Influences of greenhouse-integrated semi-transparent photovoltaics on microclimate and lettuce growth

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Abstract: Shading in greenhouses is a simple and cheap method usually used to reduce the intensity of solar radiation and air temperature. Moreover, combining Photovoltaic (PV) panels and crops on the same cropland could alleviate the increasing competition for the agricultural land between food and energy production. In addition, the integration of PV with greenhouses could reduce, or partially replace the energy consumption for greenhouse crop production. Therefore, the aim of this study was to investigate the shading effect of semi-transparent mono-crystalline silicon double glazing photovoltaic panels (STPV), mounted on top of an agricultural greenhouse, which occupied 20% of the roof area, on the microclimate conditions and the growth of lettuce plants inside a greenhouse. Results showed that the combination of STPV and polyethylene cover decreased the solar radiation by 35% to 40% compared to the use of polyethylene cover only for clear days which was in the acceptable range of photosynthetically active radiation for lettuce plants. Moreover, STPV shading decreases the air temperature by 1 ℃-3 ℃ and had no effect in the relative humidity under natural ventilation. Furthermore, there were no significant differences (p<0.05) in the growth of lettuce plants between the shaded greenhouse by the STPV and the unshaded. Shading insignificantly increased the fresh weight, leaf area and the chlorophyll contents (p<0.05). In conclusion, the integration of STPV modules can decrease the solar irradiation and the internal air temperatures as well as generate electric energy for environmental control systems without significant influence on the growth of lettuce plants. Meanwhile, it can decrease the water consumption by decreasing the evapotranspiration rate.

Keywords: semi-transparent photovoltaics, greenhouse, shading, lettuce growth, microclimate, energy consumption
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1 Introduction

The protected cultivation in greenhouses has become the preferred system as a palliative way against global climate change. Therefore, to provide the optimal air temperature, relative humidity, water, CO_2 concentration and lighting inside greenhouses, the environmental control systems are required to achieve a high production while keeping the operational and energy cost at a minimum[1-3]. However, heating and cooling systems are two major costs involved in greenhouses production. Heating is usually provided by burning fossil fuels which increase carbon dioxide (CO_2) emission, or by using electric heaters, which consume more electric energy[4]. Consequently, in the last ten years there are a number of studies have been conducted by integrating PV modules on a certain areas of the agricultural greenhouses roofs to protect plants by decreasing the solar radiation, light intensity and air temperature inside the greenhouses as well as reduce, or partially replacing the energy consumption[5,6]. Photovoltaic systems can decrease the greenhouse gas emissions as a highly attractive climate

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change mitigation option[7]. However, high levels of PV internal shading could affect growth, development and productivity of the cultivated crops due to the low light intensity and solar radiation can lead to a pathogen development. Kadowaki et al.[8] studied the effects of PV-array shading on the horticultural onion crop growth by mounting a PV array inside the south roof of an east-west oriented single-span greenhouse straight-line (PV_s) and checkerboard (PV_c) of array distribution at 12.9% of the roof area for each in Japan. The results showed that the straight-line array for shading significantly decreased the fresh weight and dry-matter weight of Welsh onions comparing to the checkerboard distribution array and control treatments. Meanwhile, the PV_c arrangement improves the unbalanced spatial distribution of received sunlight energy in the greenhouse[9]. However, the effect of flexible solar panels mounted on top of a greenhouse using a checkerboard arrangement and covering 9.8% of roof area, primarily for electricity production, on yield and quality of tomatoes in southeastern Spain has been investigated[5]. Results showed that there was no effect found in yield and price of tomatoes despite their negative effect on the fruits size and color in the same commercial class (G class; diameter 67-81 mm). In addition, Li et al.[10] reported that the annual return of the integrated photovoltaic and agricultural greenhouses in China varied almost by 9% to 20% with a payback period of 4-8 years. On the other hand, it was reported that the integration of semi-transparent photovoltaic with greenhouse were potentially suitable for greenhouses in high-irradiation regions[11,12]. Cossu et al.[13] introduced a novel algorithm to estimate the cumulated global radiation (G_{GR}) inside photovoltaic (PV) greenhouses. With this tool, they found that the yearly G_{GR} increased with the canopy height on the zones under the plastic cover (G_{GR} from 59% at 0 m to 73% at 2.0 m), and decreased under 50% PV cover ratio on the roof (G_{GR} from 57% at 0 m to 40% at 2.0 m). Furthermore, the different light distribution on the canopy heights showed that the incident solar energy on the crop changes consistently, according to the growth stage of the plants. However, most zones close to the side walls and the gable walls were the least affected by shading when considering the effects on all canopy heights. Fatnassi et al.[14] modelled the distributed microclimate (solar radiation distribution, thermal air, water vapor and the dynamics fields) inside greenhouse equipped using the photovoltaic panels by the Computational Fluid Dynamic (CFD) model. They reported that the mean solar radiation transmission in the Asymmetric greenhouse was 41.6% whereas that of the Venlo greenhouse was 46%. Meanwhile, the checkerboard photovoltaic panel distribution improved the balance of the spatial distribution of sunlight received in the greenhouse due to the checkerboard arrangement allow 85% transmission of the external light. It has been reported that PV module prices have been reduced in the past 15 years by 80%, while the prices for competing gasoline or diesel fuel have been increased by over 250%[15]. On the other hand, the financial benefits of PV systems compared with diesel generators showed that the costs of off-grid hybrid PV systems were 19% cheaper compared with electricity generation by diesel generators in most rural parts of Indonesia, whereas stand-alone PV systems were 3% cheaper than stand-alone diesel generators[16]. Greenhouse crops in the tropics and sub-tropics suffer from excessive heat load during summer and more energy consumption for cooling. Therefore, the environmental control in summer is one of the major challenges faced by greenhouse growers in those regions. Shading is usually used to reduce the intensity of solar radiation and air temperature. Consequently, it reduces the electric energy consumption for cooling, and reduces the crop transpiration as well as water consumption for irrigation in arid regions[17,18]. It was reported that shading greenhouses in hot and sunny regions, when it incorporating with a cooling method, reduces the water consumption by 25%, increases the crop productivity, reduces greenhouse air temperature lower than the outside temperature by 5℃-10℃ and increases the relative humidity by 10%-15%[19]. Moreover, shading reduces the intensity of solar radiation by 30% to 50%, and decreases the energy consumption for cooling up to 20%[20]. The growth of many plants requires an appropriate photosynthetic photon flux density (PPFD), excessively high or low (2500 μmol/s·m^2 or 50 μmol/s·m^2) PPFD intensity will prevent photosynthesis in the plant[21,22]. Consequently, plants can be classified as shade tolerant and shade intolerant[23]. Mashonjowa et al.[24] reported that shading greenhouse by painting the greenhouse cover with lime-based whitewash (whitening) reduced the light transmission for photosynthetically active radiation, total solar and thermal radiation of the greenhouse cover from 0.75 to 0.53, 0.74 to 0.55 and 0.45 to 0.43, respectively. Araki et al.[25] found that the higher growth of spinach was achieved under 45% shading ratio in June, August and September, and 60% in July compared to the 0% shading ratio. Sugar and ascorbic acid (vitamin C) contents were decreased as shading ratio increased in all seeding times. Nitrate content was highest under 45% shading ratio in July, August and September and 30% in June. Soluble oxalate content was highest in June, July and August and lowest in September in the un-shaded house in Japan. No data reported to date has shown how plants grow under a Semi-transparent Photovoltaics (STPV) shading conditions. Therefore, the aim of this study was to find out the effects of STPV panels, mounted at a distance of 0.08 m above the greenhouse polyethylene cover, on the microclimate conditions and evapotranspiration rate as well as its effect on the growth of Lettuce (*Lactuca sativa L. var. longifolia*).

2 Materials and methods

2.1 Greenhouse structure and PV configuration

This experiment was conducted in Kunming, China (longitude 102.68°E and latitude 25.07°N), in two greenhouses of a single stand-alone structure with an equal gable roof in east-west orientation. The dimensions of greenhouse were 7.5 m long, 3.5 m wide, and 3.0 m high in the middle and gutter height of 2.0 m at a roof slope of 30°. The greenhouse cover material was a 0.12 mm plastic polyethylene (PE) film with light transmittance of 80% (from Guangzhou Peng Sheng Greenhouses Company, in Kunming). The ventilation vents were located on both sides of walls (7 m × 1 m) with net curtains of white saran. Ventilation was provided by manually opened side windows when the internal air temperature exceeded 25°C. In the first season of lettuce growth, one greenhouse was divided equally into two parts, the first part as shading treatment with semi-transparent PV and the second part of greenhouse with polyethylene cover only as a control. Three STPV were fixed on the south west roof of the greenhouse at tilted angle of 30° to provide a sufficient electrical energy with minimum shading, each STPV module (1985 mm × 1038 mm × 13.52 mm) has a peak power of 170 W_p and module efficiency of 8.25%, made in China. The transmittance ratio of the STPV module was 47% (it has 64 cells 12 cm × 12 cm and the rest of its area is glass, made in China) and the total area of all STPV modules was 6.1 m^2, which is 20% of the greenhouse roof area designated for the treatment, due to the total greenhouse roof area is 30 m^2. The STPV modules located on the top of the plastic cover with a distance of 0.08 m as an isolation air layer between the plastic cover and the STPV. The STPV panels were connected in series and fed into the electricity grid by DC/AC Micro inverter APS YC250A, (Zhejiang Yu energy technology, Co., Ltd., China). Subsequently, for the second season two greenhouses were used, one as a control without STPV shading and the other as a treatment for lettuce production as shown in Figure 1.

1. Pyranometer 2. Data logger 3. Side wall ventilation system 4. Semi- transparent PV 5. Micro-inverter's cable 6. Lettuce 7. Unshaded greenhouse

Figure 1 Photos of the greenhouse and the recording station for air temperature and solar radiation

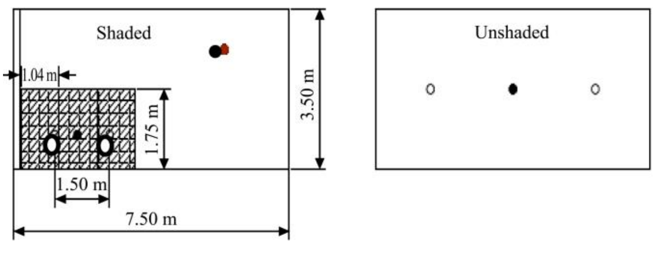
The light transmission (LT) through the polyethylene cover under the experimental conditions of the study was calculated using the Equation (1)[5]:

$$LT = \frac{K_i}{K_0} \times 100 \quad (1)$$

where, K_i (W/m^2) and K_o (W/m^2) are the internal and external solar radiation, respectively.

2.2 Microclimate monitoring

Mean daily relative humidity and air temperature were measured during the experiments in 2015 and 2016. Relative humidity was recorded every 1 h by Accurate TH12R-EX recorder, from Xin yada instrument Co., Ltd., China. The light intensity was measured by a digital portable lux meter from Taiwan, Tai Pei TES electronic industry, Co., Ltd., China at the level of plants on sunny days. Available solar radiation at crop level was measured every 1 min in each treatment with pyranometers sensors connected to data logger (TRM-2, Beijing Tianyu technology, Co., Ltd., China). Two sensors for solar radiations were installed alternatively at 0.5 m and 2 m from the ground. Two sensors for air temperatures were distributed inside each greenhouse at 1.0 m and 1.5 m above the ground at 1.5 m apart from each another and one sensor outside the greenhouse for measuring the ambient temperature as shown in Figure 2. The specifications of all sensors are shown in Table 1 and the monthly averaged weather variables in Kunming are shown in Table 2.



Note: The black circles represent the solar radiation, light intensity and relative humidity sensors. Meanwhile, the white circles represent air temperature sensors.

Figure 2 Sensors positions in shaded and unshaded greenhouses

Table 1 Specification of the instruments

Instrument name	Measurement range	Accuracy
Thermocouple	0-150℃	±0.1℃
Pyranometers	0-2000 W/m^2	±2%
Wind speed sensor	0-70 m/s	0.5 m/s
Digital portable lux meter	0-200 000 lx	±0. 1 lx
Accurate TH12R-EX	0-100%	±0.2℃ and ±2%

Table 2 Monthly-averaged of meteorological data for Kunming City

Months	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Average temperature/℃	12.2	16.4	18.2	19.3	19.2	18.9	16.6	13.0
Average relative humidity/%	55.8	50.6	60.5	71.7	74.9	75.5	77.9	82.3
Daily solar radiation - horizontal/kW h(m^2 d)$^{-1}$	5.71	6.23	5.61	5.04	4.57	4.59	4.03	3.77

Note: The data were collected from the NASA website [26].

2.3 Plants material

The first season of a romaine lettuce was sown on late March, 2015 in pots of (25 cm wide × 25 cm deep), there were 98 pots divided into two groups, each group consisting on 49 pots. Each pot had two plants, the first group as shading treatment of (98 plans) and the second group as a control of (98 plans) in the same greenhouse which divided into two parts. The distance between pots was the same (0.5 m) in rows and lines (7 lines × 14 rows). The second season was on July, 2016 in two greenhouses. All plants get the same irrigation, soil (peat moss, perlite, vermiculite and clay) and fertilization system. The lettuce measurements parameters were fresh weight of the above-ground parts, dry-matter weight, number of leaves, leaf area, and the chlorophyll content measured at 30 d, 37 d and 60 d after shading treatments, which means the age of plants under shaded and unshaded greenhouses. Twelve lettuces were picked in each group (rows in borders were excluded) and the leaf area was calculated through destructive measurement three times after treatment. The lettuce samples were dried in a hybrid solar dryer at 55℃ for 6 d until a constant weight to calculate the dry weight. The fresh weight was measured by a digital balance with a precision of 10 g and the dry matter weight was measured by analytical balance with a precision of 1 g. The relative chlorophyll contents of the leaves were measured by a portable chlorophyll meter (or SPAD meter) and leaf area by a portable leaf area meter, both instruments from Shanghai Rong Yan instruments, Co., Ltd., China.

The experimental design was randomized complete block design with three replications and the data was analyzed using the statistical software SPSS 18.0 (SPSS Inc., Chicago, IL, USA). Data and results from each sampling were analyzed separately by one-way analysis of variance (ANOVA). The data were given as the mean ± standard errors and the level of statistical significance was set at $p<0.05$.

2.4 Evapotranspiration rate (H_{CV})

The solar heat energy gained on sunny days can replace some of all heat energy needed to maintain temperature at the proper level. The solar heat gain can be estimated[27] by Equation (2):

$$H_s=I_s A_f \tau \tag{2}$$

where, H_s is the solar heat gain, W or kW·h/d; I_s is the intensity of solar radiation on a horizontal surface, kW·h/(m^2·d) or MJ/(m^2·d); A_f is the area of greenhouse floor, m^2; τ is the transmittance of the greenhouse cover to solar radiation (decimal of 0.6-0.8)[27].

The evapotranspiration rate can be computed from Equation (3):

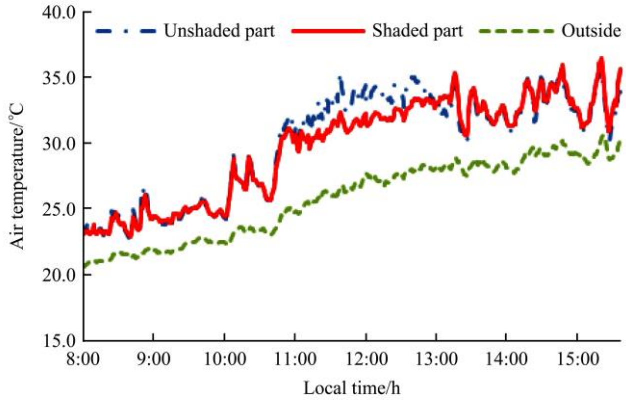
$$H_{cv}=H_sFE \tag{3}$$

where, H_{cv} is the evapotranspiration rate, kW·h/d; F is the floor use factor, ratio of ground covered by plants to total ground area (decimal); E is the ratio of evapotranspiration to solar radiation (0.5)[27].

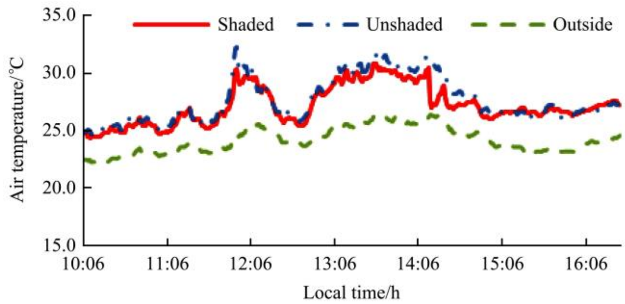
3 Results and discussion

3.1 Effect of STPV on the greenhouse air temperature and relative humidity

Microclimate distribution in greenhouses can greatly influence the growth and development of crops, particularly the air temperature distributions. It was found that the highest ambient air temperature in Kunming was in June and July, whereas, the lowest was in December and January. It was also observed that the internal air temperature under the plastic cover was higher than that of the shaded by STPV in the peak period from 12:00 to 14:00 in the range of 1℃-3℃. Consequently, the average temperature differences between the shaded and unshaded parts were high on the sunny days and the variation started from 9:00 through 15:00 the average air temperature under the shaded part with natural ventilation was higher than that of the outside air temperature by 3.0℃-8.0℃ and the average air temperature under the unshaded part was higher than that of the outside temperature by 5℃-10℃. Subsequently, the average temperature differences between the shaded and unshaded greenhouses were high on the sunny days as shown in Figure 3.



a. Inside the shaded greenhouse on 6th June, 2015

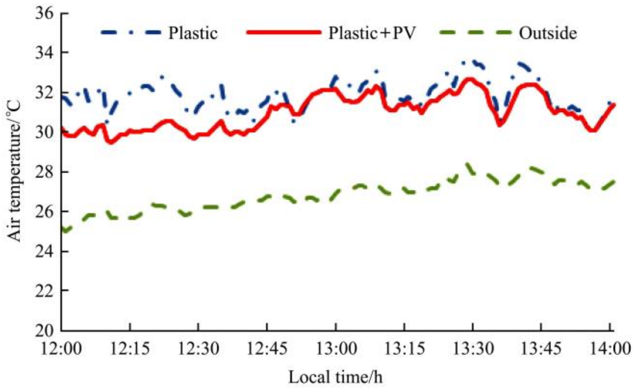


b. Inside the shaded and unshaded greenhouses on 28th June, 2016

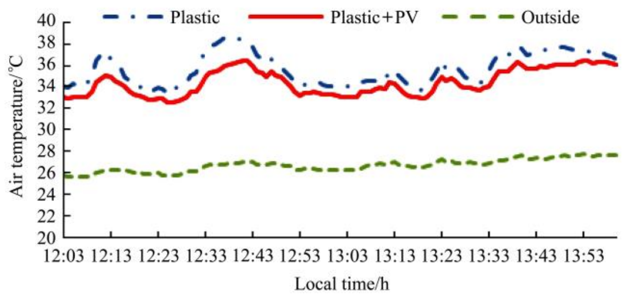
Figure 3 Air temperatures

Furthermore, the average air temperature inside the shaded greenhouse with natural ventilation was higher than that of the outside air temperature by 4℃-5℃. Meanwhile, temperatures under the plastic cover with STPV panels were lower than that of plastic cover only by 1℃-2℃ in the same greenhouse. On the other hand, when there was no ventilation system (all the sidewall ventilation were closed) on clear days from 12:00 to 14:00 the average air temperature inside the greenhouse was higher (37℃) than the outside temperature (27℃) by 8℃-10℃ as shown in Figure 4. It was reported that shading is necessary from the middle of spring, while even shading of approximately 50% was not sufficient to cool the greenhouse during noon time of summer days. Therefore, an additional cooling system is required to keep the required greenhouse air temperature at optimal level[28].

Air temperatures inside greenhouses always observed higher than that of open filed conditions, in contrast, the relative humidity was lower inside the greenhouse particular during the day time on sunny days. It was clear that using the natural ventilation all day long could decrease the internal air temperature and relative humidity especially in summer. Therefore, the mechanical ventilation operated only on hot days when the internal temperature exceeded 25℃ and/or relative humidity above 85%. Meanwhile, it was found that the relative humidity, under natural ventilations, increased in both greenhouses at night and no differences were observed between them compared to the outside relative humidity at night from 18:00 to 6:00. However, the main variation of relative humidity between the inside and outside greenhouses started from 12:00 to 17:00 in clear days of July and it decreased in average of 4% to 10% compared to the outside.



a. Under natural ventilation



b. Without any ventilation systems

Figure 4 Air temperatures of two sensors inside and outside the same shaded greenhouse from 12:00 to 14:00

Consequently, the minimum relative humidity was about 39%, 40% and 54% in the unshaded greenhouse, shaded greenhouse and outside, respectively. The average relative humidity was about 75%, 76% and 80% in the unshaded greenhouse, shaded greenhouses and outside, respectively as shown in Figure 5. Therefore, no differences were observed in relative humidity between shaded and an un-shaded greenhouse under natural ventilation, due to the natural ventilation system was applied in both greenhouses at the same time. In addition, creating a small isolated area at 0.08 m between the plastic cover and the STPV could protect the STPV from the agrochemical applications, internal air temperature and relative humidity. Consequently, it could increase the lifespan of STPV and keep the STPV efficiency stable at the standard air temperatures.

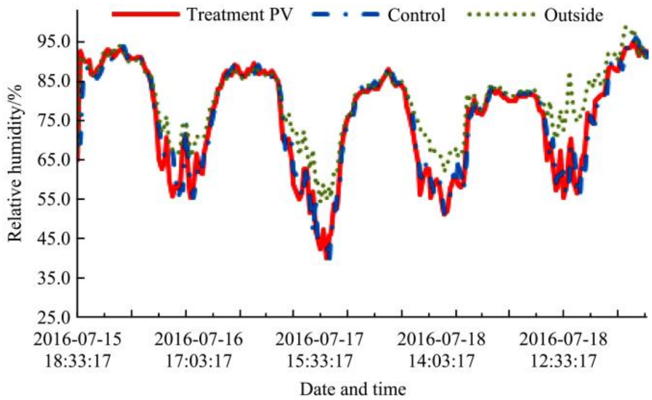


Figure 5 Relative humidity inside the shaded greenhouse with STPV, unshaded greenhouse and outside from 15 July to 20 July, 2016

3.2 Effect of STPV on solar radiation

It was found that the solar radiation under the polyethylene cover along with PV panels was lower than that of polyethylene cover only. Therefore, the plants under the plastic cover always received a higher amount of solar radiation compared to those under the STPV cover. The polyethylene cover reflected more direct-beam radiation after noon. Consequently, it was observed that solar irradiation at the canopy (0.50 m from ground) under the plastic cover with the partial shading of STPV on greenhouse was 30% to 35 % at 12:00, whereas, under the plastic cover was 75% to 80% compared to the direct sunlight outside the greenhouse on sunny days. However, there was no observed variation of solar radiation on the cloudy days between the shaded and unshaded parts of the same greenhouse (Figure 6) and in both of shaded and unshaded greenhouses. The peak values of irradiance on clear and sunny days were high outside the greenhouse at the range of 0.5-1.2 kW/m^2, inside the greenhouse under PE cover (control) at the range of 0.40-0.80 kW/m^2 and low under the PE with STPV at the range of 0.20-0.56 kW/m^2. The effect of STPV shading on solar radiation for representative days in winter and summer seasons of both greenhouses are illustrated in Figure 7. This figure demonstrates that the STPV shading has the same effect on solar radiation on sunny days of the winter and summer seasons.

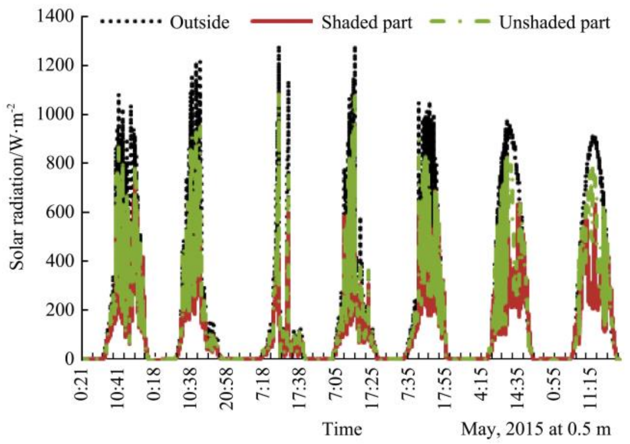
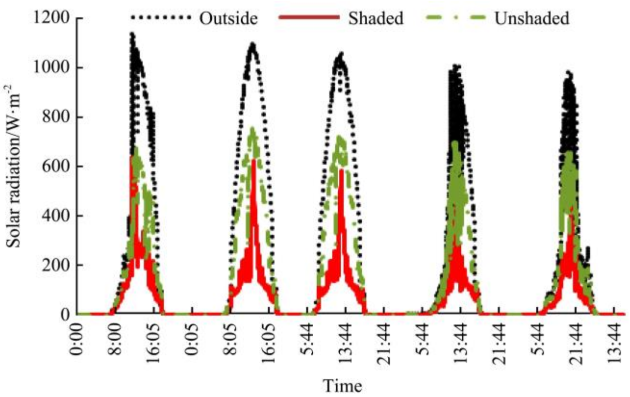
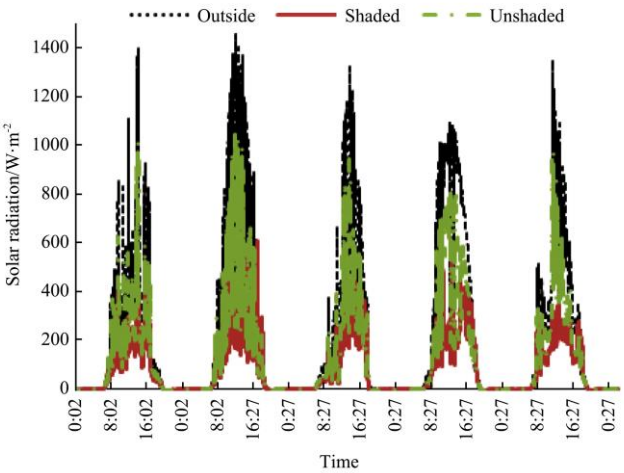


Figure 6 Solar irradiation inside and outside the shaded greenhouse with STPV at 0.5 m on cloudy and sunny days of May, 2015



a. February, 2016 at 2 m



b. June, 2016 at 2 m

Figure 7 Solar irradiation inside the shaded greenhouse with STPV, unshaded greenhouse and outside on cloudy and sunny days

The greenhouse cover plays a great role in decreasing or increasing the light permeability to the plants. Therefore, attaching PV panels inside greenhouses can decrease the electrical energy generated, due to the increasing of cell temperatures and transmissivity of the polyethylene film is known to decrease drastically withincident angle of greater than 60°[29,30]. However, the PV position of PVs inside the greenhouse could be appropriate for some regions and not very suitable for some others, due to the local weather conditions and the type of greenhouse cover. Cossu et al.[31] reported that the shading of solid PV modules (50% of the roof) reduced the availability of solar radiation inside the greenhouse by 64%, compared to the single plastic cover. Therefore, the STPV can be considered as a moderate solution between the flat hard PV and the plastic cover, due to the sunlight penetration of the STPV is higher than that of the non-transparent PV and lower than the single plastic cover and it can fit some crops in greenhouse.

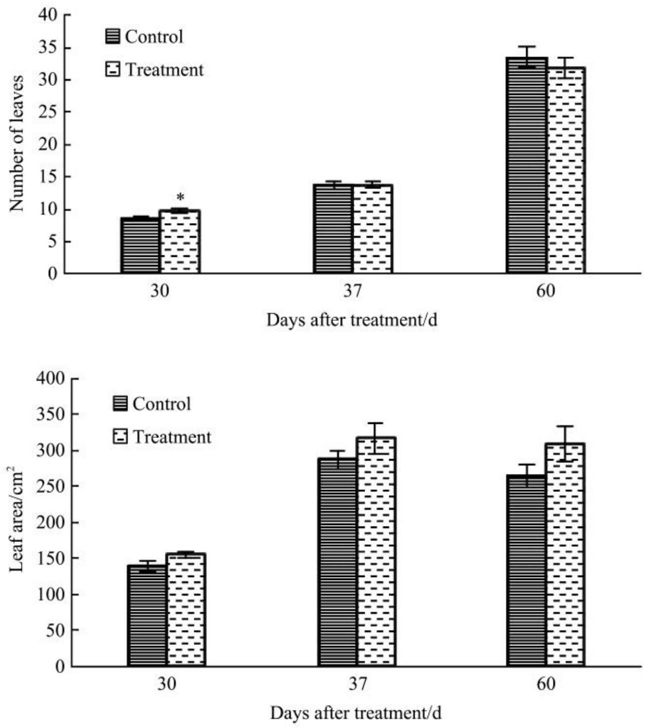
It was also observed that when the average light intensity outside the greenhouses was 112.2 klx (on a sunny day from 11:00 to 14:00, June, 2015), the average light intensity under the plastic cover only was 87.3 klx. Meanwhile, light intensity under the plastic cover with STPV was 31 klx. These results revealed that the plastic cover transmittance was about 78% and the transmittance of the plastic cover with STPV was about 30% comparing to the outside light intensity. Therefore, the STPV shading decreases the light intensity inside the greenhouse by 35% comparing to the plastic cover only.

Photosynthetically Active Radiation (PAR) is the amount of light available for photosynthesis, which is light in the wavelength range of 400 nm to 700 nm. The PAR can be measured in either micromoles of photons per square meter per second (μmol/(m^2·s)) or in watts per square meter (W/m^2). It was found that the solar radiation under STPV shading in the peak period during daytime was higher than or equal to 200 W/m^2 from 10:00 to 17:00. The minimum amount of irradiation necessary to ensure sufficient growth and flowering corresponds to a daily global radiation of 2.0-2.3 kW·h/m^2 (200 W/m^2 which equal to 1000 μmol/m^2·s). Consequently, the reduction in light transmitted through the polythene cover compared to the combination of polythene with STPV did not affect the growth of lettuce. The STPV was a consequence of the extra partial shade at 35%-40% which led to a reduction in the amount of solar radiation that enters the greenhouse. Moreover, lettuce grown in a greenhouse does not always require high light intensity and their photosynthetic rate during summer could be approximately 500 μmol/(m^2·s).

3.3 Effect of STPV shading on the growth of lettuce

3.3.1 Number of leaves and leaf area

It was observed that the STPV shading had no effect on the number of leaves in the first month. Subsequently, it insignificantly decreased the number of leaves after two months of treatments. It was clear that mean number of leaves for shading plants was 32 leaves per plant, whereas for the control (unshaded) was 34 leaves per plant after 60 d of treatment. Results also revealed that the STPV shading insignificantly increased the leaf area. The average leaf area of the large leaf per each plant was approximately 308 cm^2 for treated plant and 264 cm^2 for the control plants after 60 d of treatments as shown in Figure 8. Therefore, the lettuce leaf area increased to harvest light more efficiently. These results are in agreement with Marrou et al.[32]

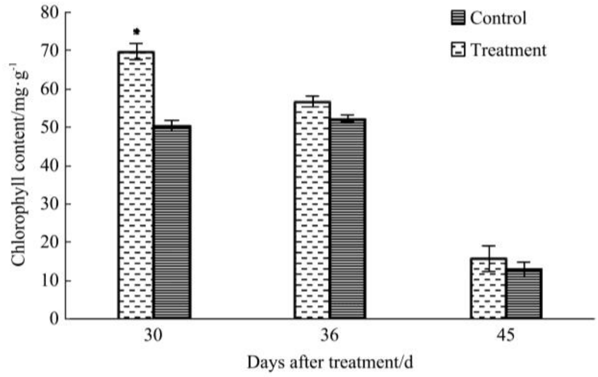


Note: Vertical bars represent mean ±standard errors at p<0.05, (n = 12); * means a significant difference.

Figure 8 Mean number of leaves and leaf area in the treatments over time

3.3.2 Chlorophyll content of leaves

Results revealed that the chlorophyll contents of leaves in shading greenhouse were significantly higher than those of the unshaded. However, this difference was not significant after a period of 36 d to 45 d of treatments as shown in Figure 9.

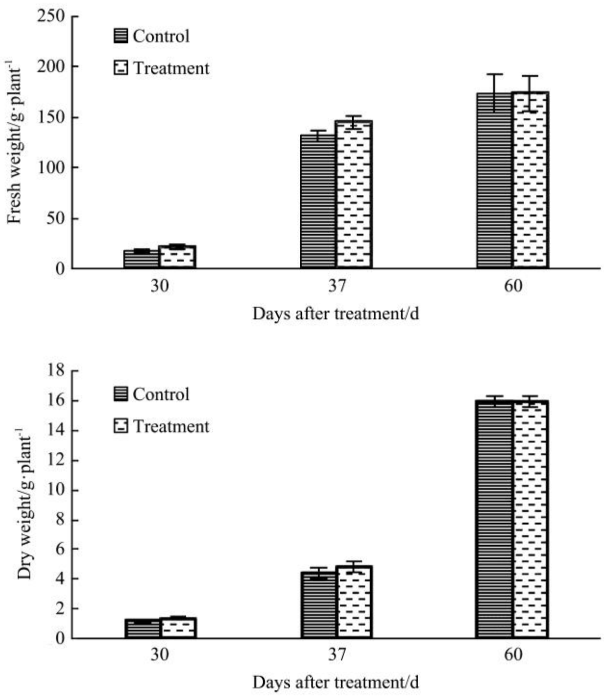


Note: Vertical bars represent mean ±standard errors at p<0.05, (n = 20); * means a significant difference.

Figure 9 Chlorophyll content of lettuce leaves

3.3.3 Fresh and dry weight

The mean fresh and dry weights of lettuce plants in three different days after treatments are as shown Figure 10. The mean fresh weight increased insignificantly (p<0.05) after 37 d. Therefore, there were no significant differences between plants in shaded and unshaded parts of greenhouse. Mean fresh weight was approximately 174 g per plant after 60 d of treatments for both treatments.



Note: Vertical bars represent mean ±standard errors at p<0.05, (n = 12).

Figure 10 Mean fresh and dry weights in the treatments over time

The mean dry weight increased insignificantly after 37 d. Subsequently, after 60 d of treatments there were no significant differences between all treatments which are similar to the fresh weight results. Mean dry matter weight was 16 g per plant after 60 d of treatments for both treatments.

Normally, different plants require different amounts of light for optimal growth. The most important growth factors for lettuce production are temperature and light. The movable shading curtains can reduce the energy load in the greenhouse crop during warm and sunny conditions and reduce heat radiation losses at night[33]. It was observed that lettuce grown under STPV shade insignificantly responds by increasing the fresh weight and leaf area. Therefore, these results are in agreement with Fabio et al.[34] due to lettuce species having a low light-saturation point in the net photosynthetic rate or small carbohydrate sink organs. Furthermore, the tolerance of lettuces to STPV shade mainly relied on the ability of lettuces to improve their capacity to intercept light[32,35]. In addition, it was recommended that light intensities of 400 μmol/(m^2·s) and 600 μmol/(m^2·s) are the best light intensities for lettuce photosynthetic active radiation in higher and lower latitudes, respectively[36]. Therefore, lettuce plants might be suitable for cultivation under the STPV as lettuce production was almost unaffected by applying this technology for a sustainable greenhouses for food and energy productions. These results are consistent with the previous results[32, 37] when the growth of lettuce was inhibited, resulting in lower dry weight and relative growth rate (R_{GR}) with longer leaves, under the fluctuating light by roof-mounted PV modules compared to that under normal greenhouse conditions. Whereas, under diffused light conditions, the ratio of leaf width to length increased and the values were comparable to those in the control in spring, summer and fall cultivations. Although the net photosynthetic rate of fully expanded leaves of lettuce grown under diffused light was lowest, their dry weight and R_{GR} were comparable to the control in summer and fall cultivations.

3.4 Evapotranspiration rate (H_{cv})

The combination of the lost water from the soil surface by evaporation and from the crop by transpiration is referred to as evapotranspiration. It is clear that the evapotranspiration rate in greenhouse can be affected by the solar radiation received by the crop and the stage of crop growth. The evapotranspiration rate is normally expressed in millimeters (mm) per unit time. The rate expresses the amount of water lost from a cropped surface in units of water depth and water depths can also be expressed in terms of energy received per unit area, which is known as the latent heat of vaporization, due to 2.45 MJ are needed to vaporize 0.001 m^3 of water. Therefore, 1 mm/d is equivalent to 2.45 MJ/(m^2·d) at 20°C. In this experiment the ratio of solar radiation to evapotranspiration for actively growing plants in a greenhouse was about 0.5, the transmittance of the greenhouse cover to solar radiation as measured was 0.75 for a single layer of polyethylene and 0.35 for both polyethylene cover with the STPV, while, the floor use factor-ratio of ground covered by plants to total ground area was assumed to be 0.5. It was reported that the evapotranspiration rate (H_{cv}) increases with the increasing of solar radiation. Subsequently, the evapotranspiration inside the greenhouse is lower than the outside, actual evapotranspiration, due to the absorption and reflection of incident solar radiation by the plastic cover, lower wind speed and higher relative humidity inside the greenhouses. Results revealed that the integration of the STPV along with polyethylene cover decreased the H_{cv} by 47% compared to the polyethylene cover. The average H_{cv} on a sunny day was 4.37 kW and 2.04 kW for the unshaded and shaded greenhouses, respectively. The solar radiation unit can be in (kw·h/(m^2·d)) or (MJ/(m^2·d)) and 1 kW·h is equal to 3.6 MJ. Therefore, by calculating the monthly H_{cv} for both greenhouses, it was observed that the maximum H_{cv} was on April at 3311.63 MJ (1.72 mm/d) for unshaded greenhouse (H_{cvPE}) and it was 1545.43 MJ (0.80 mm/d) for STPV greenhouse (H_{cvPV}). While, the minimum H_{cv} was found on October at 2070.79 MJ (1.04 mm/d) for the unshaded greenhouse and 966.37 MJ (0.48 mm/d) for the STPV greenhouse as shown in Figures 11 and 12.

The previous studies also found that the mean daily measured greenhouse reference evapotranspiration by a free-drainage lysimeters in a semi-arid area of Spain was ranged from less than 1 mm/d during winter to approximately 4 mm/d, during summer in July and when the greenhouse surface was whitened with a moderate calcium carbonate concentration (as a form of shading) from March to September the measured evapotranspiration was reduced by an average of 21.4%[38].

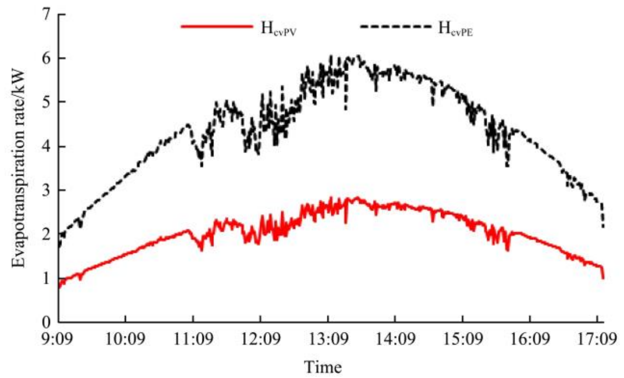


Figure 11 Evapotranspiration rates in shaded and unshaded greenhouses on a sunny day

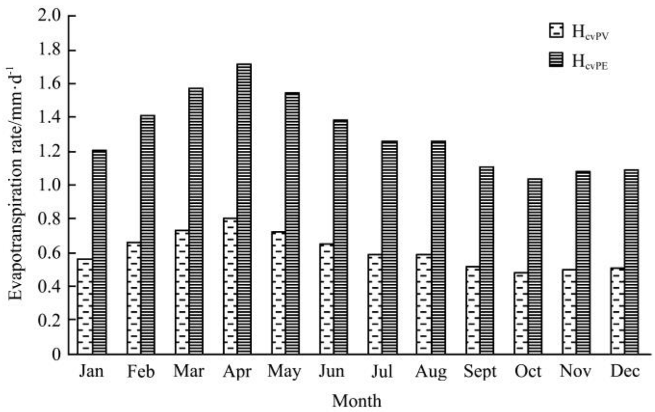


Figure 12 Monthly calculated evapotranspiration rates in shaded and unshaded greenhouses

Consequently, the integration of STPV with greenhouses for shading could decrease the water consumption for irrigation, these results are also in agreement with the previous studies of Ahemd et al.[20] and Marrou et al.[39]

3.5 Electric energy demand and STPV production

Results of the calculation revealed that the annual generated electric energy of the STPV at 20% of the greenhouse south roof area approximately 637 kW·h and it can save 341.5 kg of CO_2. The peak generated electric energy of STPV was in March and the lowest was in June and July according to the local weather conditions, particularly the solar radiation. The annual electric energy demand for greenhouses depends mainly on the type of construction, local climate and the cultivated crop. It was found that the annual required energy for heating and cooling systems for the current experimental greenhouse in Kunming is about 2600 kW·h, due to the cooling demands are lower (May to July) than the heating demands (December to February), and the lighting demand can be ignored. Thereby, the STPV can provide 20% of the annual energy demand. Consequently, using high efficiency PV modules could provide enough electric energy to meet the annual energy consumption at a minimum roof area.

4 Conclusions

The semi-transparent PV panels (STPV) shading decreases the air temperature by 1°C-3°C on clear days compared to unshaded, meanwhile it has no significant effect in the relative humidity ratio. The integration of STPV with polyethylene cover decreases the solar radiation by 35% compared to the polyethylene cover. The STPV insignificantly increases the leaf area and decreases the number of leaves for lettuce. However, it has no significant effect on the fresh weight and dry weight of lettuce plants and the light reduction was not significantly harmful for lettuce production. Furthermore, STPV could provide about 20% of the greenhouse annual electrical energy consumption and decrease the evapotranspiration rate or the water consumption and the CO_2 emission. Therefore, a specific crop management for choosing the most suitable vegetables can be suggested particularly in hot seasons such as, lettuce, spinach carrot, turnips, cabbage and broccoli which need low light intensities. These results clarify that the electric energy production and allowable shading could be changed according to the plant species, geography, meteorology, season, and greenhouse characteristics. In some other words, a mobile STPV with a light weight, high efficiency or a specific distribution on the greenhouse roof in tropic and subtropics area is recommended for shading the agricultural greenhouses at the start of warm weather in June until late August, such as the lightweight PV film can be used as an option for increasing the solar radiation in winter or cloudy days because it may be possible to change the position of the PV modules depending on the season and the local weather conditions. Therefore, further studies should be conducted to explore the ideal PV agricultural greenhouses.

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[References]

[1] Bot G, VandeBraak N, Challa H, Hemming S, Rieswijk T H, van Straten G, et al. The solar greenhouse: State of the art in energy saving and sustainable energy supply. Acta Horticulturae (ISHS), 2005; 691: 501–508.

[2] Sethi V P, Sharma S K. Survey of cooling technologies for worldwide agricultural greenhouse applications. Solar Energy, 2007; 81(12): 1447–1459.

[3] Sethi V P, Sharma S K. Survey and evaluation of heating technologies for worldwide agricultural greenhouse applications. Solar Energy, 2008; 82(9): 832–859.

[4] Chai L, Ma C, Ni J Q. Performance evaluation of ground source heat pump system for greenhouse heating in northern China. Biosystems Engineering, 2012; 111(1): 107–117.

[5] Ureña-Sánchez R, Callejón-Ferre Á J, Pérez-Alonso J, Carreño-Ortega Á. Greenhouse tomato production with electricity generation by roof-mounted flexible solar panels. Scientia Agricola, 2012; 69: 233–239.

[6] Hassanien R H E, Li M, Dong L W. Advanced applications of solar energy in agricultural greenhouses. Renewable and Sustainable Energy Reviews, 2016; 54: 989–1001.

[7] Breyer C, Koskinen O, Blechinger P. Profitable climate change mitigation: The case of greenhouse gas emission reduction benefits enabled by solar photovoltaic systems. Renewable and Sustainable Energy Reviews, 2015; 49: 610–628.

[8] Kadowaki M, Yano A, Ishizu F, Tanaka T, Noda S. Effects of greenhouse photovoltaic array shading on Welsh onion growth. Biosystems Engineering, 2012; 111(3): 290–297.

[9] Yano A, Kadowaki M, Furue A, Tamaki N, Tanaka T, Hiraki E, et al. Shading and electrical features of a photovoltaic array mounted inside the roof of an east-west oriented greenhouse. Biosystems Engineering, 2010; 106(4): 367–377.

[10] Li C, Wang H, Miao H, Ye B. The economic and social performance of integrated photovoltaic and agricultural greenhouses systems: Case study in China. Applied Energy, 2017; 190: 204–212.

[11] Yano A, Onoe M, Nakata J. Prototype semi-transparent photovoltaic modules for greenhouse roof applications. Biosystems Engineering, 2014; 122: 62–73.

[12] Cossu M, Yano A, Li Z, Onoe M, Nakamura H, Matsumoto T, et al. Advances on the semi-transparent modules based on micro solar cells: First integration in a greenhouse system. Applied Energy, 2016; 162: 1042–1051.

[13] Cossu M, Ledda L, Urracci G, Sirigu A, Cossu A, Murgia L, et al. An algorithm for the calculation of the light distribution in photovoltaic greenhouses. Solar Energy, 2017; 141: 38–48.

[14] Fatnassi H, Poncet C, Bazzano M M, Brun R, Bertin N. A numerical simulation of the photovoltaic greenhouse microclimate. Solar Energy, 2015; 120: 575–584.

[15] Foster R, Cota A. Solar water pumping advances and comparative economics. Energy Procedia, 2014; 57: 1431–1436.

[16] Veldhuis A J, Reinders A H M E. Reviewing the potential and cost-effectiveness of off-grid PV systems in Indonesia on a provincial level. Renewable and Sustainable Energy Reviews, 2015; 52: 757–769.

[17] Al-Helal I M, Abdel-Ghany A M. Measuring and evaluating solar radiative properties of plastic shading nets. Solar Energy Materials and Solar Cells, 2011; 95(2): 677–683.

[18] Lorenzo P, Garcia M L, Sanchez-Guerro M C, Medrano E, Caparros I, Giménez M. Influence of mobile shading on yield, crop transpiration and water use efficiency. Acta Horticulturae, 2006; 719: 471–478.

[19] Chauhan P M, Kim W S, Lieth J H. Combined effect of whitening and ventilation methods on microclimate and transpiration in rose greenhouse. Proceedings of the International Conference on Thermal Engergy Storage Tchnologies, Devi Ahilya University, Indore-17, India, 2003.

[20] Ahemd H A, Al-Faraj A A, Abdel-Ghany A M. Shading greenhouses to improve the microclimate, energy and water saving in hot regions: A review. Scientia Horticulturae, 2016; 201: 36–45.

[21] Dai Y, Shen Z, Liu Y, Wang L, Hannaway D, Lu H. Effects of shade treatments on the photosynthetic capacity, chlorophyll fluorescence, and chlorophyll content of tetrastigma hemsleyanum diels et gilg. Environmental and Experimental Botany, 2009; 65(2): 177–82.

[22] Zhao D, Hao Z, Tao J. Effects of shade on plant growth and flower quality in the herbaceous peony *(Paeonia lactiflora* Pall.). Plant Physiol Bioch, 2012; 61: 187–196.

[23] Wang N, Huang Q, Sun J, Yan S, Ding C, Mei X, et al. Shade tolerance plays an important role in biomass production of different poplar genotypes in a high-density plantation. Forest Ecology and Management, 2014; 331: 40–49.

[24] Mashonjowa E, Ronsse F, Mhizha T, Milford J R, Lemeur R, Pieters J G. The effects of whitening and dust accumulation on the microclimate and canopy behaviour of rose plants (*Rosa hybrida*) in a greenhouse in Zimbabwe. Solar Energy, 2010; 84(1): 10–23.

[25] Araki Y, Inoue S, Murakami K. Effect of shading on

growth and quality of summer spinach. Acta Horticulturae, 1999; 483: 105–110.

[26] Paul W. Stackhouse J. NASA Surface meteorology and Solar Energy, 2015.

[27] Aldrich R A, Bartok J W. Greenhouse engineering. In: Sanders M, editor. 3rd ed. Ithaca, New York, 14853: NRAES; 1994. p. 218.

[28] Kitta E, Katsoulas N, Savvas D. Shading effects on greenhouse microclimate and crop transpiration in a cucumber crop grown under Mediterranean conditions. Applied Engineering in Agriculture, 2012; 28(1): 129–140.

[29] Pieters J G, Deltour J M, Debruyckere M J. Light transmission through condensation on glass and polyethylene. Agricultural and Forest Meteorology, 1997; 85(1): 51–62.

[30] Yano A, Furue A, Kadowaki M, Tanaka T, Hiraki E, Miyamoto M, et al. Electrical energy generated by photovoltaic modules mounted inside the roof of a north-south oriented greenhouse. Biosystems Engineering, 2009; 103(2): 228–238.

[31] Cossu M, Murgia L, Ledda L, Deligios P A, Sirigu A, Chessa F, et al. Solar radiation distribution inside a greenhouse with south-oriented photovoltaic roofs and effects on crop productivity. Applied Energy, 2014; 133: 89–100.

[32] Marrou H, Wery J, Dufour L, Dupraz C. Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. European Journal of Agronomy, 2013; 44: 54–66.

[33] Al-Helal I M, Abdel-Ghany A M. Responses of plastic shading nets to global and diffuse PAR transfer: Optical properties and evaluation. NJAS - Wageningen Journal of Life Sciences, 2010; 57(2): 125–132.

[34] Stagnari F, Galieni A, Pisante M. Shading and nitrogen management affect quality, safety and yield of greenhouse-grown leaf lettuce. Sci hortic-amsterdam, 2015; 192: 70–79.

[35] Gimenez C, Otto R F, Castilla N. Productivity of leaf and root vegetable crops under direct cover. Scientia Horticulturae, 2002; 94(1): 1–11.

[36] Fu W, Li P, Wu Y. Effects of different light intensities on chlorophyll fluorescence characteristics and yield in lettuce. Scientia Horticulturae, 2012; 135: 45–51.

[37] Akira T, Suguru S, Kazuki N, Makio H. Improvement in lettuce growth by light diffusion under solar panels. Journal of Agricultural Meteorology, 2014; 70(3): 139–149.

[38] Fernández M D, Bonachela S, Orgaz F, Thompson R, López J C, Granados M R, et al. Measurement and estimation of plastic greenhouse reference evapotranspiration in a Mediterranean climate. Irrigation Science, 2010; 28(6): 497–509.

[39] Marrou H, Dufour L, Wery J. How does a shelter of solar panels influence water flows in a soil-crop system. European Journal of Agronomy, 2013; 50: 38–51.