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Evaluation of New Passive Heating Systems for Low-Cost Greenhouses in a Mild-Winter Area

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Abstract

The main objective of this work was to evaluate new variants of passive heating systems used for horticultural crop cycles planted in the cold period in low-cost greenhouses on the Mediterranean Spanish coast (a mild-winter area). The double low cover (DLC) is variant of the conventional fixed plastic screen that reduces the air volume and increases the airtightness around crops. Three identical DLCs were installed inside a typical greenhouse, and the microclimate measured in the three DLCs was similar. The DLCs reduced the solar radiation transmissivity coefficient by around 0.05 but increased the mean daily substrate and air temperatures (up to 1.6 and 3.6 °C, respectively). They also modified the air humidity, although this can be modulated by opening the vertical sheets located on the greenhouse aisles (DLC vents). The black plastic mulch forming an air chamber around the substrate bags (BMC), a new mulch variant used in substrate-grown crops, increased the substrate temperature with respect to the conventional black mulch covering the entire ground surface. The combination of BMC plus DLC increased the mean daily substrate temperature by up to 2.9 °C, especially at night. Low tunnels covered with transparent film and with a spun-bonded fabric sheet were also compared, and both materials were efficient heating systems regarding substrate and air temperatures. Low tunnels combined with the DLC substantially increased air humidity, but this can be partially offset by opening the DLC vents. The combination of low tunnels and DLC does not seem recommendable for greenhouse crops planted in winter, since both systems reduce solar radiation transmissivity.

Keywords: air temperature; black mulch; fixed screen; low tunnel; passive heating system; radiation; substrate temperature

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1. Introduction

Greenhouses are spreading worldwide, and many are located in mild-winter areas like the Mediterranean basin and China. In these regions, passive greenhouses (low-cost, unheated, and naturally ventilated) predominate [1,2]. In these greenhouses, the microclimate, highly dependent on outdoor conditions [3], is frequently outside the optimal range for horticultural crop production in the cold period (around winter) of the cropping season [2,4,5]. Air temperature at night and in the hours of the early morning is often

below or around the base temperature for most fruit–vegetable greenhouse crops (8–12 °C), limiting their growth and development [6–8] and inducing chilling or low-temperature plant damage [9,10]. Air humidity is often excessive, especially at night and in the early morning, and greenhouses have to be frequently ventilated with cold outside air in the early morning to avoid water condensation on crop and cover surfaces [11,12]. In addition, soil and, in particular, substrate temperatures can be suboptimal [13,14], and low root zone temperatures might reduce the normal physiological activity of shoots by inhibiting water and nutrient transport, which, in turn, reduces crop growth and yield [14,15].

In these low-cost greenhouses, passive heating systems, such as gravel–sand and plastic mulches; fixed, internal, plastic screens; low tunnels; floating row covers, etc., are often used to improve the winter microclimate [16] since active heating systems are usually considered neither economically viable nor environmentally sustainable [5,8]. Plastic mulches and fixed screens have been evaluated in Mediterranean greenhouses [12,17], but new variants of these systems have been developed, particularly for extra-late and extra-early crop cycles transplanted in the cold period, when temperature becomes the main factor limiting crop production [16].

A new fixed plastic screen, named a double low cover (DLC), is being implemented for extra-late or extra-early cycles of horticultural crops (Figure 1a,b). It consists of plastic sheets joined hermetically by wires and located horizontally directly on the wire grid of the greenhouse trellis system (roof) and vertically on all sides (walls), including the aisles of the greenhouse [18]. This DLC system, compared to the conventional fixed plastic screen located between the wire grid of the trellis system and the greenhouse roof [12], increases the greenhouse airtightness and reduces the air volume around the crop. Moreover, when needed, the vertical plastic sheets of the DLCs located on the greenhouse aisles can be opened manually in the warm daytime period to avoid thermal and hygrometric excesses. Logically, this system, often used in combination with the conventional fixed plastic screen, has to be removed before the plant reaches the wire grid of the trellis system, usually located at a 2.0–2.2 m height.

A new black mulch system forming an air chamber above the substrate bag (BMC) is also being used in extra-late cycles of sweet pepper crops grown on substrate bags. It consists of black plastic sheets (about 1.2 m wide) centered along the crop rows above the substrate bags (Figure 1c,d). The plastic sheet, supported by the microtubes of the drip irrigation system, creates a small air chamber above the substrate bags [18], thus heating the substrate and generating warm air around the plant.

Low tunnels, wire arches inserted into the soil and covered with plastic covering materials, are also used in Mediterranean greenhouses in the early growth phases of crops planted in winter to improve the crop microclimate and minimize early virus incidence by reducing pest entry and proliferation [19]. These tunnels usually increase soil/substrate, air, and crop temperatures and air humidity but decrease incoming solar radiation [19,20], and the intensity of these effects mainly depends on the covering material's characteristics and low-tunnel management. In Spanish Mediterranean greenhouses, both transparent polyethylene (PE) film and spun-bonded polypropylene fabric (Figure 1e,f) are used for covering low tunnels depending on crop cycle and species, greenhouse characteristics, pest incidence, etc. [18]. For instance, spun-bonded fabric coverings, which minimize water condensation falling onto the crops, are often used in crops that are more sensitive to diseases. Information about the microclimate effects of low tunnels in Mediterranean greenhouses is scarce [19], in particular the comparison of the microclimate of low tunnels covered with the most common plastic materials.

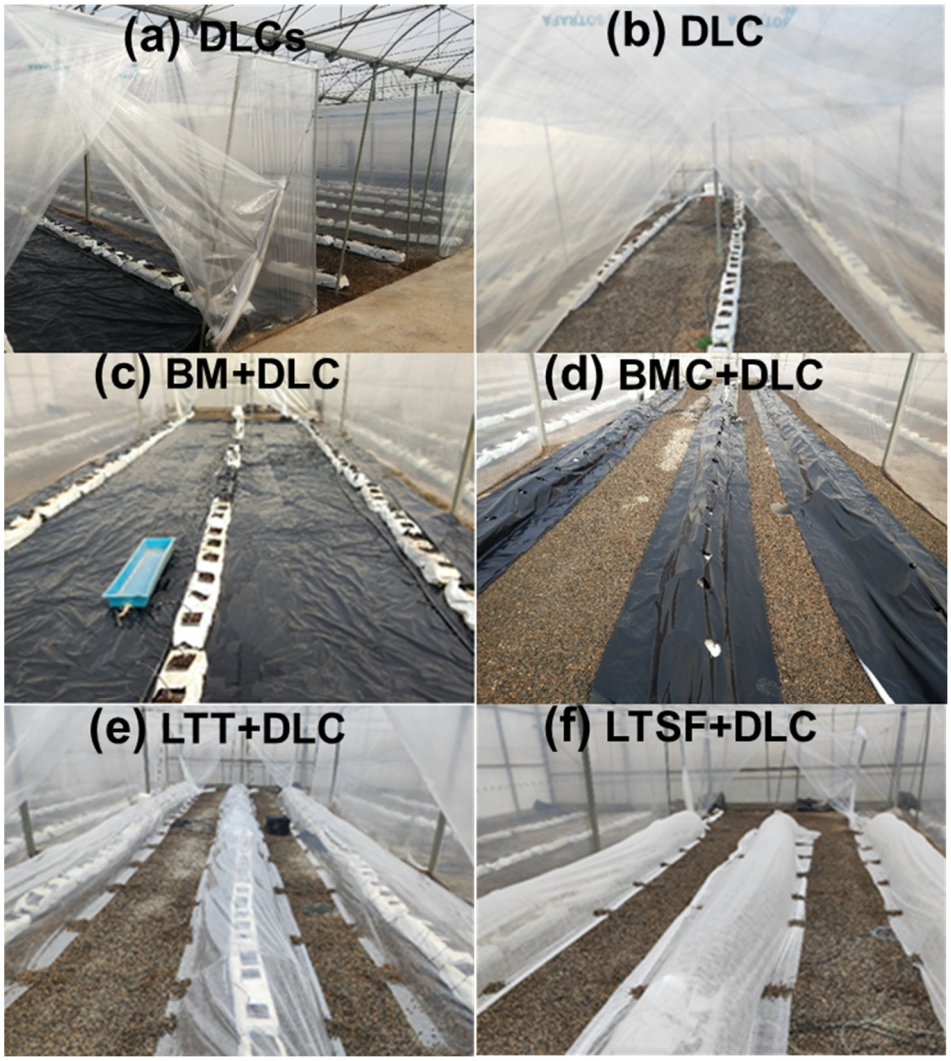


Figure 1. (**a**) External view of the double low covers (DLCs) installed inside the experimental greenhouse and internal views of (**b**) the DLC without additional heating systems and manual vents; (**c**) the conventional black mulch covering the entire ground surface inside a DLC (BM + DLC); (**d**) the black plastic mulch forming an air chamber around the substrate bags inside a DLC (BMC + DLC); (**e**) the low tunnel covered with transparent polyethylene film inside a DLC (LTT + DLC); and (**f**) the low tunnel covered with spun-bonded fabric sheets inside a DLC (LTSF + DLC). Almería, Spain.

This work analyses the microclimate in the cold crop period of a low-cost, Mediterranean greenhouse with the following passive heating systems: (i) a double low cover; (ii) conventional black mulch and black mulch forming an air chamber around the substrate bags; and (iii) a low tunnel covered with either transparent PE film or spun-bonded fabric sheets. Moreover, combined heating systems (double low cover plus black mulches and double low cover plus low tunnels) are also assessed.

2. Materials and Methods

2.1. Experiments and Treatments

Three experiments were conducted in the cold period of the 2022/23 season (November 2022 to March 2023) in a three-span greenhouse (24 m × 30 m, Figure 2) located at the IFAPA La Mojonera Research Center (36°30′ N, 2°18′ W, 140 m.a.s.l.), Almería, Spain. The arch-roofed greenhouse (5.8 m high to the ridge and 4.0 m to the eave) was east–west-oriented and had one roof vent per span and a sidewall rolling vent on the southern and northern sides automatically managed by a climate controller (HortiMaX MultiMa, Ridder,

Maasdijk, The Netherlands). The covering material was a 200 µm thick thermal plastic film (Reytec-A, Ejidofil-Reyenvas, El Ejido, Spain) with a transmissivity of 89% to visible solar radiation and 8% to longwave radiation (manufacturer's data). The growth media were 29 L coconut coir bags (Fico, Grupo Fico Ispemar, Roquetas de Mar, Spain), laid on leveled soil covered with coarse gravel. The greenhouse remained without crops, but the substrate bags were irrigated (Xilema NP-30 Start, Novagric, Novedades Agrícolas, Almeria, Spain) one to three times a day to simulate common irrigation practices during the early stages of substrate-grown crops. These experimental conditions can be considered representative of the early stages of fruit-vegetable crops transplanted in winter when they have a low leaf area index [18].

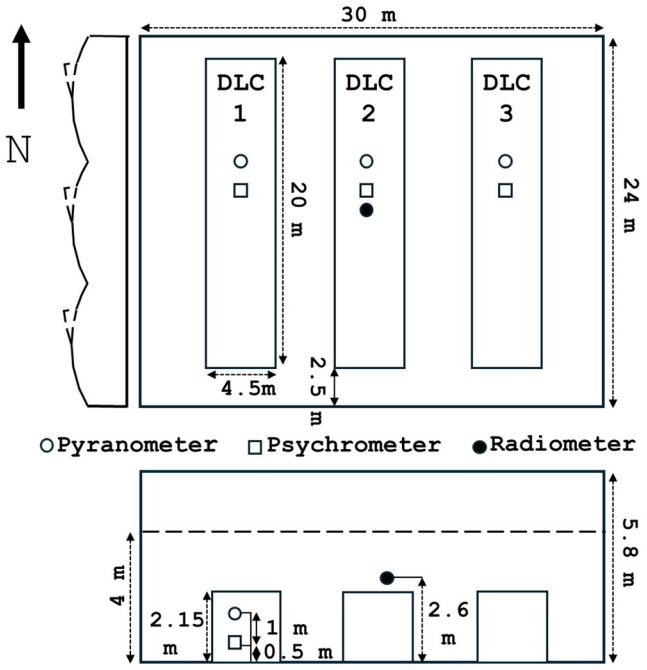


Figure 2. Schematic diagrams of the experimental greenhouse, the three identical double low covers (DLCs), and the sensor locations. Almería, Spain.

Three identical double low covers (DLCs) were installed inside the greenhouse (Figure 2). Each DLC (4.5 m wide, 20 m long, and 2.1 m high) included three crop rows 1.5 m apart and was covered with high-transparency anti-drip plastic film (anti-drip, high-transparency DC, Sotrafa SA, Almeria, Spain) with a thickness of 37.5 µm and a visible radiation transmissivity of 97%. Sheets were hermetically joined by wires and placed horizontally above the trellis wires of the greenhouse and vertically to the ground to form four side walls for each DLC. The east and west wall sheets were buried into the ground, while the north and south wall sheets were weighted down to the ground but could be opened manually (DLC vents, Figure 1a,b) to renew the air in the DLC.

In the first experiment, the greenhouse microclimate was evaluated both inside and outside each DLC. Subsequently, having concluded that the three DLCs generated a similar microclimate (Section 3.1), two additional experiments were carried out.

In the second experiment, conventional black plastic mulch (Figure 1c) was placed on the entire soil surface of one DLC (BM); in another DLC, a 1.2 m wide sheet of black plastic was placed along the crop rows, above the substrate bags (BMC, Figure 1d), while a third DLC was placed without black mulch (DCL control). Plastic sheets for the BMC treatment were supported by the microtubes of the drip irrigation system, forming an air chamber around the substrate bags. Wide holes were made in the raised part of the sheet to facilitate crop transplantation and growth. In both plastic treatments, 42.5 µm thick

bicolour (black/white) plastic film was used (black/white mulch, Solplast SA, Almería, Spain) with a shortwave radiation transmissivity of less than 0.01, a reflectivity of 0.04, an absorptivity of 0.95, and a longwave radiation transmissivity of 0.15 (manufacturer's data).

In the third experiment, low tunnels with transparent PE film (LTT, Figure 1e) or spun-bonded polypropylene fabric sheets (LTSF, Figure 1f) were installed along the crop rows in separate DLCs, while the third DLC without low tunnels was used as a control (DCL control). Low tunnels were supported on wire arches with a length of 1.6 m, separated by 1.5 m, and forming an arc with a 0.45 m height and 0.8 m width. The transparent PE film (LTT treatment) was 37.5 µm thick (DC cristal, Solplast SA, Almería, Spain) and 1.75 m wide and had 96% visible radiation transmissivity (manufacturer's data). The spun-bonded polypropylene non-woven fabric (LTSF treatment) was 1.75 m wide and weighed 17 g m^{-2}. Covering materials were secured to the ground with soil along the sides and at the ends.

2.2. Measurements

In each experiment, the greenhouse microclimate was measured inside each DLC and outside, as well as outdoors, for 4 to 8 representative days under three DLC vent strategies: (i) closed 24 h a day; (ii) open only during central daylight hours (8 h); and (iii) open 24 h a day. In commercial greenhouses, DLC vents are usually closed 24 h a day, but on sunny days, they are often open during central daylight hours.

In the middle of each DLC (Figure 2) and the middle of the greenhouse outside the DLCs (greenhouse), air temperature and relative humidity were measured with ventilated psychrometers (HMP155, Vaisala, Vantaa, Finland) and substrate bag temperature was measured with three thermistors per treatment (T107 and T108, Campbell Scientific, Inc., Logan, UT, USA). The psychrometers had an accuracy of ±0.2 °C and ±1.7%, and the thermistors had an accuracy of ±0.2 °C. Thermistors were inserted horizontally in the middle of representative substrate growth bags. The incoming solar radiation was measured with pyranometers (model CM6, Kipp & Zonen, Delft, The Netherlands) in the middle of each DLC and with a net radiometer (CNR1, Kipp & Zonen) in the middle of the greenhouse. The net radiometer was located 2.6 m aboveground. In the first (DLC evaluation) and second (black mulches) experiments, psychrometers and pyranometers were installed 0.5 m and 1.5 m aboveground, respectively. In the third experiment (low tunnels), psychrometers were placed 0.3 m aboveground and pyranometers were placed 0.2 m aboveground above the substrate bags, both inside the low tunnels. Moreover, the air temperature in the chamber formed by the black mulch above the substrate bags was measured with two thermistors (T107, Campbell Scientific Inc., Logan, UT, USA) in the second experiment. Before starting the experiments, the psychrometers, thermistors, and pyranometers used were calibrated. Climate variables were measured every two seconds, and data were averaged and stored every five minutes in dataloggers (CR3000, Campbell Scientific, Ltd., Leicestershire, UK).

In the first experiment, a boxplot analysis was conducted to assess the mean hourly values of substrate and air temperature, relative air humidity, and solar radiation measured inside the three identical DLCs installed in the greenhouse.

3. Results

3.1. Double Low Cover (DLC)

The substrate and air temperatures, air humidity, and incoming solar radiation were similar inside each of the three double low covers studied (DLCs). The mean hourly values of substrate temperature, air temperature, relative air humidity, and solar radiation measured inside the three DLCs studied had similar medians, means, interquartile ranges (25–75%), and dispersions (Figure 3). The small differences observed between the three

DLCs for each climate variable studied were lower than or similar to the sensor's accuracy. Consequently, we consider that the microclimates inside the three DLCs were similar, and the mean hourly values of the three DLCs (±SEM) are presented for each measured climate variable (Figures 4 and 5).

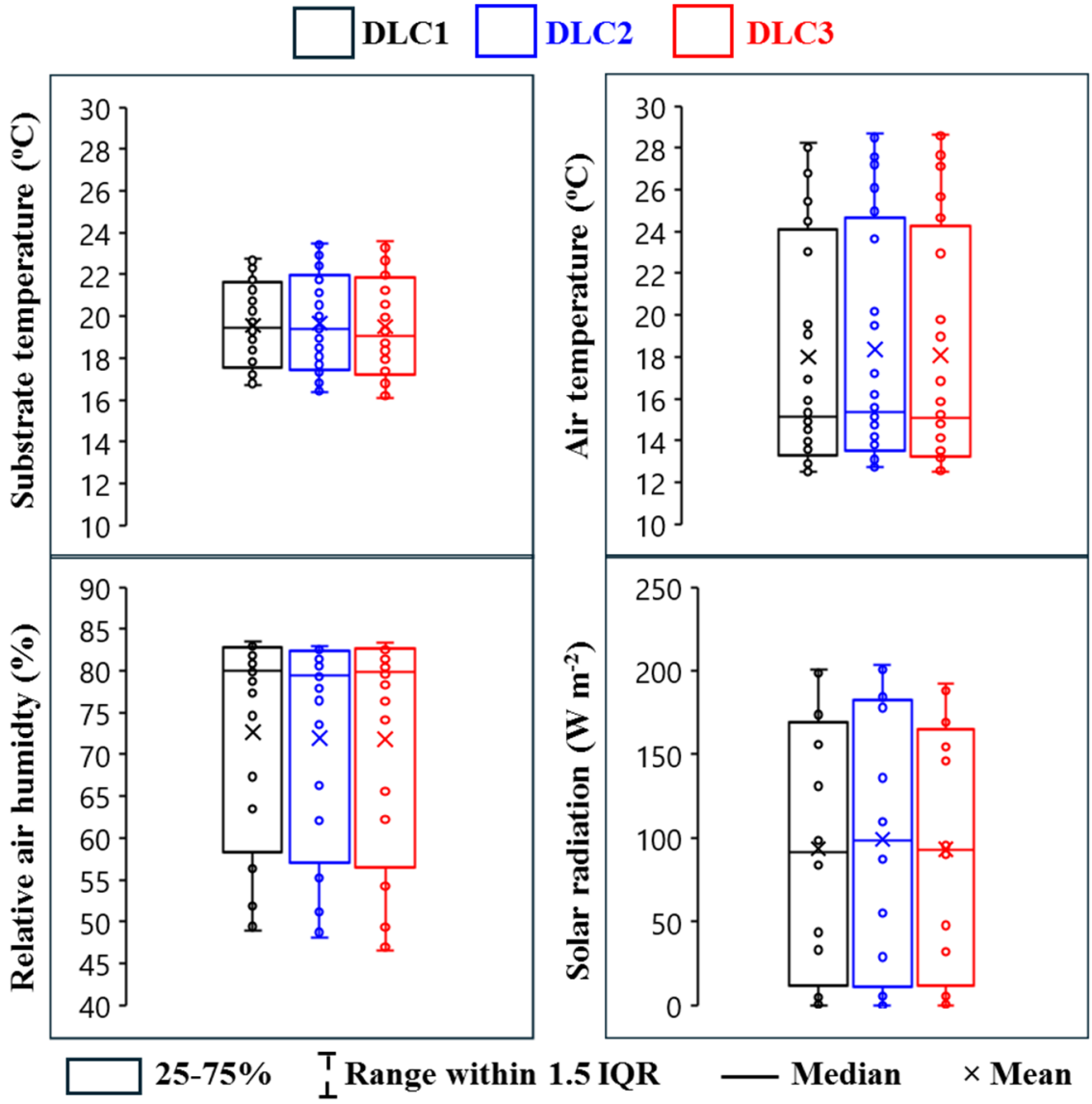


Figure 3. Descriptive statistics presented by boxplots of the climate parameters (hourly mean values of substrate temperature, air temperature, relative humidity, and solar radiation) measured inside the three double low covers studied: DLC1, DLC2, and DLC3.

The DLC increased the substrate temperature throughout the day with respect to the greenhouse, and the increment was greater as the DLC ventilation decreased (Figure 4). The mean daily substrate temperature, with respect to the greenhouse, increased on average by 0.6, 1.1, and 1.5 °C when the DLC vents were open for 24 h a day, open during central daylight hours, and closed for 24 h a day, respectively (Table 1).

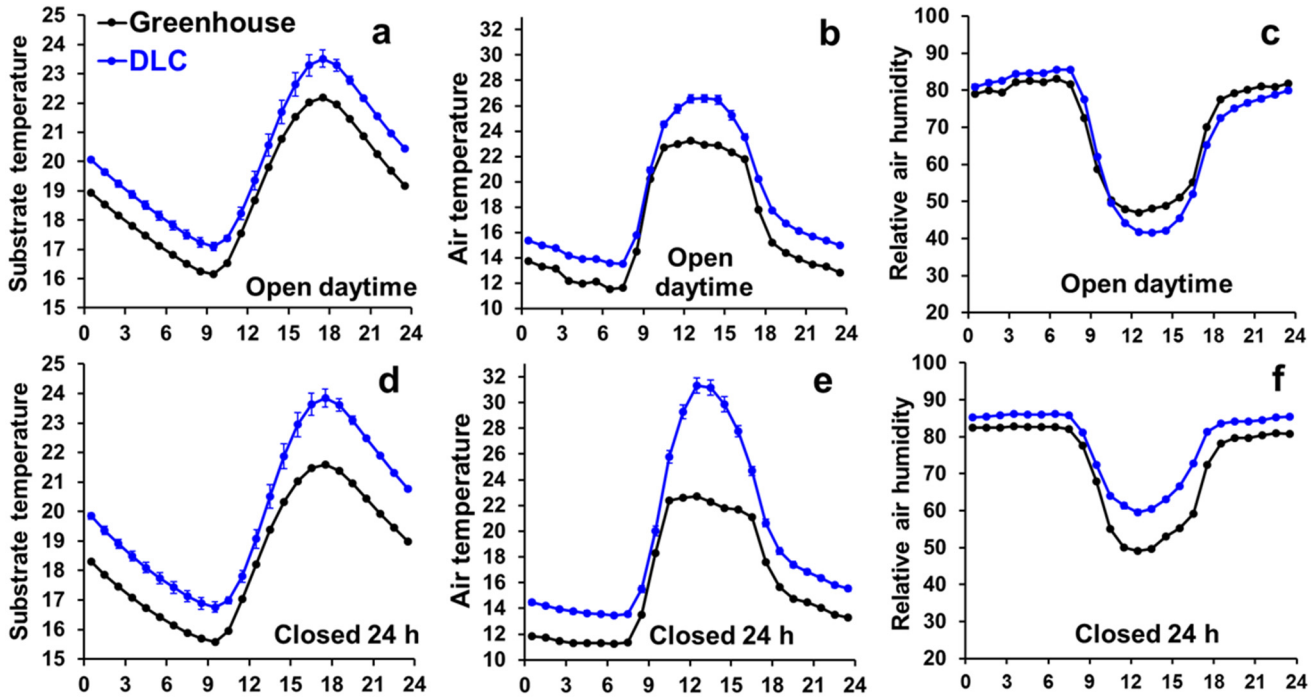


Figure 4. Hourly mean values ± standard error of the mean (SEM) of substrate bag temperature (°C), air temperature (°C), and relative air humidity (%) inside the three double low covers (DLCs) and inside the greenhouse when DLC vents were open during central daylight hours ((**a**–**c**), respectively) and closed 24 h (**d**–**f**).

Table 1. Mean values of substrate (T_S) and air (Ta) temperatures (°C) and air relative humidity (HR, %) measured in experiment 1: means for the three identical double low covers (DLCs); experiment 2: a DLC with conventional black mulch (BM + DLC), with black mulch forming an air chamber around the substrate bag (BMC +DLC), and without black mulch (DLC); and experiment 3: a DLC with low tunnels covered with a transparent film (LTT + DLC), with low tunnels covered with spoon-bonded fabric sheet (LTSF + DLC), and without low tunnels (DLC). These variables were also measured inside the greenhouse, outside the DLC (greenhouse), and outdoors. Measurements were taken while keeping the DLC vents closed for 24 h a day, open during central daylight hours and closed the rest of the day, and open for 24 h a day.

Experiment 1 (DLCs)	Open 24 h			Open daytime			Closed 24 h		
	T_S	Ta	RH	T_S	Ta	RH	T_S	Ta	RH
DLC	18.8	16.9	66.2	20.1	18.6	68.8	20.0	19.5	78.2
Greenhouse	18.3	15.6	69.5	19.0	16.4	70.0	18.5	15.9	72.0
Outdoors	-	14.1	55.0	-	-	-	-	13.6	64.0
Experiment 2 (black mulches)	Open 24 h			Open daytime			Closed 24 h		
	T_S	Ta	RH	T_S	Ta	RH	T_S	Ta	RH
BMC + DLC	18.1	14.6	54.7	19.4	16.7	64.8	20.3	18.7	66.9
BM + DLC	16.8	14.7	57.0	18.6	17.1	66.8	19.9	19.0	74.3
DLC	16.8	14.7	55.8	18.6	16.8	61.8	19.6	18.8	70.6
Greenhouse	16.2	13.1	57.0	16.9	14.1	62.3	17.5	15.1	53.3
Outdoors	-	9.5	40.0	-	10.7	52.8	-	10.1	43.7

Table 1. *Cont.*

Experiment 3 (low tunnels)	Open 24 h			Open daytime			Closed 24 h		
	T_S	Ta	RH	T_S	Ta	RH	T_S	Ta	RH
LTSF + DLC	20.6	20.6	52.2	21.6	21.1	67.7	22.1	21.0	69.7
LTT + DLC	20.4	20.6	57.9	21.3	21.1	66.4	21.3	20.6	69.6
DLC	20.0	19.8	49.1	21.0	20.4	61.4	20.9	20.1	67.5
Greenhouse	19.2	17.9	49.6	19.8	18.0	59.5	18.3	15.2	52.5
Outdoors	-	14.5	37.2	-	14.8	55.9	-	10.6	38.3

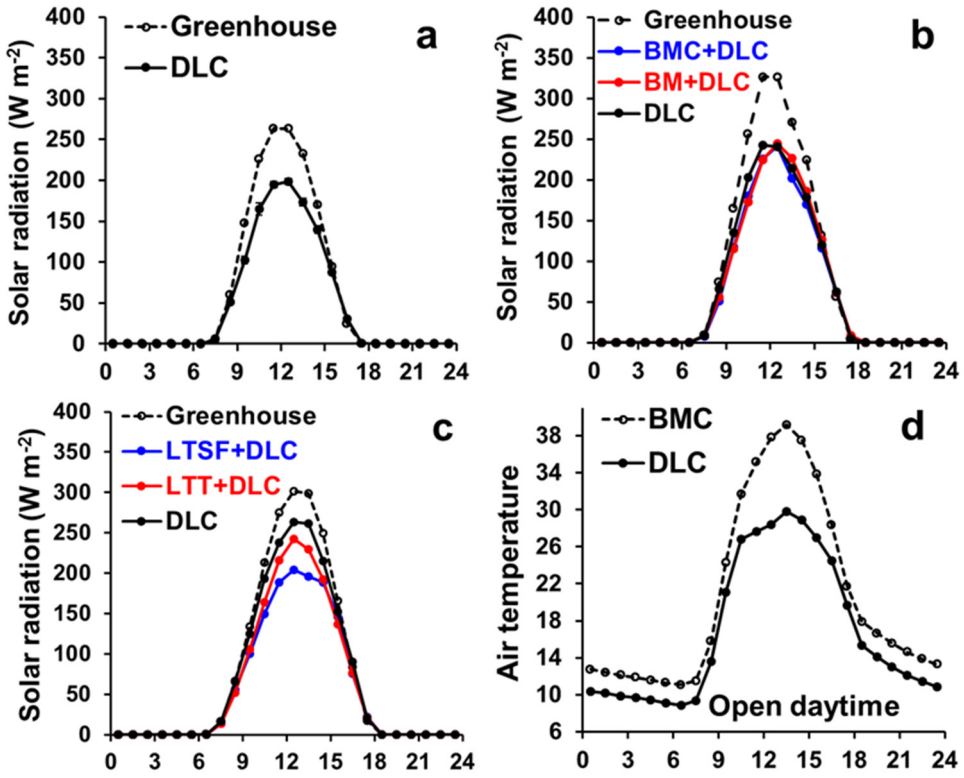


Figure 5. Hourly mean values of incoming solar radiation inside (**a**) the greenhouse and the double low covers (DLCs); (**b**) the greenhouse and the double low cover control (DLC), with conventional black mulch (BM + DLC) and with black mulch forming an air chamber around the substrate bags (BMC + DLC); (**c**) the greenhouse and the double low cover control (DLC), with low tunnels covered with PE film (LTT + DLC) and with low tunnels covered with spun-bonded fabric sheet (LTSF + DLC). (**d**) Hourly mean air temperature inside the air chamber around the substrate bag (BMC) and inside the DLC when DLC vents were open during central daylight hours.

The DLC also increased the air temperature throughout the day, especially during central daylight hours when solar radiation is usually highest, and the increment was greater as the DLC ventilation decreased (Figure 4). The mean daily air temperature increased, on average, by about 1.3, 2.2, and 3.6 °C, with respect to the greenhouse, when the DLC vents were open for 24 h, open during central daylight hours, and closed for 24 h a day, respectively (Table 1).

The DLC's effects on the relative air humidity depended on the DLC's vent management (Figure 4). When vents were open during central daylight hours, the mean daily relative air humidity increased slightly for most of the night and slightly decreased during most of the daytime, while when they were closed for 24 h a day, it increased, on average, by about 6%, with higher increments during daylight hours (Table 1).

The incoming solar radiation inside the DLCs and the greenhouse were averaged for the three vent management strategies, since this variable is not affected by DLC vent management. The DLC clearly reduced the incoming solar radiation, particularly during central daylight hours (Figure 5). The mean daily integral of the incoming solar radiation was about 22% lower inside the DLCs (4.1 MJ m^{-2} day^{-1}) than in the greenhouse (5.3 MJ m^{-2} day^{-1}), and the solar radiation transmission coefficient was 0.42 in the DLC and 0.53 in the greenhouse.

3.2. Black Mulches

Figure 6 shows the mean hourly values of substrate and air temperatures and air humidity when DLC vents were open during central daylight hours and closed for 24 h, while Table 1 presents the corresponding mean daily values for all the DLC vent management strategies. The conventional black plastic mulch combined with the double low cover (BM + DLC) hardly modified the substrate temperature with respect to the DLC without black mulch when the DLC vents were open during central daylight hours (Figure 6 and Table 1), and it slightly increased this variable when the vents were closed for 24 h. However, the black mulch forming an air chamber above the substrate bags combined with the DLC (BMC + DLC) increased the substrate temperature, compared to the DLC control, particularly at night (Figure 6), which might be due to the high air temperatures inside the air chamber (Figure 5d). The BM + DLC heating system, compared to the greenhouse, increased the mean daily substrate temperature, on average, by about 0.6, 1.6, and 2.1 °C when the DLC vents were open for 24 h, open during central daylight hours, and closed for 24 h, respectively (Table 1), while the BMC + DLC heating system increased this temperature, on average, by about 1.9, 2.5, and 2.8 °C, respectively.

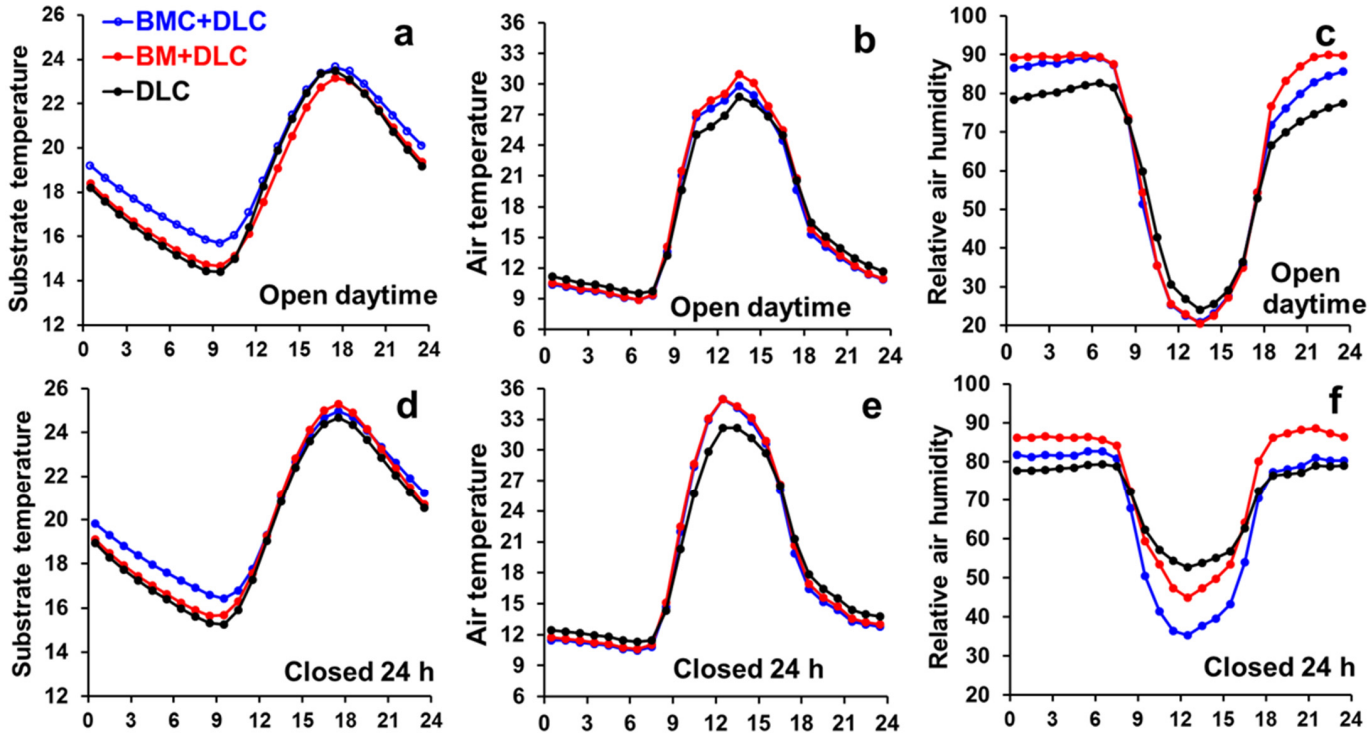


Figure 6. Hourly mean values of substrate temperature (°C), air temperature (°C), and relative air humidity (%) in the double low cover control (DLC), the DLC with a conventional black mulch (BM + DLC), and the DLC with a black mulch forming an air chamber around the bags (BMC + DLC) when DLC vents were open during central daylight hours ((**a**–**c**), respectively) and closed 24 h a day (**d**–**f**).

Both black mulch systems combined with the DLC (BM + DLC and BMC + DLC) increased daytime air temperatures and decreased nighttime air temperatures, with respect to the DLC control, regardless of DLC vent management (Figure 6), but the mean daily air temperatures of both black mulch systems were similar to that of the DLC control (Table 1). The BM + DLC heating system, compared to the greenhouse, increased the mean daily air temperature, on average, by about 1.5, 3.0, and 3.9 °C, while the BMC + DLC heating system increased this temperature, on average, by about 1.5, 2.7, and 3.7 °C when the DLC vents were open for 24 h, open during central daylight hours, and closed for 24 h, respectively (Table 1).

The effects of the black mulch systems combined with the DLC on the relative air humidity depended on DLC vent management (Figure 6). When they were open during central daylight hours and closed for 24 h, both combined heating systems increased the relative air humidity at night and decreased it during the daytime, compared to the DLC control, and these effects were more pronounced during daytime and when the vents were closed for 24 h. Moreover, both black mulch systems combined with the DLC achieved high values of relative air humidity, between 80 and 90%, at night.

The DLC control presented similar increases in substrate and air temperatures and relative air humidity, with respect to the greenhouse, to those found in Section 3.1, except for the relative air humidity, which was higher when the vents were closed for 24 h a day (Table 1).

Regardless of the black mulch treatments, the DLC reduced the incoming solar radiation, particularly around midday (Figure 5). The mean daily integral of the incoming solar radiation was about 22% lower inside the DLCs (5.2 MJ m^{-2} day^{-1}) than in the greenhouse (6.6 MJ m^{-2} day^{-1}), while the solar radiation transmission coefficient inside the DLCs was 0.11 lower than in the greenhouse.

3.3. Low Tunnels

Figure 7 shows the mean hourly values of substrate and air temperatures and air humidity when the DLC vents were open during central daylight hours and closed for 24 h, and Table 1 presents the corresponding mean daily values for all the DLC vent management strategies. With respect to the DLC control, both low-tunnel systems in combination with the DLC (LTT + DLC and LTSF + DLC) increased the substrate temperature around nighttime, particularly when covered with spun-bonded fabric (Figure 7). With respect to the greenhouse, the mean daily substrate temperature was increased, on average, by 1.2, 1.5, and 3.0 °C by the LTT + DLC heating system and by 1.5, 1.9, and 3.8 °C by the LTSF + DLC heating system when the DLC vents were open for 24 h, open during central daylight hours, and closed for 24 h, respectively (Table 1).

No differences in air temperatures were found between the two types of low-tunnel systems (LTT + DLC and LTSF + DLC) (Figure 7). With respect to the DLC control, both low-tunnel systems slightly increased the mean daily air temperature (Table 1), mainly during the daytime when the DLC vents were open during central daylight hours. With respect to the greenhouse, the mean daily air temperature was increased, on average, by 2.7, 3.1, and 5.4 °C by the LTT + DLC heating system and by 2.6, 3.1, and 5.8 °C by the LTSF + DLC heating system when the DLC vents were open for 24 h, open during central daylight hours, and closed for 24 h, respectively (Table 1). Moreover, the relative air humidity was increased by the LTT + DLC heating system, mostly during the daytime, and by the LTSF + DLC system, mostly at night, when the vents were open during central daylight hours (Figure 7). With respect to the greenhouse, the mean daily relative air humidity was increased, on average, by 8.4, 7.9, and 15.1% by the LTT + DLC heating system and by 2.7, 9.2, and 17.3% by the LTSF + DLC heating system when the DLC vents were open for

24 h, open during central daylight hours, and closed for 24 h, respectively (Table 1). The relatively high increase in relative air humidity observed when the DLC vents were closed for 24 h a day, particularly in the daytime, was mostly due to the DLC (Table 1).

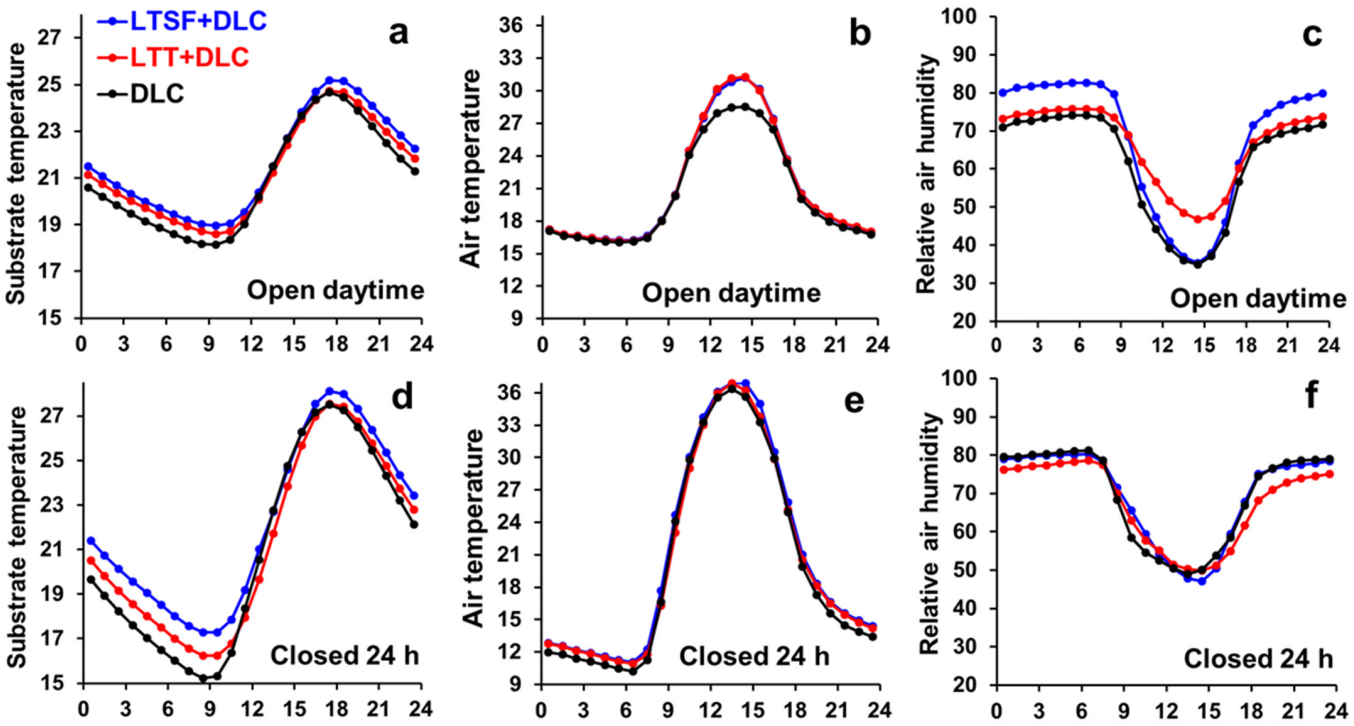


Figure 7. Hourly mean values of substrate bag temperature (°C), air temperature (°C), and relative air humidity (%) in the double low cover control (DLC), the DLC with low tunnels covered with transparent PE film (LTT + DLC), and the DLC with low tunnels covered with a spun-bonded fabric sheet (LTSF + DLC) when the DLC vents were open during central daylight hours ((**a**–**c**), respectively) and closed for 24 h a day (**d**–**f**).

The mean daily integral of incoming solar radiation in the greenhouse (6.6 MJ m^{-2} day^{-1}) was reduced by about 10% by the DLC control (5.9 MJ m^{-2} day^{-1}), 20% by the LTT + DLC heating system (5.2 MJ m^{-2} day^{-1}), and 26% (4.8 MJ m^{-2} day^{-1}) by the LTSF + DLC heating system (Figure 5), while the solar radiation transmission coefficient was reduced by 0.05, 0.1, and 0.13 by the DLC, LTT + DLC, and LTSF + DLC heating systems, respectively.

4. Discussion

Passive heating systems, commonly used in low-cost Mediterranean greenhouse crops grown around the winter period, are continuously being studied and upgraded to increase greenhouse air, crop, and soil/substrate temperatures, particularly in the vegetative stages of fruit–vegetable crops [12,17,21], which are most sensitive to suboptimal temperatures [7].

The double low cover (DLC) is a new, low-cost passive heating system that can be used in the early phases of extra-late or extra-early crop cycles for crops planted in the cold period. The DLC substantially increased the substrate and air temperatures (Figure 4) and the air humidity in the cold period (winter), and these increments could be modulated by opening or closing the vertical sheets located in the greenhouse aisles (DLC vents). The mean daily temperatures of substrate bags and the air around the crops increased by about 1.5 °C and 3.6 °C, respectively, when the DLC vents were closed for 24 h a day, which is the most common ventilation practice (Table 1). Thus, the DLC seems to be a more effective system for improving the winter greenhouse microclimate during the vegetative phases of crops than the conventional fixed plastic screen, which is frequently used for Mediterranean

greenhouse crops in SE Spain [12]. These authors found nighttime air temperatures of between 1.5 and 2.4 °C higher than outdoors. Compared to the conventional fixed plastic screen, the DLC reduces the air volume around the crop as it sits at a lower height, just above the trellis wires, and, above all, it increases the airtightness by using hermetically joined horizontal and vertical plastic sheets. The latter reduced greenhouse heat losses mainly due to less ventilation [22]. In addition (Figure 5), when radiation was measured at the top of the DLC (experiments 1 and 2), the reduction in the solar radiation transmissivity coefficient induced by the DLC was similar (around 0.11) to that found with the conventional fixed plastic screen [12]. Nevertheless, when solar radiation was measured at the bottom of the DLC, just above the substrate bags (experiment 3), the reduction in the solar radiation transmissivity coefficient was lower, around 0.05. We believe that the reduction in solar radiation transmissivity due to the DLC in commercial Mediterranean greenhouses may be smaller than that caused by the conventional fixed screen: commercial DLCs are much larger than the one used in this experimental work and, therefore, might have a much smaller proportion of vertical (walls) versus horizontal (roof) plastic surfaces. Finally, compared to the conventional fixed screen [12], DLC installation and management are simpler and cheaper, as they do not require structural elements, can be installed and managed by the growers themselves, and when needed, can be opened manually to avoid thermal and/or hygrometric excesses. Therefore, the DLC appears to be an effective passive heating system, particularly for the early stages of fruit–vegetable crops planted during winter, since it usually has to be uninstalled before the plant reaches the trellis wires. The DLC can also be used in combination with the conventional fixed screen or other passive heating systems to further improve the substrate and air temperatures around the crop and/or avoid water condensation falling onto the crops [18].

The black plastic mulch forming an air chamber around the substrate bags installed inside a DLC (BMC + DLC) increased the substrate temperature (Figure 6) with respect to the conventional black mulch covering the entire ground surface (BM + DLC). In the daytime, solar radiation heats the black mulch, which reaches very high temperatures [17]. This, in turn, heated the air inside the chamber, reaching much higher temperatures than the air outside the chamber (Figure 5). At night, the black mulch forming the air chamber, practically opaque to longwave radiation, maintained higher substrate temperatures than the conventional black mulch system by reducing energy losses (mainly longwave radiation and convective exchanges) from the substrate bag. Thus, the BMC + DLC heating system increased the mean daily substrate temperature by up to 2.8 °C, especially at night, during the cold crop period, when substrate temperatures appear to be suboptimal for greenhouse production [13,14,23]. In experiments conducted in climate-controlled chambers [24], these authors found that increasing the mean root zone temperature from 15 to 20 °C significantly promoted cucumber plant growth by increasing the dry weight of the leaves, stems, and roots and the fresh weight of cucumber fruits. In addition, both black mulch systems, regardless of DLC vent management, increased the daytime air temperature and slightly decreased (almost 1 °C) the nighttime air temperature relative to the DLC control (Figure 6), but the mean daily greenhouse air temperatures were similar (Table 1). This agrees with previous experiments [17]. Black mulch cools rapidly at night due to its high emissivity and reduces the energy exchange between soil and air/crops, as it is practically opaque to longwave radiation. Both black mulch systems also increased the relative air humidity at night, which was mostly associated with lower nighttime air temperatures. Therefore, the mulch forming an air chamber around the substrate bags appears to be a more effective substrate heating system than the conventional black mulch system in the early stages of the crops, although the effectiveness of both mulch treatments will reduce as a crop develops its leaf area. This BMC also saves plastic film compared to the conventional plastic mulch

that covers the entire soil surface. Thus, in extra-late cycles of Mediterranean greenhouse crops planted in the cold period, such as sweet pepper, cucumber, or tomato, the combined use of the double low cover plus a black plastic mulch forming an air chamber around the substrate bags, by substantially increasing root zone and air temperatures in the cold period, can promote faster crop development and increase early crop production, as well as reduce flowering and fruit set disorders in sensitive crops [25] and enhance some growth parameters, such as the leaf area index, which can increase total crop production [26].

Low tunnels covered with transparent PE films (LTT) or spun-bonded fabric sheets (LTSF), the most common covering materials in Mediterranean greenhouses, can be effective heating systems in the early stages of crops transplanted in winter, as they substantially increase substrate and air temperatures, particularly the latter (Table 1). With respect to the greenhouse, both tunnel types in combination with the DLC (LTT + DLC and LTSF + DLC) increased the mean daily substrate temperature by up to 3.0 and 3.8 °C, respectively, and the mean daily air temperature by up to 5.4 and 5.8 °C, respectively (Table 1). These temperature increases were higher than those found by [19] in a low tunnel covered with transparent PE film in a Mediterranean greenhouse without a DLC. Both tunnel types in combination with the DLC also increased the relative air humidity substantially, mostly due to the DLC when the DLC vents were closed for 24 h a day, and, therefore, this increment can be substantially reduced when required by opening the DLC vents. These increases in the air and substrate temperatures and relative air humidity were due to reduced heat losses, mainly due to less ventilation [22]. The low tunnel reduced the daily solar radiation transmission coefficient by 0.05, on average, when covered with transparent PE film and by 0.08 when covered with a spun-bonded fabric sheet. The solar radiation reduction observed in the low tunnel covered with transparent PE film was similar to that found by [19]. Overall, both low-tunnel types are effective passive heating systems when the substrate and air temperatures are the main factors limiting crop production in Mediterranean greenhouses. Moreover, a low tunnel covered with a spun-bonded fabric sheet reduces the condensation water falling onto crops. The combination of low tunnels with a DLC slightly improved the substrate and air temperatures relative to the DLC control, but both systems further reduced the incoming solar radiation, which might limit crop production in Mediterranean greenhouses [27]. Therefore, the combination of low tunnels with the DLC does not seem recommendable for horticultural crops grown around winter in Mediterranean greenhouses.

The results of this study may be applicable to the early stages of fruit–vegetable crops transplanted in the cold period (winter), when they present low leaf area indices and, therefore, have little influence on the greenhouse microclimate [17]. Seedlings of fruit–vegetable crops are usually transplanted with two or three small leaves and grow slowly, as greenhouse winter temperatures are usually low. Moreover, substrate bags were watered daily to simulate common irrigation practices during the early stages of cultivation. The experiments presented here were carried out in a Mediterranean greenhouse located on the coast of Almeria, a mild-winter climate area with the largest greenhouse concentration in Europe, and therefore, they can, in general, be extrapolated to other mild-winter greenhouse areas across the world.

5. Conclusions

New variants of passive heating systems are used in Mediterranean greenhouses for the early stages of crop cycles for crops planted in the cold period (winter). The most relevant findings of the study were as follows:

(i) The double low cover (DLC) is an effective system for increasing substrate and air temperatures in the cold period. The DLC is a new variant of the conventional fixed plastic screen that increases the airtightness and reduces the air volume around crops.
(ii) The black plastic mulch forming an air chamber around substrate bags (BMC), a new mulch variant used in substrate-grown crops, increased the substrate temperature with respect to the conventional black mulch covering the entire ground surface. The combination of this mulch variant with the DLC (BMC + DLC) increased the mean daily substrate temperature in winter by up to 2.8 °C and the mean air temperature by up to 3.7 °C during crop periods when they are usually suboptimal.
(iii) Low tunnels covered with a spun-bonded fabric sheet proved to be a more effective heating system regarding substrate temperatures than low tunnels covered with transparent PE film. The combination of low tunnels and the DLC does not seem recommendable for Mediterranean greenhouse crops planted in winter, since both systems reduce solar radiation transmissivity.

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