of 0.3 m in the soil inside both greenhouse sectors were very similar (Figure 4a–d). Soil temperature was only statistically greater in the east sector for period 5 when the maximum difference between cover transmissivity of both sectors was achieved. Although soil temperature can affect to plant growth [65], differences observed between both greenhouse sectors seem small to produce significant effects on plants development.

Soil heat flux is important because its couples surface energy balance with energy transfer processes in the soil [64] and affects the soil surface [61] and soil temperatures. The heat flux in the soil was similar in both greenhouse sectors only at the beginning of the spring–summer cycle (period 3) when similar transmissivity was observed in the non-whitened covers. For the other four periods (3 and 5–7), significantly greater maximum heat flux was observed in the east sector with the greater solar radiation values (Table 3). However, this heat flux represented less than 4% of solar radiation transmitted inside the greenhouse (Table 3).

Evolutions of soil surface temperature measured inside the greenhouse 1 (Figure 4) show a similar pattern to that of PAR radiation (Figure 3). Soil temperature is a key factor affecting chemical and biological processes in the soil essential to plant growth, such as the uptake of nutrients and water by roots, the decomposition of organic matter by microbes, and the germination of seeds [63,64]. At the end of the autumn–winter cycle (period 3), the mean soil surface temperatures were identical for both sectors (Table 3), as a consequence of the equal transmissivity of the cover (Table 2).

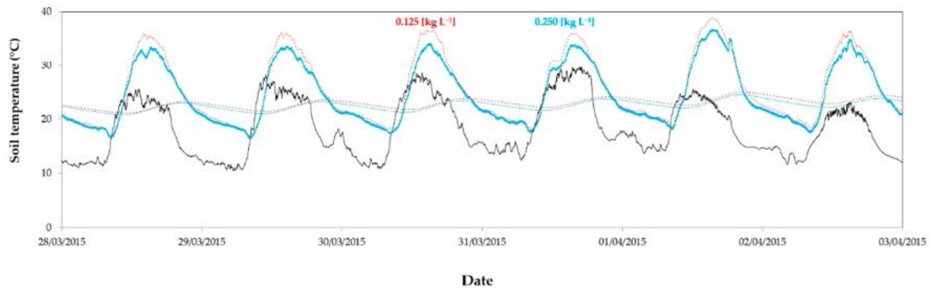
3.3. *Effect of the Whitening Doses on the Temperature and Relative Air Humidity*

In general, air temperature (Figure 5) was lower than soil surface temperature (Figure 4) as a consequence of the use of a black polypropylene mulch [54]. Furthermore, as the crop was developed in a coconut fiber substrate, the soil was not irrigated, avoiding water evaporation from the soil surface that normally reduce its temperature [66].

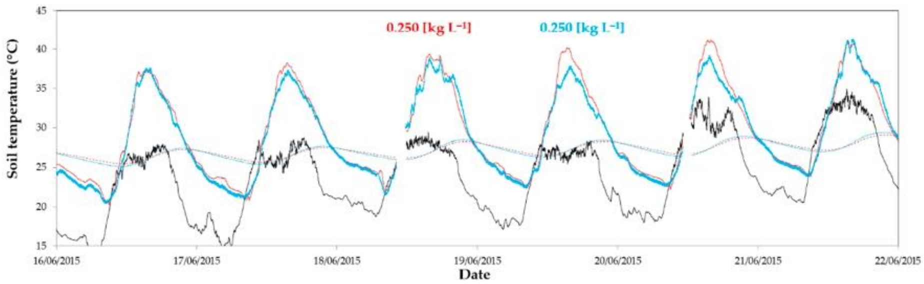


(a)

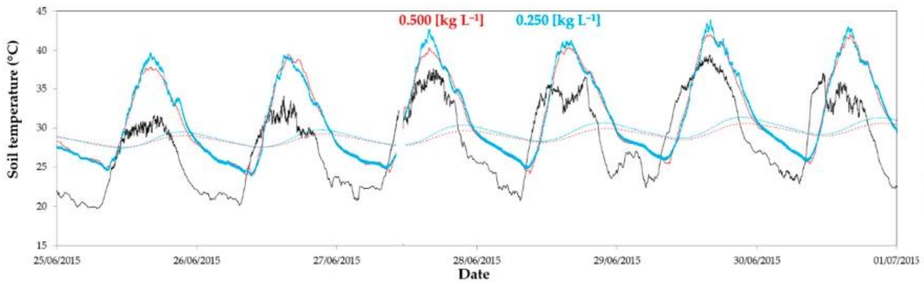
Figure 4. *Cont.*



(**b**)

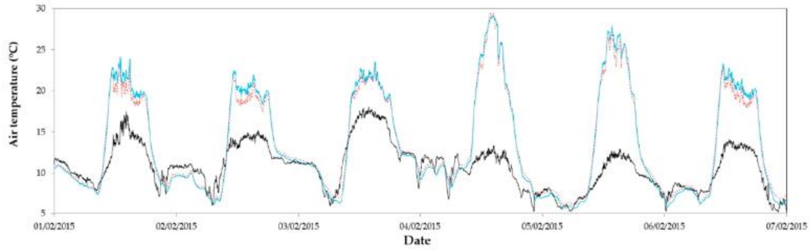


(**c**)

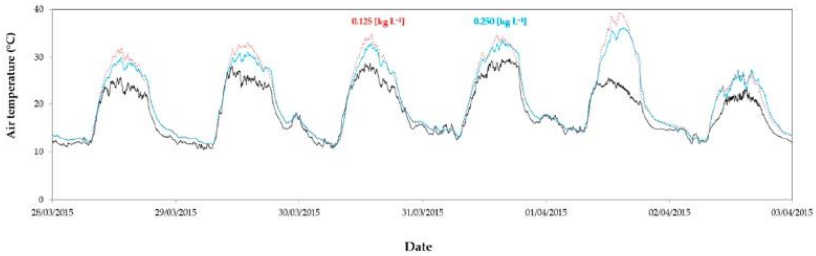


(**d**)

Figure 4. Evolution of air temperature outside (—) and soil surface temperature inside greenhouse 1 in the in the east (—) and west (—) sectors and temperature at 0.2 m deep in the soil in the east (- - -) and west (- - -) sectors: (**a**) from 1 to 7 February 2015 without whitening in both sectors; (**b**) from 28/3/2015 to 3/4/2015 with a concentration of 0.125 kg L^{-1} in the east and 0.250 kg L^{-1} in the west; (**c**) from 16 to 22 June 2015 with a concentration of 0.250 kg L^{-1} in both sectors; and (**d**) from 25 June 2015 to 1 July 2015 with a concentration of 0.500 kg L^{-1} in the east and 0.250 kg L^{-1} in the west.



(**a**)



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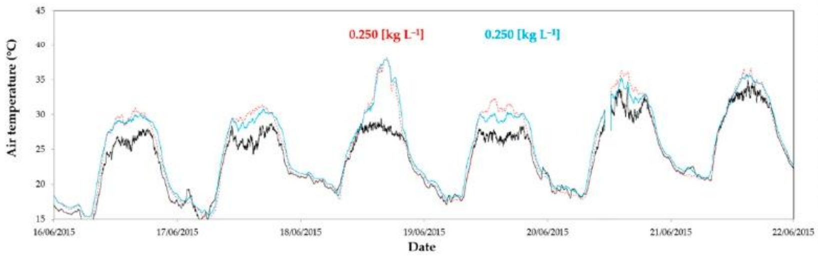

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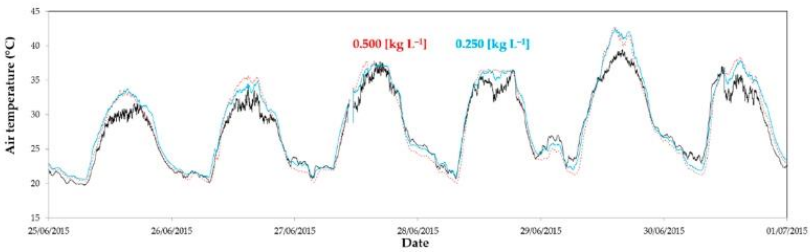

(**d**)

Figure 5. Evolution of air temperature outside (—) and inside greenhouse 1 (at 1 m height) in the east sector (·····) and the west sector (—): (**a**) from 1 to 7 February 2015 without whitening in both sectors; (**b**) from 28 March 2015 to 3 April 2015 with a concentration of 0.125 kg L^{-1} in the east and 0.250 kg L^{-1} in the west; (**c**) from 16 to 22 June 2015 with a concentration of 0.250 kg L^{-1} in both sectors; (**d**) from 25 June 2015 to 1 July 2015 with a concentration of 0.500 kg L^{-1} in the east and 0.250 kg L^{-1} in the west.

Maximum temperatures were observed in August 2014 (Tables 3 and 4), corresponding with the start of the autumn–winter crop cycle (period 1). Average daily maximum temperature reached 35.0 °C in the west sector of greenhouse 2 with the control concentration (0.250 kg L^{-1}). In the east sector, with the most concentrated whitening (0.500 kg L^{-1}), temperature was 2 °C lower.

Table 4. Mean and average maximum (±standard deviation) values of air temperature recorded inside the east and west sectors of the experimental greenhouse 2 at 2 m height T_{i2} (°C) for the different periods P and whitening concentrations C_{WH} (kg L^{-1}).

Experimental Greenhouse 2									
Autumn–Winter Cycle									
Sectors		East		West		East		West	
		Mean values				*Average daily maximum values*			
P	Dates	C_{WH}	T_{i2}	C_{WH}	T_{i2}	C_{WH}	T_{i2}	C_{WH}	T_{i2}
1	19/8/14–1/10/14	0.500	$25.6^{a} \pm 2.2$	0.250	$27.0^{b} \pm 2.1$	0.500	$33.0^{a} \pm 3.0$	0.250	$35.0^{b} \pm 2.2$
2	2/10/14–9/12/14	Rain	$17.7^{a} \pm 4.4$	Rain	-	Rain	$25.1^{a} \pm 4.5$	Rain	-
3	10/12/14–9/1/15	0	$12.7^{a} \pm 1.0$	0	$13.2^{a} \pm 1.4$	0	$20.1^{a} \pm 1.6$	0	$24.5^{c} \pm 1.1$
Spring–Summer Cycle									
4	17/2/15–26/3/15	0	-	0	-	0	-	0	-
5	27/3/15–25/5/15	0.125	$21.1^{a} \pm 2.9$	0.250	$20.6^{a} \pm 2.5$	0.125	$30.3^{a} \pm 5.2$	0.250	$28.9^{a} \pm 4.2$
6	26/5/15–21/6/15	0.250	$24.7^{a} \pm 2.4$	0.250	$24.5^{a} \pm 2.1$	0.250	$31.9^{a} \pm 4.3$	0.250	$33.3^{a} \pm 4.0$
7	22/6/15–2/7/15	0.500	$27.8^{a} \pm 2.1$	0.250	$27.5^{a} \pm 1.9$	0.500	$36.6^{a} \pm 3.5$	0.250	$35.3^{a} \pm 3.0$

[a,b,c] Values with different letters are significantly different at 95.0% confidence level (p-value ≤ 0.05).

Despite the whitening of the greenhouses, maximum temperatures exceeded 35–40 °C in the first days of plant inside both greenhouses at the end of August. At this temperature range, tomato plants can reduce photosynthesis and fruit can be damaged [29,34].

The use of the greatest whitening concentration (0.500 kg L^{-1}) in the east sector of greenhouse 2 reduced the number of days with maximum temperatures above 37 °C to only three. In the other three sectors, with lower doses, this limit was exceeded in 9 or 10 days. At this first period of crop, maximum temperatures were statistically greater in the sectors with lowest whitening concentrations of each greenhouse (Table 4). A whitening concentration of 0.500 kg L^{-1} is recommended at the time of maximum climatic requirement in August, as well as an increase in the ventilation surface.

Although the final objective of the use of cover whitening in greenhouses is to reduce air temperature, any significant difference was observed in air temperature (Figure 5a,c,d). In the spring–summer cycle, mean values measured at 1 m and 2 m height and the average maximum temperatures were similar in the two sectors of each greenhouse (Tables 3 and 4). The greatest difference between temperatures in the spring–summer cycle was observed when the dose applied in the east sector was the lowest (0.125 kg L^{-1}). At this time (period 5), differences between average maximum air temperatures achieved 1.1–1.4 °C (Table 4), with greater values in the east sectors (Figure 5b), but without statistical significance.

Inside temperature increased drastically when outside wind speed overcame 8 m s^{-1} and the climatic control system closed greenhouse windows to avoid structural damage. We can observe this abrupt increase in temperature on 4 and 5 February (Figure 5a), 1 April (Figure 5b), and 18 June (Figure 5c). This is an important drawback in the climate control of multi-span greenhouse in Almería [54].

As a consequence of the small differences in the inside air temperatures produced by the whitening, values of relative air humidity were very similar between the east and west sectors of greenhouse 1 for the five periods where this parameter was analyzed (Table 3).

3.4. Plant Morphology

Reduction of PAR radiation at the lower leaves tends to limit plant growth, mainly in the winter periods, when the solar altitude and light at the canopy are low and day length is shorter than in summer [7]. Thus, the total length of the plant and the dimeter of the stem were reduced in the east sector of greenhouse 2 as a consequence of the use of the greater shading level in the autumn–winter cycle (Table 5).

No statistically significant differences were observed between the sectors of greenhouse 1 for all the morphological parameters of the plants measured in the first crop cycle (Table 5). In the same way, no statistically significant differences were observed between sectors of both greenhouses for the spring–summer cycle (Table 5). In agreement with our results, small reductions in PAR did not affect plant morphology [57]. The general lack of differences could be due to a low plant density (1 plant m^{-2}) and L_{AI} (Table 5). Another possible cause was that the whitening was applied to the cover in mid-August, corresponding with the transplant date, and was not renewed throughout the crop cycle after the rain washed the cover (1 October 2014).

Reduction of radiation intercepted by the crop can result in an increase in hypocotyl length and specific leaf area [16]. Cockshull et al. [17] also observed an increase of total plant length with the use of slight fixed shading treatments (beneath 23.4%), but without significant differences. At moderate shading level (30% shading), Abdel-Mawgoud et al. [38] observed an increase in plant length and leaf area, but not on the number of leaves. In the autumn–winter cycle, the length of the lowest internode and the stem diameter were statistically greater in the east sector with the greatest whitening concentration (Table 5). This may indicate that in the autumn–winter cycles, when whitening is only necessary at the beginning of the cycle, the prolonged use of excessive whitening (0.500 kg L^{-1}) can affect plant development.

Significant reductions of the biomass of the vegetative aerial parts (leaves and stems) and the total fruit biomass can be produced under strong shaded condition (70%) [67]. High shading conditions (above 60%) can produce higher values of leaf area and plant length, as observed in greenhouse 1 in the autumn–winter cycle, and a lower number of leaves [67]. The small differences observed in the climatic parameters (radiation and air temperature) produced by the change of the whitening concentration do not seem to significantly affect plant growth.

Table 5. Mean (±standard deviation) morphological parameters of the plants in both growing cycles in sectors with different whitening concentration C_{WH} (kg L^{-1}): Total length of the plant L_T (cm), number of nodes per plant N_N, length of the lowest internode L_I (cm), length of the highest internode H_I (cm), diameter of the stem D_S (mm), and leaf area index L_{AI} (m^2 m^{-2}).

Sector	C_{WH}	L_T	N_N	L_I	H_I	D_S	L_{AI}
			Autumn–Winter Cycle				
G1–East	0.125	191.9 ^{a} ± 83.2	14 ^{a} ± 4.0	9.5 ^{a} ± 2.4	7.1 ^{a} ± 2.5	11.5 ^{a} ± 2.0	1.2 ^{a} ± 0.5
G1–West	0.250	191.6 ^{a} ± 82.6	14 ^{a} ± 4.4	9.2 ^{a} ± 1.9	7.1 ^{a} ± 2.2	11.8 ^{a} ± 1.9	1.2 ^{a} ± 0.5
G2–East	0.500	188.6 ^{a} ± 81.9	14 ^{a} ± 4.2	9.8 ^{a} ± 2.3	6.4 ^{a} ± 2.2	11.5 ^{a} ± 1.9	1.1 ^{a} ± 0.5
G2–West	0.250	192.4 ^{a} ± 80.7	14 ^{a} ± 4.4	8.3 ^{b} ± 2.5	6.9 ^{a} ± 2.3	10.6 ^{b} ± 2.3	1.3 ^{a} ± 0.6
			Spring–Summer Cycle				
G1–East	Variable	186.3 ^{a} ± 75.2	12 ^{a} ± 2.0	12.8 ^{a} ± 5.3	8.3 ^{a} ± 3.6	14.1 ^{a} ± 3.0	0.9 ^{a} ± 0.2
G1–West	0.250	190.4 ^{a} ± 71.3	13 ^{a} ± 2.4	14.1 ^{a} ± 4.5	8.4 ^{a} ± 4.8	14.2 ^{a} ± 2.5	0.8 ^{a} ± 0.2
G2–East	Variable	169.2 ^{a} ± 64.8	11 ^{a} ± 2.0	12.5 ^{a} ± 3.7	6.4 ^{a} ± 3.3	14.5 ^{a} ± 3.1	0.9 ^{a} ± 0.3
G2–West	0.250	173.3 ^{a} ± 61.7	11 ^{a} ± 2.1	13.2 ^{a} ± 4.2	7.3 ^{a} ± 3.5	14.9 ^{a} ± 3.4	1.0 ^{a} ± 0.4

^{a,b} Values accompanied by different letters are significantly different at the 95.0% confidence level (p-value ≤ 0.05).

3.5. Photosynthetic Activity

The mean photosynthetic activity for the first crop cycle was slightly higher in the sectors with the least concentrated whitening. This can be a consequence of the statistically significant increase in the PAR incident on surface of plant leaves (Table 6).

Table 6. Average values (±standard deviation) of parameters measured in the plant leaves for different whitening concentration C_{WH} (kg L^{-1}): Photosynthetic rate P_A (μmol CO_2 m^{-2} s^{-1}), PAR incident on leaf surface Q_{PAR} (μmol m^{-2} s^{-1}), transpiration E_L (mmol H_2O m^{-2} s^{-1}), leaf temperature T_c (°C), sub-stomatal CO_2 concentration in the leaf C_O (ppm), and stomatal conductance of H_2O C_E (mol m^{-2} s^{-1}).

Sector	C_{WH}	P_A	Q_{PAR}	E_L	T_c	C_O	C_E
			Autumn–Winter Cycle				
G1–East	0.125	13.4 ^{a} ± 3.0	491.6 ^{b} ± 157.2	2.4 ^{a} ± 0.9	26.4 ^{a} ± 4.1	326.2 ^{a} ± 90.0	0.20 ^{a} ± 0.08
G1–West	0.250	13.1 ^{a} ± 3.4	432.3 ^{a} ± 153.6	2.3 ^{a} ± 0.7	26.7 ^{a} ± 2.3	323.2 ^{a} ± 87.5	0.20 ^{a} ± 0.07
G2–East	0.500	12.2 ^{a} ± 3.3	424.1 ^{a} ± 183.7	2.2 ^{a} ± 0.9	26.6 ^{a} ± 3.8	316.7 ^{a} ± 97.7	0.19 ^{a} ± 0.07
G2–West	0.250	13.6 ^{b} ± 3.4	502.2 ^{b} ± 199.8	2.5 ^{a} ± 1.0	27.2 ^{a} ± 3.4	311.2 ^{a} ± 99.6	0.20 ^{a} ± 0.07
			Spring–Summer Cycle				
G1–East	Variable	12.6 ^{b} ± 2.6	462.6 ^{b} ± 101.4	3.5 ^{a} ± 0.8	31.6 ^{a} ± 1.7	391.9 ^{b} ± 42.6	0.22 ^{a} ± 0.05
G1–West	0.250	11.6 ^{a} ± 2.1	468.1 ^{a} ± 78.1	3.5 ^{a} ± 0.7	31.3 ^{a} ± 1.9	376.7 ^{a} ± 21.8	0.23 ^{a} ± 0.05
G2–East	Variable	12.3 ^{b} ± 2.5	458.3 ^{b} ± 131.6	3.2 ^{a} ± 0.6	31.4 ^{b} ± 1.8	378.0 ^{a} ± 8.9	0.20 ^{a} ±0.05
G2–West	0.250	11.02 ^{a} ± 1.6	338.9 ^{a} ± 44.6	3.2 ^{a} ± 0.6	30.3 ^{a} ± 1.9	374.2 ^{a} ± 20.1	0.23 ^{b} ± 0.05

^{a,b} Values accompanied by different letters are significantly different at 95.0% confidence level (p-value ≤ 0.05).

This difference in the photosynthetic activity was statistically significant in greenhouse 2. The increase of the concentration to 0.500 kg L^{-1} in the east sector reduced the transmissivity of the cover (Table 2) and the PAR incident on leaf surface (Table 6). This reduction conducted to lower values of photosynthesis than in the west sector along all the growing cycle (Figure 6b).

The evolution of the photosynthetic activity in the spring–summer crop cycle was clearly influenced by the dose of ASP administered to each experimental sector (Figure 5a,b). At the beginning of the cycle, photosynthetic activity was superior in the east sectors of both greenhouses with the variable dose. At this period, the applied concentration of 0.125 kg L^{-1} was lower than that of the sector with the control treatment (Figure 6c,d). At the end of May, when the variable dose was the same as that in the control (period 6), photosynthetic activity was very similar in both sectors (Figure 6c,d). At the end of the crop cycle, photosynthetic activity was lower in the east sector as a consequence of the increase of the whitening concentration (Figure 6c,d).

Shading of 40% can decrease significantly the stomatal conductance and transpiration [68], and roof whitening can significantly reduce temperatures and the rate of transpiration at times of higher radiation [52]. However, crop transpiration did not present any significant differences between sectors with different whitening level (Table 6), in agreement with the similar values of mean air temperature and relative humidity recorded inside greenhouse 1 (Table 3).

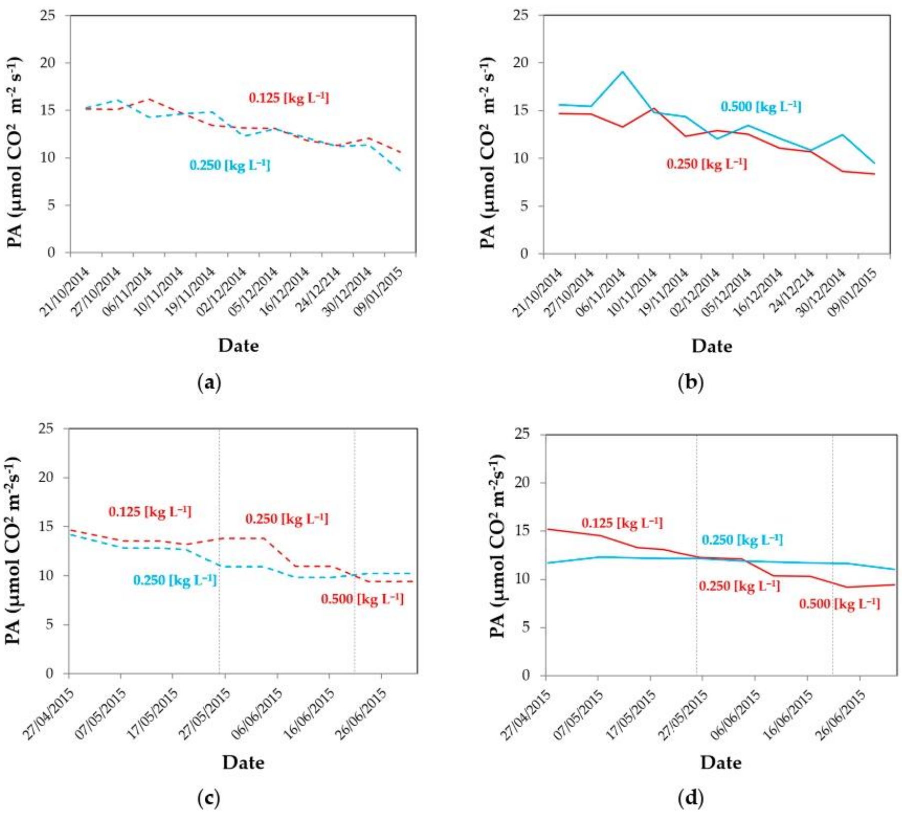

Figure 6. Evolution of photosynthetic activity PAR in the autumn–winter crop cycle (**a**,**b**) and the spring–summer crop cycle (**c**,**d**). West sector in greenhouses 1 (- - -) and 2 (—) with the control concentration of 0.250 kg L^{-1} in both crop cycles and east sector in greenhouses 1 (- - -) and 2 (—) with different doses. Date of the change of dose in the variable treatment (·····).

The whitening of the cover of an *Almería*-type greenhouse reduced the transitivity to τ_S = 0.40–0.47, causing increase in transpiration and reduction of leaves temperature [69]. Baille et al. [45] also observed how the use of the whitening (reducing transitivity of the cover from τ_S = 0.62–0.31), resulting in an increase on the transpiration rate (about 18%) and a reduction on temperature difference between plants and air (from 3 to −2 °C). According to Stanghellini [70], only half of the available solar energy on the crop can be intercepted and absorbed by the leaves of canopy plants with a foliar area index $L_{AI} < 2$ m^2 m^{-2} [71]. For high levels of solar radiation, the absorbed energy exceeds the latent heat, resulting in an increase in the temperature of the crop [70,72]. Transpiration increases non-linearly with increased solar radiation as a result of the opening of stomata caused by light [72]. Any statistical difference was observed in the plant transpiration (Table 6).

In agreement with the non-significant differences recorded in air temperature inside the greenhouse (Tables 3 and 4), leaf temperature only presented a significant difference in the spring–summer cycle inside greenhouse 2. Reduction of whitening concentration in autumn–winter produced an increase in PAR that affected positively enhancing photosynthesis without significant effects on temperature and stomatal conductance (Table 6).

3.6. Fruit Quality

Solar radiation and temperature conditions can have important effects in fruit development and quality. Day/night temperatures influence gas exchange in tomato plants, with the best temperature regime for net photosynthesis at 28/20 °C [73]. In the first crop autumn–winter cycle, the fruits of the sectors with the most concentrated whitening doses presented lower diameters, with statistically significant differences in both greenhouses (Table 7). Furthermore, this growth in the tomato fruit size was complemented by an increase in the weight, being statistically significant in greenhouse 1 (Table 7). The increase in cover transmissivity produced when the dose of whitening was reduced seemed to have a positive effect in fruit development. However, the reduction of maximum temperatures produced by the increase of the whitening at the beginning of the crop cycle (Tables 3 and 4) did not affect the fruit quality (Table 7). Fruit development seems to be more influenced by the availability of PAR and the consequently greater photosynthetic activity (Table 6).

For the spring–summer crop cycle, only a significant difference was observed in the fruit diameter, that was greater in the east sector with the variable dose of whitening (Table 7). This higher value of the average size of the tomato in the east sector (in agreement with a non-significant increase in the weight) can be related to the higher value of the photosynthetic activity during the major part of the cycle (Figure 6c).

Table 7. Mean (±standard deviation) quality parameters of fruit produced in both growing cycles in sectors with different whitening concentration C_{WH} (kg L^{-1}): Weight W_F (g), equatorial diameter D_F (mm), total soluble solids content T_{SS} (°Brix), firmness F_F (kg cm^{-2}), acidity level in the juice pH and dry matter D_M (%).

Sector	C_{WH}	W_F	D_F	T_{SS}	F_F	pH	D_M
			Autumn–Winter Cycle				
G1–East	0.125	117.4 ^{b} ± 15.7	62.9 ^{b} ± 3.1	4.3 ^{a} ± 0.6	2.5 ^{a} ± 0.8	4.1 ^{a} ± 0.1	6.5 ^{a} ± 0.8
G1–West	0.250	111.4 ^{a} ± 16.9	61.9 ^{a} ± 3.6	4.4 ^{a} ± 0.5	2.7 ^{b} ± 1.1	4.0 ^{a} ± 0.1	6.5 ^{a} ± 0.9
G2–East	0.500	114.7 ^{a} ± 14.4	62.1 ^{a} ± 5.1	4.4 ^{a} ± 0.5	2.8 ^{a} ± 0.8	4.1 ^{a} ± 0.1	6.4 ^{a} ± 0.8
G2–West	0.250	117.9 ^{a} ± 15.7	63.1 ^{b} ± 2.9	4.5 ^{a} ± 0.5	3.0 ^{b} ± 0.9	4.1 ^{a} ± 0.1	6.6 ^{a} ± 0.9
			Spring–Summer Cycle				
G1–East	Variable	282.3 ^{a} ± 59.1	87.0 ^{b} ± 7.7	4.6 ^{a} ± 0.4	1.7 ^{a} ± 0.5	4.1 ^{a} ± 0.2	6.2 ^{a} ± 1.1
G1–West	0.250	265.2 ^{a} ± 78.9	84.3 ^{a} ± 9.1	4.6 ^{a} ± 0.5	1.8 ^{a} ± 0.6	4.1 ^{a} ± 0.1	6.2 ^{a} ± 1.5
G2–East	Variable	277.6 ^{a} ± 75.9	85.9 ^{a} ± 9.8	4.5 ^{a} ± 0.4	2.7 ^{a} ± 0.6	4.0 ^{a} ± 0.1	6.2 ^{a} ± 1.3
G2–West	0.250	285.1 ^{a} ± 81.3	87.0 ^{a} ± 10.3	4.6 ^{a} ± 0.4	2.8 ^{a} ± 0.7	4.0 ^{a} ± 0.2	6.3 ^{a} ± 1.6

^{a,b} Values accompanied by different letters are significantly different at the 95.0% confidence level (p-value ≤ 0.05).

The level of whitening did not produce any statistically significant difference in other parameters of quality as the total soluble solids content, the acidity level, and the dry matter (Table 7). Although, the restriction of the solar radiation intensity, using excessive permanent shading, can reduce tomato growth and yield, fruit quality seems to be less sensible [74]. Final fruit composition and sugars and acids contents (linked to fruit gustative quality) were not considerably modified by fruit temperature and intercepted radiation [75]. However, Callejón-Ferre et al. [49] found a significant increase of fruit firmness when shading was above 40%. In the same way, the total soluble solids in fruit diminished when the shading level augmented from 40% to 60% [49]. Aroca-Delgado et al. [57] reported a decrease in diameter of tomato fruit as a consequence of the shading caused by the installation of flexible photovoltaic panels on the greenhouse roof, without significant effect on the firmness and pH. In our case, variation of about 10% of transmissivity between treatments (Table 2) did not affect the quality parameter of fruits as total soluble solids content and pH (Table 7).

Temperature had an indirect influence on plant growth, while incoming solar radiation presented a direct influence [76]. Newton et al. [48] observed a negative linear relationship between truss weight of tomato fruits and mean temperature during the truss growth for one variety (Solairo), and also a linear relationship between yield and cumulated solar radiation for other varieties. Different varieties can have diverse sensitivity to the increase of solar radiation and temperature.

3.7. Tomato Production

A reduction of temperature and solar radiation using shading of about 35%–40% can produce increases in tomato yield, with no increase or decrease in production when shading intensity overcomes these values [37,73,77]. In some cases, the reduction of temperature produced by a shade of 30% did not affect tomato fruit yield [53]. In the first crop cycle, marketable production was 3.8%–5.9% higher in the sectors with the least concentrated whitening (Table 8). Similar differences were also observed for the total production. These differences represent loss in production of 0.8%–1% for a reduction of 1% in the cover transmissivity, in agreement with the values reported in bibliography [17,18]. In the second crop cycle, marketable productions were higher in the west sector with the control concentration (0.250 kg L^{-1}), with an increase of 22.6% in greenhouse 1 and only 2.1% in greenhouse 2.

Table 8. Mean (±standard deviation) marketable Y_M and total yield Y_T (kg m^{-2}) of tomato in both growing cycles in sectors whit different whitening concentration C_{WH} (kg L^{-1}). Increase of production for marketable ΔY_M and total yield ΔY_T (%).

Sector	C_{WH}	Y_M	Y_T	ΔY_M	ΔY_T
		Autumn–Winter Cycle			
Greenhouse 1–East	0.125	5.95 ± 0.41	6.08 ± 0.44	+3.8	+4.3
Greenhouse 1–West	0.250	5.73 ± 0.32	5.83 ± 0.31		
Greenhouse 2–East	0.500	6.29 ± 0.40	6.37 ± 0.40		
Greenhouse 2–West	0.250	6.66 ± 0.40	6.80 ± 0.41	+5.9	+6.7
		Spring–Summer Cycle			
Greenhouse 1–East	Variable	4.16 ± 0.30	6.04 ± 0.36		
Greenhouse 1–West	0.250	5.10 ± 0.29	6.74 ± 0.33	+22.6	+11.6
Greenhouse 2–East	Variable	5.31 ± 0.20	6.30 ± 0.23		
Greenhouse 2–West	0.250	5.42 ± 0.33	6.30 ± 0.33	+2.1	

As a consequence of the reductions observed in cover transmissivity τ_s (Table 2), in the PAR radiation inside the greenhouses R_{PARi} (Table 3) and incident on leaf surface Q_{PAR} (Table 6), the photosynthetic activity P_A decreased (Table 6) when the whitening dose was augmented. This reduction in the photosynthetic activity negatively affected the growth of tomato fruit, reducing the size and/or weight (Table 7), that finally resulted in a lower tomato production (Table 8).

The evolution of the production during the spring–winter cycle in greenhouse 1 (Figure 7a) shows how marketable yield in the east sector, with a lower concentration of whitening (0.125 kg L^{-1}), increased in the month of January, when the lowest temperatures were recorded in the greenhouses (Table 3). However, in greenhouse 2, the augmentation from the control concentration in the west sector to double (0.500 kg L^{-1}) in the east sector caused a continuous reduction of production from the first date of yield, generating a considerable loss of production (Figure 7b).

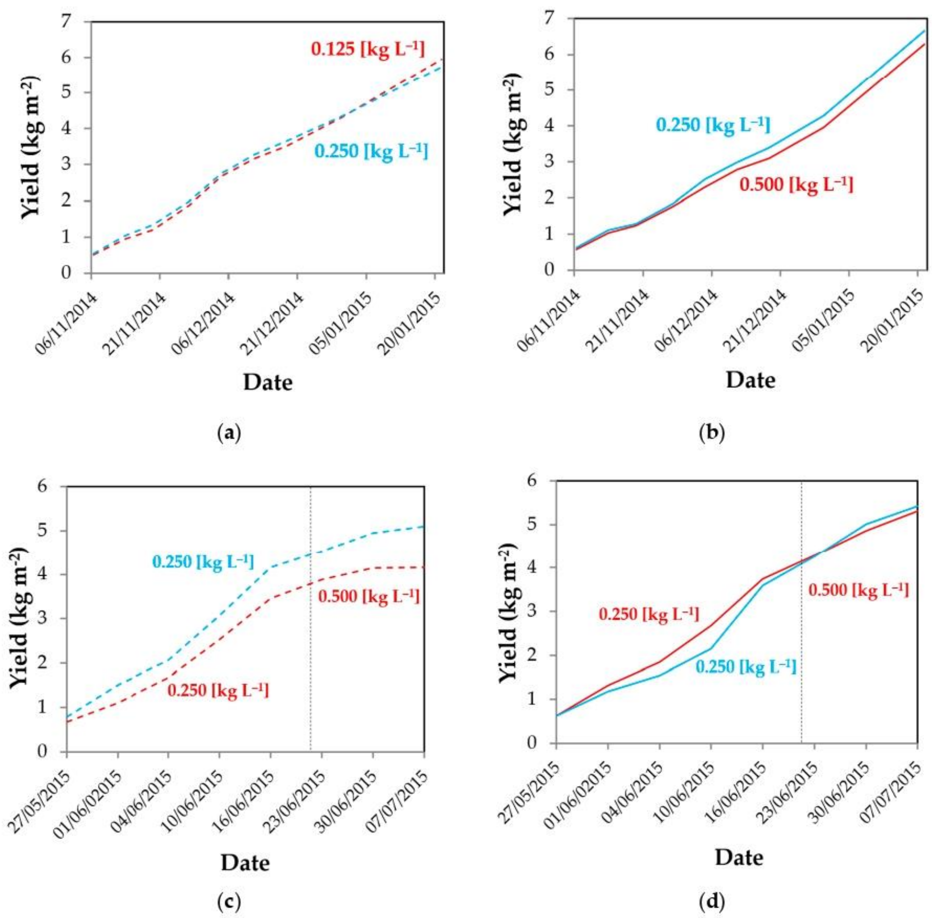

Figure 7. Evolution of tomato marketable production in the autumn–winter crop cycle (**a**,**b**) and the spring–summer crop cycle (**c**,**d**). East sector in greenhouses 1 (- - -) and 2 (—) with different concentrations and west sector with the control concentration of 0.250 kg L^{-1} in both crop cycles in greenhouses 1 (- - -) and 2 (—). Date of the change of concentration in the variable treatment (·····).

In the spring–summer cycle, production was lower inside the east sector from the first yield date, resulting in a big difference of production at the end of the season (Figure 7c). However, in greenhouse 2 (Figure 7d), production was initially greater in the east sector (with the lower dose, 0.125 kg L^{-1}). The superior photosynthetic activity observed at the beginning of the cycle increased yield (Figure 6d). The effect of photosynthesis on yield is delayed in the time. An increase of the photosynthetic photon flux density for one week can result in augmentation of yield for a period of 4–6 weeks after the start of the treatment in tomato [78]. At the end of the cycle, the increase of the concentration in the east sector (0.500 kg L^{-1}), reversed the order of all parameters, reducing PAR transmissivity, photosynthetic activity (Figure 6d), and production (Figure 7d).

The increase of the radiation intercepted by plant leaves can rise tomato yield of crops with a high plant density [6]. Although the total yield can be reduced linearly with the augmentation of shading [17,79], positive effects can be produced in the yield of marketable fruit. Shading can diminish the incidence of blossom-end rot (BER) in tomatoes [38] and, as a consequence, reduce the non-marketable yield [51]. The main drawback of cover whitening against other passive or active cooling methods (i.e., external/internal net shading, fog) is that it may negatively affect the photosynthetic rate, crop growth, and production, as it reduces light in hours when it is not in excess.

The small reduction in PAR caused using flexible photovoltaic panels on the greenhouse roof did not produce a significant effect on the total and marketable yield [57]. Results of the present work show a negative effect when the shading level was increased for all data analyzed (Figure 7), indicating that in our test conditions (greenhouses well ventilated and production period stopped before extreme temperatures in the summer), reduction of photosynthesis had more importance that a possible reduction of BER incidence.

When greenhouses present an insufficient capacity of natural ventilation, whitening is adopted as the standard practice with problems of heterogeneity and severe reductions in PAR radiation that diminish the assimilation potential of crop species with high light saturation [51]. The flow of photosynthetic activity is more uniform under the influence of a shading screen than under whitening [80], which may suggest a large spatial variation in light uniformity.

The behavior of the parameters analyzed throughout this work can be conditioned by, in addition to the dose applied, the method of application, the climatic conditions and the time of year. Furthermore, as the whitening is applied by hand, the amount of product retained in the greenhouse cover will also depend on the capacity of the applicator [55].

A high whitening concentration (0.500 kg L^{-1}) positively affected the greenhouse climate in the first days after crop transplant, reducing the number of days where air temperature overcoming 37 °C. However, this concentration produced negative effects increasing plant growth (stem diameter and internode length) and reducing photosynthetic activity and tomato yield.

4. Conclusions

The effect of three concentrations of an agricultural solar protector (0.125 kg L^{-1}, 0.250 kg L^{-1}, and 0.500 kg L^{-1}) used for the whitening of greenhouse covers on the microclimate and production and growth of two tomato crops in two greenhouses has been analyzed in this work. From the results obtained, the following practical conclusions can be drawn for growers and technicians:

1. Increase of the whitening dose reduced the transmissivity of the roof, decreasing the extreme maximum temperatures at the beginning of the autumn–winter cycle and reducing photosynthesis along the rest of the year. We recommend a dose of 35 g m^{-2} (concentration of 0.500 kg L^{-1}) for the beginning of the crop cycle in the month of August.

2. As a result of the lower levels of photosynthesis caused by increased whitening in the autumn–winter cycle, significant production losses were observed, about 0.8%–1% for every 1% reduction in the transmissivity. We recommend washing the cover in the middle of September when the maximum inside temperature is inferior to 35 °C.

3. The use of a variable dose throughout the spring–summer cycle was not effective against the use of a constant dose (0.250 kg L^{-1}), because the negative effect of photosynthesis reduction caused by the use of the higher dose (0.500 kg L^{-1}) at the end of the cycle was greater than the positive effect produced at the start of the cycle with a lower dose (0.125 kg L^{-1}). We recommend a dose of 15 g m^{-2} (0.125 kg L^{-1}) at the end of the spring when the inside temperature exceeds 35 °C.

4. In general, no major variations in crop growth or fruit quality parameters were observed; the exception to this was the size of the fruits, which was significatively reduced with the increase in the whitening dose, causing important loss of production (4%–5%).

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Capítulo 3

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

Resumen

El uso eficiente de la luz es uno de los factores más importantes para el desarrollo de los cultivos en invernadero. Cada vez es más necesario el uso de cubiertas plásticas que incrementen la transmisividad y la proporción de luz difusa generando una distribución de la luz más homogénea. El objetivo de este estudio fue evaluar el efecto que ejerce una cubierta plástica experimental con alta transmisividad y elevada difusividad lumínica frente a una cubierta plástica térmica comercial sobre el microclima y comportamiento agronómico de un cultivo de tomate (*Solanum lycopersicum* L.). El ensayo se desarrolló durante un ciclo de cultivo de primavera-verano en un invernadero tipo multitúnel dividido en dos compartimentos, separados por una lámina vertical de plástico. En el lado Este se instaló un plástico comercial (transmisividad del 85% y difusividad del 60%) y en el lado Oeste se utilizó el plástico experimental (transmisividad del 90% y difusividad del 55%). Los resultados del cultivo muestran un aumento de la producción comercial de 0.25 kg m^{-2} en el sector del invernadero con plástico de cubierta experimental, lo que supuso un incremento del 3.2%. La actividad fotosintética medida en las hojas fue un 21.5% mayor en las plantas cultivadas en el sector con plástico de cubierta de mayor transmisividad. El aumento de un 14% de la transmisividad a la radiación que generó una mayor actividad fotosintética se consiguió sin generar una mayor temperatura del aire interior a nivel del cultivo (2 m). Sin embargo, la temperatura media de la superficie del suelo fue estadísticamente superior en el lado con la cubierta plástica difusa, como consecuencia lógica de la mayor radicación solar interceptada.

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

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

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

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1. Introduction

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

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

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

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

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

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

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

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

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

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

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

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

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

2. Materials and Methods

2.1. Description of the Experimental Greenhouse

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

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

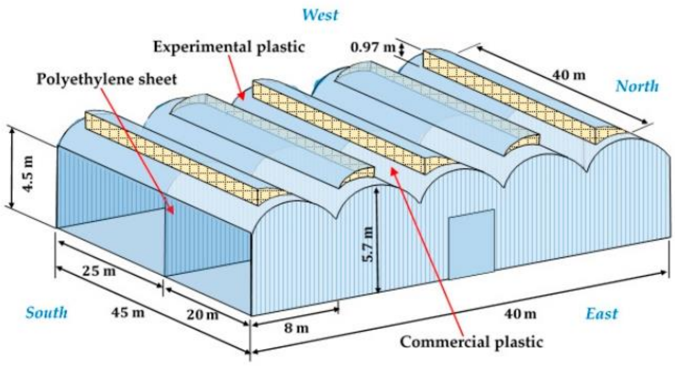


Figure 1. Greenhouse with diffuse commercial film in the East sector and greenhouse with diffuse experimental film in the West.

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

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

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

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

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

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

2.2. Microclimate Measurement Equipment

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

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

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

2.3. Crop System

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

2.4. Measurement Equipment for Crop Development and Yield Analysis

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

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

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

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

2.5. Measurement of Photosynthetic Activity

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

2.6. Statistical Analysis

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

3. Results and Discussion

3.1. Microclimatic Conditions

3.1.1. Radiation Measurements

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

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

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

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

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

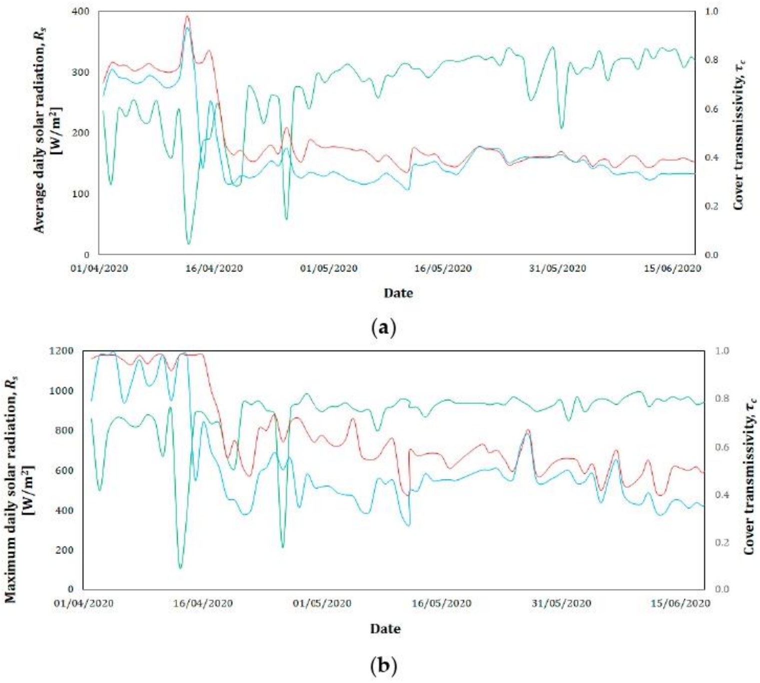


Figure 2. Evolution of solar radiation outside the greenhouse (——) and cover transmittance inside the East sector with diffuse commercial film (——) and inside the West sector with diffuse experimental film (——). Average values (**a**) and maximum (**b**) daily values.

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

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

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

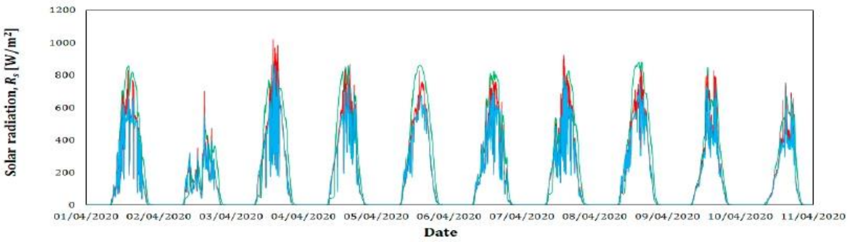
Under these circumstances, the transmittance of the cover was affected, resulting in a reduction in the radiation and transmittance difference of 13–14%. In spring–summer when cloudiness is almost non-existent in Almeria, the proportion of direct solar radiation increases considerably, and this was found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

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

3.1.2. Air Temperature

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

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



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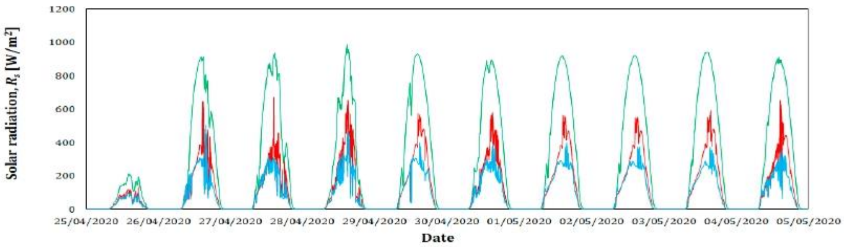

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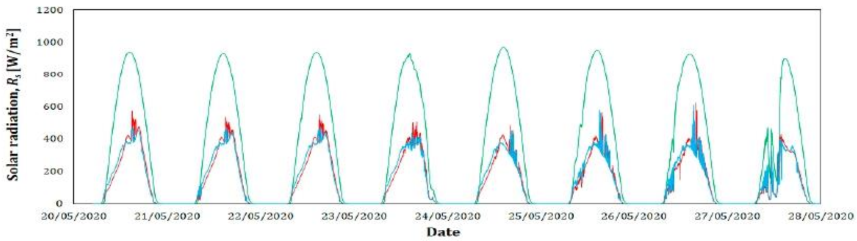

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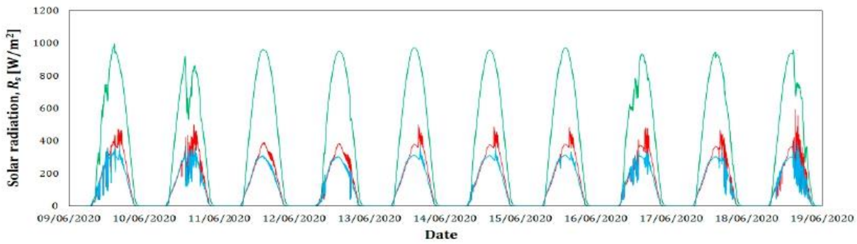


(**d**)

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

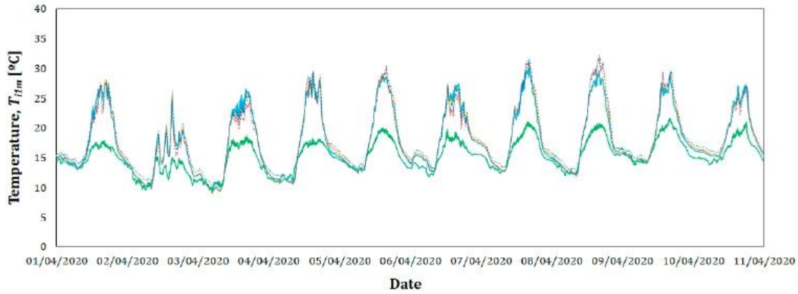
Table 4. Average, maximum, and minimum air temperature values measured at heights of 1, 2, and 4.5 m above the floor in the north and south areas of the two sectors of the greenhouse.

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

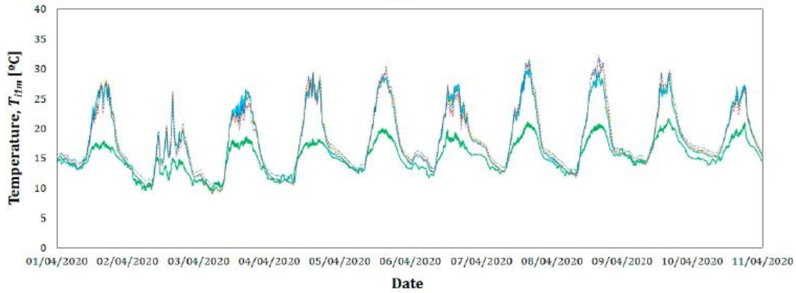
Values with different letters in the same column show statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

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

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



(**a**)



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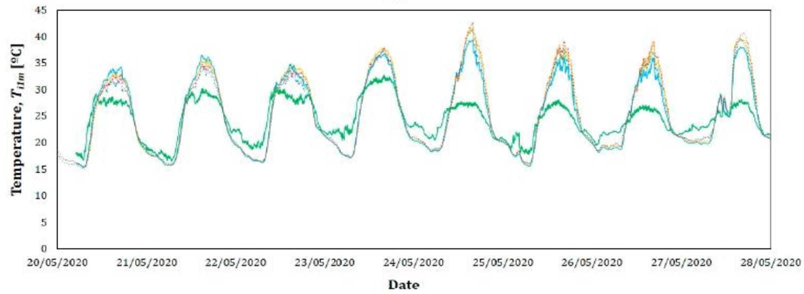

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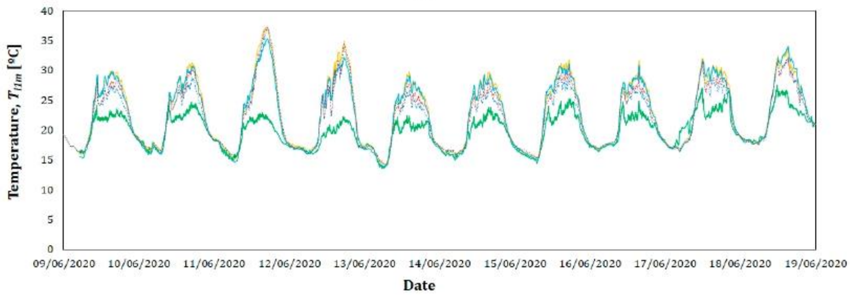
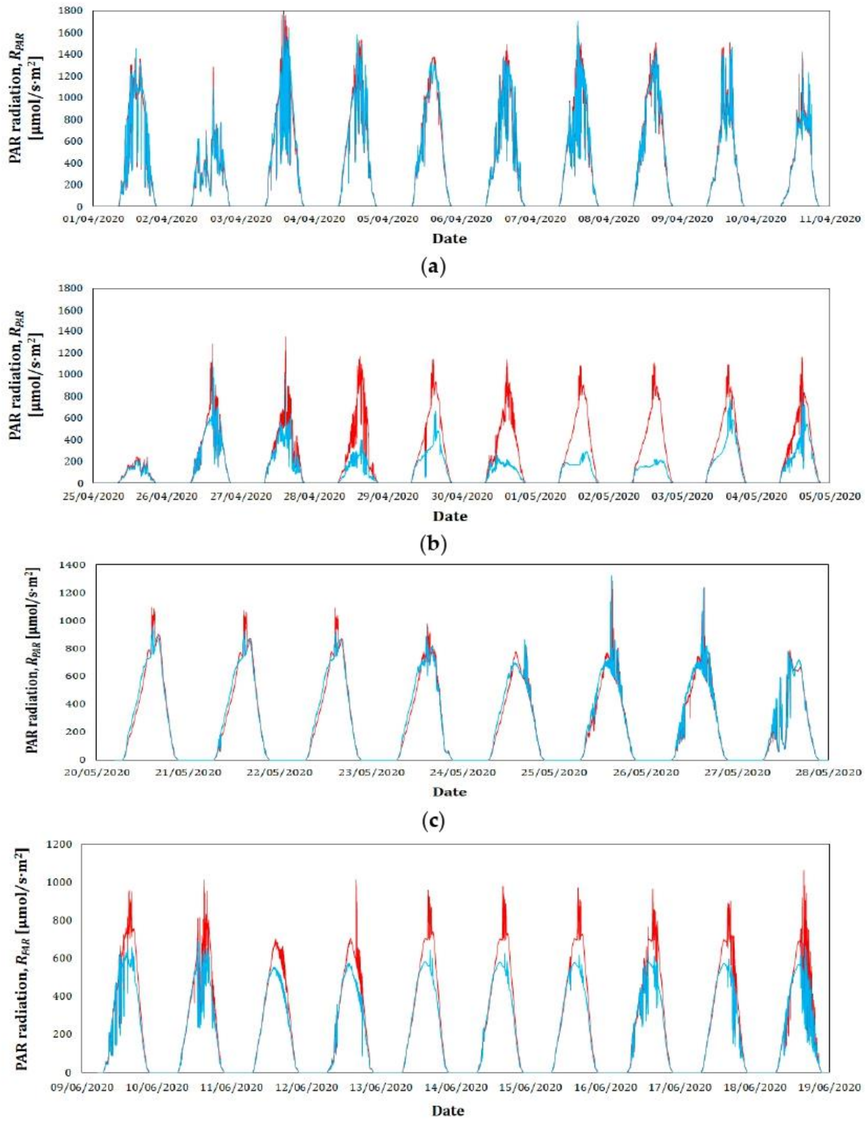


(**d**)

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



(**a**)

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

3.1.3. Crop Temperature

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

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

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

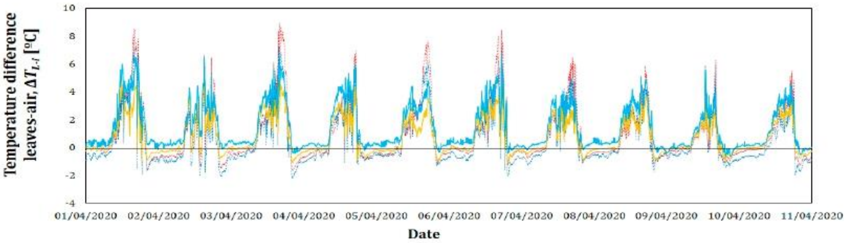
Values with different letters in the same column show statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

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

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

3.1.4. Soil Temperature

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



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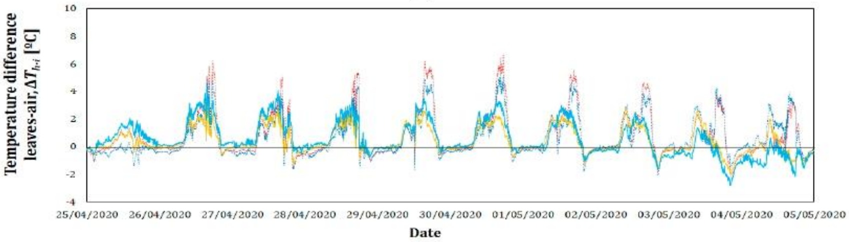

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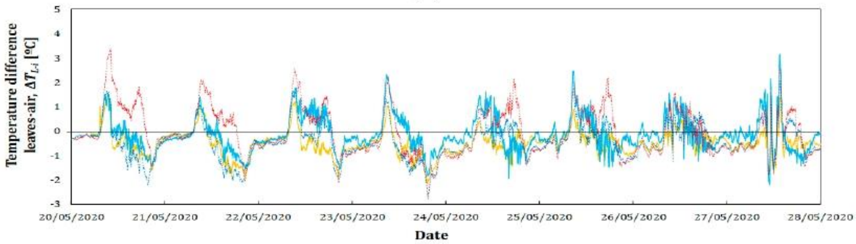

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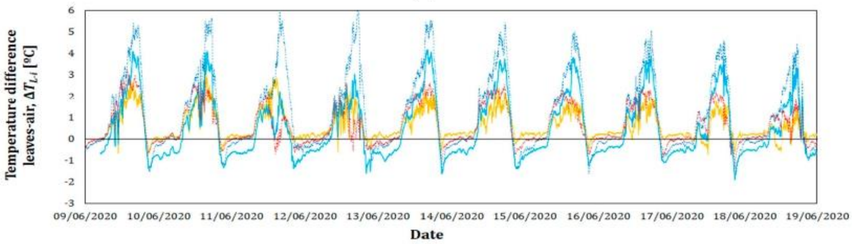

(**d**)

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

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

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

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

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

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

3.1.5. Soil Heat Flux

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

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

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

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

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

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

3.1.6. Air Humidity

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

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

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

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

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

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

3.2. Photosynthetic Activity

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

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

Table 9. Average values of the measurements made on the leaves of plants grown in the two greenhouse sectors with different cover films. Photosynthetic activity P_A [μmol CO_2 $m^{-2} \cdot s^{-1}$], radiation Q_{PAR} [μmol m^{-2} s^{-1}], leaf temperature T_L [°C], concentration of CO_2 C_O [ppm], transpiration E_L [mmol $m^{-2} \cdot s^{-1}$], and stomatal conductivity C_E [mol $m^{-2} \cdot s^{-1}$].

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

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

3.3. Plant Morphology

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

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

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

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

3.4. Fruit Quality

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

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

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

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

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

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

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

Greenhouse Sectors	L^*	a^*	b^*	a^*/b^*
East—Commercial diffuse film	43.1 [b] ± 2.2	21.1 [a] ± 4.2	18.8 [a] ± 2.3	1.13 [a] ± 0.2
West—Experimental diffuse film	42.4 [a] ± 2.1	21.8 [a] ± 3.8	19.1 [a] ± 2.8	1.17 [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).

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

3.5. Tomato Production

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

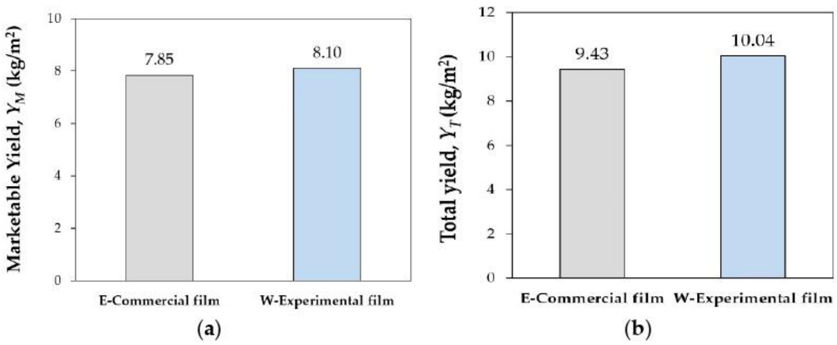

Figure 7. Marketable yield (**a**) and total yield (**b**) of tomato crops in the East sector with diffuse commercial cover film (■) and in the West sector with diffuse experimental cover film (■).

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

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

4. Conclusions

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

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

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

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

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

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

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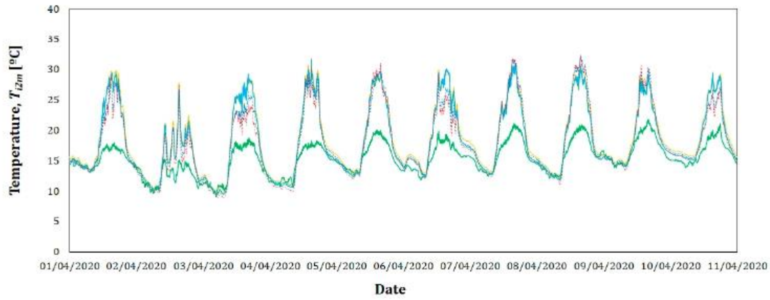
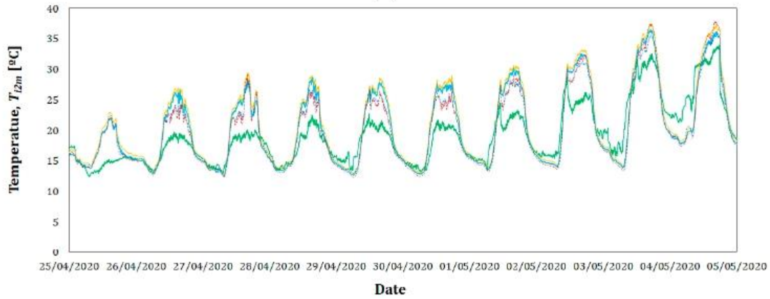
Table S1. Characteristics of all sensors used for the microclimate measurements.

Parameter	Sensor	Manufacturer	Rank	Accuracy
		Outside climatic parameters measured at the weather station		
R_0—Outside solar radiation	Kipp Solari—MII	HortiMax B.V. (Maasdiijk, Holland)	±2000 W m^{-2}	±20Wm^{-2}
U_o—Wind speed	Anemometer—MII		0—40 m s^{-1}	±5%
θ_w—Wind direction	Vane Meteostation II		0—360°	±5°
T_e—Outside temperature	Pt1000 IEC 751 1/3B	Vaisala Oyj	–25 to 75 °C	±0.2 °C
HR_e—Outside humidity	HUMICAP HMT100	(Helsinki, Finland)	0—100%	±2.5%
Data storage system	MultiMa Series II	HortiMax B.V.	Software Synopta	
		Inside climate parameters measured by the climate control system		
T_i—Inside temperature	Pt1000 Class B—EE210	Eleltronik Ges. M.b.H.	–10 to 60 °C	±0.5 °C
HR_i—Inside humidity	EE210	(Engerwitzdor, Austria)	0—100%	±2.3%
R_i—Inside solar radiation	Pyranometer SP-212	Apogee Instruments, Inc (Logan, USA)	0—2000 W m^{-2}	±5%
		Inside climate parameters		
R_{Si}—Inside solar radiation	2× Pyranometers SP1110	Campbell Scientific Spain	350—1100 nm	±5%
Q_{Si}—Inside PAR radiation	2 × SKP215 Quantum Sensor	(Barcelona, Spain)	400—700 nm	±5%
T_i—Inside air temperature	12 × HOBO® Pro Temp-HR U23-001	Onset Computer Corp. (Pocasset, USA)	–4 to 70 °C	±0.18 °C
HR_i—Inside relative humidiy			0—100%	±2.5%
T_i—Inside air temperature	12 × CS215 Sensirion SHT75	Sensirion AG. (Staefa, Swizerland)	–40 to 70 °C	±0.4°C
HR_i—Inside relative humidity		Campbell Scientific Spain (Barcelona, Spain)	0—100%	±2%
T_C—Crop temperature	8 × Thermistances Betatherm 100K6A		–5 to 95 °C	±0.16 °C
T_2—Soil temperature				
q_s—Heat flux in the soil	2 × HFP01	Hukseflux Thermal Sensors B.V. (Delft, Holland)	±2000 W m^{-2}	–15 to 5%
C_h—CO_2 concentration	LCi-SD photosynthesis analyser	ADC BioScientific Ltd. (Hertfordshire, UK)	0—2000 ppm	1 ppm



(a)



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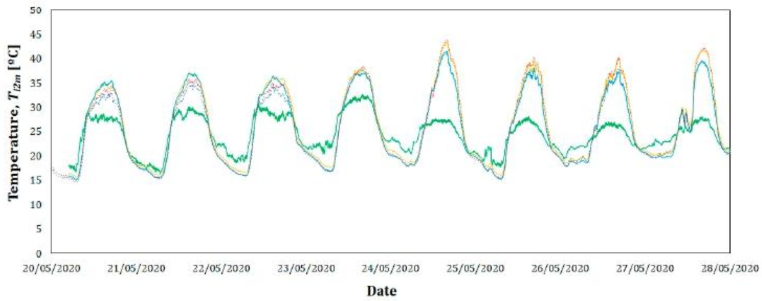

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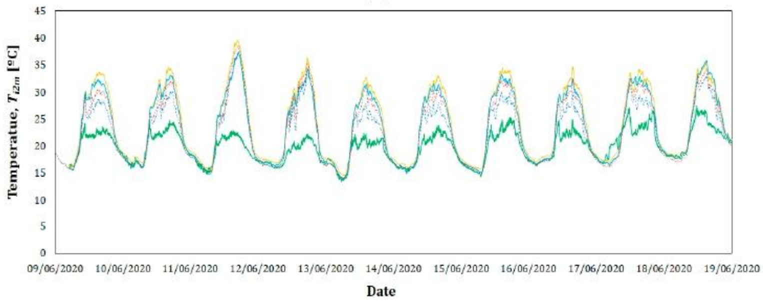
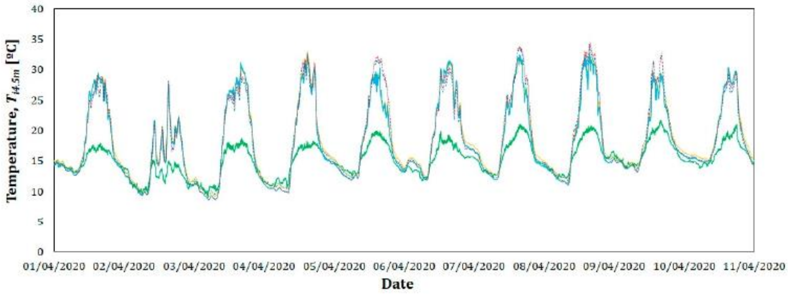
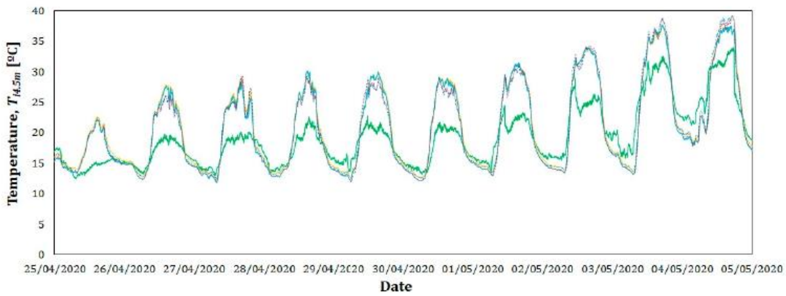


(d)

Figure S1. Evolution of the air temperature outside (—) and inside the East sector with diffuse commercial cover film on the North (—) and South (- - -) sides and inside the West sector with diffuse experimental cover film on the North (—) and South (- - -) sides at a height of 2 m above the floor.



(a)



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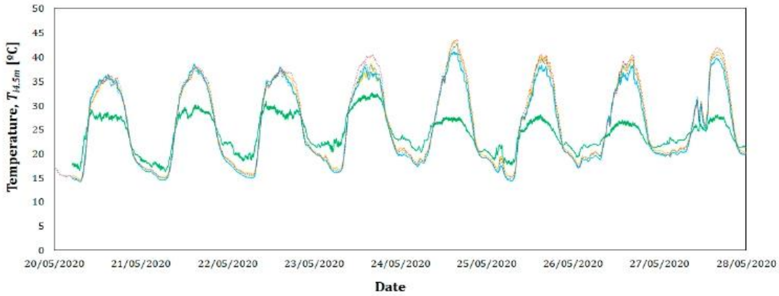

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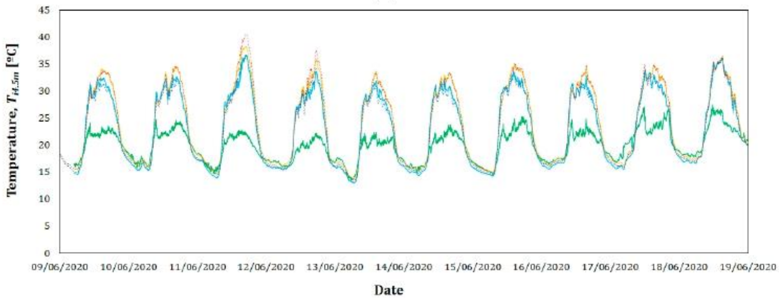
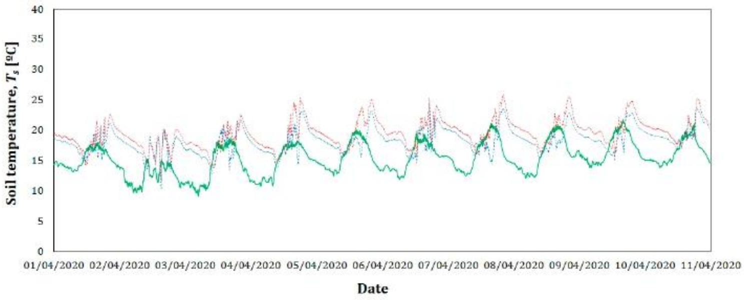


(d)

Figure S2. Evolution of air temperatures outside (——) and inside the East sector with diffuse commercial cover film on the North (——) and South (- - -) sides and inside the West sector with diffuse experimental cover film on the North (——) and South (- - -) sides at a height of 4.5 m above the floor.



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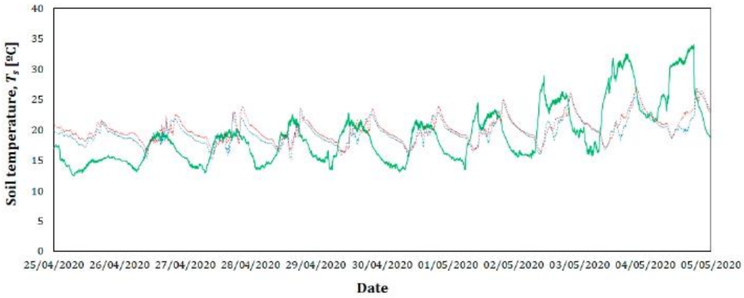

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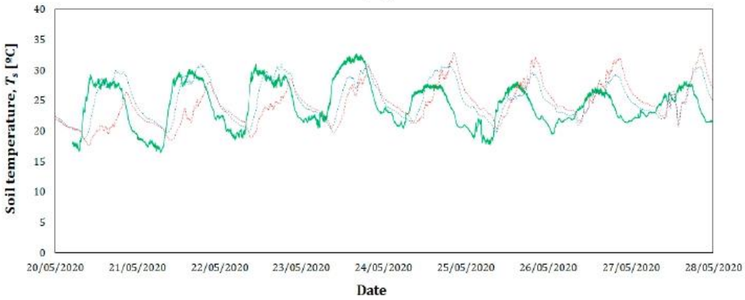

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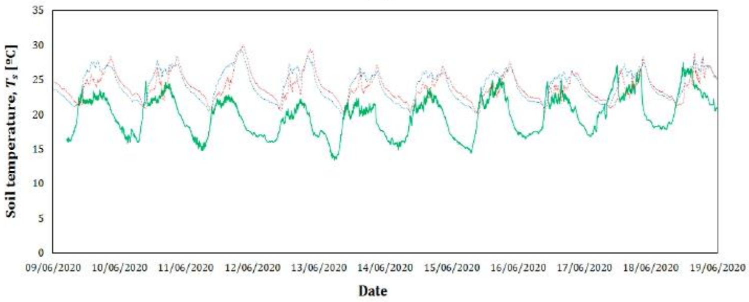


(d)

Figure S3. Evolution of the outside air temperature (——) and soil surface temperature in the center of the East sector with diffuse commercial cover film (- - -) and in the West sector with diffuse experimental cover film (- - -).

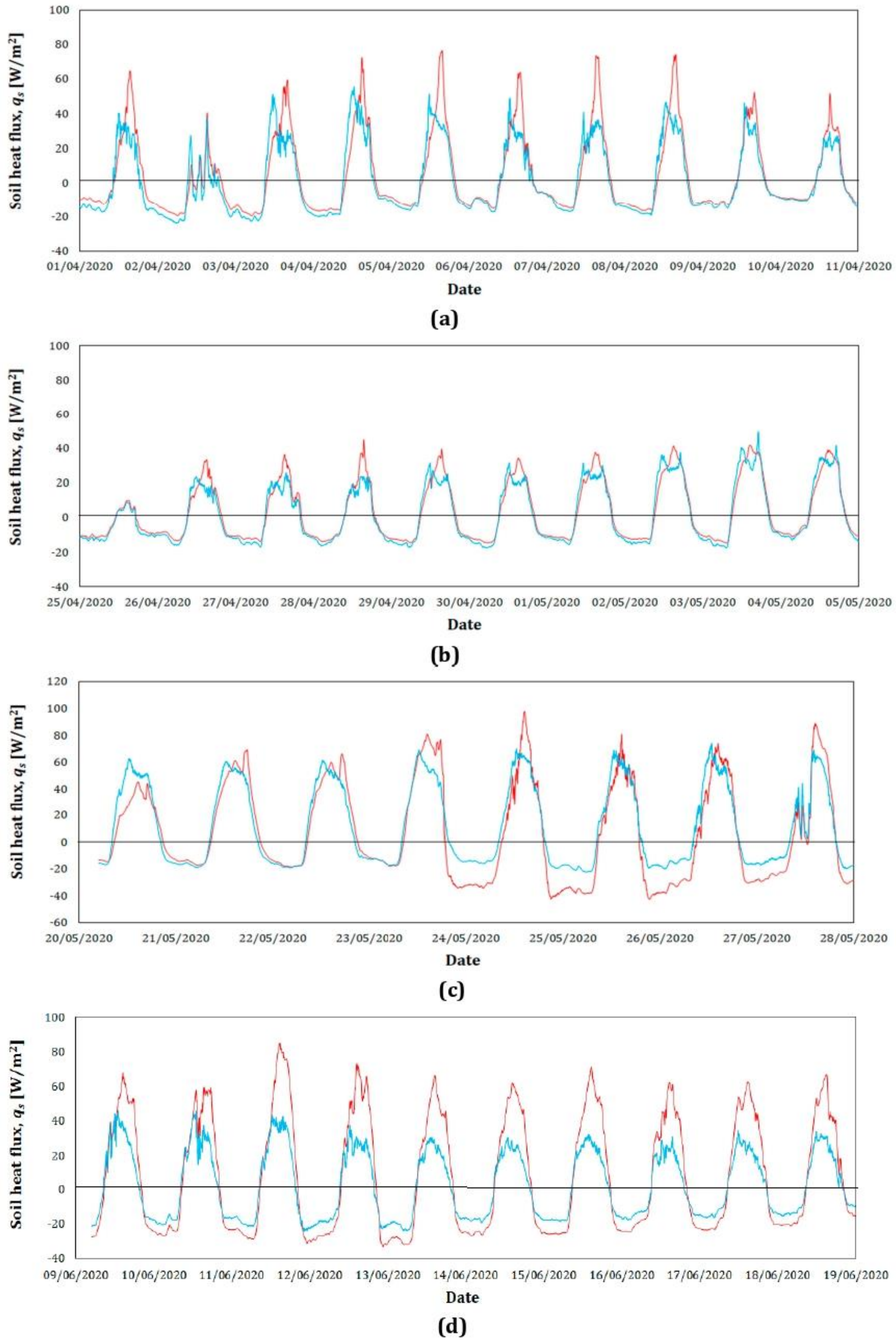
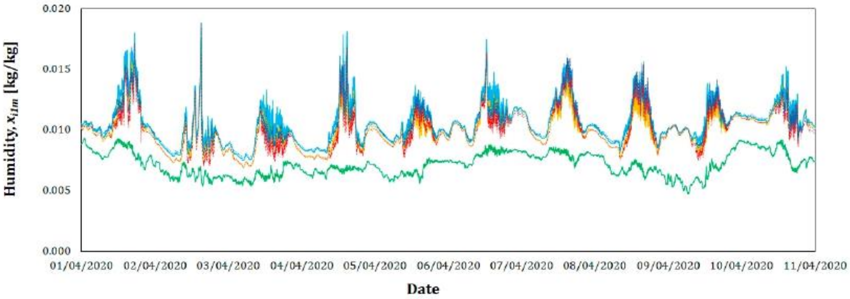


Figure S4. Evolution of the soil heat flux in the center of the East sector with diffuse commercial cover film (- - -) and in the West sector with diffuse experimental cover film (- - -).



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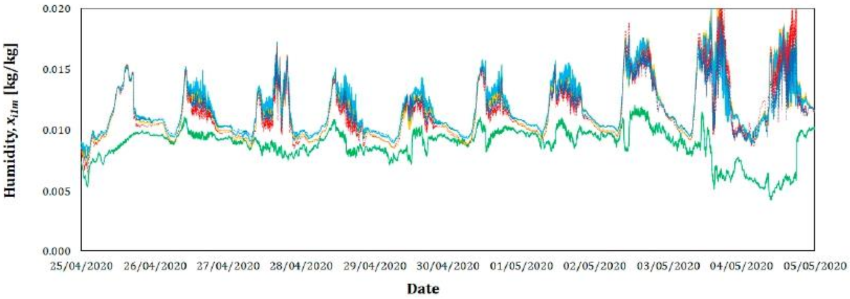

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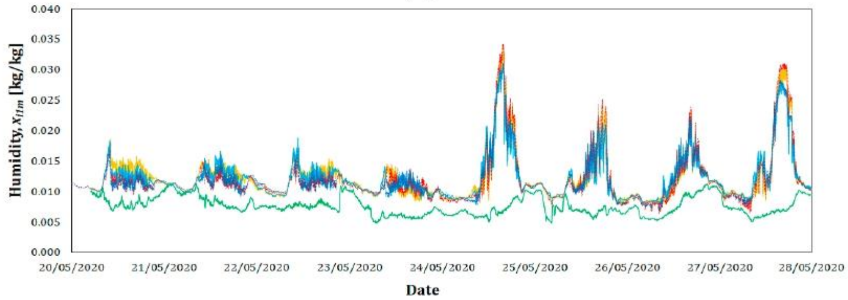

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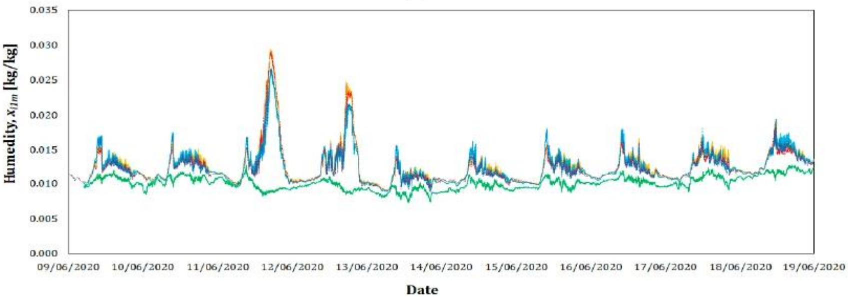
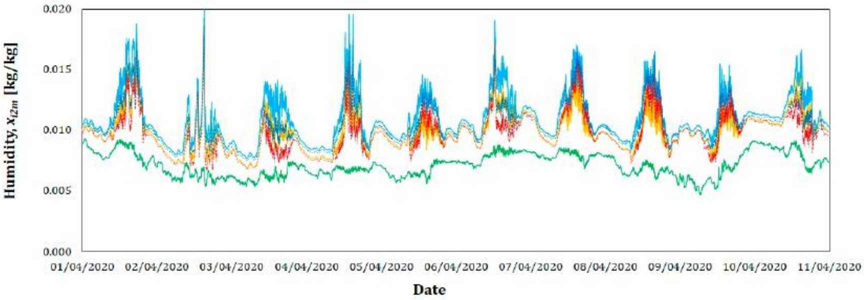
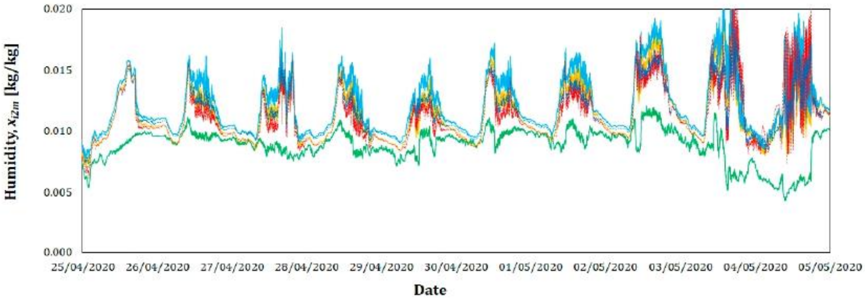


(d)

Figure S5. Evolution of the absolute humidity in the air outside (——) and inside the East sector with diffuse commercial cover film on the North (——) and South (- - -) sides and inside the West sector with diffuse experimental cover film on the North (——) and South (- - -) sides at a height of 1 m above the floor.



(a)



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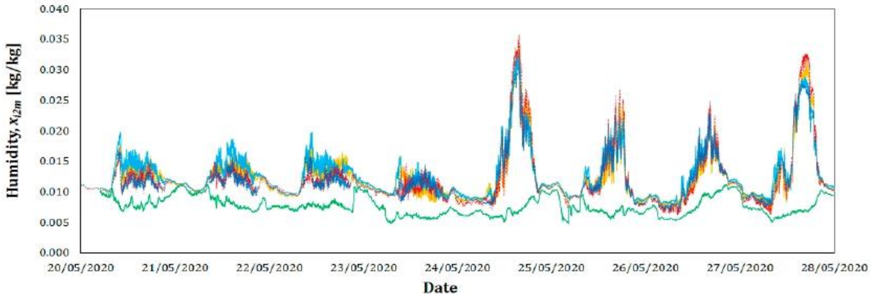

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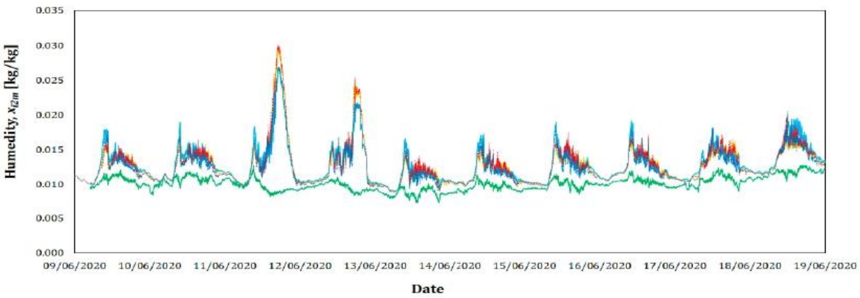

(d)

Figure S6. Evolution of the absolute humidity of the air outside (——) and inside the East sector with diffuse commercial cover film on the North (——) and South (- - -) sides and inside the West sector with diffuse experimental cover film on the North (——) and South (- - -) sides at a height of 2 m above the floor.

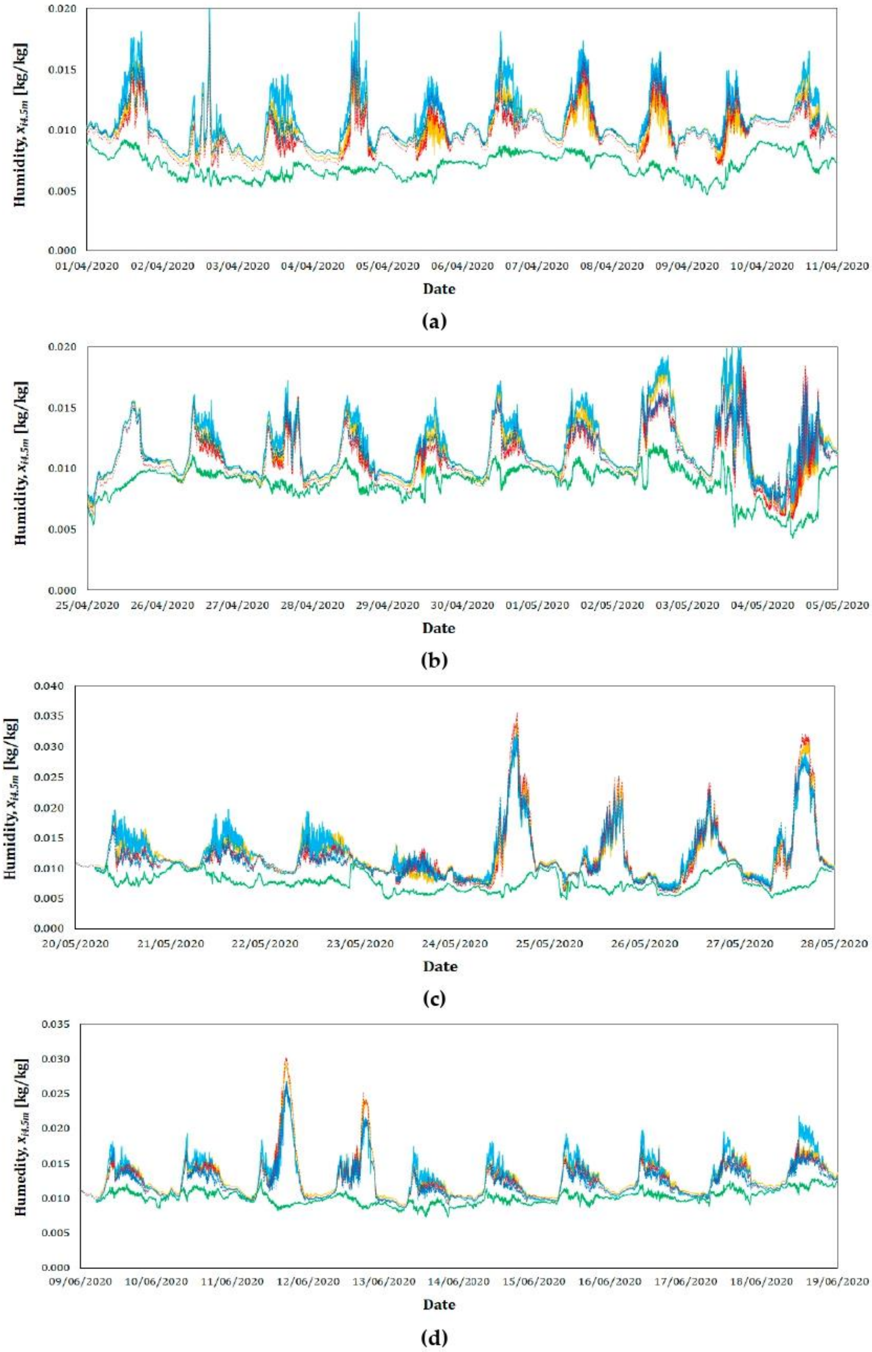

Figure S7. Evolution of the absolute humidity of the air outside (——) and inside the East sector with diffuse commercial cover film on the North (——) and South (- - -) sides and inside the West sector with diffuse experimental cover film on the North (——) and South (- - -) sides at a height of 4.5 m above the floor.

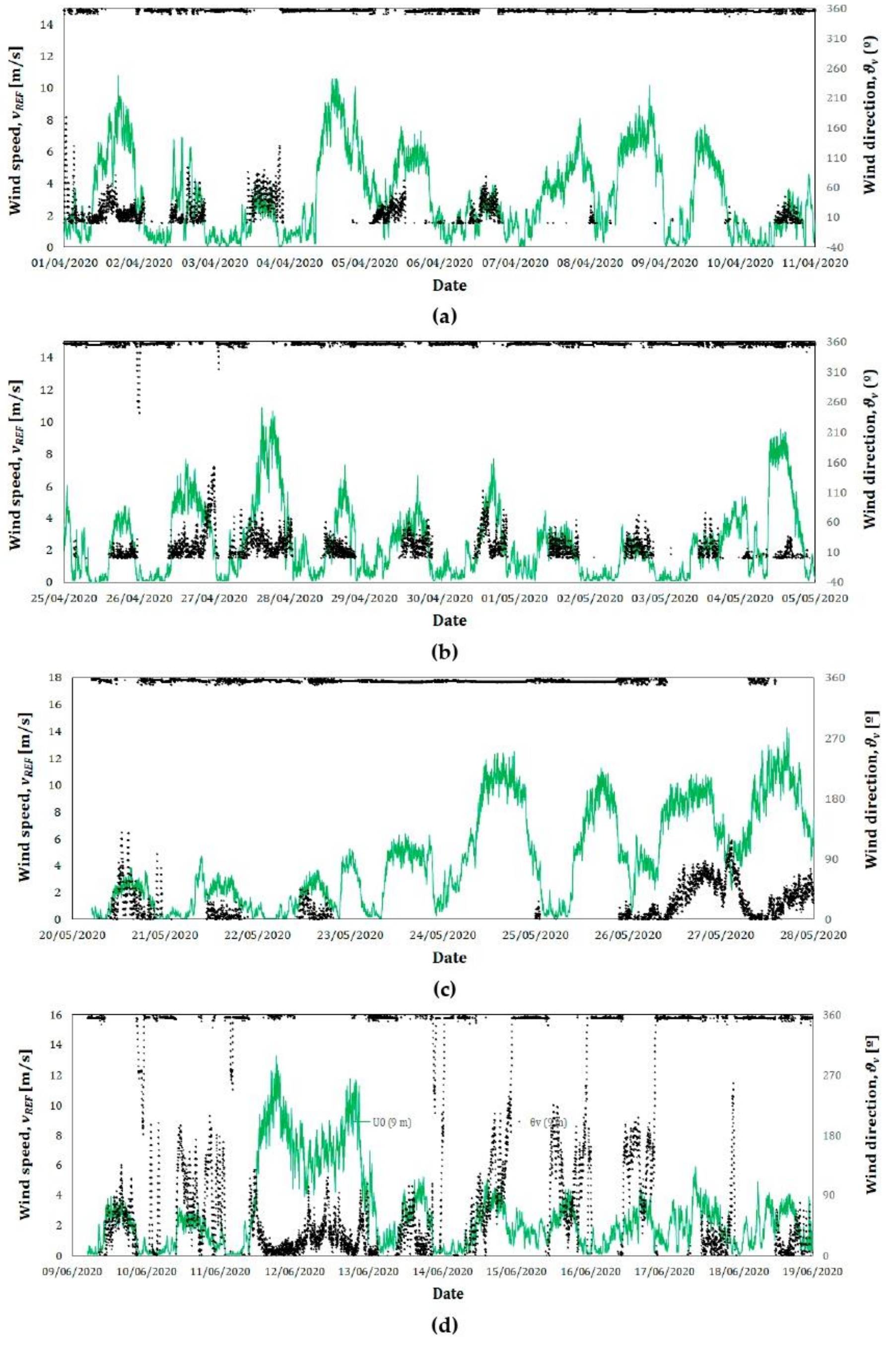

Figure S8. Evolution of the wind speed (—) and direction (—) at a height of 9 m above the floor.

CONCLUSIONES

CONCLUSIONES

En el **capítulo 1** se determinó el efecto de una técnica tradicional como es el blanqueo de la cubierta de los invernaderos, sobre la transmisividad de la cubierta plástica y sobre la temperatura en el interior de los invernaderos. Para ello, se evaluaron diferentes dosis de aplicación de cuatro productos de blanqueo comerciales, el producto tradicional "Blanco España" y otros tres productos que incorporan adhesivo que aporta mayor resistencia a la lluvia. Como conclusiones, la presencia de este adhesivo no parece influir en el efecto de los diferentes productos sobre la temperatura dentro del invernadero, los cuatro productos se comportan de manera similar a las mismas concentraciones. Los presentes hallazgos respaldan la dosis máxima de producto recomendada por otros autores: 0,50 kg L^{-1} (50/100), por encima de la cual la transmisividad de la cubierta de invernadero produce una disminución estadísticamente significativa de más del 50%. El efecto del ASP sobre la transmisividad de la cubierta del invernadero depende principalmente de la dosis aplicada, pero también de las condiciones climáticas (radiación solar, nubosidad, etc.) y la época del año (elevación solar). Esto hace que sea difícil recomendar una sola dosis de producto a los agricultores, se deben recomendar diferentes dosis dependiendo de la época del año y la reducción deseada de la transmisividad. Se ha demostrado que uno de los productos que contienen adhesivos ($ASP_{F)}$ permanece en la cubierta del invernadero después de períodos de lluvia intensa, mientras que el producto no adhesivo utilizado tradicionalmente ($ASP_{BE)}$ se lava. El método de aplicación de ASP debe estandarizarse para establecer un medio de aplicación de una concentración determinada de producto en g m^{-2} de cubierta. El método tradicional de aplicación establece una dosis (en kg $L^{-1)}$, pero la cantidad de producto que finalmente permanece en la cubierta es imposible de determinar ya que se aplica manualmente.

En el **capítulo 2**, una vez analizado el efecto del blanqueo sobre la transmisividad de la cubierta y la temperatura interior (capítulo 1), el segundo paso a seguir fue investigar los efectos de diferentes dosis de blanqueo en un cultivo de tomate (*Solanum Lycopersicum* L.). Para ello se evaluó el microclima en el interior de los invernaderos, la producción, la actividad fotosintética, la morfología de las plantas y la calidad de los frutos cosechados en dos ciclos de cultivo consecutivos. En este trabajo se ha analizado el efecto de tres concentraciones de un protector solar agrícola (0,125 kg L^{-1},0,250 kg L^{-1} y 0,500 kg L^{-1}) utilizado para el blanqueo de las cubiertas de los invernaderos. Se pueden extraer las siguientes conclusiones prácticas para los agricultores y técnicos:

1. El aumento de la dosis de blanqueo redujo la transmisividad de la cubierta, disminuyendo las temperaturas máximas extremas al comienzo del ciclo otoño-invierno y reduciendo la fotosíntesis durante el resto del año. Recomendamos una dosis de 35 g m^{-2} (concentración de 0,500 kg L^{-1}) para el inicio del ciclo de cultivo en el mes de agosto.
2. Como resultado de los niveles más bajos de fotosíntesis causados por el aumento del blanqueo en el ciclo otoño-invierno, se observaron pérdidas significativas de producción, alrededor del 0,8%-1% por cada reducción del 1% en la transmisividad. Recomendamos lavar la cubierta a mediados de septiembre cuando la temperatura máxima interior sea inferior a 35 °C.
3. El uso de una dosis variable a lo largo del ciclo primavera-verano no fue eficaz contra el uso de una dosis constante (0,250 kg L^{-1}), porque el efecto negativo de la reducción de la fotosíntesis causada por el uso de la dosis más alta (0,500 kg L^{-1}) al final del ciclo fue mayor que el efecto positivo producido al inicio del ciclo con una dosis más baja (0,125 kg L^{-1}). Recomendamos una dosis de 15 g m^{-2} (0,125 kg L^{-1}) al final de la primavera cuando la temperatura interior supere los 35 °C.
4. En general, no se observaron variaciones importantes en el crecimiento de los cultivos ni en los parámetros de calidad de la fruta; la excepción a esto fue el tamaño de los frutos, que se redujo significativamente con el aumento de la dosis de blanqueo, causando una importante pérdida de producción (4%–5%).

En el **capítulo 3**, se presenta un trabajo que forma parte de un proyecto de investigación cuyo objetivo es aumentar la productividad de los invernaderos mediterráneos mediante el aumento de la fotosíntesis de los cultivos. Para aumentar la radiación fotosintéticamente activa en el período invernal, se prueban plásticos con mayor transmisividad a la radiación PAR, mayor capacidad difusa y con efecto transformador de espectro. Para permitir el uso de estos plásticos en los períodos cálidos, será necesario mejorar la capacidad de enfriamiento de los invernaderos aumentando la capacidad de ventilación natural y aumentando la reflexión de radiación a nivel del suelo. Además, también es posible mejorar la capacidad de enfriamiento, optimizando la técnica de blanqueo que reduce drásticamente la actividad fotosintética de los cultivos.

La mayoría de los estudios previos se han centrado en mediciones de las propiedades radiativas espectrales de las películas de polietileno en laboratorios o bajo invernaderos experimentales de tamaño reducido. En este trabajo se ha analizado el efecto de una cubierta experimental de invernadero (comparada con una cubierta comercial como control) con alta

transmitancia PAR (90%), difusividad elevada (55%) y un alto bloqueo a la radiación UV (76%) sobre el microclima interior, la actividad fotosintética de la planta de tomate y la producción en un invernadero de grandes dimensiones (800-1000m^2).
De los resultados obtenidos comparando la cubierta plástica experimental difusa con alta transmitancia (95%) con una cubierta de plástico comercial difusa (85% de transmitancia), se pueden extraer las siguientes conclusiones:

1. El plástico experimental produjo un aumento del 14 al 15% en la transmisión media de la cubierta para la radiación solar y la radiación fotosintéticamente activa (PAR).
2. La actividad fotosintética promedio medida en las hojas de cultivo de tomate fue un 21,5% mayor con plástico experimental como resultado de un aumento del 13% en la radiación PAR.
3. Como resultado del aumento de la actividad fotosintética, el rendimiento comercial de la cosecha de tomate fue un 3,2% mayor con el plástico experimental con mayor transmitancia (aumento del 6,5% en la producción total).
4. La mejora de la producción se debió tanto al aumento del peso medio de los frutos como al número de frutos por planta, aunque no se observaron diferencias estadísticas para ninguno de estos dos parámetros.
5. No se observaron diferencias estadísticamente significativas en ninguno de los parámetros de crecimiento de la planta (longitud y diámetro del tallo, número de nudos y longitud de los entrenudos).
6. El aumento de la radiación solar producido por el aumento de la transmisión del plástico comercial generó una temperatura más alta en la superficie del suelo, pero no hubo diferencias estadísticamente significativas en la temperatura del aire a la altura del cultivo (2 m).

En el futuro estudiaremos el efecto de la cubierta de plástico con alta transmisividad en el período primavera/verano combinado con el uso de aberturas de ventilación laterales más grandes. También se analizará el efecto del envejecimiento en la degradación del plástico y en la variación de la transmisividad de la cubierta durante tres temporadas. El objetivo principal de nuestra investigación es reducir o eliminar el blanqueo de la cubierta que reduce la radiación PAR interceptada por el cultivo, y como resultado disminuye su productividad en invernaderos mediterráneos.

ANEXO. PUBLICACIONES CIENTÍFICAS

ANEXO. PUBLICACIONES CIENTÍFICAS

En este apartado se enumeran todos los trabajos científicos derivados de esta tesis doctoral, incluidos los tres que conforman los tres capítulos principales de la misma:

I. **Autores (P.O. de Firma):** Alejandro López-Martínez [1], Diego Luis Valera-Martínez [1], Francisco Domingo Molina-Aiz [1], **María de los Ángeles Moreno-Teruel** [1], Araceli Peña-Fernández [1] and Karlos Emmanuel Espinoza-Ramos [2].

Afiliaciones: [1]Ciaimbital-Centro de Investigación en Agrosistemas Intensivos Mediterráneos y Biotecnología Agroalimentaria. Universidad de Almería Ctra. de Sacramento s/n, 04120 Almería, España.

[2] Departmento de Ingenierías, Centro Universitario de la Costa Sur, Universidad de Guadalajara. Av. Independencia Nacional 151, Autlán de Navarro, Jalisco 48900, Mexico.

Título: Analysis of the Effect of Concentrations of Four Whitening Products in Cover Transmissivity of Mediterranean Greenhouses

DOI: https://doi.org/10.3390/ijerph16060958

Nombre de la Revista: International Journal of Environmental Research and Public Health. (Special Issue Greenhouse and Horticulture).

Volumen y Páginas: 16 (6), 958.

Editorial: MDPI.

País de Publicación: Suiza.

Año de Publicación: 2019.

ISSN: 1660-4601.

Clasificación en la categoría: JCR-Science Edition: 105/265 (Q2) Environmental Sciences; 58/183 Q2 Public, Environmental & Occupational Health.

Índice de Impacto: 2.849 (2019).

Revisión por pares.

II. **Autores (P.O. de Firma): María de los Ángeles Moreno-Teruel[1]**, Diego Valera[1], Francisco Domingo Molina-Aiz[1], Alejandro López-Martínez[1], Araceli Peña[1], Patricia Marín[1] and Audberto Reyes-Rosas[1].

Afiliación: [1]Ciaimbital-Centro de Investigación en Agrosistemas Intensivos Mediterráneos y Biotecnología Agroalimentaria. Universidad de Almería Ctra. de Sacramento s/n, 04120 Almería, España.

Título: Effects of Cover Whitening Concentrations on the Microclimate and on the Development and Yield of Tomato (Lycopersicon esculentum Mill.) Inside Mediterranean Greenhouses

DOI: https://doi.org/10.3390/agronomy10020237

Nombre de la Revista: Agronomy

Volumen y Páginas: 10 (2), 237.

Editorial: MDPI.

País de Publicación: Suiza.

Año de Publicación: 2020.

ISSN: 2073-4395.

Clasificación en la categoría: JCR-Science Edition: 18/91 (Q1) Agronomy.

Índice de Impacto: 2.603 (2019).

Revisión por pares.

III. **Autores (P.O. de Firma): María de los Ángeles Moreno-Teruel**[1], Francisco Domingo Molina-Aiz[1], Araceli Peña-Fernández[1], Alejandro López-Martínez[1], Diego Luis Valera-Martínez[1].

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

DOI: https://doi.org/10.3390/agronomy11050860

Nombre de la Revista: Agronomy

Volumen y Páginas: 11 (5) 860.

Editorial: MDPI.

País de Publicación: Suiza.

Año de Publicación: 2021.

ISSN: 2073-4395.

Clasificación en la categoría: JCR-Science Edition: 18/91 (Q1) Agronomy.

Índice de Impacto: 2.603 (2019).

Revisión por pares.

IV. **Autores (P.O. de Firma):** Diego Luis Valera-Martínez1, Francisco Domingo Molina-Aiz[1], **María de los Ángeles Moreno-Teruel**[1], Alejandro López-Martínez[1], Patricia Marín Membrive[1].

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Título: Ventilation surface area: key to modify morphology, quality and photosynthetic activity of tomato crops in Mediterranean greenhouses
DOI: https://doi.org/10.17660/ActaHortic.2020.1296.24
Nombre de la Revista: Acta Horticulturae

Volumen y Páginas: 1296, 185-192.

Editorial: International Society for Horticultural Science

País de Publicación: Bélgica

Año de Publicación: 2020.

ISSN: 2406-6168

Clasificación en la categoría: JCR-Science Edition (Q4) Horticultura.

Índice de Impacto: 0.184 (2019).

Revisión por pares.

V. **Autores (P.O. de Firma):** Francisco Domingo Molina-Aiz[1], Diego Luis Valera-Martínez[1], Alejandro López-Martínez[1], **María de los Ángeles Moreno-Teruel**[1], Patricia Marín Membrive[1], María del Mar García Valverde[1].

Afiliación: [1]Ciaimbital-Centro de Investigación en Agrosistemas Intensivos Mediterráneos y Biotecnología Agroalimentaria. Universidad de Almería Ctra. de Sacramento s/n, 04120 Almería, España.
Título: Effects of the increase of ventilation surface area on the microclimate and yield of a tomato crop in Mediterranean greenhouses.
DOI: https://doi.org/10.17660/ActaHortic.2020.1296.23
Nombre de la Revista: Acta Horticulturae

Volumen y Páginas: 1296, 177-184.

Editorial: International Society for Horticultural Science

País de Publicación: Bélgica

Año de Publicación: 2020.

ISSN: 2406-6168

Clasificación en la categoría: JCR-Science Edition (Q4) Horticultura.

Índice de Impacto: 0.184 (2019).

Revisión por pares.

VI. **Autores (P.O. de Firma):** Patricia Marín Membrive[1], **María de los Ángeles Moreno-Teruel**[1], Francisco Domingo Molina-Aiz[1], Diego Luis Valera-Martínez[1], Alejandro López-Martínez[1].

Afiliación: [1]Ciaimbital-Centro de Investigación en Agrosistemas Intensivos Mediterráneos y Biotecnología Agroalimentaria. Universidad de Almería Ctra. de Sacramento s/n, 04120 Almería, España.

Título: Influence of the greenhouse type and cooling system on the production of a tomato crop during the spring/summer cycle under Mediterranean climate.

DOI: https://doi.org/10.17660/ActaHortic.2017.1170.106

Nombre de la Revista: Acta Horticulturae

Volumen y Páginas: 1170, 829-838.

Editorial: International Society for Horticultural Science

País de Publicación: Bélgica

Año de Publicación: 2017.

ISSN: 2406-6168

Clasificación en la categoría: JCR-Science Edition (Q4) Horticultura.

Índice de Impacto: 0.184 (2019).

Revisión por pares.

RESUMEN

El futuro de la agricultura intensiva en invernadero en Almería pasa por hacerla más sostenible mediante el principio de producir más con menos. Es ahí donde los sistemas pasivos de control climático adquieren especial relevancia, puesto que su consumo energético es mínimo. Con la optimización de estas técnicas de ahorro energético podemos mejorar la radiación fotosintéticamente activa que llega hasta nuestros cultivos y, por lo tanto, incrementar la actividad fotosintética y por consiguiente la productividad.

En esta tesis doctoral se pretende afrontar el reto de optimizar el uso de técnicas de ahorro energético tanto tradicionales como de última generación. Como primer paso se determinó el efecto de una técnica tradicional como es el blanqueo de la cubierta de los invernaderos, sobre la transmisividad de la cubierta y sobre la temperatura en el interior de los invernaderos sin cultivo. Evaluándose para ello diferentes dosis de aplicación de cuatro productos de blanqueo comerciales. El segundo paso en este trabajo fue determinar los efectos de diferentes dosis de blanqueo y diferentes estrategias de aplicación del producto más usado en la cuenca mediterránea (Blanco España) sobre un cultivo de tomate (*Solanum Lycopersicum* L.). Para ello se evaluó el microclima en el interior de los invernaderos, la producción, la actividad fotosintética, la morfología de las plantas y la calidad de los frutos cosechados en dos ciclos de cultivo consecutivos.

Finalmente, se evaluó el efecto de otra técnica de ahorro energético más novedosa, como es el uso de cubiertas plásticas con alta difusividad lumínica. Para ello se analizó el comportamiento de una cubierta de plástico difuso experimental de alta transmisividad frente al uso de una cubierta plástica difusa comercial sobre un cultivo de tomate (*Solanum Lycopersicum* L.). Para ello se analizó su efecto sobre el microclima dentro del invernadero, la actividad fotosintética, el crecimiento del cultivo, el rendimiento y la calidad de los frutos en un ciclo de primavera-verano.

Los resultados obtenidos muestran que es necesario recomendar a los agricultores diferentes dosis de blanqueo en función de la época del año y de la reducción deseada de la transmisividad de la cubierta del invernadero. Los niveles más bajos de actividad fotosintética causados por una dosis de blanqueo elevada en el ciclo otoño-invierno, mostraron pérdidas significativas de producción, alrededor del 0,8%-1% por cada reducción del 1% en la transmisividad. Por lo que es recomendable lavar la cubierta a mediados de septiembre cuando la temperatura máxima interior sea inferior a 35 °C. En el ciclo de primavera-verano el uso de una estrategia con dosis variable no fue eficaz contra el uso de una estrategia de dosis constante (0,250 kg L^{-1}), porque el efecto negativo de la reducción de la fotosíntesis causada por el uso de la dosis más alta (0,500 kg L^{-1}) al final del ciclo fue mayor que el efecto positivo producido al inicio del ciclo con una dosis más baja (0,125 kg L^{-1}). Por lo que es recomendable una dosis de 15 g m^{-2} (0,125 kg L^{-1}) al final de la primavera cuando la temperatura interior supere los 35 °C.

Los resultados del último ensayo de investigación que compone esta Tesis Doctoral muestran que, el plástico experimental produjo un aumento del 14 al 15% en la transmisión media de la cubierta para la radiación solar y la radiación fotosintéticamente activa (PAR) respectivamente. La actividad fotosintética promedio medida en las hojas de cultivo de tomate fue un 21,5% mayor con plástico experimental como resultado de un aumento del 13% en la radiación PAR. Como resultado de este aumento, el rendimiento comercial de la cosecha de tomate fue un 3,2% mayor con el plástico experimental con mayor transmitancia (aumento del 6,5% en la producción total).

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