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Study On Photovoltaic Modules On Greenhouse Roof For Energy And Strawberry Production

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Abstract. The aim of this study was to investigate the effect of PV modules mounted on top of a greenhouse, on the growth of strawberries and microclimate conditions as well as to estimate the generated energy. In this study, two greenhouses with the same volume were established. One greenhouse was equipped with the opaque photovoltaic (OPV) modules which accounted for 25.9% of the roof area, and the other was equipped with the semi-transparent photovoltaic (STPV) modules which accounted for 20% of the roof area. The maximum annual power generation of OPV and STPV modules was 880 and 388 kWh with 30° tilt angle, respectively, by simulating different tilt angles. The temperature under the OPV and STPV modules was 2.9 and 1.1 °C lower than the unshaded part in the greenhouses, respectively, at noon in clear weather, and had little effect on relative humidity. The photosynthetically active radiation (PAR) under OPV and STPV modules was reduced by 43.5% and 31.7%, respectively, under the PE film greenhouse. The contents of soluble solids in strawberries in OPV and STPV greenhouses were 16.4 and 15.7 mg/g respectively, which were higher than those in unshaded samples. The quality and yield of the strawberry samples under the shade of OPV were better than those of the STPV shade.

1 Introduction

The photovoltaic (PV) modules installed on the roof of greenhouse can not only generate electricity, but also reduce the solar radiation through the roof, and fall to the plants in the greenhouse, affecting their light, thus affecting crop growth [1]. PV power generation can meet greenhouse energy demand in cooling, heating, ventilation, artificial lighting and other energy needs [2]. The energy generated by PV modules with different tilt angles and installations has different effects on the greenhouse microclimate, so that information that can be used to support farmers and create PV greenhouses can generate income from electrical and agricultural activities. [3-7]. Generally, opaque or semi-transparent polysilicon or monocrystalline silicon PV panels are integrated on the south-facing roof of the greenhouse [8-11]. The shading of PV modules affects the solar radiation entering the greenhouse [7, 12, 13], and affects the temperature, humidity and light in the greenhouse [14-17]. However, temperature and light strongly interact and affect plant growth [18]. Environmental control of greenhouses during the summer is one of the main challenges in tropical and subtropical climates. Shading is an effective way to reduce light transmission [19], furthermore, shading agricultural greenhouses and cooling systems in hot and sunny areas can reduce water consumption by 25%, reduce greenhouse temperature to 5-10 °C below outdoor temperature, and increase relative humidity by 15-20%. In addition, shading reduces solar radiation by 30-50% and cooling energy consumption by 20% and 15% [20].

Strawberry (Fragaria x ananassa) is a delicious and healthy fruit, loved by people all over the world [21, 22]. The growth of strawberries in greenhouses is a widespread cultivation method that prevents damage from natural disasters and provides a suitable environment for strawberry growth [23, 24]. Strawberry has obvious response to the change of growing environment especially temperature and light have significant influence on strawberry production [25-27]. In recent years, some scholars have studied the effects of 20% roof power generation of photovoltaic modules and shading on plant growth [1, 16]. However, there are few studies on strawberry planting in PV greenhouses, especially the research on the influence of shading of PV modules on the growth environment and strawberry production. Therefore, the purpose of this study is to find out the electrical energy generated by opaque polycrystalline silicon PV module and translucent monocrystalline silicon PV module at different inclination angles and the environmental parameters in greenhouses, and the influence of shading on strawberry production in greenhouses under different placement modes of PVmodules.

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2 Materials and methods

2.1 Construction of greenhouses and configuration of PV Modules

This experiment was built in Kunming, China (102.68° E longitude and 25.07° N latitude). Two east-west greenhouses were installed on the roof of the solar energy research institute building. As shown in Fig. 1, the two greenhouses had the same size, 7.5 m long and 3.5 m wide, covering an area of 26.25 m^2 and 78.75 m^3 in volume. The greenhouse roof was covered with a layer of 0.12 mm polyethylene (PE) film. The opaque photovoltaic (OPV) modules and semi-transparent photovoltaic (STPV) modules were installed on the southern roofs of the two greenhouses for the control experiment. All PV modules have a mounting angle of 30° , four opaque polysilicon silicon modules occupy 25.9% of the first greenhouse roof, and three semi-transparent monocrystalline silicon modules account for 20% of the second greenhouse roof.

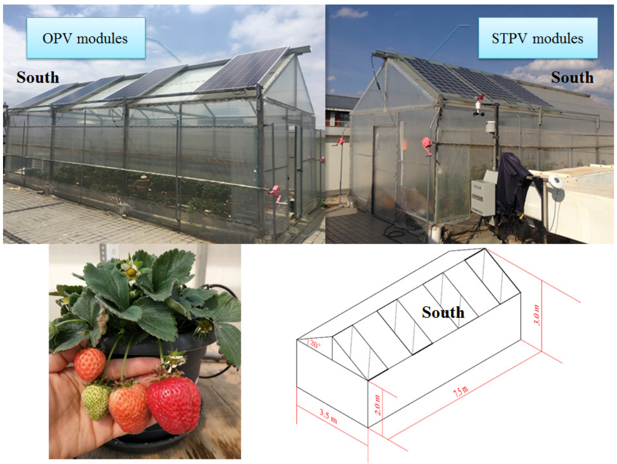

Fig. 1. OPV and STPV greenhouses diagram.

The characteristic parameters of two types of PV modules are shown in Table 1. Before installing PV modules, the annual power generation of PV modules with different tilt angles was simulated by using POLYSUN software. Finally, the tilt angle of 30° was selected. A pyranometer (produced by Beijing Tianyude Co., Ltd.) was mounted parallel to PV modules plane to measure the incoming solar radiation on them. The greenhouse environmental parameters were controlled by shading of PV modules, including temperature, relative humidity and light. Because of the opacity of OPV modules, in order to meet the lighting needs of plants in greenhouse, the distance between OPV panels was 1.1 m, while the STPV modules with their own spacing (Toughened glass(6 mm)+PV(2.28 mm)+(125×125 mm) sc-Si cells+toughened glass(6 mm) were continuously installed on the west side of the south roof of the greenhouse.

Table 1. Characteristics of OPV and STPV modules.

Characteristic	STPV	OPV
Peak power (Pmax)	170W	310 W
Open circuit voltage (Voc)	39.6V	45.8 V
Short circuit (Isc)	5.65A	8.90 A
Voltage (Vmp)	33.2V	38.2 V
Current (Imp)	5.12A	8.10 A
Weight	63.0kg	23.5 kg
Module efficiency	8.25%	17.00%

2.2 Microclimate monitoring in greenhouses

The temperature, humidity, and photosynthetically active radiation (PAR) of both greenhouses were measured for both shaded and unshaded data for comparison. As shown in Fig. 2, the temperature, humidity and PAR sensors were placed at a position 1.0 m above the ground in the greenhouse locations A, B, C and D where the OPV modules were installed. The accuracy of the test instruments is shown in Table 2.

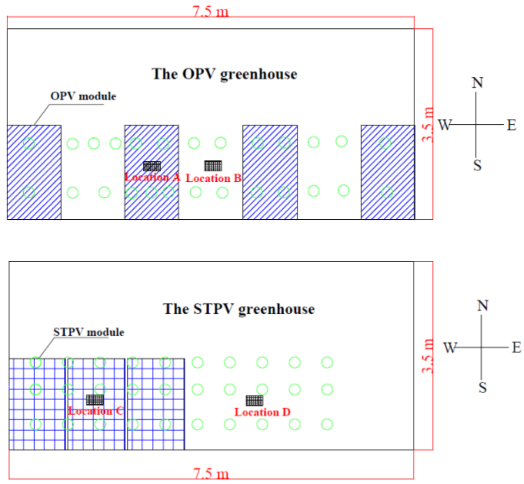

Fig. 2. Top view and sensors location of OPV and STPV greenhouses.

Table 2. The specification of instruments.

Instrument name	Model	Measurement range	Accuracy
Pyranometer	TRT-2-B	0-2000 W·m^{-2}	±2%W·m^{-2}
Temperature and humidity recorder	TH12R-EX	-40-85 ° C 0-100%	±0.2° C ±2%

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PAR sensor	GLZ-C	0-2700 μmol· m^{-2}· s^{-1}	±1 μmol· m^{-2} ·s^{-1}

2.3 Selection and measurements of strawberry sample

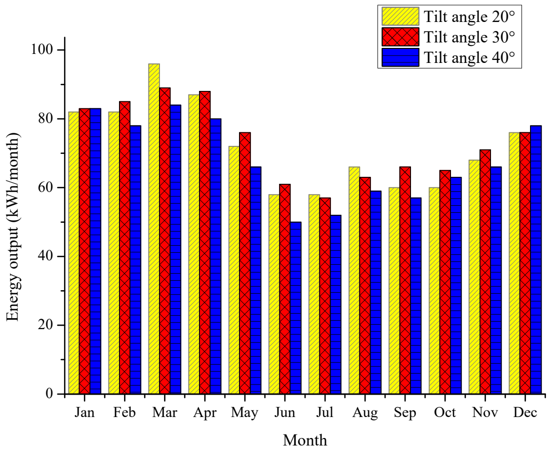
The 'Jingzangxiang' strawberry cultivar, which is derived from the cross between 'Benihoppe' as the male parent and 'Earlibrite' as the female parent was selected for use in PV greenhouses [28]. The survival rate of this cultivar is 98%, moreover, this strawberry cultivar is listed 8 to 20 days earlier than other cultivars under the same planting conditions [29]. In addition, 'Jingzangxiang' strawberry fruit has excellent comprehensive quality, and it is suitable for large-scale production in Kunming [30]. Therefore, the 'Jingzangxiang' strawberry was selected as the experimental cultivar for greenhouse cultivation. There were 30 pots for each greenhouse, accurately planting a strawberry seedling in each pot. All plants had the same cultivation substrate, irrigation and fertilization systems. The experimental design was a randomized block design with two treatments (shaded and unshaded strawberry samples) in each greenhouse.

The measurements of strawberry samples included chlorophyll content in leaves, shortest flowering and fruiting periods, yield per plant, maximum fruit weight and soluble solids content. The chlorophyll content of the leaves was measured by a portable chlorophyll meter (±1.0 SPAD) from Shanghai Rong Yan instruments. Co., Ltd, China. The weight and soluble solid content of the fruits were measured by an electronic scales (0.001 g) and a digital display saccharimeter (±0.2%). The data measured in OPV and STPV greenhouses were compared and analysed.

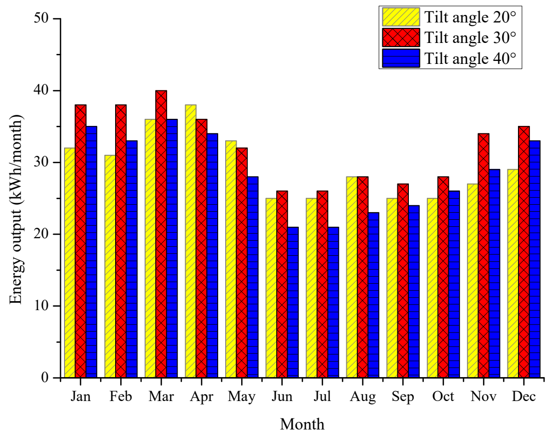
3 Results and discussions

3.1. Electric energy production of OPV and STPV modules on greenhouse roof

Before installed the PV modules, the annual power generation had been simulated by using POLYSUN software. As shown in Fig. 3, the installation inclination angles of OPV and STPV modules were compared according to 20°, 30° and 40°, respectively. The results showed that the annual power generation of OPV modules was 865, 880 and 816 kWh, respectively. Correspondingly, the annual power generation of STPV modules was 354, 338 and 343 kWh. It was theoretically confirmed that the 30° tilt angle was more suitable for installation in low-latitude subtropical regions, where the PV modules produced the largest annual power generation.



(a) OPVG



(b) STPVG

Fig. 3. Simulation of electric energy for PV modules by POLYSUN software at different tilt angles.

To further investigate the solar radiation and generated electrical energy received by the greenhouse roof PV modules during the summer, solar radiation was monitored for 30 days (14th July to 12th August 2018) and the total amount of solar radiation per day was analyzed.

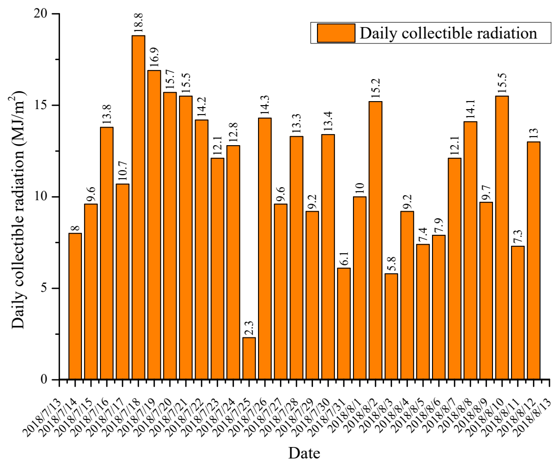


Fig. 4. Daily irradiation per square meter (14th July to 12th August 2018)

As shown in Fig. 4, the daily total irradiation did not reach the ideal value of 20 MJ/m^2, and the minimum irradiation was only 2.3 MJ/m^2, due to more rainy and cloudy weather in summer in the experimental area. During the sunny weather during the experiment, the maximum daily total radiation received by the PV modules was 18.8 MJ/m^2, the daily power generation of OPV module was 0.89 kWh/m^2, and the daily power generation of STPV module was 0.43 kWh/m^2.

3.2 Effects of OPV and STPV modules installed on roofs on greenhouse microclimate

The temperature inside greenhouse was always observed higher than that of the ambient temperature. In contrast, the relative humidity was lower inside the greenhouse than outside particularly during the daytime on sunny days. The PV modules installed on the roof of the greenhouse had an impact on the microclimate in the greenhouse. In order to study the effects of shading, the temperature, humidity and light in the greenhouse were divided into shaded and unshaded parts for data collection and analysis in the typical days from 15th July 2018 to 24th July 2018.

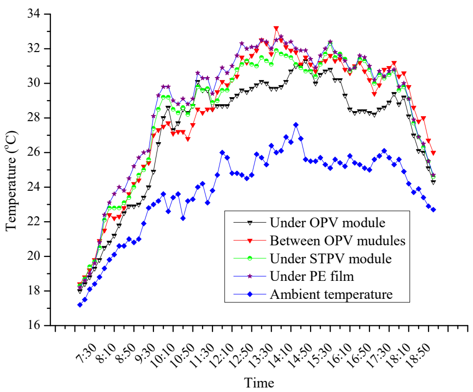


Fig. 5. Comparison of temperature between OPV and STPV greenhouses.

As shown in Fig. 5, when the average ambient temperature was 23.8 °C in daytime, the unshaded temperature in greenhouse was 28.9 °C, and the shaded temperature in OPV and STPV was 28.4 and 27.3 °C, respectively. When the temperature in the unshaded part of greenhouse reached the highest 32.7 °C, the shaded temperature in OPV and STPV was 29.8 and 31.6 °C, respectively. The temperature under OPV and STPV modules were 2.9 and 1.1 °C lower than the unshaded temperature in the greenhouses, respectively, at noon in clear weather.

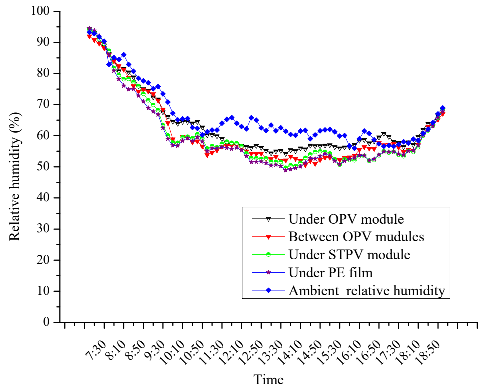


Fig. 6. Comparison of relative humidity between OPV and STPV greenhouses

The relative humidity in the greenhouses generally decreased with increasing temperature. The shading of OPV and STPV modules had less effect on relative humidity. As shown in Fig. 6, the trends between the curves were basically the same, and the difference in relative humidity is not obvious. The minimum relative humidity of 49.2% in the unshaded part of the greenhouse appeared at 13:50 pm, at which time the relative humidity under OPV and STPV shading was 55.4% and 50.5%, respectively.

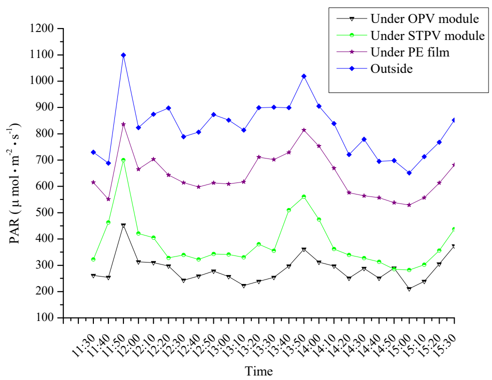


Fig. 7. Light comparison between OPV greenhouse and STPV greenhouse in sunny weather.

Compared to temperature and relative humidity, the effect of shading of PV modules on the light in the greenhouse was most pronounced, especially at noon. Therefore, the data of 11:30-15:30 was selected to compare the PAR. As shown in Fig. 7, compared to the outside PAR curve, the most significantly reduced curve was under the OPV module, and the second reduced curve was under the STPV module. At 13:50 pm, when the outdoor PAR was 1019 μmol·m^{-2}·s^{-1}, the PAR of unshaded part in the greenhouse was 814 μmol·m^{-2}·s^{-1}, the PAR was only 361 μmol·m^{-2}·s^{-1} under the OPV module, and the PAR was 559 μmol·m^{-2}·s^{-1} under the STPV module. The average transmittance of PE film was 78.1%, in addition, the transmittance of STPV was 31.7% lower than PE film, and the transmittance of OPV was 43.5% lower than PE film. The shading of the PV modules significantly reduced the PAR, avoided excessive burns on the strawberry leaves and provided a better light environment for the growth of the strawberry plants.

3.3 Effects of OPV and STPV shading on strawberry production

Strawberry growth is susceptible to environmental influences, especially temperature and light. Strawberry samples shaded by PV modules in greenhouse showed better growth than those unshaded samples. The chlorophyll content of strawberry samples in OPV and STPV greenhouses was measured. After 30, 60 and 90 days shaded by PV modules, the chlorophyll content of leaves changed as shown in Fig. 8. The chlorophyll content of strawberry growing period increased gradually, and the chlorophyll content of strawberry shaded by PV module was higher than that of unshaded samples. The chlorophyll content of strawberry samples shaded by OPV was higher than that shaded by STPV. The chlorophyll content of shaded strawberry samples for 90 days was the highest. The chlorophyll content of shaded and unshaded samples in OPV greenhouse were 91.8 and 47.2 mg/g, while the chlorophyll content in STPV greenhouse were 87.6 and 45.0 mg/g.

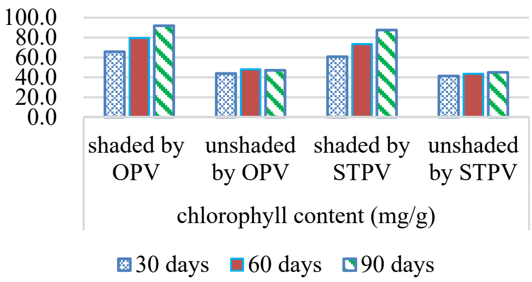


Fig. 8. Comparison of chlorophyll content in leaves of strawberry samples.

The phenological period of the first batch of strawberries after shading treatment of PV modules was recorded and the yield and quality of strawberry fruits were measured. The results from Table 3 showed that the quality and yield of the strawberry samples under the shade of OPV were better than those of the STPV shade.

Table 3. Phenophase and production parameters of strawberry samples.

	OPV greenhouse		STPV greenhouse	
	Shaded	Unshaded	Shaded	Unshaded
Flowering stage (day)	33	40	35	41
Fruiting stage (day)	24	29	28	32
Maximum weight of fruit (g)	19.7	15.2	17.1	13.9
Yield per plant in the first fruiting (g)	69.3	55.0	62.9	47.8
Soluble solids (Brix)	16.4	13.1	15.7	13.2

The photos of strawberry fruits in OPV and STPV greenhouses are shown in Fig. 9. It is very obvious that the single fruit of strawberries shaded by PV panels is larger than that of unshaded ones, and strawberries in OPV greenhouse are larger than those in STPV greenhouse.

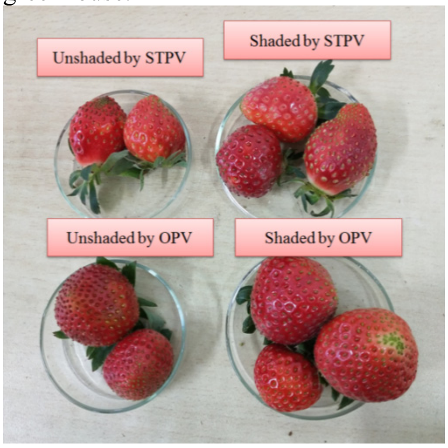


Fig. 9. Photos of strawberry fruits in OPV and STPV greenhouses.

4 Conclusion

In this study, two greenhouses with OPV and STPV modules installed at the top of the greenhouse were established. OPV and STPV modules accounted for 25.9% and 20% of the roof area, respectively. The annual power generation of OPV and STPV modules was simulated. It was proved that proper shading of PV modules would not affect the growth of strawberry plants in greenhouse, and could also improve the yield and quality of strawberry fruits. The results showed that strawberry samples in OPV greenhouse were better than those in STPV greenhouse in growth and production, and strawberry samples under OPV component shade showed a better development trend.

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