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Effects of Agricultural Photovoltaic Systems Development on Sweet Potato Growth

Novel Agrivoltaics for Water Food Energy Nexus

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Abstract. Agricultural Photovoltaic (APV) has become more popular worldwide. Its core idea is to generate electricity and grow crops simultaneously on the same farmland. We developed two APV, Spectrum Splitting and Concentrated APV (SCAPV) and Even-lighting Agricultural Photovoltaic (EAPV). Our previous studies have investigated electricity generation, enhanced growth of plants/crops, and reduced water evaporation simultaneously on the same farmland. Furthermore, SCAPV and EAPV examined the better quality and increased yield of many plants, such as lettuce and cucumber. However, the effects of SCAPV and EAPV on sweet potato quality and yield have not been studied. Therefore, this study aims to investigate the impact of SCAPV and EAPV on evapotranspiration (ET) and sweet potato quality and yield. We conducted three treatments: SCAPV, EAPV, and open-air (CK). We planted 32 m2 of sweet potatoes and placed a weather station in each treatment. Our results showed that the 32 m2 of sweet potato yield under SCAPV, EAPV, and CK were 121.53 kg, 99.55 kg, and 77.84 kg, respectively. The dry rate in CK was 11.75% lower than 13.41% and 13.81% under SCAPV and EAPV, respectively. Soluble sugar content increased under EAPV. Anthocyanin content under SCAPV improved. Therefore, SCAPV and EAPV positively affect dry matter accumulation and enhance the sweet potato's growth. Average ET under SCAPV and EAPV compared with CK significantly reduced by 31% and 23%. SCAPV and EAPV could reduce irrigation and provide feasible green energy and sustainable APV solutions.

Keywords: Agricultural photovoltaic development, Spectral separation, Even-lighting, Sweet potatoes, Evapotranspiration, Saving water

1. Introduction

The Agricultural Photovoltaic (APV) concept was first proposed in the 1980s [1]. APV was implemented in many countries to combine renewable energy and agricultural production in the same area [2-5]. For plants to perform photosynthesis, plants require suitable light. In an appropriate light environment, plants can develop normally morphologically and perform photosynthesis efficiently. Among the sunlight, red and blue lights play the most critical role in plant photosynthesis [6]. While far-red light influences plant morphology at different stages [7]. Photovoltaic (PV) panels elevated above farmland produced a negative shading effect on crop and plant growth [8-10]. Crops and plants cannot receive sufficient sunlight as they grow in the open air.

We proposed two solutions to provide plants with suitable sunlight for photosynthesis. The first solution is Spectrum Splitting and Concentrated APV (SCAPV) [11]. It is based on spectral separation using Multilayer Polymer Film (MPF) to select and transmit red, blue, and far-red light from sunlight for plant photosynthesis. The rest of the sunlight concentrates on being reflected on PV panels for electricity generation, as shown in Fig. 1 a and b. The basic idea of SCAPV, design, and work principle is demonstrated in our previous studies [12, 13]. Designing a low-cost MPF is a critical solution [14, 15]. A multiplication co-extrusion process was adopted to prepare alternately superimposed MPF, enabling continuous, economical production [16-18]. Furthermore, MPF significantly reduced water evaporation [19]. The other solution is an Even-lighting Agricultural Photovoltaic (EAPV) [20]. Placing a grooved glass plate between two PV panels improves traditional APV structure, as shown in Fig. 1c. Our previous studies have demonstrated the basic idea of the system, design structure, and work principle [20, 21]. The key to EAPV is to put a grooved glass plate to provide the crop planted under the system with uniform illumination and suitable light intensity. The rest of the sunlight hits the top of the PV panels to generate electricity in EAPV, as shown in Fig. 1d and Table 1. Water evaporation from soil and pan surfaces was significantly reduced by 21% and 14% under SCAPV and 33% and 19% under EAPV [22].

Culturing plants under the SCAPV and EAPV, such as cabbage, lettuce, and cucumber, have resulted in better growth, increased quality, and crop yield than the open-air [11, 20, 21]. However, the effects of SCAPV and EAPV on sweet potato growth have not been studied yet. Therefore, this study's main objectives are to investigate the impact of SCAPV and EAPV on sweet potato quality and yield, water evaporation, and evapotranspiration (ET).

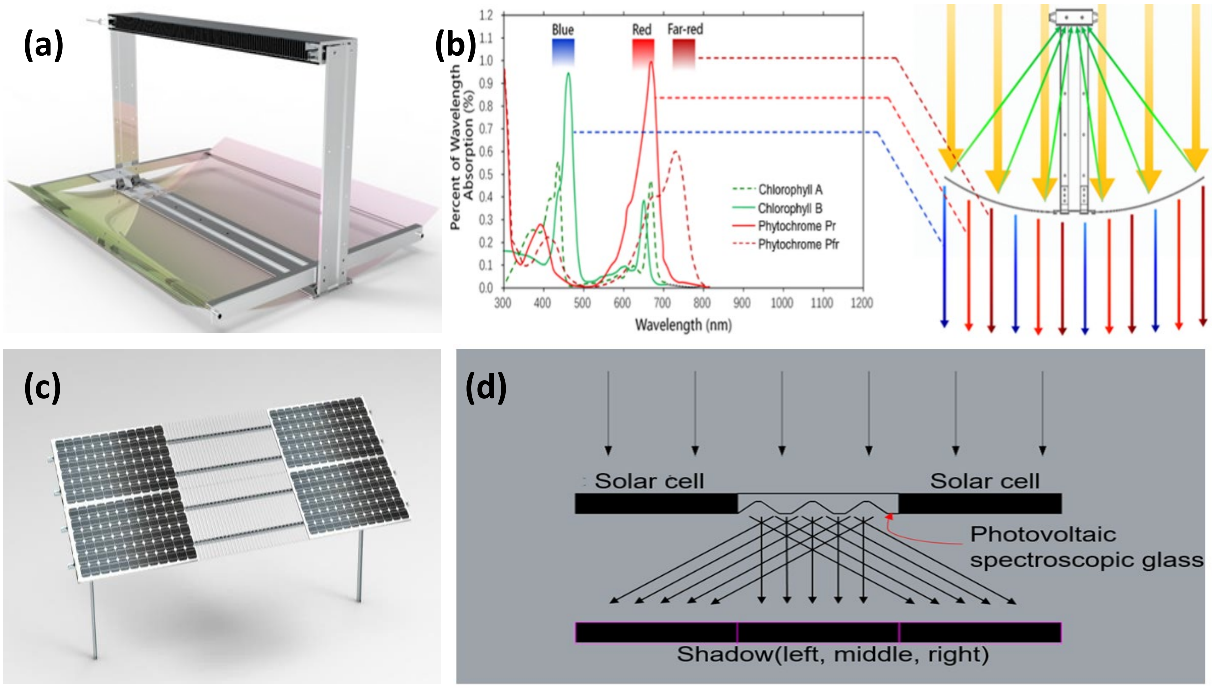

Figure 1. Structural design of SCAPV and EAPV (a) Polymer multilayer film attached to curved glass panels and (b) spectral required for plant photosynthesis and solar power generation [22, 23]. (c) a grooved glass plate inserted between two conventional photovoltaic panels to achieve beam splitting and (d) the light path of the optical simulation [20, 22].

Table 1. The light intensity ratio of transmittance when the size of the Photovoltaic panel and grooved glass plate is 1:1.

	Left shadow	**Middles shadow**	**Right shadow**
Photovoltaic panel	12 percent	12 percent	12 percent
Photovoltaic panel with grooved glass plate	30 percent	36 percent	30 percent
Increase transmittance compared between Photovoltaic panel and Photovoltaic panel with grooved glass plate	18 percent	24 percent	18 percent

2. Materials and Methods

2.1 Experimental Site

The experimental field is located at an East Longitude of 115º55, North Latitude of 32º58, and 4 m above sea level, Yingdong District, Fuyang City, Anhui Province. Fuyang City is located at the southern end of the Huanghuai Plain in the northwest of Anhui Province, on the south edge of the warm temperate zone, which belongs to the warm temperate zone semi-humid Monsoon climate. The annual average rainfall is 820-950 mm. The annual sunshine hours are 2200-2500. The frost-free period is 220-230 days, and the average relative humidity is 58.5%. The average temperature in summer is 27.1°C, 0.5°C higher than the same period of the previous year. The average precipitation in summer is 606 mm, about 20% more than the same period of the typical year—the seasonal precipitation changes obviously, with less rainfall in June and more precipitation in July-August. The rain in July is 342 mm, which is more than usual. Over the same period, it was about 50% more, which was the eighth most since 1961.

2.2 Experimental Materials and Method

The experiment was divided into three treatments: planting sweet potatoes under SCAPV, EAPV, and CK. The soil texture is black mortar soil, with a clay content of 8.49% from 0 to 2 μm, 81.19% of silt from 2 to 50 μm, and sand content of 10.32% from 50 to 2000 μm. The soil's organic matter content is high. The sweet potato variety is Fuzishu No. 1. The Plot is set as a 5-row area, the row length is 3 m, the space between rows is 0.8 m, the distance between plants is 0.21 m, and the total area of each treatment plot is 3 x 3 m2. The plant density is 4000 plants/667m2. The fertilization measures are 15-15-15 potassium sulfate type compound fertilizer 750 kg/ha, 24 kg/ha of chlorpyrifos (2% chlorpyrifos, 3% phoxim) during rotary tillage. On April 15th, the land was manually prepared. The sweet potato was planted with water on April 17th, micro-spraying and watering after planting. Plants were watered on May 5th, May 29th, June 9th, July 14th, and September 25th. The harvest was on October 20th, and the total growth period was 186 days.

Chinese standard pan evaporation was used in this experiment (Model ADM7), with a stainless-steel metal cylinder and a bottom cover. The wall thickness is 5 mm, the diameter is 20 cm, and the depth is 11 cm [24, 25]. Evaporation pans were placed under SCAPV, EAPV, and CK.

The pan evaporation rate was measured in Eq (1) [24] from May 8th to September 30th during the summer.

$$E_{pan} = W_{base} + R - W_{left} \quad (1)$$

where E_{pan} is an evaporation pan (mm/day), W_{base} is the base water amount and is 20 mm, R refers to the rainfall during the corresponding period of pan evaporation measured using a rain gauge, W_{left} is the water amount remaining in the pan after 24-hours.

The evapotranspiration (ET) was calculated using the FAO 56-PM method. The FAO56-PM equation for calculating ET is written below by [26].

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{mean} + 273.3} u_2(e_s - e_a)}{\Delta + \gamma(1 + u_2)} \tag{2}$$

where: ET_o is reference evapotranspiration [mm/day], R_n is net radiation at the crop surface [MJ/m2 day], G is soil heat flux [MJ/m2 day], T_{mean} is mean air temperature (°C), T_{mean} = (T_{max} +T_{mix})/2, u_2 is the wind speed at 2 m (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 the vapor pressure curve (kPa/°C), and γ is psychrometric constant (kPa/°C).

According to [25], net radiation (Rn), soil heat flux (G), wind speed (u_2), Saturation Vapour Pressure (e_s), Actual Vapour Pressure (e_a), saturation vapor pressure deficit $(e_s - e_a)$, Slope Vapour Pressure Curve (Δ) and Psychrometric Constant (γ) were calculated by the following equations, respectively:

The net Radiation (Rn) is Calculated by

$$R_n = R_{ns} - R_{nl} \tag{3}$$

where: R_n *is* net radiation, R_{ns} *is* the incoming net shortwave radiation and R_{nl} *is* the outgoing net longwave radiation.

$$R_{ns} = (1 - \alpha)R_s \tag{4}$$

where R_{ns} is net solar or shortwave radiation [MJ/m2 day], α is albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop [dimensionless], R_s is the incoming solar radiation [MJ/m2 day].

$$R_{nl} = \sigma\left(\frac{T^4_{max,k} + T^4_{min,k}}{2}\right)\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \tag{5}$$

where R_{nl} is net outgoing longwave radiation [MJ/m2 day], σ is Stefan-Boltzmann constant [4.903 ×10-9 MJ/K4 m2 day], T_{max}, K is the maximum absolute temperature during the 24 hours [K = °C + 273.16], T_{min}, K is the minimum absolute temperature during the 24 hours [K = °C + 273.16], e_a is actual vapor pressure [kPa], $\frac{R_s}{R_{so}}$ is relative shortwave radiation (limited to ≤ 1.0), R_s is solar radiation [MJ/m2 day], Rso calculated (Equation 6) clear-sky radiation [MJ/m2 day].

$$R_{so} = (0.075 + 2 \times 10^{-5}z)\, R_a \tag{6}$$

where z is the station elevation above sea level [m]. R_a is extraterrestrial radiation [MJ/m2 day] and R_a can be estimated by (Allen et al.) in Annex (Table 2.6) according to latitudes.

The soil heat flux (G) is estimated for monthly periods by the following Eq (7)

$$G_{month,i} = 0.07(T_{month,i+1} - T_{month,i-1}) \tag{7}$$

or, if $T_{month,i+1}$ is unknown:

$$G_{month,i} = 0.14(T_{month,i} - T_{month,i-1}) \tag{8}$$

where: $T_{month,i}$ is mean air temperature of month i [°C], $T_{month,i-1}$ is the mean air temperature of the previous month [°C], $T_{month,i+1}$ is the mean air temperature of next month [°C].

Wind speed (u_2) is Calculated from the Following Eq (9)

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \tag{9}$$

where u_2 is wind speed at 2 m above ground surface [m/s], u_z measured wind speed at z m above ground surface [m/s], z is height of measurement above ground surface [m].

Saturation Vapour Pressure (e_s)

$$e_s = \frac{e^0_{(T_{max})} + e^0_{(T_{min})}}{2} \tag{10}$$

where e_s is saturation vapour pressure [kPa], e° (T_{min}) is saturation vapour pressure at a daily minimum temperature [kPa], e°(T_{max}) is saturation vapour pressure at a daily maximum temperature [kPa].

Actual Vapour Pressure (e_a)

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e^0_{(T_{max})} + e^0_{(T_{min})}}{2}\right] \tag{11}$$

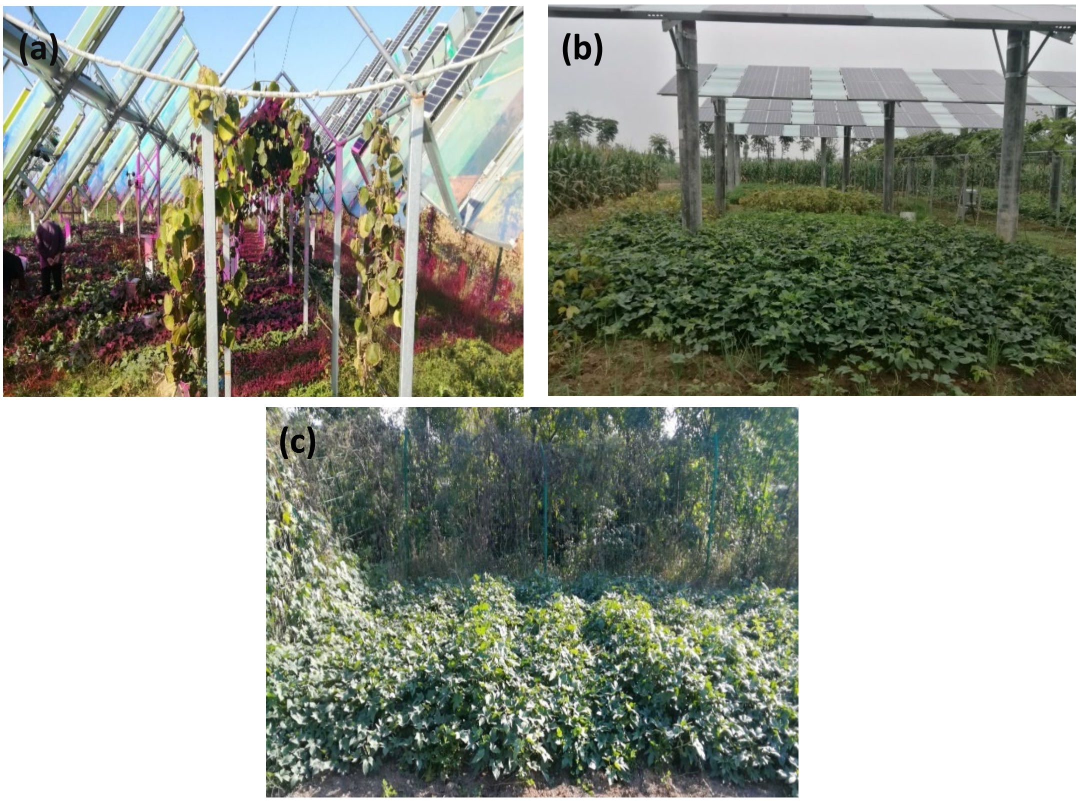

Figure 2. The growth of sweet potato in (a) Spectrum Splitting and Concentrated APV (SCAPV), (b) Even-lighting Agricultural Photovoltaic (EAPV), and (c) an open-air (CK).

3. Experimental Results and Analysis

3.1 Sweet Potato Quality under Effects of SCAPV, EAPV, and CK Treatments

Table 2 shows the effects of SCAPV, EAPV, and CK treatments on underground sweet potato quality. The SCAPV and EAPV treatments improved the dry matter rate of sweet potatoes, which is beneficial to the accumulation of dry matter in sweet potatoes. The protein, starch, and reduced sugar content are also significantly increased. EAPV treatment increases the soluble sugar content, and SCAPV treatment helps improve the anthocyanin content. Therefore, SCAPV and EAPV treatments positively affect the accumulation of dry matter and the quality improvement in the underground growth of the sweet potato. EAPV treatment increased the sweetness of the sweet potato, and SCAPV treatment improved the purple potato's anthocyanin content. Both SCAPV and EAPV are beneficial to purple meat. They are suitable for planting sweet potatoes.

Table 2. Sweet potato quality under effects of SCAPV, EAPV, and CK treatments.

Treatments	Soluble sugar in fresh sweet potato (%)	Anthocyanins in fresh sweet potato (mg/100g)	Protein in fresh sweet potato (g/100g)	Dry matter in fresh sweet potato (g/100g)	Starch in fresh sweet potato (g/100g)	Reducing sugar in a fresh sweet potato (g/100g)
SCAPV	7.5	15.2	1.5	30.8	24.1	1.3
EAPV	8.0	11.4	1.4	31.4	24.4	1.4
CK	7.6	13.6	1.3	30.7	23.7	1.1

3.2 Sweet Potato Yield under Effects of SCAPV, EAPV, and CK Treatments

It can be seen from Fig. 3 that the fresh yield of sweet potatoes of SCAPV treatment increased by 56.13% compared with the CK planting, and the dry yield increased by 56.64%. In EAPV treatment, the fresh yield increased by 27.89%, the dry yield increased by 30.81%, and the increase rate reached a very significant.

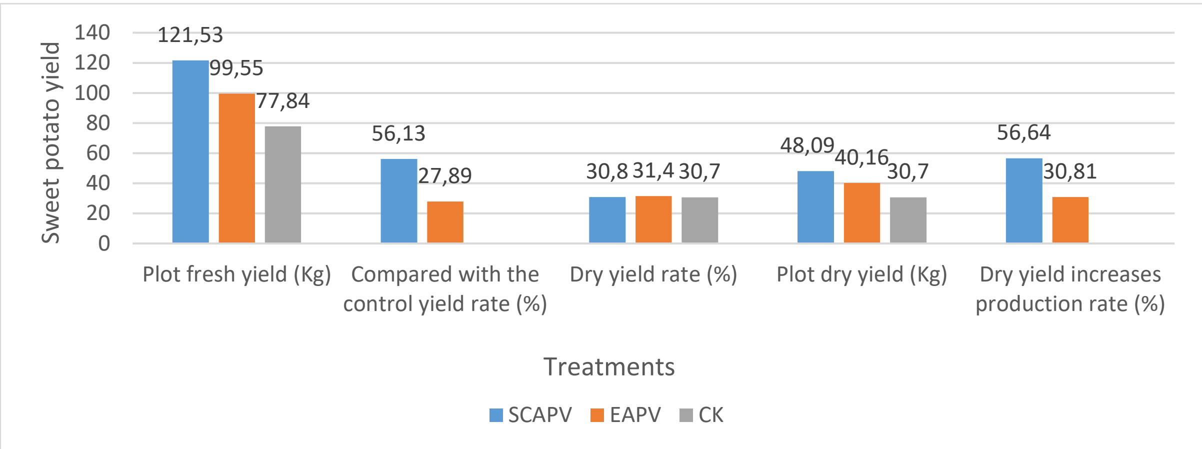

Figure 3. Sweet potato yield under effects of SCAPV, EAPV, and CK treatments.

3.3 Water Pan Evaporation (mm/day) under Effects of SCAPV, EAPV, and CK Treatments

Figure 4 presents the average monthly water pan evaporation of SCAPV, EAPV, and CK treatments for five months (May, June, July, August, and September). It can be seen that the EAPV has the lowest water evaporation each month than the SCAPV, and the SCAPV is lower than the CK. It proved that SCAPV and EAPV reduce water evaporation significantly compared with CK. The results showed a significant reduction in average water evaporation under SCAPV at 27% and EAPV at 38% compared with CK.

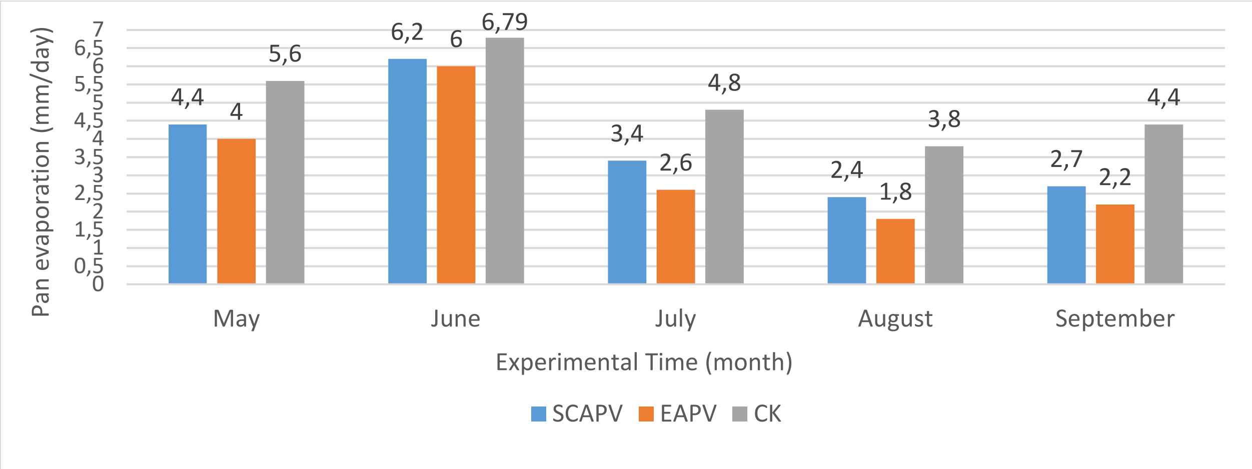

Figure 4. Water pan evaporation under effects of SCAPV, EAPV, and CK treatments.

3.4 Evapotranspiration (mm/day) under Effects of SCAPV, EAPV, and CK Treatments

Figure 5 presents the average monthly evapotranspiration of SCAPV, EAPV, and CK treatments for six months (May, June, July, August, September, and October). It can be seen from Fig. 5 that the SCAPV has less evapotranspiration each month than the EAPV, and the EAPV is lower than the CK. That proved that SCAPV and EAPV significantly reduced evapotranspiration compared with CK. The results showed a significant reduction of average evapotranspiration during experiment time by 31% under SCAPV and 23% under EAPV compared with CK.

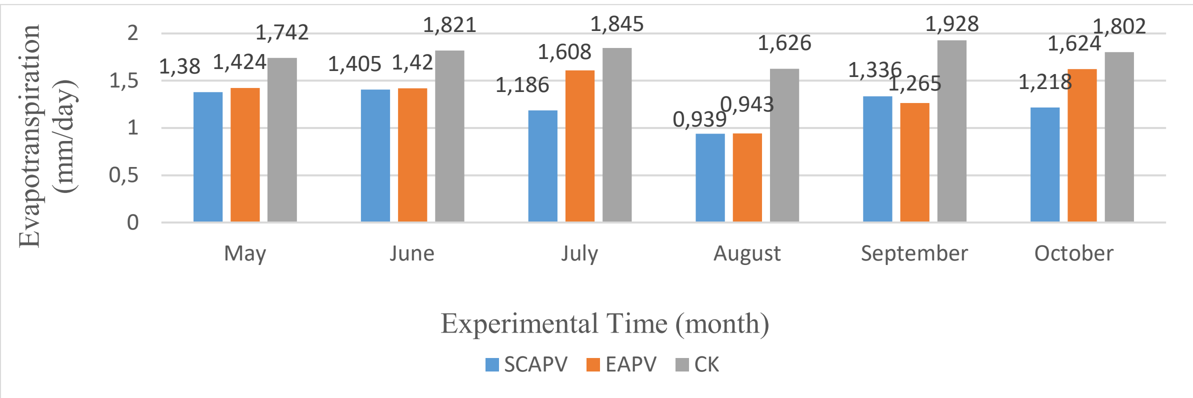

Figure 5. Evapotranspiration under effects of SCAPV, EAPV, and CK treatments.

4. Discussion

There was a lot of rain in the sweet potato growing season in 2021. Agricultural Photovoltaic development treated with light splitting and uniform light blocks the damage of part of the rainfall to sweet potato fields. It reduces the water content of the sweet potato fields. It controls the growth of the aboveground parts. The suitable temperature for sweet potato growth is 18-32 °C, and the temperature conducive to tuberous root expansion is 22-24 °C. If it exceeds 35 °C, sweet potato will stop growing. The environment of high temperatures and intense light in summer in the open air, however, installed SCAPV and EAPV above farmland reduces the influence of the high temperature on sweet potato fields and provides suitable temperatures for sweet potato growth. SCAPV and EAPV benefit the development of sweet potatoes and have apparent effects on increasing production. However, the large-scale production of sweet potatoes impacts land utilization rate and mechanization progress. So, more studies and economic evaluations need to be conducted to judge which application is beneficial to use mechanization progress and provide food supply and energy production on the same farmland. According to the growth of sweet potatoes characteristics, choose a suitable installation method of output. SCAPV and EAPV are ideal for planting sweet potatoes.

5. Conclusion

In this study, Spectrum Splitting and Concentrated APV (SCAPV) and Even-lighting Agricultural Photovoltaic (EAPV) have been sustainable in the growth of sweet potatoes. We have summarized our results below:

1. Planting sweet potatoes under the SCAPV improved the utilization rate of phosphorus and potassium fertilizers, effectively controlled the aboveground parts' growth, and increased protein starch content, reducing sugar and anthocyanin. The yield of fresh potatoes is 56.13% higher than open-air planting, which benefits sweet potato planting.
2. Planting sweet potatoes under EAPV improved the utilization rate of phosphorus and potassium fertilizers, effectively controlled the growth of aboveground parts, and increased protein starch content, reducing sugar and soluble sugar. The yield of fresh potatoes is 27.89% higher than open-air planting, which benefits sweet potato planting.
3. In the SCAPV and EAPV treatments, evaporation pans results showed significantly reduced water evaporation compared to open-air (CK).
4. Compared to CK, the results showed a significant reduction in evapotranspiration under SCAPV and EAPV.

We believe that SCAPV and EAPV could help overcome the challenges of water scarcity, food supply, and energy production on the same farmland.

Author Contributions

Altyeb Ali Abaker Omer: Conceptualization, Methodology, Software, Formal Analysis Writing - Original Draft, and Writing - Review & Editing. Xinliang Liu Methodology, Data curation. Ming Li Writing - Review & Editing. Xinyu Zhang Methodology, investigation, and Resources. Fangcai Chen Investigation. Jianan Zheng Software and Investigation. Wenjun Liu Investigation. Fangxin Zhang Investigation. Wen Liu Writing - Review & Editing, Supervision, and Funding Acquisition.

Competing interests

The authors declare that they have no competing interests.

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