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SCAPV Creates the Possibility of Less Irrigation and Higher Productivity

A Case Study of Evapotranspiration, Peanuts, and Soybeans

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Abstract. In agrivoltaic (APV), photovoltaic (PV) panels are positioned above farmland to produce energy and food simultaneously. However, PV panels above farmland block most sunlight from reaching plants for photosynthesis. Plants require sunlight for photosynthesis. We proposed Spectrum-splitting and Concentrated APV (SCAPV) to address contradictions between photosynthesis and energy production simultaneously. This study examines the effect of SCAPV on the evapotranspiration and growth of peanuts and soybeans. Peanuts and soybeans were planted under SCAPV and open-air (CK) treatments, and a weather station was placed in each treatment. Results showed that evapotranspiration under SCAPV significantly decreased by 31% compared to CK. Thus, it improved physiological characterization, enhanced quality, and increased the yield of peanuts and soybeans. Peanuts' protein, fat, and linoleic acid increased by 5.54%, 0.28%, and 1.14% under SCAPV compared to CK. Fat, soluble sugar, linoleic acid, and alpha-linolenic acid of soybean were increased by 6.75%, 15.24%, 13.72%, and 15.14%, respectively, under SCAPV compared to CK. The average land equivalent ratio of SCAPV is 1.7. We trust that SCAPV could provide food and energy while reducing irritation on the same farmland.

Keywords: SCAPV, Spectrum Separation, Evapotranspiration, Peanuts, Soybeans

1. Introduction

It is estimated that over 40% of all calories are derived from crop irrigation, which utilizes 70% of the world's water [1–3]. There are driven to reduce water consumption and increase irrigation efficiency, especially in water-scarce areas [1, 4–6]. Governments typically encourage improvements in irrigation efficiency, promoting innovative techniques to enhance "crop per drop." Irrigation efficiency refers to how effectively water is delivered to plants and how much water plants use for growth and productivity. In other words, it measures how much water applied to crops benefits the plants and how much is lost through evaporation, runoff, or other means. Extensive scientific data [7] has long demonstrated that increasing irrigation efficiency rarely results in the assumed public-good advantages of higher water availability [3]. Grafton, R.Q et al. illustrates the paradox of irrigation efficiency and judgment of possible transpiration values, evaporation, runoff, and recharge estimated for different irrigation systems. They assumed that surface irrigation results in 40-70% crop transpiration, 10-25% evaporation, and 15-50% surface runoff and subsurface recharge. Sprinkler irrigation is estimated to produce 65-85% of crop transpiration, 10-30% evaporation, and 5-15% surface runoff and subsurface recharge. The drip irrigation system shows 85-95% crop transpiration, 5-10% evaporation, and 0-10% surface runoff and subsurface recharge [3]. In addition, fossil fuel resources are becoming more limited, greenhouse gas emissions are rising, and global climate change urgently needs more sustainable technologies to enable climate-smart agriculture [8].

Photovoltaic (PV) is among the most attractive renewable energy technology due to PV's minimal carbon dioxide emissions, durability, and availability of reliable and plentiful power sources [9]. The electricity generation efficiency of commercial PV modules has increased from about 15% in 2010 to about 23% today [10]. In addition, the production cost of PV modules has significantly decreased, with the price per watt dropping from 5 RMB per watt in 2012 to 1.8 RMB per watt in 2022 [11]. In the 1980s, agrivoltaic (APV) was proposed to produce agriculture and energy simultaneously on the same farmland [12]. Plants require red, blue, and far-red lights for photosynthesis and plant morphology at various stages of plant development [13, 14]. As a result of the PVs placed above the farmland, the PVs hindered the sunlight, and crops could not obtain sufficient irradiance compared to plants grown in a natural state [15]. The experimental results showed that yield reductions of 20 ~ 40% were experienced even when growing shade-tolerant crops like lettuce [16, 17]. Therefore, more innovative APV is needed to address contradictions between photosynthesis and energy production on the same farmland.

To address the shade challenge on farmland, we proposed Spectrum-splitting and Concentrated APV (SCAPV) [18], which allows simultaneous plant photosynthesis and electricity generation from PVs. SCAPV combines two innovative ideas: spectrum splitting and concentration PV technology, which enables the selective transmission of red, blue, and far-red light beneficial for plant growth through parabolic curved glass covered with polymer multilayer films (PMF) while reflecting the remaining sunlight to PVs for electricity generation [19, 20]. Although SCAPV is a conceptual and intelligent approach, it is a more complex solution that involves higher costs, which may remain high even when scaled up in large volumes. However, one significant advantage of SCAPV is that plants always receive the wavelengths necessary for photosynthesis. This benefit ensures optimal plant growth and development, regardless of the shading conditions.

Previous studies have demonstrated the benefits of using PMF in agriculture. For instance, the cultivation of lettuce, cabbage, cucumber, and other plants under PMF resulted in better yields and quality photosynthetic index compared to non-film control plants [18]. Additionally, the cumulative water evaporation from soil and pan surfaces under PMF decreased by 29% and 26%, respectively [21]. Moreover, the use of SCAPV has been shown to increase sweet potato yields by 56.13% [22] and reduce water evaporation by over 21% [23]. In this study, we aim to investigate the impact of SCAPV on evapotranspiration, soil nutrients, as well as the physiological characteristics, quality, and yield of peanuts and soybeans.

2. Experimental Site and Methods

The experiment was conducted in Fuyang City, Anhui Province. The experimental site is located at latitude 32°58′ N and longitude 115°55′ E and is four meters above sea level. The experiment was divided into CSAPV and CK treatments. The peanut variety is Baisha, and the soybeans variety is Zhonghuang 13. Each treatment planted in the plot is set as a 5-row area. The row length is 3 m, the row spacing is 0.8 m, the plant spacing is 0.21 m, and the plot area is 3 x 3 m^2. The land was prepared manually for the land preparation, planting, watering, and field management on April 15th. Peanuts and soybeans were planted on April 16th with water, micro-spraying, and watering after planting. Plants flooded on May 5th, May 29th, June 9th, and July 14th. The soybeans were harvested on September 3rd, and the total growth period was 139 days. The peanuts were harvested on September 14th, and the growth period was 150 days.

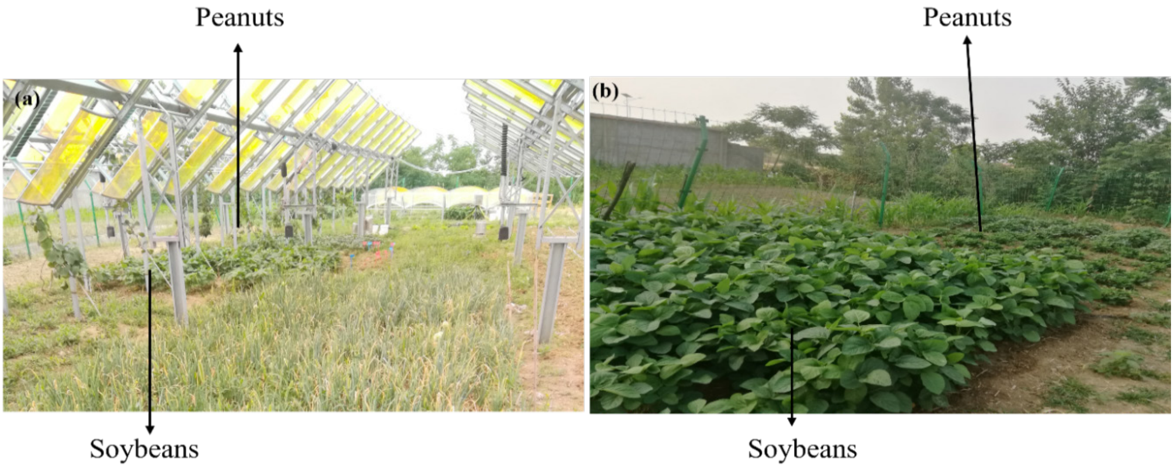

Figure 1. Experimental setup on two treatments. Peanuts and soybeans planted (a) SCAPV and (b) CK

FAO56-PM equation was used to calculate evapotranspiration, written below by [24].

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{mean} + 273.3} u_2(e_s - e_a)}{\Delta + \gamma(1 + u_2)} \quad (1)$$

where: ET_o is reference crop evapotranspiration (mm/day), R_n is net radiation at the crop surface (MJ/m^2day), G is soil heat flux (MJ/m^2day), T_{mean} is mean air temperature (°C), $T_{mean} = (T_{max}+T_{min})/2$, u_2 is the wind speed at 2 (m/s), e_s is saturation vapor pressure (kpa), e_a is actual vapor pressure (kpa), $(e_s - e_a)$ is saturation vapor pressure deficit (kpa), Δ is the slope of vapor pressure curve (kpa/°C), γ is psychrometric constant (kpa/°C).

After harvesting, five plants were randomly chosen from each treatment. After removing the roots and the yellow senescent leaves, the fresh weight of each plant was measured. Afterward, the plants were put into an electric blast drying oven using the electric oven drying method, put the vines into a mesh bag, put in an oven at 105 °C for 30 minutes, and dry it at 60 °C to constant weight. The fresh and dry weights were measured using an electronic balance (OHAUS Scout SE, OHAUS, New Jersey, USA).

The plant's quality, Soil properties before planting and after harvest were tested by Sichuan Huabiao Testing Technology Co. Ltd., Chengdu, Sichuan 610016, China.

The dry rate was measured using the following equation

$$\text{Dry rate} = \frac{\text{Sample dry weight}}{\text{Sample fresh weight}} \times 100 \quad (2)$$

Determination of dry yield using the following equation

$$\text{Dry yield} = \frac{\text{Fresh yield} \times \text{Dry rate}}{100} \quad (3)$$

A Land Equivalent Ratio (LER) is an indicator for assessing land productivity in mixed-cultivated patterns, which is suitable for evaluating SCAPV performance [25, 26]. LER was determined using the following equation:

$$\text{LER} = \frac{\text{Crop Yield}_{\text{SCAPV}}}{\text{Crop Yield}_{\text{natural state}}} + \frac{\text{Electricity}_{\text{SCAPV}}}{\text{Electricity}_{\text{PV Station}}} \quad (4)$$

If LER > 1, SCAPV is more effective than the pattern of separately planting crops and building solar power stations on the same land area.

3. Results and Discussion

Table 1 shows the effects of SCAPV and CK treatments on soil nutrients. SCAPV and CK treatments increased the soil pH value. SCAPV partially blocked the rainwater from falling. The soil organic matter of SCAPV and CK increased compared with before planting. CK treatment increased the total nitrogen content of the soil, while SCAPV treatment decreased evenly compared with that before planting soybean under SCAPV. The formation of crop yield consumed a lot of nitrogen, and hydrolyzable nitrogen decreased in all treatments. The content of available soil phosphorus was evenly left over among the treatments, which provided sufficient phosphorus fertilizer for producing peanuts and soybeans. SCAPV had a higher utilization rate of available phosphorus. The content of available soil potassium, SCAPV, was higher than before planting the pre-insertion. CK treatment has significantly improved, which has nothing to do with the peanuts and soybeans in CK being generally lower and less utilized.

Table 1. Effects of SCAPV and CK treatments on soil nutrients

Soil Nutrient	Treatment	Before Planting	Peanut	Soybean
pH	SCAPV	7.76	7.93	8.13
	CK	7.99	8.1	7.94
Organic matter (g/kg)	SCAPV	10.6	20.5	29.1
	CK	14.9	38.8	28.8
Total nitrogen (%)	SCAPV	0.072	0.087	0.07
	CK	0.083	0.108	0.093
Hydrolyzable nitrogen (mg/kg)	SCAPV	150.3	59	64.6
	CK	69.9	64.8	66
Available phosphorus (mg/kg)	SCAPV	28.7	35.5	34.6
	CK	14.9	26.2	32.1
Fast-acting potassium (mg/kg)	SCAPV	204	270	215
	CK	170	234	187

Table 2 shows the average monthly weather data for SCAPV and CK treatments. Results showed that the solar radiation under SCAPV was lower than that of CK. Accordingly, the plants in CK always received a higher amount of solar radiation than those under SCAPV, as shown in Table 2. SCAPV reflected more direct-beam radiation during the afternoon. Air temperatures CK was always observed to be higher than SCAPV.

In contrast, the relative humidity was lower in SCAPV during the day on sunny days. Table 2 shows that utilizing SCAPV may lower the underneath air temperature. It is evident that, compared to SCAPV, CK provided the highest value during the whole period of treatments.

Figure 2 illustrates the evapotranspiration rates in the SCAPV and CK treatments. In September, the evapotranspiration rate reached its maximum value in the CK treatment at 1.928 mm/day, while in the SCAPV treatment, it was 1.336 mm/day. Compared to CK, SCAPV reduced the monthly evapotranspiration rates in May, June, July, August, September, and October by 21%, 23%, 36%, 42%, 31%, and 32%, respectively. As a result, the average evapotranspiration rate during the experiment was 31% lower in SCAPV compared to CK. These findings indicate that the CK treatment had the highest evapotranspiration rates in all months due to its exposure to increasing solar radiation. Furthermore, the PMF cover, which allows 40% of visible light to pass through, contributed to the decreased evapotranspiration rates. Therefore, it can be concluded that SCAPV significantly impacts water use efficiency (WUE) by reducing evapotranspiration rates compared to CK.

Table 2. Average monthly weather data under SCAPV and CK treatments

	Solar Radiation MJ/m²day		**Wind speed (m/s)**		**Air temperature (ºC)**		**Relative humidity (%)**	
Data	SCAPV	CK	SCAPV	CK	SCAPV	CK	SCAPV	CK
May	2.33	3.72	0.57	0.79	23	24	59.5	60.45
June	2.07	3.63	0.51	0.67	28	28	56.2	57.9
July	1.81	5.01	0.57	0.82	29	30	73.1	74.6
August	1.64	4.58	0.29	0.53	28	29	76.7	77.35
September	1.73	4.41	0.48	0.71	26	27	65.8	67.4
October	1.47	3.11	0.66	0.87	21.5	23	68.75	69.45

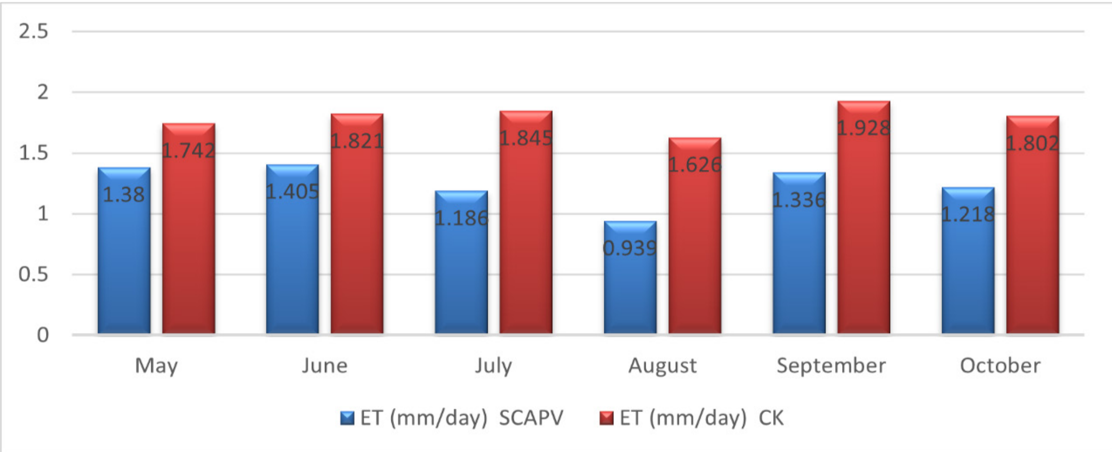

Figure 2. Monthly evapotranspiration (ET) of SCAPV and CK treatments

The effects of SCAPV and CK treatments on peanut physiological characterization are presented in Table 3. The height of the main stem, length of lateral branches, and number of total branches of peanuts treated with SCAPV were significantly higher than those in the CK treatment. The number of seedlings also increased. SCAPV increased the fresh weight of the aerial part, the underground number of peanuts, and the dry weight of 5 plants compared to CK, which was attributed to the high fresh weight and fast growth of the SCAPV treatment. Table 4 shows the effects of SCAPV and CK treatments on soybean physiological characterization. There was little difference in plant height, number of branches, number of pods per plant, number of empty pods per plant, etc., between the two soybean treatments. However, the fresh and dry weight of 5 SCAPV treatment plants was higher than that of the CK. SCAPV treatment was found to be beneficial for soybean nutrient accumulation.

SCAPV treatment resulted in longer plant lengths for both peanuts and soybeans than the CK treatment. Furthermore, there were fewer branches of soybeans in SCAPV treatment than in CK treatment. These findings suggest that SCAPV treatment promoted the growth of peanuts and soybean plants while reducing excessive branching, potentially leading to more efficient resource allocation and improved crop yields. The results indicate that SCAPV offers a promising approach to sustainable agriculture, promoting plant growth and development while also generating clean energy.

Table 3. Effects of SCAPV and CK treatments on peanut physiological characterization

Treatment	SCAPV	CK
Main stem height (cm)	54.54	36.06
Side branch length (cm)	55.1	40.66
Total number of branches	18.6	14.6
Number of branches	13.6	10.6
Number of full pods	45	35
Blight pods per plant	17.2	6.2
Five fresh plant weight (g)	1173.9	835.7
The dry weight of 5 plants (g)	350	310.76
The dry rate of the whole plant above ground (%)	29.82	37.19
Fresh weight of 5 underground plants (g)	530.3	426.8
The dry weight of 5 underground plants (g)	290.38	260.54
Dry rate of the underground part of the whole plant (%)	54.76	61.04

The results of the physiological characterization are presented in Tables 3 and 4. The findings demonstrate that SCAPV plays a crucial role in optimizing the growth and development of peanut and soybean plants. Specifically, the study shows that blue light promotes the growth of green leaves, even when only red and far-red wavelengths are allowed to pass through the SCAPV system. Furthermore, the plants exhibit faster growth rates when exposed to a combination of red and blue light. The ratio of blue to red light is also found to be a crucial factor in promoting longer plant growth. These results highlight the significant impact of SCAPV on improving the cultivation conditions for peanut and soybean growth by covering various environmental parameters such as light quality, intensity, and duration.

Table 4. Effects of SCAPV and CK treatments on soybean physiological characterization

Treatment	SCAPV	CK
Plant height (cm)	78.97	78.63
Number of branches (plant)	4.25	4.27
Number of pods per plant	87.86	87.6
Number of empty pods per plant	3.07	3.13
Number of grains per plant (grain)	213.44	222.13
Five fresh weights (g)	376.8	359.7
The dry weight of 5 plants (g)	340.81	310.92
Dry rate of the whole plant (%)	90.45	86.44

Table 5 shows the effects of SCAPV and CK treatments on peanuts quality. The two different treatments had no noticeable impact on the quality of peanuts. Compared with CK, the protein content of the SCAPV treatment increased by 5.54%, and the linoleic acid content increased by 1.14%, which was beneficial to improving the quality of peanuts and reducing the content of oleic acid; SCAPV treatment increased the fat content while decreasing the oleic acid content.

Table 5. Effects of SCAPV and CK treatments on peanuts quality

Treatment	Protein (g/100g)	Fat (g/100g)	Oleic acid (%)	Linoleic acid (%)
SCAPV	28.6	40.3	42.2	35.5
CK	27.1	40.2	42.8	35.1

Table 6 shows the effects of SCAPV and CK treatments on soybean quality. SCAPV treatment significantly increased the soybean Fat, soluble sugar, linoleic acid, and alpha-linolenic acid by 6.75%, 15.24%, 13.72%, and 15.14%, respectively, compared to CK. The protein and oleic acid content were significantly reduced. SCAPV could improve the quality of soybean oil, which benefits human health.

Table 6. Effects of CSAPV and CK treatments on soybean quality

Treatment	Protein (g/100g)	Fat (g/100g)	Ash (g/100g)	Soluble sugar (%)	Oleic acid (%)	Linoleic acid (%)	Alpha-linolenic acid (%)
SCAPV	39.3	17.4	5.4	9.68	37.2	43.1	5.78
CK	52.9	16.3	5.8	8.4	43.6	37.9	5.02

There was heavy rainfall in the 2021 growing season, but using SCAPV with spectral splitting helped alleviate the damage caused to the peanut and soybean fields. This technology reduced the water content in the fields compared to the CK treatment while also controlling the growth of the plants. Unlike the CK treatment, which experienced high air temperatures and intense sunlight in the summer, installing SCAPV above farmland reduced the negative impact of these factors on crop growth, providing a more suitable environment for plant development. The fresh weight of peanut stems and leaves were 3.19 kg and 2.58 kg, respectively, under both SCAPV and CK treatments. The fresh weight of soybean grain and leaves was 18.2 kg and 17 kg under SCAPV and CK, respectively. Consequently, the biomass yield of peanuts and soybeans increased by 23.60% and 7.06% under SCAPV compared to CK.

The current SCAPV provides about 90 W/m2, while regular solar panels deliver around 180 W/m2. Based on our experiments with peanuts and soybeans, we estimated that the average land equivalent ratio (LER) of SCAPV is about 1.7, which is higher than the typical LERs of mixed cropping systems (between 1.0 and 1.3). This means that by adopting a hybrid approach, the production of a 100-ha farm could be as high as that of a 170-ha farm with separate productions, resulting in significant productivity increases. We anticipate that an optimized dichroitic polymer film could further increase the value from about 90 W/m2 to 140 W/m2, potentially increasing the LER up to 2.30.

4. Conclusion

In this study, we investigated the potential of Spectrum Splitting and Concentrated APV (SCAPV) for the sustainable growth of peanuts and soybeans. Our results showed that the SCAPV treatment improved soil nutrients, enhanced physiological characteristics, and increased the biomass of the peanuts and soybeans. Specifically, the content of soybean linoleic acid and α-linolenic acid were significantly increased. At the same time, the soluble sugar content was also improved, indicating an increase in the quality of the soybean. Moreover, SCAPV improved the cultivation conditions by significantly reducing evapotranspiration by 31% compared to the control treatment (CK), which could reduce the irrigation required. The equivalent land ratio (LER) under SCAPV was found to be 1.70, indicating a 70% increase in the productivity of peanuts and soybeans. Our findings suggest that SCAPV simultaneously provides a feasible solution for both green energy and sustainable agriculture, contributing to developing eco-friendly and efficient agricultural practices.

Data availability statement

Data is contained within the article.

Underlying and related material

There is no other underlying and related material.

Author Contributions

Altyeb Ali Abaker Omer: Conceptualization, Methodology, Software, Formal Analysis Writing - Original Draft, and Writing - Review & Editing. Wen Liu: Writing - Review & Editing, Supervision, and funding acquisition. Ming Li: Writing - Review & Editing. Fangcai Chen: Investigation and Writing - Review & Editing. Wenjun Liu: Methodology, Investigation. Jan Ingenhoff: Writing - Review & Editing Liulu Fan: Methodology, Data curation. Fangxin Zhang: Investigation. Xinyu Zhang: Methodology, investigation, and Resources. Jianan Zheng: Software and Investigation. And Zhisen Zhang: Writing - Review & Editing.

Competing interests

The authors declare that they have no competing interests.

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