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The Potential of Spectrum Splitting Technology on Soybean Physiology, Quality, and Yield

A Case Study in Suzhou City

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Abstract. Agricultural photovoltaic (APV) systems that integrate farming activities with energy production on the same farmland face challenges due to shadowing effects caused by elevated photovoltaic (PV) panels, which hinder the spectrum necessary for photosynthesis. Spectrum splitting technology (SST) has emerged as a potential solution to balance the spectrum required for photosynthesis and PV energy generation. This study aims to investigate SST's potential in enhancing soybean physiology, quality, and yield. Four treatments were implemented: soybeans planted under a glass shed covered with multilayer film (GMF), glass shed (GS), in open-air (CK), and spectrum splitting and concentrated APV (SCAPV). Results demonstrated notable improvements in soybean physiology, quality, and yield. GMF and SCAPV treatments exhibited increased soluble sugar content by 13.5% and 4.1% compared to CK. Furthermore, GMF and SCAPV treatments showed increased oleic acid content by 5.1% and 2.1%, respectively, compared to CK. Fresh weight of grain and leaves of soybeans increased by 24.7% and 4.1% in GMF and SCAPV treatments compared to CK. At the same time, GS treatment decreased by 14.4% compared to CK. Utilization of SST in GMF and SCAPV systems presents a promising avenue to optimize soybean cultivation, improving soybean yield and quality. This study highlights the potential of SST as a solution for integrating APV systems with crop cultivation and production, leading to enhanced crop physiology, increased yield, and improved quality.

Keywords: Spectrum Splitting Technology, SCAPV, Soybean Physiology, Quality, and Yield

1. Introduction

Agricultural photovoltaic (APV) systems, blending farming with energy production, encounter shadowing effects from elevated PV panels that can impact crop photosynthesis [1–3]. While shading reduces solar radiation, potentially decreasing crop yield, it also lowers evapotranspiration, proving beneficial during dry spells [4]. APV systems can protect crops from extreme weather events, contributing to climate change adaptation and sustainable crop production [5]. Shadowing effects in APV systems significantly impact crop photosynthesis. The presence of shadows can lower the accuracy of feature extraction and change detection in remote-sensing images, hindering classification and impacting ecological processes such as photosynthesis and carbon balance [5]. Research has shown that shadows from APV structures reduce solar radiation and photosynthetic efficiency in crops like rice, potato, sesame, and soybean, ultimately affecting plant growth and yield [6].

Spectrum splitting technology (SST) is based on multilayer films (MF) covered in curved glass and is proposed to address shadowing effects in APV systems. The core concept of SST is to selectively transmit red, blue, and far-red light for plant photosynthesis while reflecting and concentrating the remaining light for electricity generation [7,8]. This technique leverages MF to combine and separate merged wavelength paths into narrow bands, allowing spectral separation [7,9]. SST resolves the conflict between simultaneous PV power generation and plant photosynthesis [10]. Low-cost multi-passband filter films can be economically produced, with the filters designed to include the necessary spectrum for plant photosynthesis, such as red, blue, and far-red light. These polymer filters find applications in UV protection, heat insulation, infrared shielding, and APV systems [8,11]. The aim of SST allows the red wavelength of 630–680 nm, blue wavelength of 400–470 nm, and far-red wavelength of 650–730 nm to pass through, as shown in Fig. 1 [8,11]. The reflection band provides 60% visible, infrared, and ultraviolet light. Then, it adjusts spectral composition to study the influence of factors such as light quality and monochromatic light ratio on crops.

Implementing spectrum splitting and concentrated APV (SCAPV) has demonstrated significant crop growth and yield benefits. Lettuce, cucumber, and water spinach have shown improved growth and yield under SCAPV compared to open-air (CK), with the land equivalent ratio (LET) increasing by more than 1.7 times [12]. Notably, the fresh yield of sweet potatoes under SCAPV treatment increased by an impressive 56.13% compared to conventional planting methods [13]. Furthermore, SST is also employed in greenhouse rooftops to investigate the effects of partial sunlight (red, blue, and far-red light) on water evaporation and optimal weather parameters. Experiments conducted in Fuyang City demonstrated that SCAPV significantly reduced evapotranspiration by 31% compared to CK, potentially leading to reduced irrigation requirements. Additionally, the biomass yield of peanuts and soybeans increased by 23.60% and 7.06% under SCAPV compared to CK [14].

In this study, the experiment was conducted in Suzhou City, where four treatments were implemented to examine the effects of SST on soybeans. The treatments included a glass shed covered with multilayer film (GMF), a glass shed (GS), CK, and SCAPV. The objective was to achieve sustainable yield production. The results demonstrated that GMF and SCAPV significantly enhanced soybean physiology and quality by providing an optimized spectrum based on SST for the growth and development of soybeans. Moreover, soybean yield increased considerably under GMF and SCAPV. These findings highlight the potential of employing SST in greenhouse agriculture and APV systems to improve crop performance and achieve sustainable crop production.

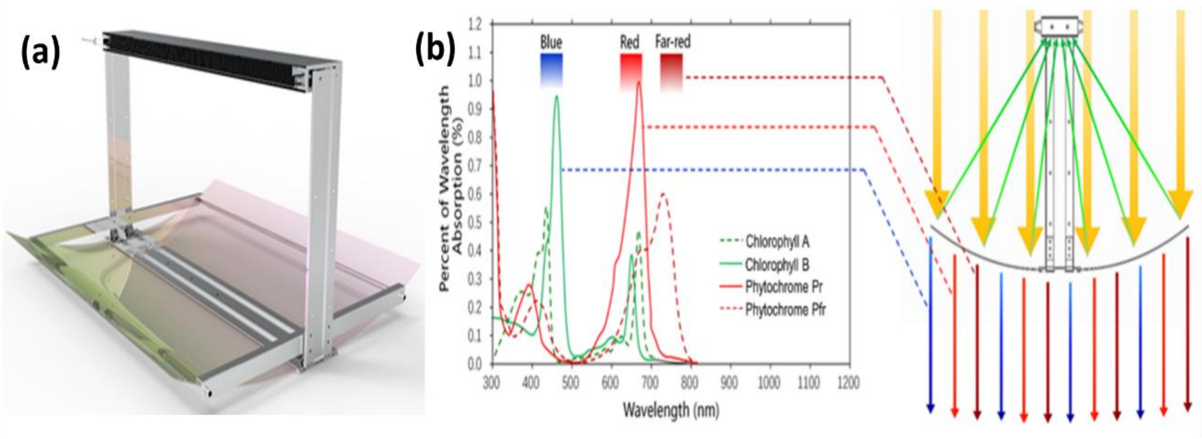

Figure 1. *The structural design of the SCAPV (a) multilayer film attached to curved glass panels and (b) spectral required for plant photosynthesis and solar power generation [8,11].*

2. Materials and Methods

This experiment was conducted in Suzhou City, northeast of Anhui Province. It is located at East Longitude 117º0'33, North Latitude 33º35'31, and 26 m above sea level. The climate is warm, temperate, and semi-humid, with annual precipitation of 774-895 mm and an average annual temperature of 15.7°C. In this experiment, four treatments were implemented: Soybeans (Glycine max (Linn.) Merr) planted under a glass shed covered with multilayer film (GMF), a glass shed (GS), open-air conditions (CK), and using spectrum splitting and concentrated APV (SCAPV). Each treatment was planted in the plot with an area of 1×1.7 m2, row spacing was 0.8 m, and plant spacing was 0.21 m, as shown in Fig 2. The land was prepared manually for the land preparation, planting, watering, and field management on July 5, 2022. The soybeans were harvested on September 26, and the growth period was 111 days.

Five plants were randomly selected from each treatment after harvesting. The fresh weight of each treatment was measured. Afterward, the plants were dried using the electric oven drying method, weighing 1000 g, putting them in an aluminum pan outside for air-drying, and then drying them in a discharge oven at 105 °C to constant weight. Sichuan Huabiao Testing Technology Co. Ltd., Chengdu, Sichuan 610016, China, tested the soil properties and plant quality.

Figure 2. *Four treatments were implemented: Soybeans were planted under (a) GMF, (b) GS, (c) CK, and (d) SCAPV.*

3. Results and Discussion

3.1 The soil nutrients before planting and after harvesting soybeans under the effects of GMF, GS, CK, and SCAPV treatments

The comparison of soil nutrient levels before and after planting soybeans under different treatments provides valuable insights into the effects of GMF, GS, CK, and SCAPV treatments on soil fertility, as presented in Table 1. The results indicate the following:

The SCAPV treatment had the highest pH before planting, indicating alkaline soil conditions. In contrast, the GS treatment exhibited the lowest pH after harvesting, suggesting a decrease in pH that could impact nutrient uptake. The GMF treatment resulted in the highest increase in organic matter content after harvesting, enhancing soil structure, water-holding capacity, and nutrient availability. Conversely, the CK treatment showed the lowest growth in organic matter content, implying limited organic matter input or slower decomposition rates.

GMF treatment decreased total nitrogen after harvesting but maintained a higher level than other treatments, indicating efficient nitrogen uptake by the peanuts. The CK treatment had the lowest total nitrogen content, suggesting lower availability or inefficient utilization. GMF treatment initially had the highest hydrolyzable nitrogen content, indicating greater nitrogen availability before planting. However, it experienced a significant decrease after harvesting, possibly due to nitrogen uptake by the soybeans. After harvesting, the GS treatment exhibited relatively higher hydrolyzable nitrogen content, indicating better nitrogen preservation. GMF treatment demonstrated the highest increase in available phosphorus content after harvesting, promoting phosphorus release and accessibility for plant growth. SCAPV treatment showed the highest available phosphorus content after harvesting, suggesting a higher level of phosphorus availability in the soil. Fast-acting potassium: GMF treatment maintained stable levels of fast-acting potassium before and after harvesting, ensuring a consistent supply for plant physiological processes. GS treatment exhibited a slight decrease, potentially due to potassium uptake by soybeans. GMF treatment positively impacted soil fertility, including increased organic matter and available phosphorus content.

Table 1. *The soil nutrients before planting and after harvesting soybeans under the impacts of GMF, GS, CK, and SCAPV treatments*

Soil nutrients	**Units**	**Treatments**	**Before planting soybean**	**After harvesting soybean**
pH		GMF	7.86	7.63
		GS	7.86	7.08
		CK	7.86	7.64
		SCAPV	8.02	7.26
Organic matter	g/kg	GMF	29.8	34.4
		GS	29.8	26.4
		CK	29.8	20.5
		SCAPV	25.8	31.4
Total nitrogen	%	GMF	0.181	0.158
		GS	0.181	0.148
		CK	0.181	0.119
		SCAPV	0.113	0.151
Hydrolyzable nitrogen	mg/kg	GMF	256.9	130.2
		GS	256.9	214.3
		CK	256.9	73.7
		SCAPV	257.2	144.0
Available phosphorus	mg/kg	GMF	78.3	355.4
		GS	78.3	310.5
		CK	78.3	279.1
		SCAPV	53.1	344.4
Fast-acting potassium	mg/kg	GMF	198	200
		GS	198	172
		CK	198	161
		SCAPV	199	207

3.2 Compared soybean's physiology characterization under effects of GMF, GS, CK, and SCAPV treatments:

Table 2 compares the physiology characteristics of soybean plants under different treatments: GMF, GS, CK, and SCAPV. The GMF treatment resulted in the tallest plants (44.78 cm), followed by GS (39.84 cm), CK (36.62 cm), and CSAPV (36.24 cm). GMF treatment appears to affect plant height positively compared to the other treatments. GMF treatment had the highest number of branches per plant (5.8), while GS had the lowest (3.8). This suggests that GMF may promote branching increase foliage and overall plant growth. SCAPV treatment had the highest number of pods per plant (69.6), followed closely by CK (67.2). GMF treatment had the lowest number of pods (65.6). SCAPV and CK treatments seem to be more effective in pod development. The difference in the number of empty pods between treatments is relatively tiny. However, the GS treatment had the fewest empty pods (1.8), indicating better pod development than other treatments.

SCAPV treatment had the highest number of grains per plant (122.8), followed by CK (120.2). GS treatment had the lowest number of grains (87.8). SCAPV and CK treatments appear to enhance grain production compared to other treatments. GMF treatment resulted in the highest fresh weight of five plants (799.4 g), while GS had the lowest (422.0 g). GMF treatment seems to contribute to greater overall plant biomass. Similar to fresh weight, GMF treatment had the highest dry weight (308.2 g), followed by CK (274.2 g) and SCAPV (272.5 g). GS treatment had the lowest dry weight (220.8 g). GMF treatment shows a positive influence on plant biomass accumulation. Dry rate: GS treatment had the highest dry rate of the five plants (52.32%), followed by SCAPV (43.72%), CK (41.22%), and GMF (38.55%). The dry rate indicates the proportion of dry weight to fresh weight and reflects the efficiency of water utilization and plant growth. GS treatment appears to have the highest efficiency in converting fresh to dry weight.

The results suggest that GMF treatment positively affects plant height, fresh weight, and dry weight, indicating better plant growth. SCAPV and CK treatments show favorable pod development, grain production, and dry weight outcomes. GS treatment exhibits branch number, empty pod reduction, and dry rate advantages. These findings provide insights into the physiological responses of soybean plants under different treatments and can aid in determining the most effective approach for soybean cultivation.

Table 2. *Effects of GMF, GS, CK, and SCAPV treatments on soybeans physiological characterization*

Treatment	**GMF**	**GS**	**CK**	**SCAPV**
Plant height (cm)	44.78	39.84	36.62	36.24
Number of branches (plant)	5.8	3.8	4.6	5
Number of pods per plant	65.6	51.4	67.2	69.6
Number of empty pods per plant	2.4	1.8	2.6	2.4
Number of grains per plant (grain)	122.8	87.8	120.2	115.2
Five fresh weights (g)	799.4	422.0	665.2	623.3
The dry weight of five plants (g)	308.2	220.8	274.2	272.5
Dry rate of the five plants (%)	38.55	52.32	41.22	43.72
The dry weight of five plants (g) increases or decreases compared to the CK	12.40	-19.47		-0.62

3.3 The quality of the soybeans under the effects of GMF, GS, CK, and SCAPV treatments

Table 3 presents information on the effects of different treatments (GMF, GS, CK, and SCAPV) on the quality of soybeans. CK treatment had the highest protein content (35.8 g/100g), followed by GMF (34.3 g/100g), GS (34.1 g/100g), and SCAPV (33.9 g/100g). CK treatment resulted in the highest protein content among the treatments, indicating that it may positively impact soybean protein levels. GMF treatment had the highest fat content (10.1 g/100g), followed by CK (9.9 g/100g), GS (8.3 g/100g), and SCAPV (8.0 g/100g). GMF treatment showed a higher fat content than other treatments, suggesting a potential influence of GMF treatment on soybean fat accumulation. CK treatment had the highest ash content (11.3 g/100g), followed by GS (10.6 g/100g), SCAPV (9.1 g/100g), and GMF (9.1 g/100g). CK treatment resulted in the highest ash content among the treatments, indicating a potential impact on mineral content in soybeans. GS treatment had the highest soluble sugar content (10.22%), followed by SCAPV (8.97%), CK (8.62%), and GMF (9.78%). GS treatment exhibited the highest soluble sugar content, suggesting a potential effect on soybeans' sweetness or carbohydrate composition. GMF treatment had the highest oleic acid content (49.1%), followed by SCAPV (47.7%), CK (46.7%), and GS (44.7%). GMF treatment resulted in the highest oleic acid content among the treatments, indicating its potential influence on the fatty acid composition of soybeans. CK treatment had the highest linoleic acid content (32.9%), followed by SCAPV (32.7%), GS (32.7%), and GMF (31.6%). CK treatment showed the highest linoleic acid content among the treatments, suggesting its potential impact on the fatty acid profile of soybeans. CK treatment had the highest alpha-linolenic acid content (5.74%), followed by SCAPV (5.63%), GMF (5.46%), and GS (5.34%). CK treatment resulted in the highest alpha-linolenic acid content among the treatments, indicating its potential influence on soybeans' omega-3 fatty acid composition.

Table 3. *Effects of GMF, GS, CK, and SCAPV treatments on soybeans quality*

Treatment	**GMF**	**GS**	**CK**	**SCAPV**
Protein (g/100g)	34.3	34.1	35.8	33.9
Fat (g/100g)	10.1	8.3	9.9	8
Ash (g/100g)	9.1	10.6	11.3	9.1
Soluble sugar (%)	9.78	10.22	8.62	8.97
Oleic acid (%)	49.1	44.7	46.7	47.7
Linoleic acid (%)	31.6	32.7	32.9	32.7
Alpha-linolenic acid (%)	5.46	5.34	5.74	5.63

3.4 The soybeans yield under the effects of GMF, GS, CK, and SCAPV treatments

Table 4 provides information on the effects of different treatments (GMF, GS, CK, and SCAPV) on soybean yield. GMF treatment resulted in the highest fresh weight (1.82 kg), followed by SCAPV (1.52 kg), CK (1.46 kg), and GS (1.25 kg). This indicates that the GMF treatment positively impacts overall soybean yield regarding fresh weight. GMF treatment showed a significant increase (24.7%) in fresh weight compared to CK. On the other hand, GS treatment exhibited a decrease (-14.4%), suggesting a negative effect on soybean yield in terms of fresh weight. SCAPV treatment showed a slight increase (4.1%), while no specific value is provided for the decrease in the GS treatment. GMF treatment had the highest dry weight (0.62 kg), followed by SCAPV (0.64 kg), GS (0.56 kg), and CK (0.51 kg). This indicates that the GMF and SCAPV treatments contribute to the higher dry weight of soybean grain and leaves. GS treatment showed the highest dry rate of the whole plant (44.8%), followed by SCAPV (42.1%), CK (34.9%), and GMF (34.1%). A higher dry rate suggests efficient water utilization and biomass accumulation. Therefore, GS treatment appears more effective in converting fresh to dry weight. GMF treatment showed a significant increase (21.6%) in dry weight compared to CK. SCAPV treatment also exhibited an increase (25.5%). However, no specific value has been provided for the rise in the GS treatment.

These results suggest that GMF and SCAPV treatments contribute to the higher dry weight of soybean grain and leaves than CK. GMF treatment resulted in the highest dry grain weight (0.30 kg), followed by SCAPV (0.29 kg), GS (0.26 kg), and CK (0.21 kg). This indicates that the GMF treatment positively impacts soybean yield, specifically in dry grain weight. GMF treatment showed the highest increase (42.6%) in dry grain weight compared to CK. SCAPV treatment also exhibited a significant increase (38.1%). However, no specific value is provided for the rise in the GS treatment. These findings suggest that GMF and SCAPV treatments contribute to higher dry grain weight than CK. Thus, GMF treatment consistently showed positive effects on soybean yield, both in terms of fresh weight and dry weight, including grain and leaves. SCAPV treatment also demonstrated favorable results in terms of yield, while GS treatment had mixed outcomes with a decrease in fresh weight but higher dry rates. These findings highlight the potential of GMF and SCAPV treatments in enhancing soybean yield, but further research is necessary to understand the specific mechanisms and optimize the treatments for maximum yield improvement.

Table 4. *Effects of GMF, GS, CK, and SCAPV treatments on soybeans yield*

Treatment	**GMF**	**GS**	**CK**	**SCAPV**
Fresh weight grain and leaves of soybean (kg)	1.82	1.25	1.46	1.52
Fresh weight grain and leaves increase or decrease compared to the CK (%)	24.7	-14.4		4.1
Dry-weight grain and leaves of soybean (kg)	0.62	0.56	0.51	0.64
Dry rate of the whole plant (%)	34.1	44.8	34.9	42.1
Dry-weight grain and leaves increase or decrease compared to the CK (%)	21.6	9.8		25.5
Dry grain weight (kg)	0.30	0.26	0.21	0.29
Dry grain weight increases or decreases compared to CK (%)	42.6	23.8		38.1

4. Conclusion

In conclusion, the analysis of soil nutrients, the physiological characterization of soybean quality, and yield under the effects of GMF, GS, CK, and SCAPV treatments revealed valuable insights into these treatments' potential benefits and implications of spectrum splitting technology. Regarding soil nutrients, the GMF treatment positively impacted soil fertility, including increased organic matter and available phosphorus content. This finding emphasizes the importance of GMF treatment for maintaining optimal soil conditions for soybean cultivation. Regarding soybean's physiological characterization, GMF treatment positively influenced plant growth and development, while GS treatment showed mixed outcomes with both positive and negative effects. SCAPV treatment demonstrated promising results in enhancing physiological attributes.

These findings indicate that GMF and SCAPV treatments can improve soybeans' physiological performance. Soybean yield analysis indicated that GMF treatment significantly increased both fresh and dry weights of soybeans, highlighting its positive impact on yield enhancement. SCAPV treatment also showed favorable results, albeit to a lesser extent. GS treatment exhibited inconsistent outcomes, with decreased fresh weight but higher dry rates. This suggests that GMF and SCAPV treatments can effectively improve soybean yield. Regarding soybean quality, CK treatment consistently resulted in higher protein, ash, and fatty acid contents, indicating its potential for enhancing soybean quality attributes. GMF treatment showed higher fat and oleic acid contents, suggesting its influence on the fatty acid composition of soybeans. GS treatment demonstrated higher soluble sugar content, while SCAPV treatment had lower fat and soluble sugar contents. These findings indicate that different treatments can have distinct effects on the nutritional composition of soybeans.

The results highlight the importance of considering GMF, GS, CK, and SCAPV treatments in soybean cultivation to optimize soil fertility, enhance physiological characteristics, increase yield, and improve quality attributes. Farmers and researchers can utilize these findings to make informed treatment selection and implementation decisions. Further research and development of SST can pave the way for sustainable and efficient agricultural practices in energy production and crop cultivation.

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, Formal Analysis Writing - Original Draft, and Writing - Review & Editing. Wen Liu: Writing - Review & Editing, Supervision, and funding acquisition. Ming Li: Methodology and Writing - Review & Editing. Xinyu Zhang: Methodology, investigation, and Resources. Fangxin Zhang: Investigation. And Juan Liu: Methodology and Investigation.

Competing interests

The authors declare that they have no competing interests.

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