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Radiometric Characterization, Solar and Thermal Radiation in a Greenhouse as Affected by Shading Configuration in an Arid Climate

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Abstract: Shading the greenhouses is necessary in summer to reduce the solar radiation load. This however generates a considerable amount of thermal radiation heat load that needs to be removed via cooling systems. This study aimed to evaluate the effect of different shading configurations on the solar and thermal radiation in a greenhouse. Nets at four different locations were employed to shade the roof and side-walls of a polycarbonate, mechanically ventilated greenhouse. The spectral radiative properties of all these plastic materials were measured in short and long wave spectrum bands. The net solar and thermal radiations and air temperature were measured outside and inside two identical shaded and unshaded greenhouses. The results showed that external roof-shading is desirable, as it reduced the generated thermal radiation in the greenhouse by 21% and 15% during the day and night time, respectively and reduced the greenhouse air temperature during the day. The internal shading (roof and side walls) is undesirable, since it drastically increased the generated thermal radiation in the greenhouse by 147% and strongly increased the greenhouse air temperature during the day. Shading the side-walls is not recommended because it significantly reduces the transmitted solar radiation in the morning and afternoon (when the outside irradiance is low) and is useless at around noon when the outside irradiance is extremely high.

Keywords: shading nets; solar; thermal; radiation; greenhouse; hot regions

1. Introduction

In regions characterized by an arid climate with brackish water resources such as in the Arabian Peninsula, preventing heat from entering the greenhouse is the most appropriate technique for cooling greenhouses in hot summer seasons [1,2]. Through appropriate heat prevention methods, the radiation heat load can be eliminated or reduced before entering the greenhouse by cutting-off (via absorption or reflection) a portion of the incident radiation on the greenhouse cover [2–4]. This is accomplished by using commercial shading devices (curtains, clothes, or plastic nets). Shading the roof of a greenhouse is usually performed by various conventional methods such as: (i) whitening by spraying the exterior cover surface with an aqueous solution of hydrated calcium oxide [$Ca(OH)_2$] as in [5,6]; (ii) external shade cloths as in [7–9]; (iii) deploying fixed or movable refractive screens or curtains as in [10–13] and (iv) deploying fixed or movable plastic nets of various types and colors as in [14–18]. Whitening the roof is inexpensive; it can be used for reducing the heat load during summer. However, it reduced the average greenhouse transmittance to solar radiation by about 50%; it is washed away if rains fall on the greenhouse and its shading density cannot be changed once applied [5,6].

An external or internal shade can also be obtained by using movable plastic nets, curtains or refractive screens applied above or below the roof of the greenhouse. Plastic nets are widely used all over the world for shading residential buildings to reduce heating and cooling loads [19–21] and in agricultural sectors for plant and animal protection purposes. This is because plastic nets offer many environmental and economical advantages [1–4,18,22]. Protection from heavy meteorological actions (*i.e.*, hail, wind, snow, or strong rainfall) in fruit-farming and ornamentals, as well as shading the greenhouses in sunny regions for modifying the micro-environment through the realization of confined airspaces with better microclimatic conditions, are the most common cases. Plastic nets are also used as standalone cover, or in connection with structures for growing arboreal cultivation, for the protection against virus-vector insects and birds [22,23].

Some previous studies evaluated shading nets either independently or to investigate their influence on the greenhouse macroclimate (e.g., air temperature, relative humidity and solar radiation). The purpose of all shading methods is to regulate the amount of solar energy entering the greenhouse and to reduce the heating load in summer. Previous experimental studies [24–26] have showed that, as expected, the transmissivity of nets decreases as the mesh net becomes closer. Even so, the definition of a relationship between porosity and transmissivity of a net appears hard to obtain. Porosity is not a sufficient parameter to quantify the shading effect that is influenced by many other factors (polymer, thickness, color, distance between the net and the plane receiving the radiation, additives, shape and diameter of the thread, *etc.*). Anyway it's a matter of fact that, at present, only a global shading factor is usually reported by the manufacturers in the technical information on the leaflet that accompanies the material. However, information about the transmittance value of the net at the principal wavelength ranges (solar: 200–2500 nm; PAR: 400–700 nm; thermal-IR: 7500–12500 nm) would seem to be very meaningful, taking into account the different effects that they have on the crops and on the protected environment. Transmittance coefficients at the different wavelength ranges appear therefore as an indispensable tool, able to classify the covering materials in relation with the micro-climatic parameters of the protected environment, the quality of the radiation, the temperature and the air flow. Spectro-radiometrical tests have shown that the nets determine effective qualitative changes in the incoming solar spectrum that is the variation of the distribution of the radiant energy at different wavelengths. Unfortunately at present there is a lack of a specific standard defining the spectro-radiometrical characteristics that agricultural nets should demonstrate, in order to adequately perform the application for which they are designed [26].

Besides protecting plants against excessive heat load, shading significantly reduces the crop water consumption in arid regions [14,26]. A disadvantage of shading systems that use curtains or screens below the roof of the greenhouse is that when the curtain or screen is fully deployed, it will decrease the effectiveness of the natural roof ventilation and negatively affect the greenhouse microclimate. Moreover, shading materials deployed inside the greenhouse absorb a portion of solar the radiation and reemit it again into the greenhouse, and reflect back a portion also inside the greenhouse. As a result, thermal radiation will be generated in the greenhouse due to the presence of the shading nets and the effect of internal shading on reducing the greenhouse air temperature is therefore expected to be small. The main objective of this study is to quantify the generated thermal radiation in the greenhouse as affected by the different locations of shading nets. This is important, since it enables one to determine the optimum location for shading nets to be deployed that gives the lowest thermal radiation inside the greenhouse during the day, so leads to a reduction of the cooling load in summer.

2. Materials and Methods

2.1. Experimental Set-up and Shading Configuration

The experiments were conducted in two identical crop-free greenhouses, each with a floor area of 165 m^2, covered with a double-layer, hollow-channeled, polycarbonate sheet of 8.15 mm thickness, a gutter height of 4 m and a gable height of 2.5 m. The greenhouses were oriented in a N-S direction on the Agricultural Research and Experiment Station, Agriculture Engineering Department, King Saud University (Riyadh, Saudi Arabia, 46° 47′ E, longitude and 24° 39′ N, latitude). Each greenhouse was ventilated using two identical exhaust fans, each with an air flow rate of 350 $m^3 \cdot min^{-1}$ and a power consumption of 1100 W. In fact, the fans in each greenhouse are for the wet pad-fan evaporative cooling system. However, in the current study the water pumps (for wetting the pads) were stopped and the fans were operated only for ventilation. This was to exclude the effect of water vapor that may absorb a considerable amount of thermal radiation in the greenhouse [27]. One greenhouse was kept without shading (control) and the other was shaded using five different configurations: (1) horizontally above the roof using a black plastic net of 250 μm thickness and 30% porosity (I in Figure 1a); (2) horizontally below the roof using a white plastic net of 185 μm thickness and 50% porosity (II_{net} in Figure 1b); (3) horizontally below the roof using a thermal screen of 183 μm thickness and 15% porosity (II_{tsc} in Figure 1b); (4) horizontally below the roof using the white plastic net and vertically, inside the side-walls, using the black plastic net (III in Figures 1c and 5) horizontally above the roof using the black plastic net and vertically inside the side-walls using the black net (IV in Figure 1d).

2.2. Measuring the Required Parameters

The experiments were conducted on clear sunny days in the period from 18 to 26 December 2014; one day (24 h) for each shading configuration and one day for the control (the greenhouse without shading). The measured parameters were: (i) the net (downward-upward) solar and thermal radiation, at 2.5 m height above the floor, inside and outside the greenhouse using net radiometers (CNR-2, Kipp & Zonen Inc., Bohemia, NY, USA) and (ii) the air temperature inside and outside the greenhouse, at 2 m height above the floor, using aspirated psychrometers. These parameters were measured every 1 min, averaged at every 15 min, and recorded in a data logger (CR23X Micrologger, Campbell Scientific, Inc., Logan, UT, USA).

In order to connect the experimental results with the spectro-radiometrical characteristics of the shading nets that were employed, these characteristics were determined through experiments conducted through a modular spectro-radiometer in the Laboratory of Material Tests of the SAFE School of the University of Basilicata (Potenza, Italy). The spectral transmittance and reflectance for the tested materials (*i.e.*, black plastic net, white plastic net, thermal screen and double layer polycarbonate sheet as the greenhouse cover) were measured in the short wave solar spectrum (200–2500 nm) and long wave thermal radiation (LWIR, 2500–25000 nm) spectrum ranges.

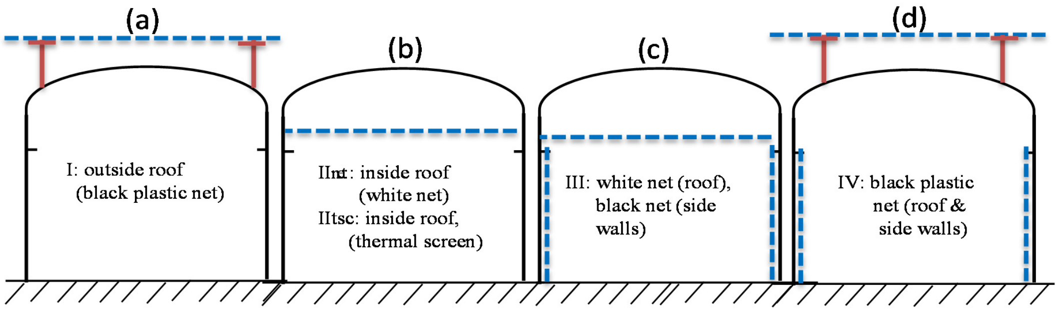

Figure 1. Schematic diagram for the greenhouse shaded at different locations.

3. Results and Discussion

The spectro-radiometrical analysis results (*i.e.*, the radiative properties under short and long wave radiation) for the tested materials were measured over the wavelength range from 200 nm to 2500 nm and illustrated in Figures 2–5. Figure 2a,b are solar and thermal radiation spectra, respectively for the hollow-channeled, polycarbonate sheet greenhouse covering material. Similarly, Figure 3a,b are for the thermal screen, Figure 4a,b are for the white net, and Figure 5a,b are for the black net. For overall evaluation, the spectral properties of the tested materials were integrated in terms of the main characteristic (global, PAR and IR-thermal radiation) and reported in Table 1. The reported results showed that the solar radiation absorptance of the black net is the highest (68.6%); therefore, using black nets inside the greenhouse would significantly increase the thermal load. On the other hand, the high transmittance of the white net to solar radiation (over 60%) together with its significant reflectance (24%) and low absorptance (13%–15%) suggest the possibility of using white nets inside the greenhouse when necessary. The thermal screen seems very effective in absorbing and emitting the IR-thermal radiation (86.6%). This characteristic combined with its high reflectance to solar radiation (55%), makes this material very useful for improving the energy balance of a greenhouse.

Due to the limitations of the net-radiometer devices, at our laboratory, the experiment was conducted in one greenhouse for different days to apply shading at the suggested locations. Different sunny days were selected for the experiments from 18 to 26 December 2014 and the diurnal variation of solar irradiance during these days was almost similar.

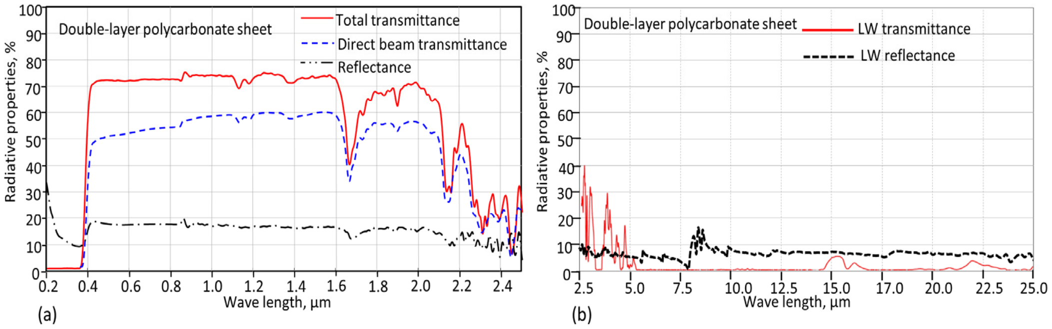

Figure 2. Spectral radiative properties of double-layer polycarbonate sheet (the covering material) in solar (**a**) and LWIR thermal (**b**) radiation spectrum.

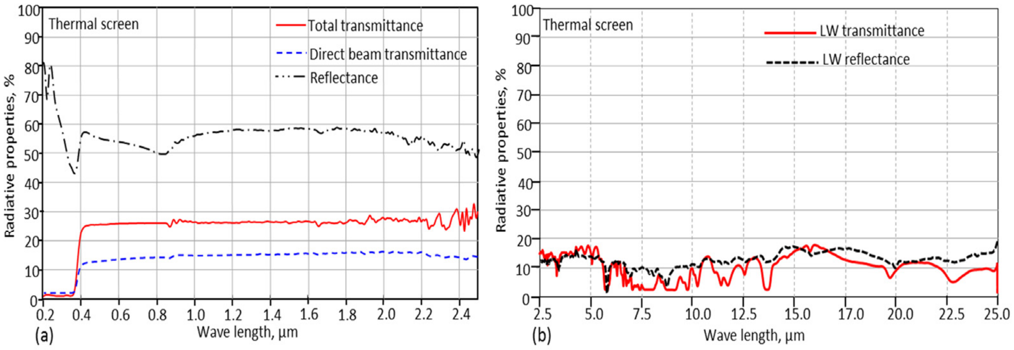

Figure 3. Spectral radiative properties of the thermal screen (used for internal roof shading) in solar (**a**) and LWIR thermal (**b**) radiation spectrum.

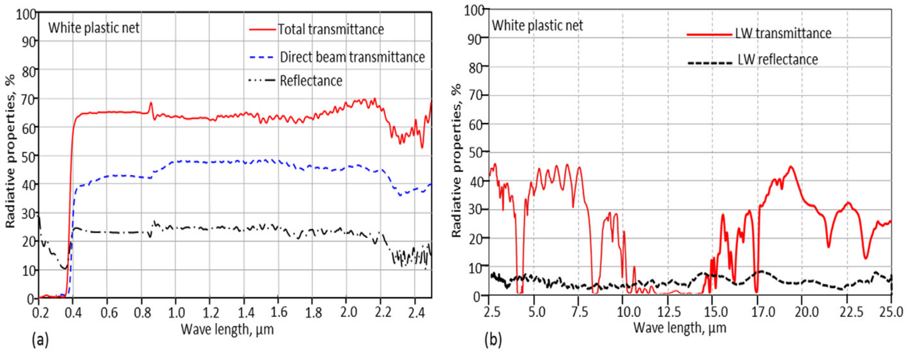

Figure 4. Spectral radiative properties of the white plastic net (used for internal roof shading) in solar (**a**) and LWIR thermal (**b**) radiation spectrum.

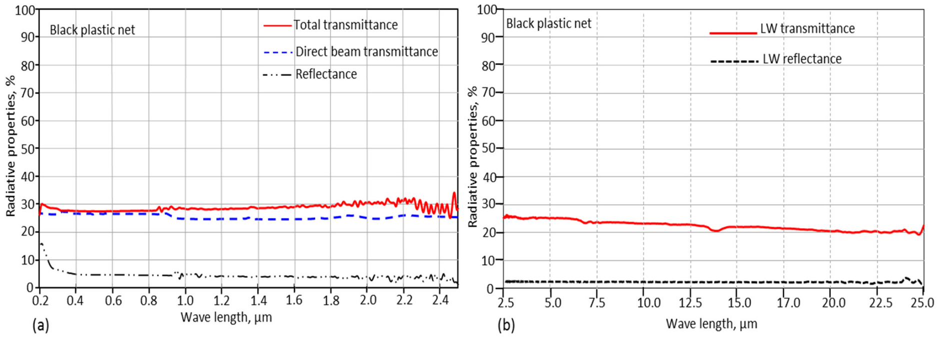

Figure 5. Spectral radiative properties of the black plastic net (used for external roof and internal side wall shading) in solar (**a**) and LWIR thermal (**b**) radiation spectrum.

Table 1. Results of the spectro-radiometrical analysis of the experimental materials.

Material	Range	Wavelength [nm]	Transmittance [%]		Reflectance [%]	Absorptance [%]
			Total	Direct		
Black plastic net	Global solar	200–2500	27.9	26.1	3.5	68.6
	PAR	400–700	27.5	26.6	3.7	68.8
	IR-thermal	7500–12500	23.2	-	0.9	75.9
White plastic net	Global solar	200–2500	61.0	43.4	24.1	14.9
	PAR	400–700	62.6	42.0	24.0	13.4
	IR-thermal	7500–12500	7.9	-	2.8	89.3
Thermal Screen	Global solar	200–2500	26.1	13.4	55.2	18.7
	PAR	400–700	26.3	12.8	55.4	18.3
	IR-thermal	7500–12500	4.7	-	8.7	86.6
Double-layer Pc sheet	Global solar	200–2500	69.8	52.8	15.0	15.2
	PAR	400–700	71.2	51.3	15.5	13.3
	IR-thermal	7500–12500	1.0	-	6.3	93.7

The diurnal variation of the greenhouse transmittance to solar radiation, with different shading configurations and without shading (control) is illustrated in Figure 6a. The transmittances in Figure 6a result from the combined effect of the covering and shading materials on the solar radiation transmission. The transmittance value inflections the around the times of sunrise and sunset are mainly due to the predominance of diffuse radiation at that time, which is ascribed to a relatively high transmittance of the translucent materials (e.g., polycarbonate sheets, glass, plastic films, thermal screens and plastic nets) to diffuse radiation [28,29]. The diurnal variations of the net solar radiation fluxes (downward-upward) inside the greenhouse for different shading configurations are illustrated in Figure 6b.

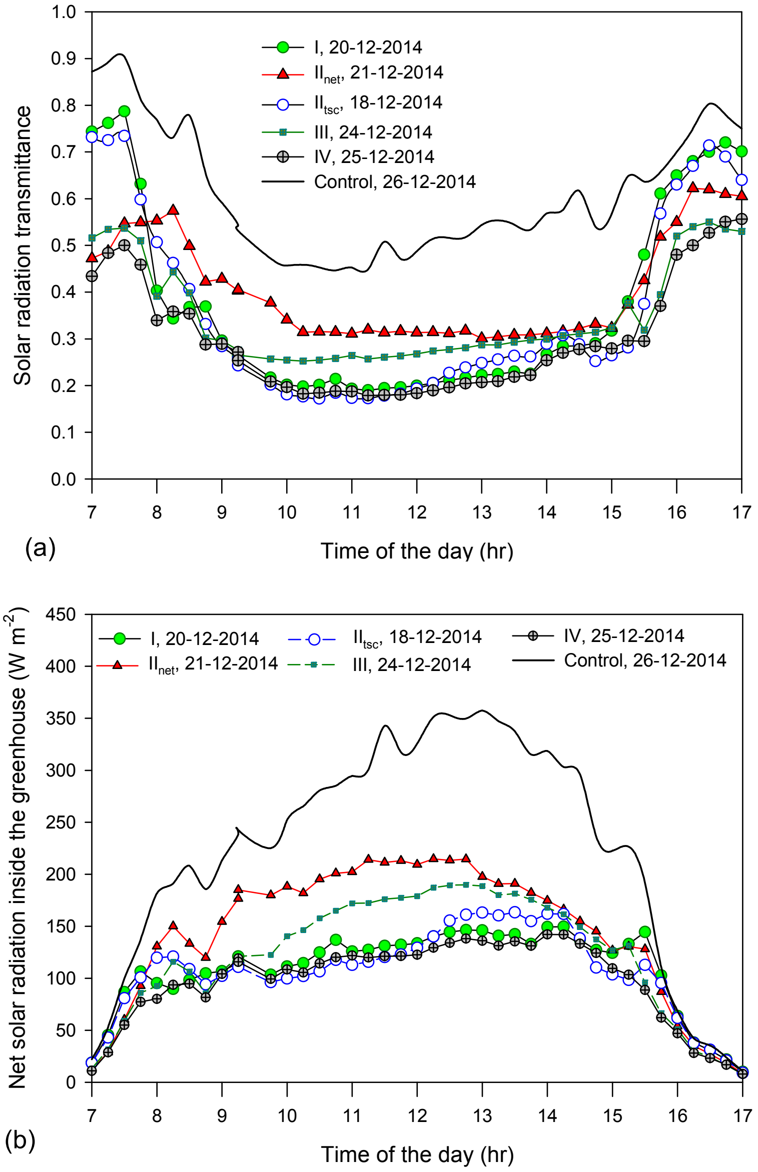

Figure 6. Diurnal variations of: (**a**) the greenhouse transmittance to solar radiation and (**b**) net (downward-upward) solar radiation flux in the greenhouse, measured under different shading locations.

Results in this figure show that deploying the white net, as in Figure 1b, resulted in a higher solar radiation transmission than with the black net and the thermal screen. The inside and outside roof shading would have the same effect in reducing the solar radiation transmitted into the greenhouse if we used the same net inside or outside. In the morning and afternoon, the outside solar irradiance is usually low and its effect on overheating the greenhouse is even lower. Moreover, enhancing the PAR in the greenhouses for plant growth requirement is extremely important in the morning and afternoon. Accordingly, shading the side walls is not appropriate because it significantly reduces the transmitted solar radiation as well as the PAR during these times. Thermal screens generate mutual progressive reflections with the greenhouse cladding sheet inside the greenhouse, confirming once more that shading materials should be employed horizontally outside the greenhouse in order to fully express their shading potential and reduce the incoming solar radiation. The effects of shading configuration on the net thermal radiation (downward-upward) in the greenhouse during a 24 h period are illustrated in Figure 7. During the night time (in the absence of solar radiation), the net temperature as well as the emitted thermal radiation is low. Deploying nets or thermal screen inside or outside the greenhouse enhances, by a small amount, the net thermal radiation in the greenhouse compared with that without shading (Figure 7 at night). The location of the net had no significant effect on the net thermal radiation in the greenhouse because this mainly depends on the combined effect of the net temperature and its emissivity rather than its location. During the day time (under extensive solar irradiance), shading moderates the transmitted solar radiation as well as the air temperature in the greenhouse. Shading may increase the thermal radiation in the greenhouse due to the net emission. The results in Figure 7 show the answer to the question "Is the net configuration having an effect on the generated thermal radiation in the greenhouse during the day?"

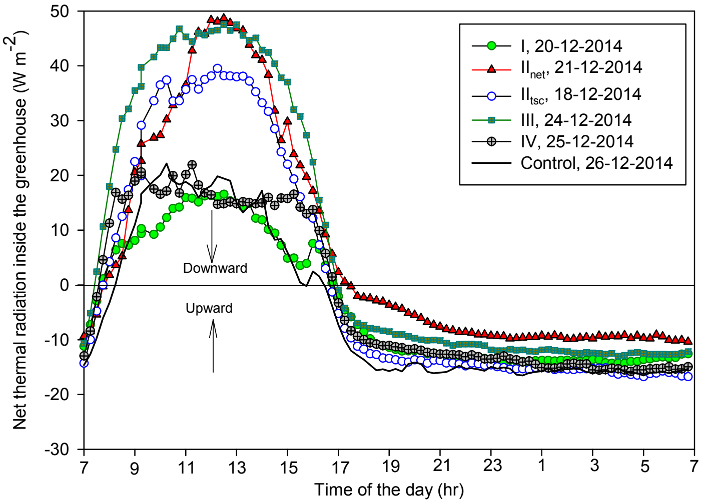

Figure 7. Diurnal variation of net thermal radiation generated in the greenhouse as affected by the shading location.

Figure 7 shows that the internal side wall shading increased the thermal radiation in the greenhouse in the morning and afternoon. The internal (roof and side walls) shading significantly increased the thermal radiation in the greenhouse compared to the control greenhouse (without shading) due to the thermal emission of the nets in the greenhouse. The external roof shading reduced the temperature of the greenhouse cladding, and significantly reduced the thermal radiation in the greenhouse. This is because the thermal emission of the nets is outside the greenhouse cladding; *i.e.*, it is nearly opaque for transmitting thermal radiation into the greenhouse (the cladding transmittance for IR-thermal radiation is 1%, Table 1). Accordingly, the internal roof and side walls shading are not appropriate for use in greenhouses under arid conditions; however, the outside roof shading is strongly recommended. Table 2 summarizes the integrated (over time) solar and thermal radiations and thermal loads in the greenhouse (in MJ m^{-2} day^{-1}) estimated under the different shading configurations. The results in Table 2 show that the transmitted solar radiation is the dominant factor controlling the thermal load in the greenhouse. The maximum load (6.29 MJ m^{-2}day^{-1}) was observed under the white net (II$_{net}$, Figure 1b), while the minimum load (4.16 MJ m^{-2}day^{-1}) was observed under the black net (IV, Figure 1d). This is in conjunction with the maximum and minimum solar radiation load in the greenhouse (Table 2). It is worth mentioning that the air in the greenhouse does not absorb solar or thermal radiation, so the radiation load will be absorbed by the greenhouse components (soil, cladding, nets, structure, *etc.*), then convected to the air as sensible heat. Shading reduces the evapotranspiration as well as the relative humidity in the greenhouses. In the greenhouses (Section 2.1) with evaporative cooling, the different configurations of shading (Figure 1) reduced the relative humidity by about 5%–10% in the morning (before 8:30 AM) and afternoon (after 5:0 PM); however, no significant effect of shading on the relative humidity was observed from 8:30

AM to 5:0 PM (data not shown). Adding or removing water vapor to or from the greenhouse air (*i.e.*, latent heat) will not affect the cooling or heating load.

Table 2. Time integral of the net thermal and solar radiation in the greenhouse as affected by shading configuration.

Shade designation	Net radiation (MJ m^{-2} day^{-1})				Radiation load	
	Shading Description	**Thermalday↓**	**Thermalnight↑**	**Solar day↓**	**day↓**	**night↑**
I	External roof shading (black net), Figure 1a	0.40	0.57	4.0	4.4	0.57
II$_{net}$	Internal roof shading (white net), Figure 1b	0.99	0.38	5.3	6.29	0.38
II$_{tsc}$	Internal roof shading (thermal screen), Figure 1b	0.95	0.65	4.0	4.95	0.65
III	Internal roof and side walls shading, Figure 1c	1.26	0.50	4.5	5.76	0.50
IV	External roof and internal side walls shading Figure 1d	0.58	0.60	3.58	4.16	0.60
Control	Without shading	0.51	0.67	8.23	8.74	0.67

Even though shading prevents a considerable amount of solar radiation from entering the greenhouse, the inside air temperature sometimes increases drastically due to the thermal emission of the nets used for internal shading. Because the measurements were conducted in different days, therefore the temperature difference of air between inside and outside the greenhouse (T_{in}-T_{out}) was estimated to show the effect of shading configuration on the air temperature increases. Figure 8 illustrates the time course of (T_{in}-T_{out}) as affected by the shading configurations. Figure 8 showed that, the outside roof shading (I, Figure 1a) provides the lowest air temperature raise in the greenhouse. The internal roof and side walls shading (II$_{net}$, II$_{tsc}$ in Figure 1b and III in Figure 1c) increased the greenhouse air temperature drastically during the day time. The side wall internal shading increased the greenhouse air temperature before and after noon. Even though, the external roof shading (I) showed the lowest air temperature raise, when the side walls internal shading was embedded (IV in Figure 1d), the greenhouse air temperature increased drastically. For warming the greenhouse at night in cooled seasons, plastic nets must be deployed inside the greenhouse to provide warming effect on the greenhouse air (Figure 8 during the night time).

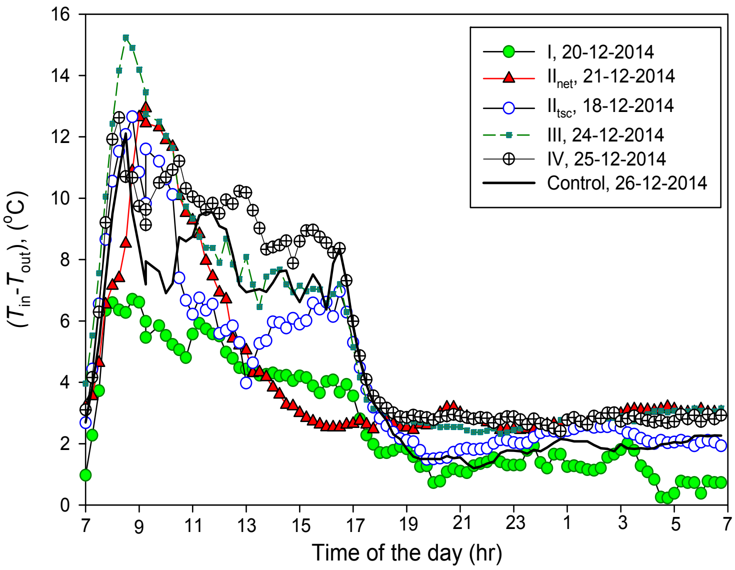

Figure 8. Diurnal variation of air temperature difference between inside and outside the greenhouse (Tin-Tout) as affected by the shading configurations.

4. Conclusions

In arid regions, extensive use of plastic nets for shading greenhouses in summer is recorded because of their beneficial effects on the greenhouse microclimate and productivity of crops. Nets are often employed as greenhouse elements without any engineering design. This study provided radiometric characterization for some plastic nets used for shading greenhouses in arid climates. The optimum shading configuration, for greenhouses in arid climate, was optimized based on the generated thermal radiation and air temperature raise in the greenhouse. The main conclusions that could be drawn from the present study are summarized as follows:

- The external roof-shading is the most desirable method, it reduced the generated thermal radiation in the greenhouse by 21% and 15% during the day and night times, respectively, and significantly reduced the greenhouse air temperature during the day time.
- With the external roof-shading, the required solar radiation in the greenhouse can be controlled by selecting a net with the desired shading factor.
- Internal shading (roof and side walls) is an undesirable method, since it drastically increases the generated thermal radiation in the greenhouse by 147% and strongly increases the greenhouse air temperature during the day.
- Shading the side-walls, externally or internally, is not recommended because it significantly reduces the transmitted solar radiation in the morning and afternoon (when the outside irradiance is low) and is useless around noon when the outside irradiance is extremely high.

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Author Contributions: Abdel-Ghany was responsible for overall coordination of the research team. Shady and Ibrahim did the literature review, conducted the experiment and collected data. Picuno measured the radiative properties of the materials. All the authors were involved in writing, discussing the results and have read as well as approved the manuscript.

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

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