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Combined Passive Heating Systems in Mediterranean, Low-Cost, Greenhouse Cucumber Crops

Santiago Bonachela [1,*], María Rosa Granados [1], Joaquín Hernández [1], Juan Carlos López [1] and Juan José Magán [2]

[1] Department of Agronomy, Centro de Investigación en Agrosistemas Intensivos Mediterráneos y Biotecnología Agroalimentaria (CIAMBITAL), Universidad de Almería, Ctra. de Sacramento s/n, La Cañada de San Urbano, 04120 Almería, Spain; mgranado@ual.es (M.R.G.); jhrodri@ual.es (J.H.); jcpalmerillas@gmail.com (J.C.L.)
[2] Estación Experimental de Cajamar, Cajamar Caja Rural, Paraje Las Palmerillas 25, 04710 Almería, Spain; juanjosemagan@fundacioncajamar.com
* Correspondence: bonache@ual.es

Abstract: Greenhouse microclimate and crop response of winter cucumber cycles grown in unheated Mediterranean greenhouses with representative combinations of passive heating systems (fixed, plastic screen with and without black mulch; movable thermal screen with black mulch; and double-layer plastic covering with black mulch) were evaluated in Almería, SE Spain. In the first experiment, the black mulch in combination with a movable or fixed screen increased the marketable cucumber yield by 14%, which appears to be mostly attributable to higher substrate temperatures induced by the black mulch in the cold period. Moreover, the black mulch in combination with a fixed screen frequently led to screen water condensation. The use of a movable screen, rather than a fixed one, in combination with a black mulch increased the first-class cucumber yield in the second experiment and reduced the non-marketable one in the first experiment. This might be mainly attributable to the higher incoming shortwave radiation in the cold period. Moreover, the movable screen reduced the risk of water condensation on the screen and the crop. The cucumber in the greenhouse with the double-layer covering and black mulch, compared to that with movable screen and black mulch, received lower daily incoming shortwave radiation, particularly, during the second half of the cycle (mainly due to the formation of water condensation droplets on the lower surface of the external plastic film), which reduced crop yield. Further field research is needed to better quantify the most limiting factor for growth (substrate/soil or air temperature, radiation, or water condensation) in Mediterranean greenhouse crops.

Keywords: black mulch; radiation; screen; substrate; temperature; yield

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1. Introduction

The greenhouse industry is increasingly adopting energy-saving technologies to reduce fossil energy use and related environmental impacts. Most greenhouses located in mild-winter areas are low-cost structures covered with single plastic films and without active systems of climate control [1]. In these greenhouses, the winter microclimate, particularly air temperature and humidity, and soil/substrate temperature, are frequently outside the optimum range for vegetable production, but active systems of heating are seldom used because they are not considered economically feasible [2].

Passive heating methods are widely used in horticultural crops grown in Mediterranean greenhouses (cucumber, melon, tomato, etc.) to improve their energy efficiency [3–5]. In south-eastern (SE) Spain, which has the largest greenhouse concentration in Europe, black plastic mulches are used for weed control, but also for soil and air heating [3]. These authors found that black mulches substantially improved the greenhouse microclimate during the cold period (winter): they increased soil and air temperatures, particularly in the early stages of crop cycles starting at the end of autumn or in winter. Fixed plastic screens, located between the crop canopy and the greenhouse roof, are increasingly being used around winter, especially for vegetable crops very sensitive to fungal diseases, such as late cucumber cycles [4]. These screens improved the night temperature and humidity of the air below the screen, and reduced the water condensation on its inner plastic surface [4], preventing the fall of condensation/rainfall water onto crops, thus reducing fungal disease proliferation [6]. Movable thermal screens, while an integral feature of high-technology greenhouses in temperate regions for energy saving [7], are scarcely used in commercial Mediterranean greenhouses due to their relatively high cost, but they could be interesting in Mediterranean greenhouses with automatic ventilation control systems [4]. Double-layer, air-inflated plastic films (two flexible plastic films separated by an air chamber) are used in temperate greenhouse areas of North America [8,9] for reducing energy losses in heated horticultural greenhouse crops (cucumber and aubergine) [10,11]. Though this covering system has hardly been evaluated in unheated Mediterranean greenhouse crops, it may also improve the winter microclimate and prevent the fall of condensation/rainfall water onto crops.

Common passive heating systems in Mediterranean greenhouse crops (black and gravel/sand mulches, fixed screens, etc.) improved the winter greenhouse microclimate [3–5], but their effects are limited, and air and soil temperatures at winter are still below the optimum for most cultivated horticultural species (cucumber, melon, tomato, etc.), especially at night [12,13]. To our knowledge, little is known about the combined or integrated use of passive heating systems in Mediterranean greenhouse crops: e.g., black plastic mulch plus fixed plastic screen or black plastic mulch plus movable thermal screen. These combined systems can improve further the winter microclimate and, consequently, the crop response, particularly in crop cycles initiated or centred around the cold period. This work analyses the microclimate and crop response of two winter cucumber cycles grown in unheated Mediterranean greenhouses with the following: low-cost, fixed, impermeable plastic screen, either with or without black plastic mulch; movable thermal screen plus black plastic mulch; and double-layer air-inflated plastic covering film plus black plastic mulch.

2. Materials and Methods

2.1. Greenhouses and Experiments

Experiments were conducted at the "Cajamar Foundation" station (2°43′ W; 36°48′ E; 155 m elevation), Almería (Spain) in three identical, three-span, multitunnel greenhouses of 630 m^2 ground area (28 m × 22.5 m). These east–west-oriented greenhouses were arch-roofed, 4.5 m high to the ridges and 3.0 m to the eaves (Figure 1). Each greenhouse had three continuous roof vents and sidewall rolling vents on the southern and northern sides, which were automatically controlled. The greenhouse plastic cover, installed in October 2014, was a three-layer, anti-fog thermal film of 200 µm thickness (Sotrafa SA, Almería, Spain) with a shortwave (τ_{SW}) and longwave (τ_{LW}) radiation transmission of 90% and 10%, respectively, and a haze factor of 55% (Table 1, manufacturer's data). The soil was a typical layered soil, known as enarenado, with an imported layer of loamy texture. This soil is widespread on the SE Spanish Mediterranean coast [14].

Table 1. Crop cycles and main radiometric properties of greenhouse covering material, black mulch (BM), and fixed (FS) and movable (MS) thermal screens [plastic transmission coefficient (%) to shortwave (τ_{SR}) and longwave (τ_{LR}) radiation].

	Cover				BM	FS	MS
	External Film		Internal Film				
Cucumber 2014/15	τ_{SW}	τ_{LW}	τ_{SW}	τ_{LW}	τ_{SW}	τ_{SW}	τ_{SW}
NM + FS	90	10	-	-	-	94	-
BM + FS	90	10	-	-	1	94	-
BM + MS	90	10	-	-	1	-	87

Table 1. *Cont.*

	Cover				BM	FS	MS
	External Film		Internal Film				
Cucumber 2015/16							
BM + FS	90	10	-	-	1	94	-
BM + MS	90	10	-	-	1	-	87
BM + DL	*92*	*14*	*92*	*14*	*1*	-	-

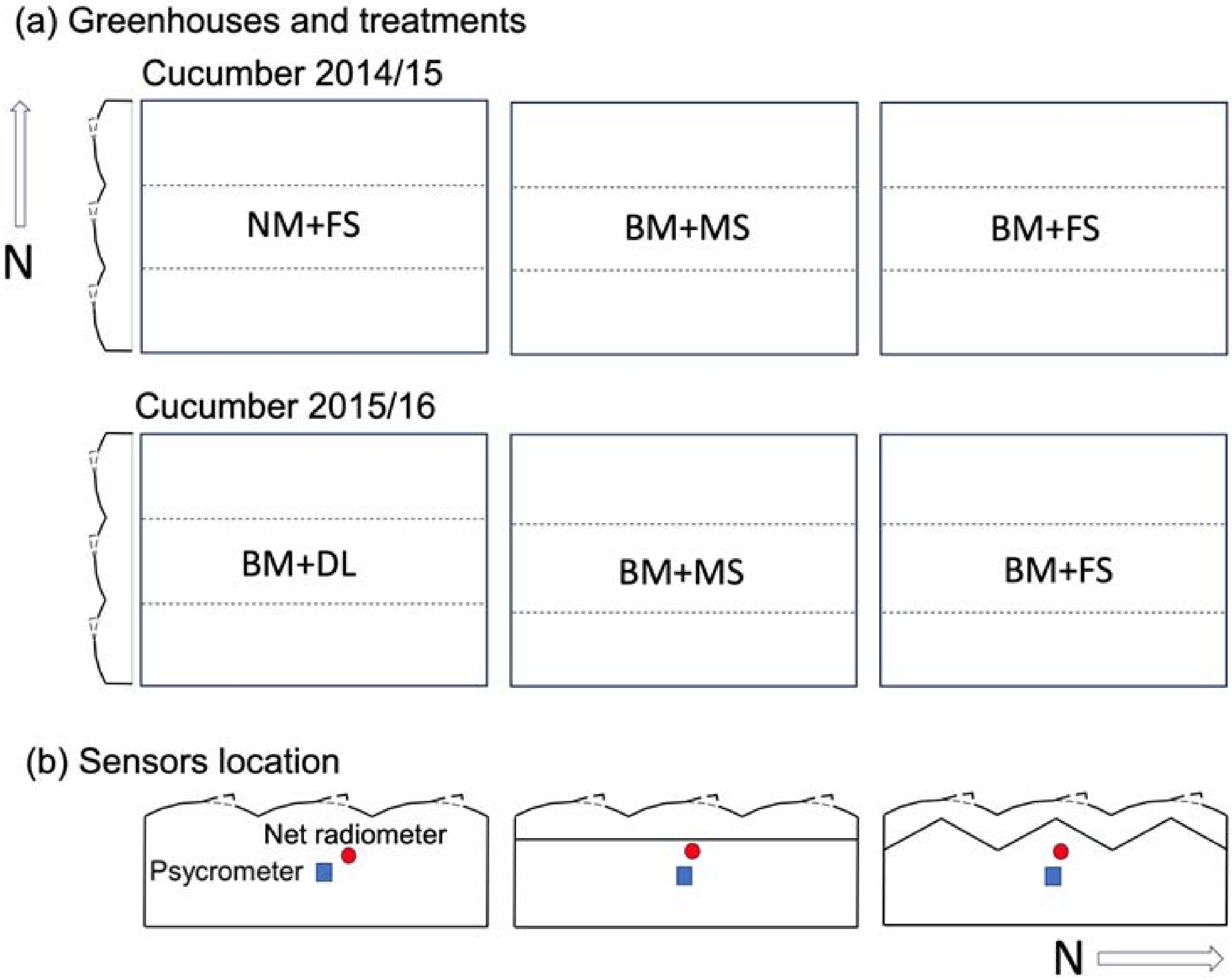

Figure 1. (**a**) Schematic plan view of experimental greenhouses including greenhouse structures and treatments during the 2014/15 (NM + FS: greenhouse without black mulch but with fixed screen; BM + MS: greenhouse with black mulch and movable screen; BM + FS: greenhouse with black mulch and fixed screen) and 2015/16 cucumber crop cycles (BM + DL: greenhouse with black mulch and double-layer covering; BM + MS: greenhouse with black mulch and movable screen; BM + FS: greenhouse with black mulch and fixed screen). (**b**) Schematic elevation view of experimental greenhouses, including internal screens and sensors locations. El Ejido, Almería, Spain.

Two cucumber *(Cucumis sativus* L., 'Valle') crop cycles were grown in 30 L coconut coir grow-bags (FICO, Ispemar S.C.A., Almería, Spain), laid over polystyrene channels for drainage collection and located above the enarenado soil. The first cucumber experiment (16 October 2014 to 4 March 2015) compared three treatments (Figure 1): a greenhouse with a low-cost, internal, fixed, plastic impermeable screen without black mulch (NM + FS); another greenhouse with an internal, movable, thermal screen, and black plastic mulch (BM + MS); and a third greenhouse with an internal, fixed, plastic impermeable screen and black mulch (BM + FS). The second crop experiment (10 November 2015 to 7 March 2016) compared (Figure 1) a greenhouse with an internal, fixed, plastic impermeable screen and black mulch (BM + FS), another greenhouse with an internal, movable, thermal screen, and black plastic mulch (BM + MS), and a third greenhouse with double-layer, air-inflated covering, and black plastic mulch (BM + DL). The plastic mulch was a micro-perforated black film of 25 μm thickness (Sotrafilm NG, Sotrafa SA) with a shortwave transmission, reflection, and absorption of 1, 4, and 95%, respectively (Table 1), and 15% longwave transmission (manufacturer's data). The low-cost, fixed, plastic impermeable screen, constructed following local practices [4], consisted of 37.5 μm-thick anti-fog plastic sheets (Sotrafilm DC AF, Sotrafa, Almería, Spain) joined hermetically by wires, located between the crop canopy and the greenhouse roof, and forming a symmetrical planar roof of 9° slope (Figure 1). Plastic sheets had a shortwave radiation transmission of 94% (manufacturer's data). The movable thermal screen consisted of polyester sheets (XLS 10 REVOLUX, Ludving Svensson, Kinna, Sweden) with direct and diffuse shortwave radiation transmission of 87 and 80%, respectively and about 47% energy saving. Sheets, supported by tensioned wires forming a horizontal roof above the crop (2.7 m aboveground), were automatically unfolded (Multima, HortiMax S.L., Almería, Spain) when the outdoor solar radiation was less than 50 W m^{-2} [15] and the greenhouse air temperature was below 18 °C. The greenhouse with double layer was covered with an internal anti-fog, high-transparency film of 150 μm thickness (TRC TH AF, Sotrafa SA) and an external high-transparency film (no anti-fog) of 200 μm (TRC TH 3C, Sotrafa SA). Both films presented similar radiometric properties (Table 1): a shortwave transmission of 92%, an infrared transmission (7–13 μm) of 14% and a haze factor of 30% (manufacturer's data). The N-S oriented plant rows were 1.60 m apart (1.0 plant m^{-2}). Local practices of crop management (irrigation, fertigation, pest control, etc.) were applied. In each experiment, the same irrigation rate and frequency, and the same nutrient solution was supplied to all the crop treatments using a non-recirculating drip irrigation system. A water level sensor, placed in a tray containing two representative substrate grow-bags, triggered irrigation according to crop transpiration. A new irrigation event was initiated when the water level fell below a pre-set threshold, which was periodically adjusted to maintain similar drainage percentages for all crop treatments [16].

One-way analysis of variance was used to test for statistical differences between treatments, which were arranged in a randomised complete block design (four replications per treatment). When differences were significant ($p < 0.05$), the least significant difference (LSD) procedure at $p = 0.05$ was used for mean comparisons using Statgraphics Centurion 18 (Statgraphics Technologies, Inc., The Plains, VA, USA).

2.2. Measurements

Temperature inside the substrate and in the middle of the enarenado soil (0.25 m depth) was measured with thermistors (T107, Campbell Scientific, Delft, The Netherlands). In each greenhouse, three thermistors were buried in the middle of representative coconut coir grow-bags and two in the middle of the soil layer. Air relative humidity and temperature over the crop canopy (about 2.1 m aboveground, Figure 1) were measured in the middle of each greenhouse with ventilated psychrometers (HMP155, Vaisala, Campbell Scientific, Inc., Logan, UT, USA). The temperature of the crop was measured in the upper, middle, and lower leaves of the canopy with three contact thermocouples at each height (type T, ∅ 0.9 mm copper-constantan, RS Amidata, Madrid, Spain). Thermocouples were placed below the leaves to protect them from solar radiation. In the 2014/15 experiment, the upper surface temperature of the greenhouse cover and the lower surface temperature of fixed and movable screens were measured with three contact thermocouples on each surface. In the 2015/16 experiment, three contact thermocouples were installed on the upper and lower cover surfaces in the greenhouses with fixed and movable screens, and on the upper surface of the external film and the lower surface of the internal film in the greenhouse with double-layer, air-inflated cover. These thermocouple measurements were corrected to take into account shortwave radiation effects [4]. Net radiation was measured above the crop canopy and below the internal screens in each greenhouse with net ratiometers (CNR1 Kipp and Zonen, Delft, The Netherlands) installed in the middle of each greenhouse (Figure 1). Incoming and net shortwave and longwave radiation were determined separately. Outdoor air temperature and relative humidity, and solar radiation were measured with a ventilated psychrometer (mod. 1.1130, Thies Clima, Göttingen, Germany) and a pyranometer (model CM21, Kipp and Zonen), respectively, mounted at 1.5 m height on bare land 100 m away from the experimental greenhouses. Data were averaged and registered every five minutes with data acquisition systems (dataloggers CR1000 and CR3000, Campbell Scientific, Delft, The Netherlands). Air CO_2 concentration around the upper part of the crop canopy was measured in each greenhouse with Vaisala GMP 343 probes. Data were registered and stored every five minutes. For each greenhouse and crop cycle, the daily mean transmission of the greenhouse to shortwave radiation was measured on sunny days with a linear sensor (mod. LP80 AccuPAR, PAR/LAI Ceptometer, Decagon Devices Inc., Pullman, WA, USA). Measurements were taken inside and outside the greenhouses every 2–3 h during daylight hours. Measurement inside the greenhouse were taken along longitudinal and transversal transects above the crop and below the internal screens.

Shoot biomass (dry weight), its partitioning into leaves, stems and fruits, and leaf area index (LAI) were measured at the end of each crop cycle in two plants per replication (four replications per treatment). Young fruits and axillary stems pruned during the cycle were included in the corresponding biomass fraction. Leaf area was measured with a planimeter (AM7626, Delta T Device Area Meter, Cambridge, UK). In addition, total and marketable yield, and marketable yield components (mean fruit weight and number of fruits) were determined in both crop cycles on six plants per replication (four replications per treatment).

3. Results

3.1. Cucumber 2014/15

3.1.1. Greenhouse Microclimate

Substrate and Air Temperature, and Air Humidity

Figure 2 shows daily mean values of coir grow-bag and air temperatures, and air humidity throughout the whole cucumber cycle, as well as the averages over the cold crop period (December to February) of these variables. The daily mean temperature inside coir grow-bags was slightly higher in the crops with black mulch than in those without throughout the whole cycle (Figure 2). Averaged over the cold crop period (December to February), it was 16.9 °C in the crop with black mulch and fixed screen (BM + FS), 16.4 °C in the crop with black mulch and movable screen (BM + MS) and 15.4 °C in the crop without black mulch but with a fixed screen (NM + FS, Table 2). Hourly mean temperatures over the cold period were also higher in the crops with black mulch throughout the whole day, especially around nighttime (Figure 2).

The daily mean temperature in the middle of the enarenado soil layer, where most roots of soil-grown vegetable crops usually grow, was also higher in the crops with black mulch (Table 2). Averaged over the cold period, it was 19.3 and 18.5 °C in the BM + FS and BM + MS crops, respectively, and 17.8 °C in the NM + FS crop.

The daily mean greenhouse air temperature over the crop canopy was relative similar in the three studied treatments throughout the whole cucumber cycle (Figure 2). Averaged over the cold period, they were 15.3, 15.1, and 14.4 °C in the NM + FS, BM + FS and BM + MS crops, respectively (Table 2). However, hourly mean greenhouse air temperatures averaged over the cold period were slightly higher in the crop without black mulch around nighttime and slightly lower in the crop with the movable screen at daylight hours (Figure 2, Table 2).

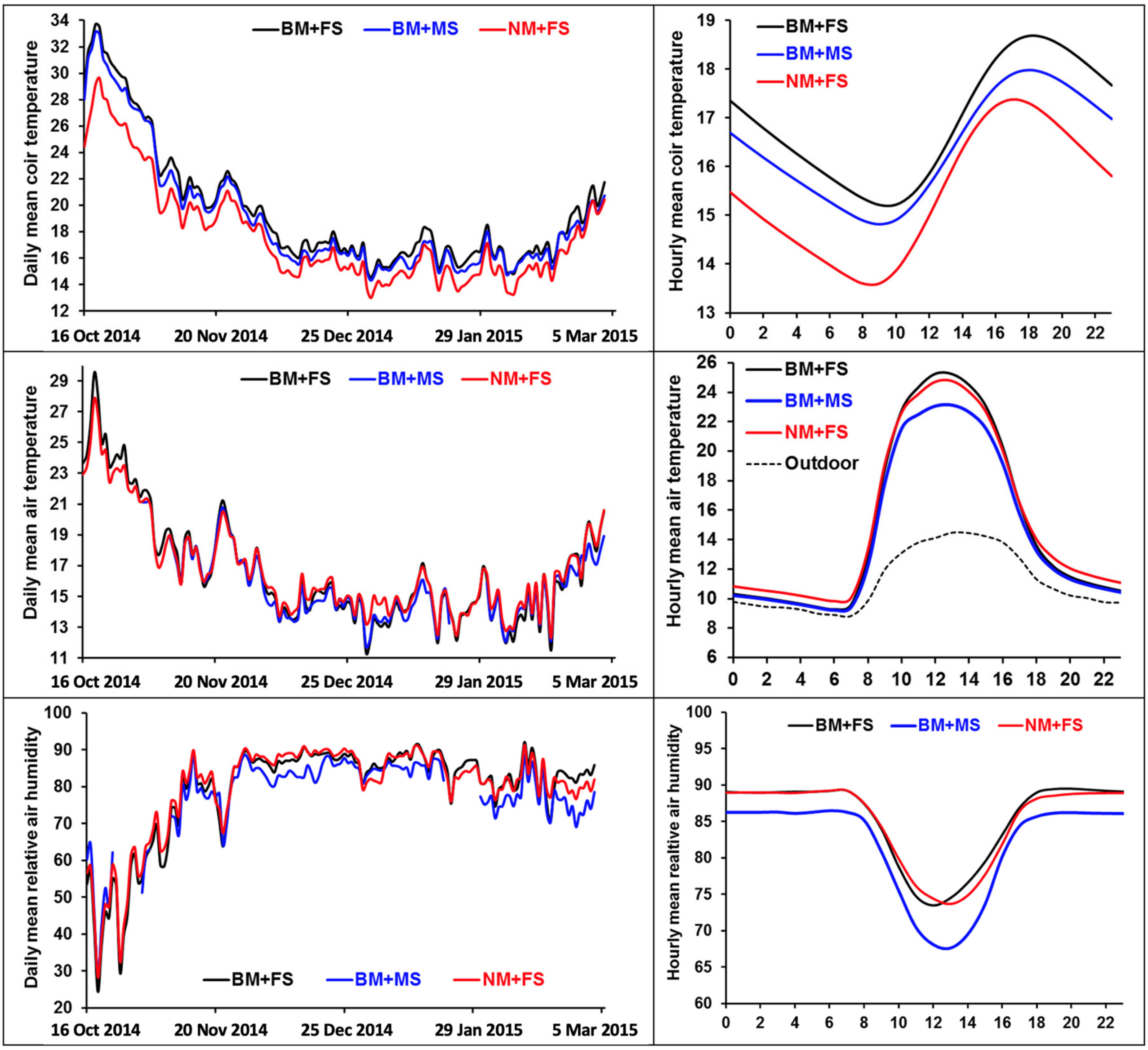

Figure 2. Daily mean values throughout the 2014/15 cucumber cycle and hourly mean values during the cold crop period (December to February) of coir grow-bag temperature (°C), air temperature (°C), and relative air humidity (%) in greenhouse crops with black mulch and fixed screen (BM + FS), black mulch and movable screen (BM + MS), and without black mulch but with fixed screen (NM + FS).

The daily mean air relative humidity over the crop canopy was generally lower in the crop with movable screen during the cold period (Figure 2). Averaged over this period, it was 84.7, 84.6, and 80.4% in the NM + FS, BM + FS, and BM + MS crops, respectively (Table 2). Hourly mean values averaged over the cold period were lower in the crop with movable screen throughout the whole day (Figure 2).

Crop and Screen Temperature, and Water Condensation

Hourly mean crop temperatures over the cold period were generally higher in the crop without black mulch at night-time and lower in the crop with the movable screen at daytime (Figure 3, Table 2). Averaged over the cold period, the mean crop temperature at night was 11.9, 10.7, and 10.8 °C for the NM + FS, BM + FS, and BM + MS crops, respectively, as compared to 20.6, 19.5, and 20.2 °C during daytime (Table 2).

Table 2. Daily, daytime, and nighttime mean values, averaged over the cold growth period (December, January, and February) of main greenhouse climate variables of two winter cucumber cycles grown in identical greenhouses with integrated passive heating systems. In the 2014/15 cycle, crops were grown in a greenhouse with black mulch and fixed screen (BM + FS), with black mulch and movable screen (BM + MS), and without black mulch and with fixed screen (NM + FS). In the 2015/16 cycle, crops were grown in a greenhouse with BM + FS, with BM + MS and with BM and double-layer covering (BM + DL).

	2014/2015			2015/2016		
	BM + FS	BM + MS	NM + FS	BM + FS	BM + MS	BM + DL
Daily soil temperature (°C)	18.5	19.3	17.8	20.7	21.1	21.0
Daily coir temperature (°C)	16.4	16.9	15.4	18.2	18.4	18.2
Daily air temperature (°C)	15.1	14.4	15.3	16.2	15.9	16.1
Night-time	10.8	10.6	11.3	12.7	12.6	12.8
Daytime	20.8	19.4	20.6	20.9	20.3	20.5
Daily crop temperature (°C)	14.8	14.4	15.6	16.5	16.1	16.1
Night-time	10.8	10.7	11.9	12.6	12.7	12.8
Daytime	20.2	19.5	20.6	21.9	20.7	20.7
Night-time lower surface screen temperature (°C)	10.2	10.3	11.3	-	-	-
Night-time lower surface cover temperature (°C)	-	-	-	9.0	9.3	11.2
Daily relative air humidity (%)	84.6	80.4	84.7	83.9	82.4	85.7
Night-time	88.8	85.5	88.6	88.6	87.4	91.8
Daytime	79.7	73.8	79.3	77.5	75.7	77.6
Daytime [CO_2] (µmol mol^{-1})	316	344	329	370	367	353

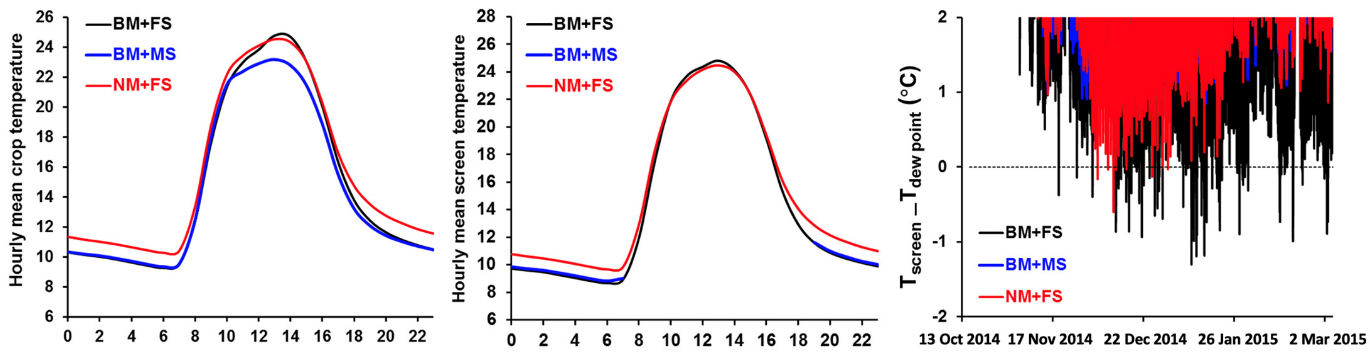

Figure 3. Hourly mean values throughout the cold period (December to February) of the 2014/15 cucumber cycle of crop temperature (°C), lower surface temperature of the fixed and movable screens (°C), and temperature differences between the lower surface temperature of movable and fixed screens, and the dew-point temperature of the air below the screens in the greenhouse with black mulch and fixed screen (BM + FS), black mulch and movable screen (BM + MS), and without black mulch but with fixed screen (NM + FS).

Hourly mean screen temperatures, measured on the lower surface, were also higher in the crop without black mulch around nighttime during the cold period (Figure 3, Table 2). Averaged over this period, the nighttime mean screen temperature was 11.3, 10.2, and 10.3 °C for the NM + FS, BM + FS, and BM + MS crops, respectively (Table 2). Moreover, hourly mean screen temperatures over the cold period were slightly lower than the corresponding crop temperatures around nighttime (Figure 3).

Water condensation occurred frequently on the lower screen surface of the BM + FS crop during the cold period since the dew-point air temperature was clearly higher than the lower surface temperature of this screen (Figure 3). This might be attributable to both the lower nighttime temperature on the lower surface of the fixed screen in the crops with black mulch (Figure 3) and the higher air humidity in the crops with fixed screens (Figure 2).

Water condensation rarely occurred in the crop without black much and did not occur in the crop with movable screen since the dew-point temperature of the air was generally (NM + FS) or always (BM + MS) lower than the lower surface temperature of the screen (Figure 3).

Solar Radiation and air CO_2 Concentration

Daily integral of the incoming shortwave radiation above the crop canopy was higher in the crop with the movable screen than in those with a fixed screen throughout most of the cucumber cycle (Figure 4a). Daily values of incoming shortwave radiation were similar in the two crops with a fixed screen.

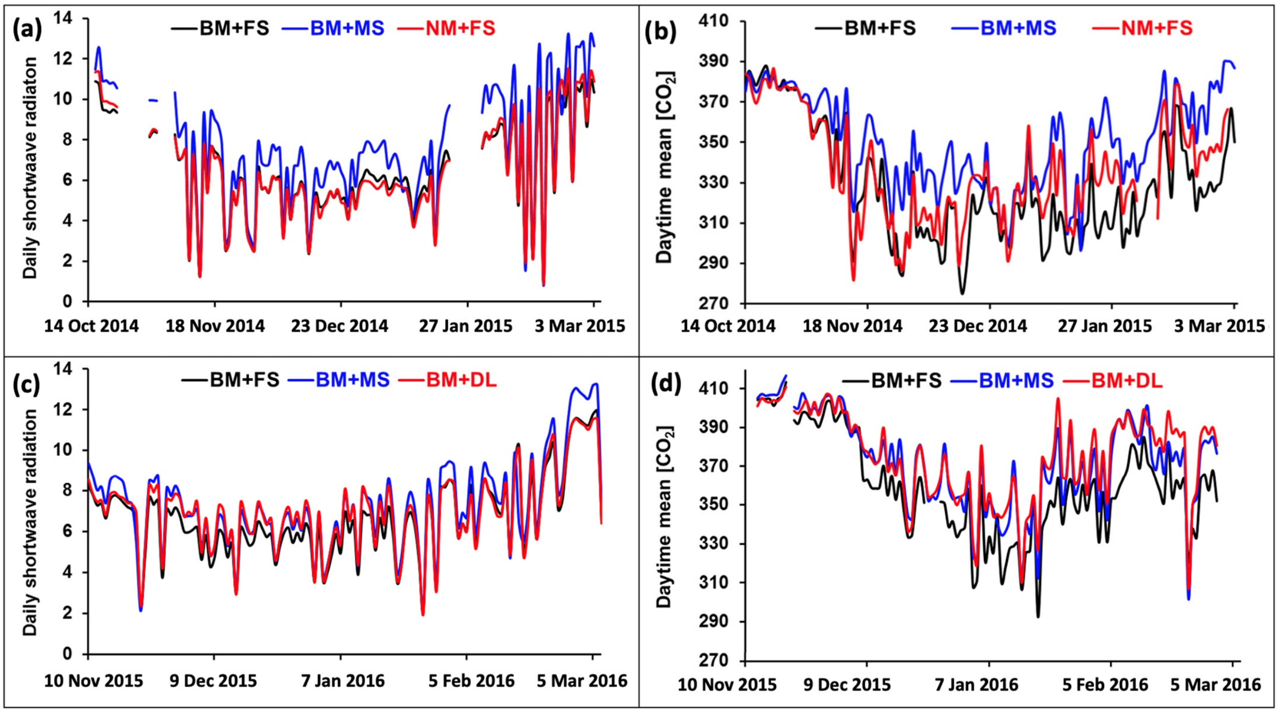

Figure 4. Daily integral of incoming shortwave radiation (MJ m^{-2} day^{-1}) and daytime mean CO_2 air concentration (µmol mol^{-1}) over the crop canopy throughout the following: (**a**,**b**) 2014/15 cucumber cycle in the greenhouse crops with black mulch and fixed screen (BM + FS), black mulch and movable screen (BM + MS), and without black mulch but with fixed screen (NM + FS); and (**c**,**d**) the 2015/16 cucumber cycle in the greenhouse crops with black mulch and fixed screen (BM + FS), with black mulch and movable screen (BM + MS), and with black mulch and double-layer covering (BM + DL).

Daytime mean CO_2 concentration in the air over the crop canopy was higher in the crop with the movable screen than in those with a fixed screen throughout most of the cucumber cycle, although differences were relatively small (Figure 4b). Averaged over the cold period, the daytime mean CO_2 concentration was 344, 329 and 316 µmol mol^{-1} in the BM + MS, NM + FS, and BM + FS crops, respectively.

The movable screen was folded during most of the daytime throughout the cucumber cycle, leading to higher incoming shortwave radiation above the crop and higher air renewal thorough the greenhouse vents.

3.1.2. Crop Growth and Productivity

At the end of the cycle, no significant differences were found between treatments for shoot biomass and its partitioning, although crops grown with black mulch presented slightly higher values of shoot biomass (Table 3): 786.1, 752,1, and 716.3 g m^{-2} for the BM + MS, BM + FS, and NM + FS crops, respectively.

Table 3. Shoot biomass and partitioning (vegetative and generative) and leaf area index (LAI) values at the end of two winter cucumber cycles grown in identical greenhouses with integrated passive heating systems. In the 2014/15 cycle, crops were grown in a greenhouse with black mulch and fixed screen (BM + FS), with black mulch and movable screen (BM + MS) and without black mulch and with fixed screen (NM + FS). In the 2015/16 cycle, crops were grown in a greenhouse with BM + FS, with BM + MS and with black mulch and double-layer covering (BM + DL). *: Different letters in the same column indicate significant differences ($p < 0.05$).

2014/15	Biomass (g m^{-2})			LAI
	Shoot	Vegetative	Generative	(m^{-2} m^{-2})
BM + FS	752.1 a *	257.3 a	494.9 a	3.5 a
BM + MS	786.1 a	293.8 a	492.3 a	3.6 a
NM + FS	716.3 a	273.1 a	443.2 a	3.7 a
2015/16				
BM + FS	648.0 a	233.5 a	414.6 a	3.2 a
BM + MS	670.7 a	254.1 a	416.6 a	3.5 a
BM + DL	658.5 a	220.1 a	438.4 b	3.5 a

At the end of this cycle, crops grown with black mulch produced a significantly higher fresh weight of marketable cucumber fruits (10.4 and 10.9 kg m^{-2} for the BM + MS and BM + FS crops, respectively) than that grown without black mulch (8.7 kg m^{-2}). They increased both yield components, the number of fruits and the fruit weight (Table 4). The non-marketable yield was significantly lower in the crop grown with black mulch and movable screen: 0.9 kg m^{-2} for the BM + MS crop versus 1.5 and 1.7 kg m^{-2} for the BM + FS and NM + FS crops, respectively. Crops grown with black mulch also produced a significantly higher fresh weight of first-class cucumber fruits (Table 4).

Table 4. Total, marketable and non-marketable yield, and yield components of marketable fruits at the end of two winter cucumber cycles grown in three identical greenhouses with integrated passive heating systems. In the 2014/15 cycle, crops were grown in a greenhouse with black mulch and fixed screen (BM + FS), with black mulch and movable screen (BM + MS), and without black mulch and with fixed screen (NM + FS). In the 2015/16 cycle, crops were grown in a greenhouse with BM + FS, with BM + MS and with black mulch and double-layer screen (BM + DL). *: Different letters in the same column indicate significant differences ($p < 0.05$).

2014/15	Yield (kg m^{-2})				Marketable Yield Components	
	Total	Marketable		Non-Marketable	Fruit Number (Fruit m^{-2})	Fruit Weight (g $Fruit^{-1}$)
		Total	First Class			
BM + FS	11.9 a *	10.4 b	9.9 b	1.5 b	26.9 ab	397 a
BM + MS	11.8 a	10.9 b	10.3 b	0.9 a	28.6 b	381 b
NM + FS	10.4 a	8.7 a	8.1 a	1.7 b	24.0 a	364 a
2015/16						
BM + FS	11.4 a	10.7 a	10.1 a	0.7 a	25.5 a	417 a
BM + MS	11.7 a	11.2 a	10.6 b	0.5 a	28.6 a	419 a
BM + DL	11.4 a	10.9 a	10.1 a	0.5 a	26.3 a	407 a

3.2. Cucumber 2015/16

3.2.1. Greenhouse Microclimate

Substrate, Soil, and Crop Temperature, and Air Humidity

Figure 5 shows daily mean values of coir grow-bag, air and crop temperatures, and air humidity throughout the cucumber 2015/16 cycle, as well as the averages over the cold crop period (December to February) of these variables. Daily mean temperatures in the coir grow-bags were similar for the three studied crop treatments throughout most of this cucumber cycle (Figure 5). They started at about 26 °C, rapidly decreased and then ranged between 16 and 22 °C throughout most of the remaining cycle. Averaged over the cold period, they were 18.2, 18.4, and 18.2 °C for the crops with a fixed screen, movable screen, and double-layer covering, respectively (Table 2). Hourly mean coir temperatures, averaged over the cold period, were similar for the three treatments, ranging between 16 and 20 °C (Figure 5). Moreover, the daily mean temperature in the middle of the enarenado soil layer was also relatively similar for the three treatments. Averaged over the cold period, they were 20.7, 21.1, and 21.0 °C for the crops with a fixed screen, movable screen, and double-layer covering, respectively (Table 2). Therefore, they were between 2 and 3 °C higher than the corresponding daily mean substrate temperatures.

The daily mean temperature of the air over the crop canopy was, in general, similar for the three treatments throughout most of the cycle (Figure 5), except for some days during the cold period, when they were slightly higher in the crop with a fixed screen. Averaged over the cold period, they were 16.2, 15.9, and 16.1 °C for the crops with a fixed screen, movable screen, and double-layer covering, respectively (Table 2). Hourly mean temperatures, averaged over the cold period, were slightly higher in the greenhouse with the fixed screen at daytime and similar for the three treatments at night (Figure 5). Daytime mean values over the cold period were 20.9, 20.3, and 20.5 °C for the crops with a fixed screen, movable screen, and double-layer covering, respectively (Table 2).

The daily mean crop temperature was, in general, similar for the three treatments throughout most of this cucumber cycle (Figure 5), except during the last part of the cold period, when they were sometimes higher for the crop with a fixed screen. Hourly mean values, averaged over the cold period, were slightly higher in the greenhouse with a fixed screen at daytime, and similar for the three treatments at night (Table 2, Figure 5).

The daily mean relative air humidity over the crop canopy was generally higher in the crop with double-layer covering throughout most of the first half of the cycle (Figure 5). Daily mean values were relatively high for the three treatments since mid-December. Hourly mean values over the cold period were higher in the crop with double-layer covering around nighttime and lower in the crop with movable screen throughout most of the day (Figure 5). Nighttime mean relative air humidity over the cold period was 88.6, 87.4, and 91.8% for the crops with a fixed screen, movable screen, and double-layer covering, respectively (Table 2), while daytime means were 77.5, 75.7, and 77.6%, respectively.

Cover Temperature and Water Condensation

In the greenhouse with double-layer covering the night mean cover temperature, averaged over the cold period, was about 2.3 °C higher on the lower surface of the internal film than on the upper surface of the external one (Figure 6), while in the greenhouses with movable and fixed screens, the night temperature on the lower and upper surfaces of the cover was similar.

Averaged over the cold period, night hourly mean dew-point temperatures of the air below the cover were higher than the corresponding temperatures measured on the lower cover surface of the greenhouse with the movable screen and on the lower surface of the internal film of the greenhouse with double-layer covering (Figure 6). Therefore, water condensation might have occurred frequently at night on the lower cover surface of both treatments. Nevertheless, condensation water did not usually fall onto the crops because the movable screen was unfolded at night and retained most of the water falling from the cover, while the water condensed on the lower surface of the internal anti-fog plastic material of the greenhouse with double-layer covering usually formed a water film, most of which ran off the surface and was collected.

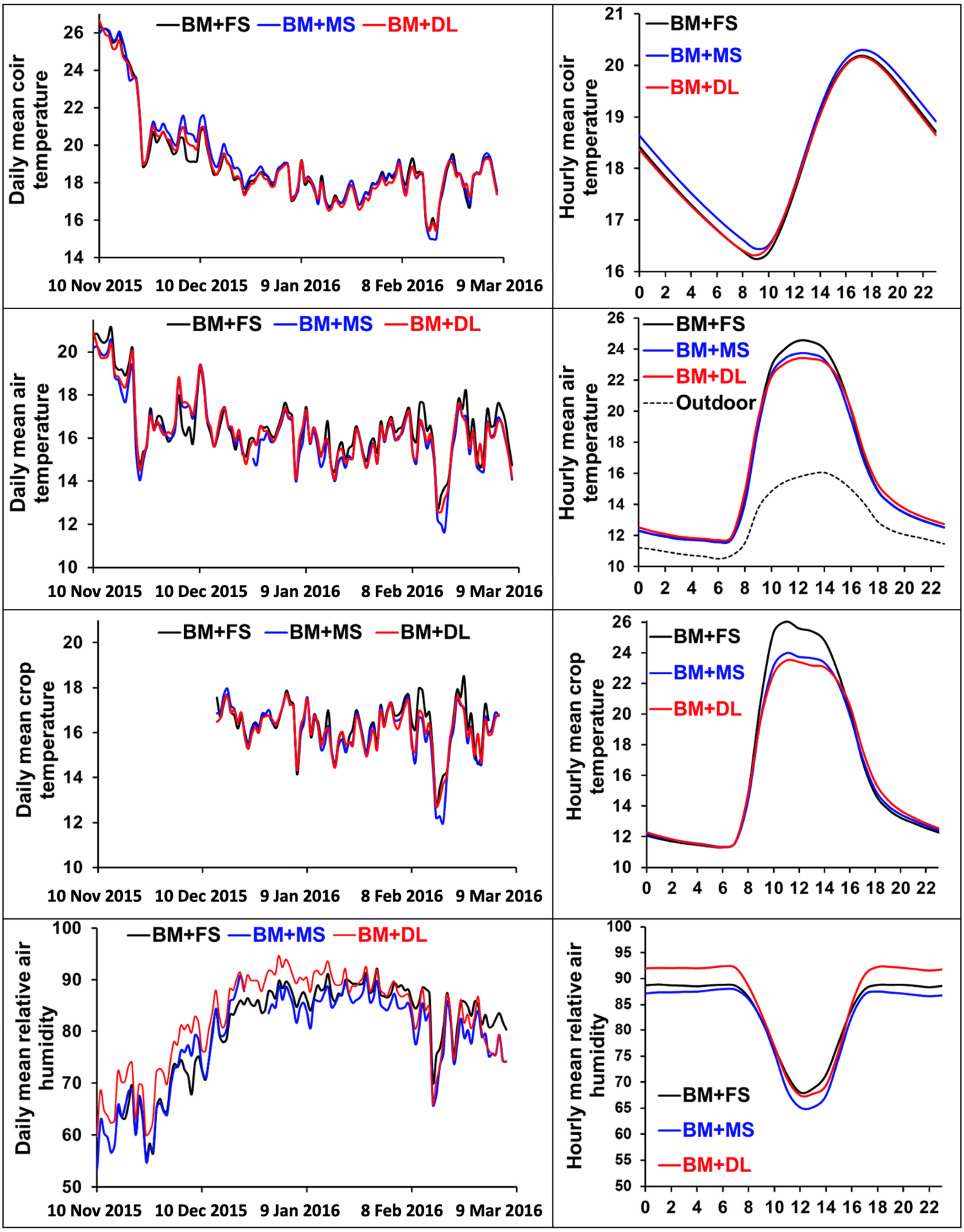

Figure 5. Daily mean values throughout the 2015/16 cucumber cycle and hourly mean values during the cold crop period (December to February) of coir grow-bag temperature (°C), air temperature (°C), crop temperature (°C), and relative air humidity (%) in greenhouse crops with black mulch and fixed screen (BM + FS), black mulch and movable screen (BM + MS), and black mulch and double-layer covering (BM + DL).

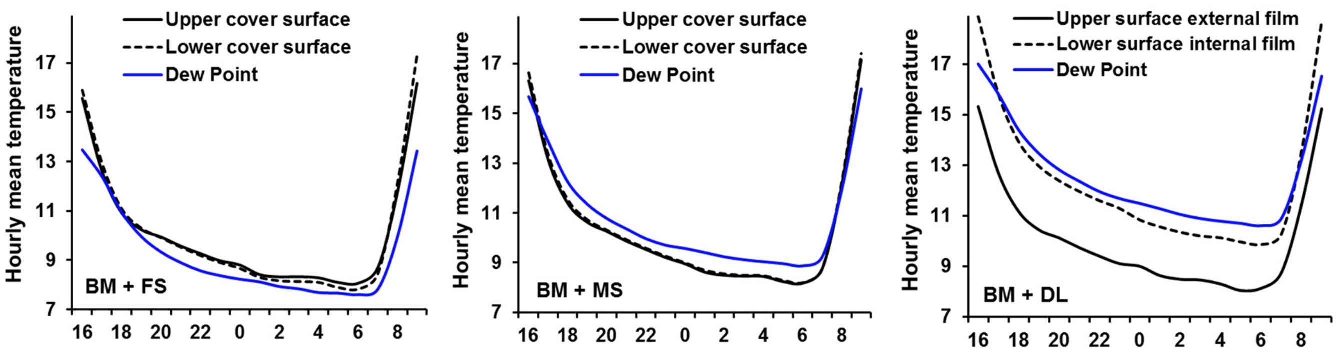

Figure 6. Night hourly mean values during the cold period (2015/16 cucumber cycle) of dew-point temperature of the air below greenhouse covers (°C), upper and lower cover surface temperatures (°C) of greenhouses with black mulch and fixed screen (BM + FS), and black mulch and movable screen (BM + MS), and upper surface temperature of the external film and lower surface temperature of the internal film of the greenhouse with double-layer covering (BM + DL).

Solar Radiation and Air CO_2 Concentration

The daily integral of the incoming shortwave radiation above the crop canopy was higher in the greenhouse with a movable screen than in that with a fixed one throughout most of this cycle (Figure 4c). The movable screen, as compared to the fixed one, increased the greenhouse solar radiation transmissivity by about 5%. The daily shortwave radiation in the greenhouse with double-layer covering was similar or slightly lower than that measured in the greenhouse with movable screen until mid-January (Figure 4c), but hereafter it relatively decreased and was close to that measured in the greenhouse with a fixed screen. This differential response was due to the occurrence of water condensation forming droplets on the lower surface of the external plastic film of the double-layer covering during the latter half of the cycle. The daily greenhouse transmission to shortwave radiation, measured at the end of this crop cycle (without condensation of water on the screen or the cover), was 0.54, 0.61, and 0.58 in the greenhouse with a fixed screen, folded movable screen, and double-layer covering, respectively, while it decreased to 0.43 when the movable screen was unfolded.

In general, daytime mean air CO_2 concentration was slightly higher in the greenhouses with double-layer covering and movable screen than in that with a fixed screen throughout most of the cycle (Figure 4d), but differences were relatively small. Averaged over the cold period, it was 353, 367, and 370 µmol mol^{-1} in the crops with a fixed screen, movable screen, and double-layer covering, respectively (Table 2), while the corresponding outdoor mean value was 396 µmol mol^{-1}.

3.2.2. Crop Growth and Productivity

At the end of this cucumber cycle, no significant differences between crop treatments were found for shoot, vegetative, or generative biomass (Table 4). Shoot biomass of the BM + FS and BM + MS crops were, on average, 14% lower than those measured in the previous 2014/15 cycle.

At the end of the crop cycle, the marketable and first-class fresh weight of cucumber fruits was slightly higher (5%) for the crop grown with movable screen (Table 4), although only the fresh weight of first-class cucumber fruits was significantly greater: 10.6 kgm^{-2} for the BM + MS crops versus 10.1 kg m^{-2} for the BM + FS and BM + DL crops. Cumulative fresh weight of total and marketable cucumber fruits were, in general, similar to those measured in the previous 2014/15 cucumber cycle (Table 4).

4. Discussion

To our knowledge, no information is available about the microclimate in Mediterranean greenhouse crops with black plastic mulch and movable thermal or fixed screen, and how crop cycles initiated or centred around the cold period (winter) respond to these combined passive heating systems. The use of black plastic mulch with a movable thermal or fixed impermeable screen increased the fresh weight of marketable and first-class fruits of a winter cucumber crop grown in a Mediterranean greenhouse (Table 4). The higher yield in these crop treatments appears to be mostly attributable to the higher substrate temperatures induced by the black mulch during the cold growth period (Figure 2, Table 2) since daily mean air temperatures, daily incoming shortwave radiation, and daytime mean air CO_2 concentration were similar for the crops with and without black mulch and with a fixed screen (Figures 2–4; Table 2). Daily mean substrate temperatures were around or below 15 °C for the crop without black mulch during most of the cold growth period. These substrate temperatures appear to be suboptimal for greenhouse cucumber production [17–23]. Our results agree with previous works showing that low root zone temperatures reduced the normal physiological activity of shoots by inhibiting water and nutrient transport, which reduced the growth and yield of tomato [24] and cucumber [25] seedlings. In addition, in experiments carried out in climate-controlled chambers, the authors of [23] found that increasing the mean root zone temperature from 15.5 to 20.3 °C significantly promoted the growth of cucumber plants during the entire growth period, increasing the dry weight of leaves, stems, and roots, and the fresh weight of cucumber fruits, and in the case of using carbon fertilization, it reduced acclimation effects. However, further field research is still needed to better quantify the most limiting factor for growth (substrate/soil or air temperature) in Mediterranean greenhouse crops grown during the cold period of the season and the range of suboptimal temperature values. The use of black plastic mulch in combination with a movable/fixed screen also increased soil temperatures, which were substantially higher (between 2 and 3 °C) than substrate temperatures for all studied treatments (Table 2). In the same area, the authors of [4] also found substantially higher soil temperatures, compared to substrate temperatures, for winter cycles of cucumber and melon crops grown in unheated Mediterranean greenhouses.

The black plastic mulch in combination with a movable/fixed screen resulted in a decrease of between 0.5 and 1.5 °C in night-time air, crop, and screen temperatures (Figures 2 and 3), since the black mulch cools quickly at night due to its high emissivity and reduces the energy exchange between soil and air, crop, and screen [3], as it is practically opaque to longwave radiation. Lower night-time air temperatures due to the use of black mulches in Mediterranean greenhouse crops grown in areas with outdoor air temperatures close to zero might increase the risk of crop frost damage, and their possible agronomical effects, if any, must be considered and further evaluated. To minimize these effects, floating row covers can be used in the early stages of crop cycles starting in early winter [4].

The lower crop and screen temperatures in the crops with black mulch at night, in combination with the high relative air humidity in the crops with a fixed screen, frequently resulted in water condensation on the lower screen surface during the cold growth period, since dew-point air temperatures around the night were clearly higher than the lower surface temperature of this screen (Figure 3). In order to reduce fungal disease proliferation in Mediterranean greenhouses with black mulch and a fixed screen, the screen has to be constructed with anti-fog plastic sheets forming a planar surface with enough slope to avoid screen condensation water falling on the crops [4].

The use of a movable, rather than a fixed screen, in combination with a black mulch increased the fresh weight of first-class fruits and reduced the fresh weight of non-marketable fruits of winter cucumber crops grown in Mediterranean greenhouses (Table 4). This effect might mainly be attributed to the higher incoming shortwave radiation (the screen was folded at daytime), and, to a lesser extent, to the higher daytime mean air CO_2 concentration during the cold period (Figure 4), when these inputs usually limit crop production in Mediterranean greenhouses [26,27]. Daytime air and crop temperatures and daily substrate temperatures were similar in the crop with a movable screen than in that with a fixed screen (Figures 2, 3 and 5). Moreover, the movable screen, compared to the fixed one, reduced the relative humidity of the air below the screen and above the crop (Figures 2 and 5) and, consequently, reduced the risk of condensation water on the lower screen surface and the crop (Figure 3). Water condensation might frequently have occurred at night on the lower surface of the cover of the greenhouse with movable screen since dew-point air temperatures around the night were clearly higher than the lower surface temperature of this cover (Figure 6), but this water did not fall onto the crops because the screen was unfolded and retained most of the water falling from the cover. In the same area, the authors of [4] also compared two identical greenhouses, one with a fixed and another with a movable impermeable screen, for a winter cucumber crop, but did not find crop yield differences because the folded movable impermeable screen used reduced the incoming shortwave radiation as much as the fixed impermeable screen. Overall, the use of movable thermal screens, which hardly reduce the incoming shortwave radiation transmissivity, could be of interest in Mediterranean greenhouses with climate controllers to improve winter microclimate and, consequently, crop yield. However, in common traditional Mediterranean greenhouses with low airtightness and without automatic ventilation controllers, the use of fixed, impermeable screen appears to be advisable [4].

The double-layer covering was an effective passive heating system for a Mediterranean greenhouse. The cucumber grown in the greenhouse with double-layer covering and black mulch showed similar substrate, air, and crop temperatures, and daytime mean air CO_2 concentrations to that grown in the greenhouse with movable screen and black mulch, but a higher relative air humidity above the crop canopy (Figures 4 and 5). The lower daily incoming shortwave radiation measured in the 2015/16 cucumber crop, particularly in the second half of the cycle, compared to the greenhouse with movable screen (Figure 4), was, at least partially, due to the formation of water condensation droplets on the lower surface of the external plastic film during daylight hours, which reduced the greenhouse shortwave radiation transmissivity [28,29]. This lower incoming shortwave radiation might explain its lower crop yield. In Mediterranean areas, the use of greenhouses with double-layer covering requires the installation of internal and external anti-fog and high-transparency films to minimize shortwave radiation losses and optimize the winter microclimate.

5. Conclusions

Representative combinations of passive heating systems (fixed, impermeable plastic screen with and without black plastic mulch; movable thermal screen with black plastic mulch; and double-layer plastic covering with black plastic mulch) were evaluated in two winter cucumber cycles grown in unheated Mediterranean greenhouses in Almería, SE Spain.

The use of black mulch in combination with a porous movable or fixed impermeable screen increased the cucumber yield, which appears to be mostly attributable to higher substrate temperatures induced by the black mulch in the cold crop period. In addition, the black mulch in combination with a movable/fixed screen decreased between 0.5 and 1.5 °C night-time air, crop, and screen temperatures, which contributed to the frequent occurrence of screen water condensation, particularly in the crop with black mulch and fixed screen. In Mediterranean greenhouses with black mulch and fixed screen, the screen should be constructed with anti-fog plastic sheets forming a planar surface with enough slope to avoid the screen condensation water falling on the crops.

The use of movable thermal screens, which hardly reduce the incoming shortwave radiation transmissivity, appears to be of interest in Mediterranean greenhouses with climate controllers to improve winter microclimate, while fixed, impermeable screens are recommended for common traditional Mediterranean greenhouses with low airtightness and without automatic ventilation controllers.

The use of greenhouses with double-layer coverings in Mediterranean areas requires the installation of internal and external anti-fog and high-transparency films to minimize shortwave radiation losses and optimize the winter microclimate, although further experimental research is needed to optimise their installation and use.

Passive systems of heating are being more and more used in Mediterranean greenhouse crops during the cold period of the season to improve the greenhouse solar radiation efficiency and, consequently, the microclimate, sustainability, and productivity of these crops. However, further field research is needed to identify the most limiting factor for growth (substrate/soil or air temperature, water condensation, etc.), to define the range of suboptimal temperatures and to evaluate new or improved passive heating systems for the main crop cycles.

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