

Impact of the multilayer polymer film on plant growth

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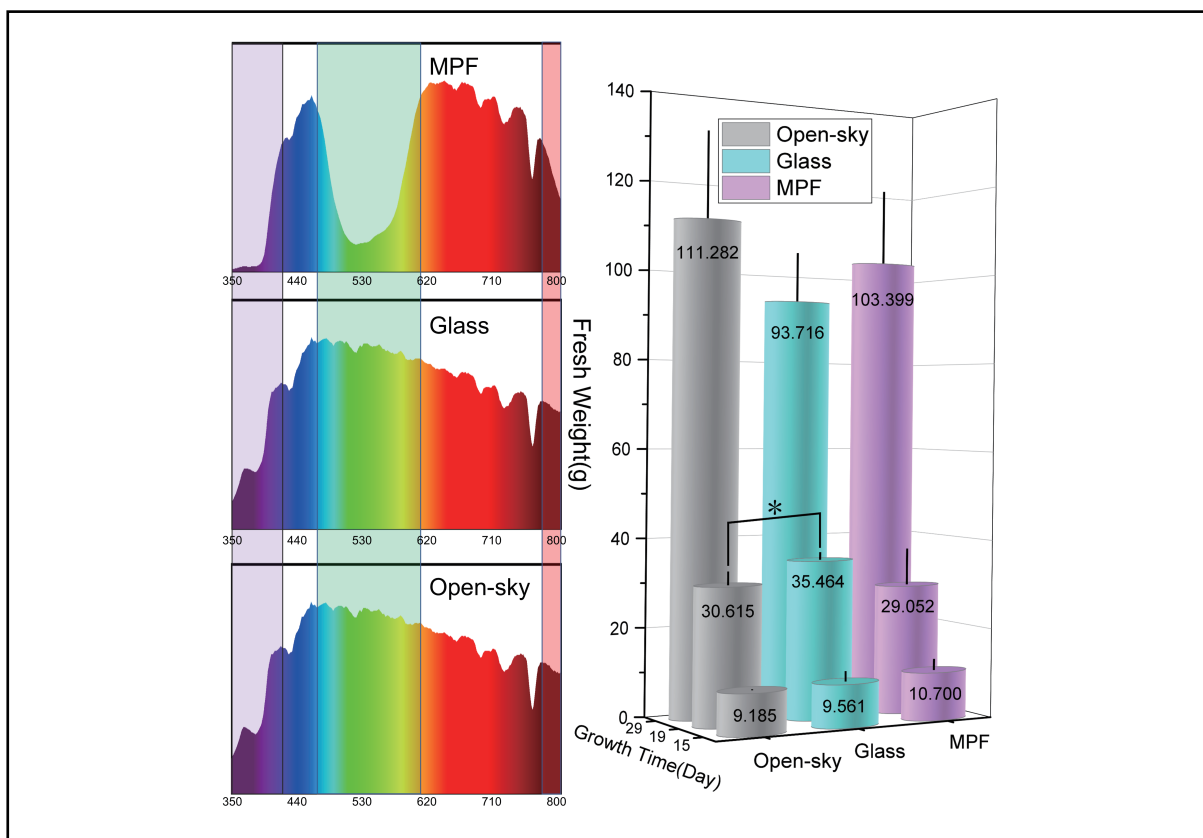
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Graphical abstract



Multilayer polymer films (MPF) enhances plant photosynthetic efficiency and biomass accumulation by reflecting part of the solar radiation.

Public summary

- The solar radiation filtered by multilayer polymer films (MPF) effectively reduces the ambient temperature around plants and soil temperature, thereby alleviating environmental stress on plants.
- Under MPF coverage, the midday photosynthetic efficiency of romaine lettuce improves, offsetting the biomass reduction caused by insufficient solar radiation and leading to a significant increase in yield.
- This study provides empirical evidence for agrivoltaic development by confirming the feasibility of light-separation strategies in agriculture.

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Supporting Information

Abstract: The main photosynthetic pigments utilized by plants for photosynthesis include chlorophyll A and chlorophyll B, while the primary photosensitizing pigments employed for physiological regulation are Pr and Pfr. These pigments exhibit absorption peaks predominantly in the blue, red, and near-infrared regions. Consequently, through a light-separation strategy, plants can selectively receive the required solar radiation while reflecting the remaining wavelengths for photovoltaic power generation. In this study, multilayer polymer films (MPFs) were employed as light filters to investigate their impact on plant growth. Comparative experiments were conducted to validate the efficacy of the light filtering system. Compared with those in the other groups, the environmental temperature and soil temperature of the plants in the MPF coverage group were lower, thereby alleviating the environmental stress faced by the plants. The fluorescence data confirmed that during noontime hours, the plants under the MPF presented increased photosynthetic efficiency, compensating for the reduced rates caused by insufficient solar radiation exposure. Furthermore, biomass analysis demonstrated MPF cover group had a 10.3% increase in plant yield compared with glass group. This investigation validates the feasibility of employing a light separation strategy in agriculture while providing robust empirical evidence supporting advancements in agricultural photovoltaics.

Keywords: plant growth; multilayer polymer films; light separation

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1 Introduction

Due to the reduction in component costs, the cost of centralized photovoltaic power generation has dropped to approximately 0.13 CNY/kWh. However, the electricity generated by photovoltaic power needs to be transported over long distances, so compared with traditional thermal power generation, the cost of photovoltaic power generation is still relatively high. Consequently, distributed photovoltaic power generation is particularly important in the eastern region of China.

However, due to the limitations of installation conditions, large-scale implementation of distributed photovoltaic power generation in eastern China remains challenging. Consequently, agricultural land is extensively chosen as the installation site for photovoltaic equipment, commonly referred to as agricultural photovoltaics (APVs)^[1–2]. Nevertheless, this practice significantly impacts crop growth under such panels^[3–4]. To ensure optimal crop growth on cultivated land, researchers have employed various methods to mitigate the effects of photovoltaic equipment, including mosaic semitransparent photovoltaic panels^[5–6], strip tracking photovoltaic panels^[7], and spectral separated semitransparent photovoltaic panels^[8–12]. Zhang et al.^[13] implemented a light-filtering photovoltaic power generation system that allows the transmission of red and blue light conducive to plant growth while

reflecting other solar radiation wavelengths for photovoltaic power systems. They investigated the device's impact on overall system performance, and the maximum achievable increase in the device's power conversion efficiency was found to be 11.6%. Additionally, the constructed a 10 kW power generation station with an annual average power output exceeding 10700 Wh/m². Nonetheless, there is limited research available regarding the influence of APV systems on plant growth. This study aims to further validate its feasibility in cultivation by examining plant growth data from such systems.

The photosynthetically active radiation (PAR) within the wavelength range of 400–740 nm accounts for approximately 48.7% of the total solar radiation energy, implying that approximately 51.3% of the energy is not utilized by plants for photosynthesis^[14]. Light is essential for normal plant development, and chlorophyll A and chlorophyll B are the primary photosynthetic pigments used by plants to capture radiant energy for photosynthesis^[15,16]. As depicted in Fig. 1, their absorption peaks are predominantly found in the blue region (400–500 nm) and red region (600–700 nm). Additionally, Fig. 1 illustrates that certain photosensitizing pigments, such as Pr and Pfr, exhibit absorption peaks in the red, ultraviolet, and infrared regions to assist with photosynthesis and protect leaves from light-induced damage^[17]. Although near-infrared

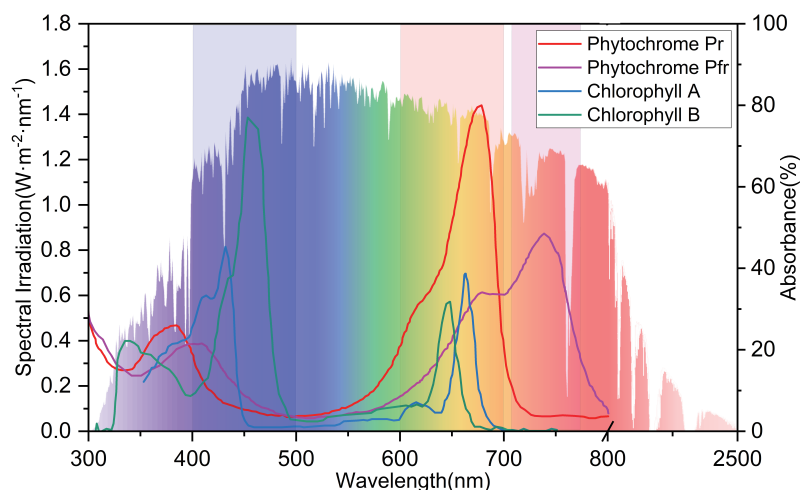


Fig. 1. Solar spectrum (AM1.5) and the absorption spectrum of photosynthetic pigments in plants.

light cannot be directly utilized for photosynthesis, it significantly influences plant growth regulation, accounting for approximately 85% of photosynthesis. While various wavelengths of light have complex effects on plants, red, blue, and near-infrared light primarily contribute to physiological regulation by providing energy for photosynthesis, whereas other wavelengths of light play a supplementary role^[18].

Plants are unable to fully absorb solar radiation energy, with a significant portion being dissipated through reflection and heat^[19], which cannot be used for photosynthesis. Excessive solar radiation can even trigger plant self-protection mechanisms^[20], thereby reducing photosynthetic activity. By segregating unabsorbable solar radiation energy, it becomes feasible to harness and utilize this surplus energy for photovoltaic or photothermal power generation, consequently increasing land use efficiency^[21]. Nevertheless, the potential impact of such light-separation strategies on plants remains inadequately examined and discussed^[12].

2 Materials and methods

2.1 Filtration system

The filtration system employed in this study consists of two main components: a multilayer polymer film (MPF) and an arc-shaped glass plate. The filtering film utilizes the interference of the multilayer film interface to create a highly reflective band within a specific wavelength range. For this experiment, we selected the blue band (approximately 380–480 nm) and the red/near-infrared band (approximately 600–900 nm), as depicted in Fig. 2, while reflecting wavelengths below 380 nm (ultraviolet band), between 480–600 nm (green band), and above 900 nm (near-infrared band). However, considering that incident angles can influence the performance of the interference filtering film by causing shifts in its reflective bands, we attached the filtering film to an east–west oriented arc-shaped glass plate inclined in the southern direction, as illustrated in the Supporting information Fig. S1. This arrangement ensures that direct sunlight is incident vertically onto the surface of the filtering film throughout the daytime. Generally, the aforementioned

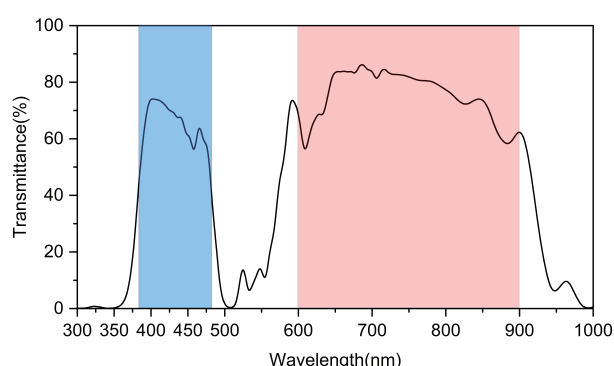


Fig. 2. Transmittance of the MPF.

method can ensure that solar radiation always enters at a perpendicular angle in a short period of time. However, as time passes, the angle of incidence changes with the season. Therefore, if the growth cycle of a plant is relatively long or if it spans different seasons, the orientation of the MPF needs to be adjusted. If adjustment of the orientation is necessary, one method is single-axis tracking in the north–south direction, which can ensure perpendicular incidence into the MPF system even when the solar azimuth angle changes. Another method is dual-axis tracking, which can guarantee that solar radiation enters perpendicularly at any time.

2.2 Experimental design and arrangement

To investigate the impact of light-separation strategies on plants, a combination of a light filter film and a glass plate was used in the experimental group, and two control groups were also included: one with only an arc glass plate but no light filter film and another with an open-sky control group without either component. Each of the three planting experiments included these three control groups. The specific experimental details and arrangement can be found in Supporting information Tables S1, S2, and S3.

2.3 Parameter measurement

2.3.1 Measurement of microenvironmental parameters

In those experiments, an irradiance sensor, multiple sets of temperature and humidity sensors, light intensity sensors, a

wind speed sensor, soil temperature sensors, and direction sensors (Shandong Renke Control Technology Co., Ltd.) were utilized to record the relevant micro environmental and soil data of each experimental group. Additionally, an optical spectrometer (PLA-30) from EVERFINE was used to measure the spectroscopic data of various experimental groups.

2.3.2 Measurement of plant fluorescence parameters

The chlorophyll fluorescence data were tested via the MINI-PAM-II (Zealquest Scientific Technology Co., Ltd.). The testing period spanned from sunrise to sunset throughout the entire day, with measurements taken once every hour. Notably, the reason for conducting tests hourly is that the leaves require sufficient time for light adaptation to ensure the accuracy of the measurements. On the other hand, it is inevitable that the leaves will be slightly damaged when they are clamped with the leaf clip. Therefore, to ensure the accuracy of the data and that the data volume reflects the trend throughout the day, we chose to perform chlorophyll fluorescence tests on the leaves once every hour. Two healthy leaves were randomly selected from random plants in each pot in each experimental group, and their fixed positions were used for measurement. The commonly employed method for studying chlorophyll fluorescence is the chlorophyll induction curve, which involves inducing fluorescence through photochemical light after sufficient dark adaptation to ensure the closure of photosystem II. The resulting curve represents the chlorophyll induction process^[22].

After sufficient dark adaptation, weak photoluminescence light can be employed to induce pigments and generate background fluorescence without any photosynthesis. The resulting fluorescence is recorded as the minimum fluorescence F_0 . An intense saturating pulse light is subsequently applied to rapidly drive photosystem II into saturation. At this point, all the absorbed light energy is converted into both fluorescence and heat, with the detected fluorescence representing the maximum value F_m . By utilizing these two parameters, the maximum photosynthetic efficiency of photosystem II can be calculated as follows^[23,24]:

$$\frac{F_v}{F_m} = \frac{(F_m - F_0)}{F_m}.$$

For healthy higher plants, the maximum photosynthetic efficiency value of photosystem II typically ranges between 0.8 and 0.85. A decrease in this value indicates environmental stress on the plant, making F_v/F_m a crucial indicator for studying such stressors.

When chlorophyll is excited by stable photochemical light, plant photosynthesis tends to stabilize over time. In this state, chlorophyll can efficiently carry out normal fluorescence and dissipate heat, resulting in a fluorescence value denoted as F . However, when saturated pulse light is abruptly applied after stability is achieved, the energy that should be utilized for photosynthesis is instead consumed through fluorescence and heat dissipation processes. The corresponding fluorescence value at this point is referred to as F'_m . On the basis of these two parameters, it becomes possible to calculate the actual photosynthetic efficiency of photosystem II:

$$Y(\text{II}) = \frac{\Delta F}{F'_m} = \frac{(F'_m - F)}{F'_m}.$$

The fluorescence value F is lower than the maximum fluorescence value F_m during normal photosynthesis, indicating the occurrence of fluorescence quenching. This phenomenon can be attributed to the utilization of energy for photochemical reactions and dissipation as heat. Photochemical quenching (qL) refers to fluorescence quenching caused by photochemical reactions, whereas non-photochemical quenching (NPQ) refers to fluorescence quenching resulting from heat dissipation. qL serves as a measure of plant photosynthetic activity because of its association with the energy utilized in photochemical reactions, whereas NPQ reflects the light protection capability of plants by dissipating excess energy through heat^[25].

Photochemical quenching (qL) and non-photochemical quenching (NPQ) can be calculated as follows:

$$qL = \frac{(F'_m - F)}{(F'_m - F_0)} \cdot \frac{F_0}{F},$$

$$NPQ = \frac{(F_m - F'_m)}{F'_m}.$$

However, the formula for calculating qL includes F'_0 . Since measuring F'_0 requires far-infrared light, which is inconvenient and challenging, many literature sources use F_0 instead of F'_0 . Although there may be slight differences in the obtained values, comparing their magnitudes allows for a consistent assessment of plant photosynthetic activity^[26-28].

The photosynthetic efficiency of photosystem II, denoted as $Y(\text{II})$, quantifies energy utilization in the process of photosynthesis. The remaining energy is partitioned into fluorescence and heat dissipation, with passive dissipation occurring through heat loss and fluorescence emission, which is referred to as the quantum yield of non-modulated energy dissipation in photosystem II:

$$Y(NO) = \frac{1}{(NPQ + 1 + qL(F_m/F_0 - 1))}.$$

The portion of energy dissipated as heat is referred to as the quantum yield of energy dissipation regulated by photosystem II:

$$Y(NPQ) = \frac{F}{F'_m} - \frac{F}{F_m}.$$

The parameter $Y(NO)$ serves as a crucial indicator of light-induced damage, whereas $Y(NPQ)$ plays a crucial role in assessing the efficacy of light protection measures.

$Y(\text{II})$, $Y(NPQ)$, and $Y(NO)$ have the following relationship:

$$Y(\text{II}) + Y(NPQ) + Y(NO) = 1.$$

2.3.3 Measurement of biomass

After harvest, all underground parts beneath the leaf were excised, and the weight recorded at this point was considered the fresh biomass of the samples. These samples were

subsequently introduced into a preheated drying oven set to 110 °C for initial desiccation. After 30 min of chlorophyll degradation, the drying oven temperature was adjusted to 80 °C. These samples were dried at this temperature for 48 h until a constant weight was achieved. The weight recorded at this point was considered the dry biomass of the samples.

For the biomass analysis of lettuce planted in June 2023, to investigate the impact of different growth stages on plant biomass and overcome the drying oven volume issue encountered in the initial experiment, the planting trial was divided into three separate occasions: 15, 19, and 29 days after transplantation. The plant samples were collected at different stages, and their biomass data were measured via the above-mentioned methods.

3 Results and discussion

3.1 Impact of the filtration system on the microenvironment

According to the environmental data in Fig. S2a, the highest irradiance of 1057 W/m² occurred at 12:09 and 12:17 at noon on May 14, which was relatively stable without an obvious sudden drop. The entire day was basically sunny and cloudless. Since the minimum range of the solar irradiance sensor is 1 W/m², which is far greater than the 1 lx of the light intensity sensor, when the scattering light appears in the environment but the sun has not yet risen, the light intensity sensor can detect and record the scattering light. Therefore, the first time the solar irradiance sensor recorded the light was at 5:45, and the light intensity sensor received the light at a ratio of 4:58. As shown in Fig. S2c, the highest irradiance of 1016 W/m² occurred at 12:51 at noon on June 1. The first time the irradiance sensor detected the light was 5:34, but the first time the light intensity sensor detected the light was 4:46. The behavior of the two sensors on that day is consistent with the above reasons. However, the solar irradiance on June 1

varies greatly, which can be reasonably explained by the cloudy day. The sun was often blocked by clouds, resulting in the fluctuation of the received irradiance. According to the wind speed and direction charts in Fig. S2b and d, breezes occurred on May 14 and June 1; the night of June 1 was windless.

Fig. 3a and b depict the changes in the light intensity of the three experimental microenvironments over these two days. The light intensity in the MPF experimental environment was significantly lower than that in the other two control experimental groups. Fig. 3c–e show the spectral distributions of these microenvironments, as measured by a spectrometer. Notably, the light intensity within the MPF experimental group significantly decreased across ultraviolet, green, and near-infrared wavelengths; however, it did not completely vanish. This portion primarily comprises ambient scattered light and solar radiation that is not reflected by the MPF. These scattered lights can partially fulfill plant physiological regulations without disrupting them entirely. Moreover, the red and blue components of sunlight remain largely unaffected, thereby meeting the plants' photosynthetic requirements. The study confirmed that glass has a minimal impact on the solar spectrum but only slightly absorbs in the ultraviolet band, resulting in a reduced solar radiation intensity specifically within this range.

To facilitate the comparison of light intensity differences across the three experimental microenvironments, this study calculated the average light intensity from initial detection to final detection on these two days, and the results are presented in Table S4. As shown in Table S4, Fig. 3a, and b, the light intensity in the MPF coverage experimental group was significantly lower than that in the open-sky group and glass coverage group. On May 14, the average light intensity under MPF was approximately 32% of that under open-sky conditions. In addition, on June 1, it was approximately 37%. Therefore, the MPF reflects approximately 65% of solar

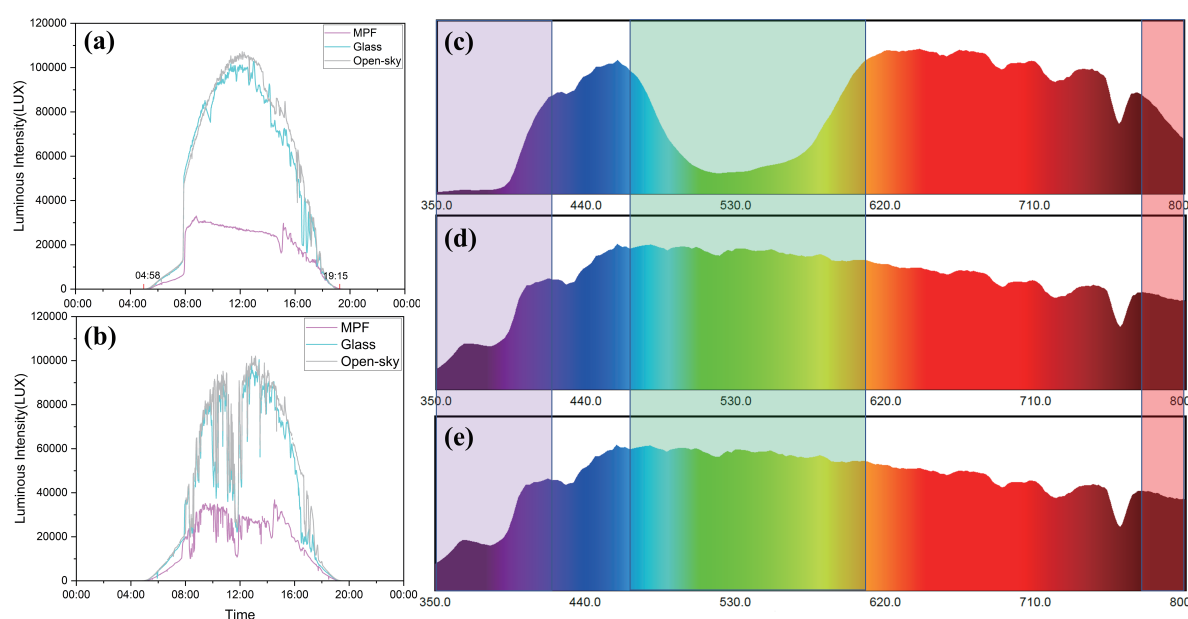


Fig. 3. Light intensity in the microenvironments of the three control groups on (a) May 14 and (b) June 1. Solar spectrum under (c) MPF coverage, (d) glass coverage, and (e) open-sky.

radiation, with only one-third of the total solar radiation transmitted through it. On May 14 and June 1, the average light intensities under glass were approximately 94% and 91%, respectively, compared to those under open-sky conditions. The loss of light can be attributed to three main factors: Fresnel reflection occurs when light enters glass with a higher refractive index from the air with a lower refractive index; absorption of energy within the ultraviolet band by glass results in partial energy loss; and stains or damages the glass, leading to partial reflection and absorption, thereby reducing the transmitted light intensity.

As shown in Fig. 4a and b, the temperatures recorded at 8:00 a.m. and 6:00 p.m. are similar on these two days; thus, this study designates temperatures after 6:00 p.m. and before 8:00 a.m. as nighttime temperatures and temperatures from 8:00 a.m. to 6:00 p.m. as daytime temperatures. Table S5 presents the average temperatures of the three experimental microenvironments during these two days. Remarkably, the open-sky microenvironment presented the lowest temperature at night, with a night-time temperature approximately 1 °C lower than that of the glass coverage microenvironment, and approximately 0.5–1 °C lower than that of the MPF coverage microenvironment. Humidity has an inverse relationship with ambient temperature, whereby the glass coverage microenvironment at higher temperatures has a slightly lower humidity than the other two experimental environments.

The microenvironment under MPF presented the lowest daytime temperature, approximately 1 °C lower than that of the open-sky group on May 14, over 2 °C lower than the ambient temperature on June 1, and more than 3 °C lower than that of the glass coverage microenvironment. Moreover, it consistently maintained higher humidity levels than did the other two experimental groups. These favorable conditions during the daytime ensure optimal plant transpiration and photosynthesis while minimizing photoinhibition and light-induced damage, ultimately extending the duration of photosynthetic activity.

The microenvironment temperatures of the three experimental groups were influenced to varying degrees by the MPF light filtering effect and glass plate convection. Additionally, there were differences in the soil temperatures among the three groups. Fig. 4c illustrates the temperature data for May 14 throughout the day. Prior to 9:00 a.m., due to convection, the soil temperature under the glass plate was significantly greater, with a difference of up to 1.04 °C compared with that of the open-sky group; moreover, the soil temperature of the MPF group was notably lower, with a maximum temperature difference of 1.23 °C compared with that of the glass coverage group. Similar results were observed on June 1, as depicted in Fig. 4d. The soil temperature under the glass-covered plate reached its peak and differed by a maximum value of 0.8 °C from that under open-sky

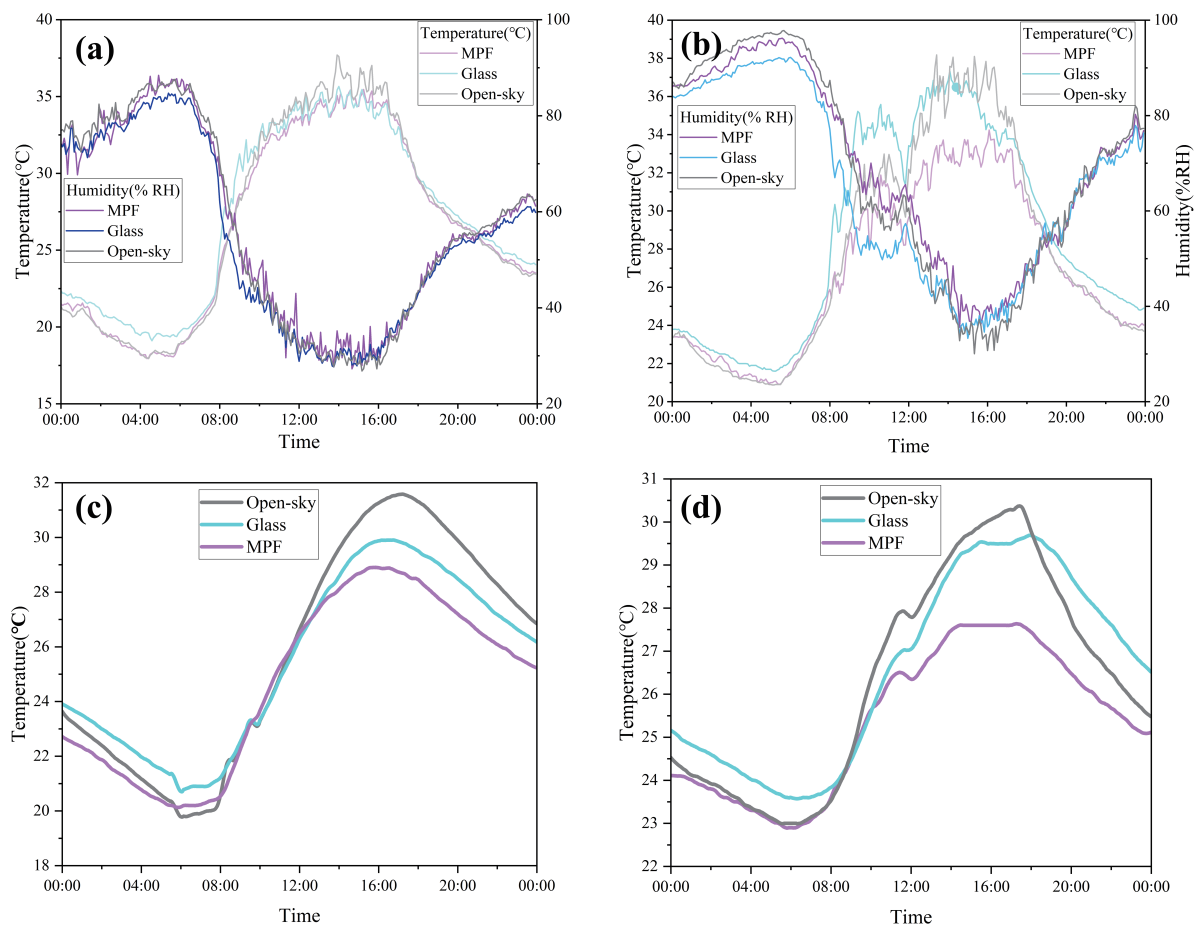


Fig. 4. Temperature and humidity in the microenvironment (a) May 14, 2023, (b) June 1, 2023. Soil temperature on (c) May 14, 2023 and (d) June 1, 2023.

conditions and by a maximum value of 1.1 °C from that under the MPF experimental conditions. A comparison of the daytime soil temperature data after 9:00 a.m. on May 14 and June 1 revealed that the open-sky soil temperature reached its peak on both May 14 and June 1. In contrast, the soil temperature in the MPF group significantly decreased, with differences of approximately 2.96 °C and 2.8 °C on these two days. This disparity can be attributed primarily to the ability of the MPF to reflect approximately 60% of solar radiation during daylight hours. However, as solar radiation gradually weakened, the cooling rate of the open-sky soil surpassed that of the glass group (as depicted in Fig. 4d), resulting in lower soil temperatures than those recorded in the glass control group at sunset.

3.2 F_v/F_m of the chlorophyll fluorescence test

As previously mentioned, F_v/F_m serves as a crucial indicator for investigating the presence of environmental stress in plants. The maximum photosynthetic efficiency value of photosystem II typically ranges between 0.8 and 0.85; any decrease in this value signifies plant stress. Therefore, during the initial tobacco planting experiment, F_v/F_m was measured throughout the entire period from predawn to the absence of direct sunlight. For the fixed-point marking test, three robust blades were randomly selected in each experimental group, with a testing interval of 1 h. Before the test, dark-adapted blade clamps were used to ensure that the tested area had undergone at least 30 min of dark adaptation. The average F_v/F_m results for each experimental group are presented in Fig. 5.

The F_v/F_m values of the three experimental groups tested at different time intervals are closely aligned. Additionally, both before 11:30 and after 14:30, all three groups presented F_v/F_m values exceeding 0.8, thereby meeting the criteria for healthy higher plants. Furthermore, even under ample sunlight conditions at noon, a slight decline in F_v/F_m values is observed following a sufficient dark adaptation process, which can be attributed to potential stress induced by the environmental temperature and humidity. Nevertheless, throughout the entire fluorescence testing procedure of the samples, it can be inferred from the recorded F_v/F_m values that neither plant health nor leaf condition was affected. Therefore, the F_v/F_m values were assessed only once before dawn in subsequent tests, ensuring that the blade remained undamaged from repeated fixed-point dark adaptation clamping. This precautionary measure aimed to mitigate any potential interference caused by other fluorescence induction tests conducted under photoluminescence conditions in subsequent experiments.

3.3 $Y(II)$ of chlorophyll fluorescence test

$Y(II)$ represents the quantum yield of photosynthetic reaction II under these specific conditions, reflecting the actual photosynthetic efficiency of plants. Therefore, a higher $Y(II)$ indicates greater photosynthetic efficiency in plants under these light conditions. Fig. 6a presents the $Y(II)$ data for the three experimental groups at different periods throughout these days. The $Y(II)$ values remained at approximately 0.8 in all three experiments, indicating that, regardless of the

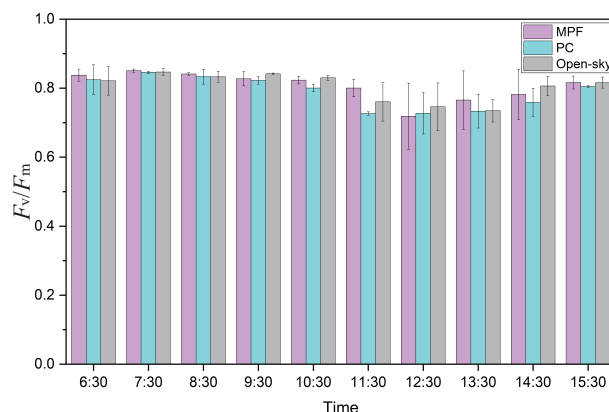


Fig. 5. Daytime testing of F_v/F_m for tobacco on September 30, 2022.

experimental environment, the plant photosynthetic efficiency was relatively high before sunrise. However, as solar radiation increased, the ambient temperature increased, the humidity decreased, and the plant photosynthetic efficiency decreased under environmental stress conditions. Although there was a decline in photosynthetic efficiency across all three experimental groups, the rate of decline varied. At noon, when solar radiation was highest, plants in the MPF microenvironment presented greater photosynthetic efficiency than did those in the other two groups.

As shown in Fig. 6a and b, plants in the MPF coverage microenvironment maintained a $Y(II)$ level above 0.5 at noon, whereas those in the other control groups dropped below 0.2. This is attributed primarily to the increase in solar radiation, which induces an increase in ambient temperature and a decrease in humidity, thereby triggering the self-protective mechanism of plants known as the “afternoon nap”. Consequently, the radiation energy that is typically absorbed and utilized for photochemical reactions by plants is diverted from photosynthesis. This leads to partial deactivation of the reaction centers, a reduction in photochemical capacity, and dissipation of excess energy through heat generation and fluorescence emission.

However, the plants protected by MPF exhibited substantial photosynthetic activity in an environment with intense illumination, enabling continuous energy transport to photochemical reactions for photosynthesis with a photosynthetic efficiency exceeding 0.5. Thus, despite partially blocking solar energy absorption by plants, MPF protection increased their photosynthetic efficiency and sustained high rates of photosynthesis over extended periods. This compensatory mechanism offset the reduced photosynthesis during other times and ensured that plants under the MPF did not experience decreased output while effectively filtering most of the solar radiation. This effect was particularly pronounced in environments with intense solar radiation, as depicted in Fig. 6b. On May 14, 2023—a sunny day (Fig. S2)—solar radiation at noon was exceptionally strong; however, under cloudy or even overcast conditions, differences among the three experimental groups were less apparent (Fig. 6c). During an extended period of cloud cover at noon on that day, all three experimental groups maintained similar levels of photosynthetic efficiency; although slightly greater under MPF conditions, this difference was not significant. Nevertheless,

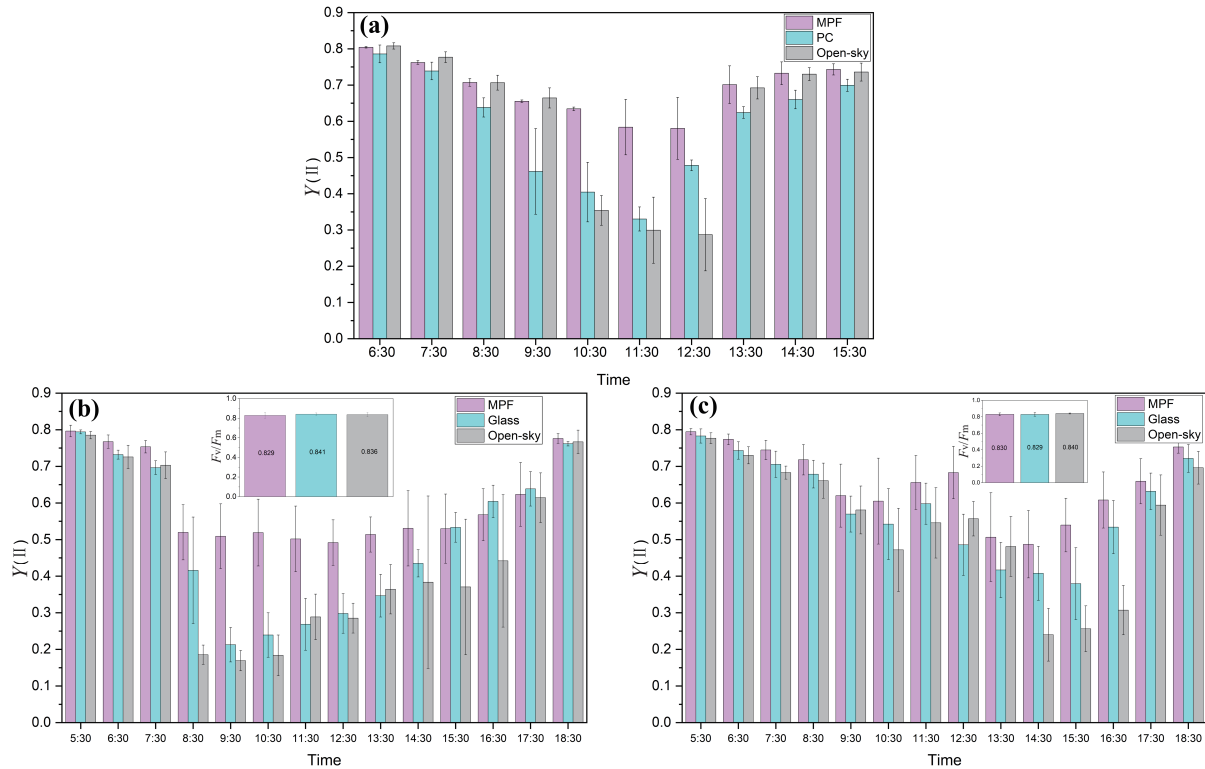


Fig. 6. $Y(II)$ values for three full-day fixed-point fluorescence induction tests: (a) September 30, 2022—tobacco; (b) May 14, 2023—lettuce; (c) June 1, 2023—lettuce.

at approximately 2:00 p.m., when continuous sunny days with intense solar radiation prevailed, the advantage of extremely high photosynthetic efficiency in the MPF environment became evident.

3.4 NPQ of chlorophyll fluorescence test

NPQ reflects the fraction of energy dissipated as heat in photosystem II, and $Y(NPQ)$ indicates the proportion of energy dissipated as heat in photosystem II. A high NPQ or $Y(NPQ)$ signifies an excessive influx of radiant energy that necessitates its dissipation in the form of thermal energy. In a similar

environment, the values of NPQ and $Y(NPQ)$ can also serve as indicators of a plant's self-regulatory capacity and can be used to assess the photo-protective abilities of different leaves or plants within the same environment.

Fig. 7a–c and Fig. 7d–f show the NPQ and $Y(NPQ)$ values for September 30, 2022, May 14, 2023, and June 1, 2023, respectively, in three different microenvironments. The plants under MPF coverage were consistently the lowest among the three environments except at sunrise. As the light intensity increased, the differences among these three environments

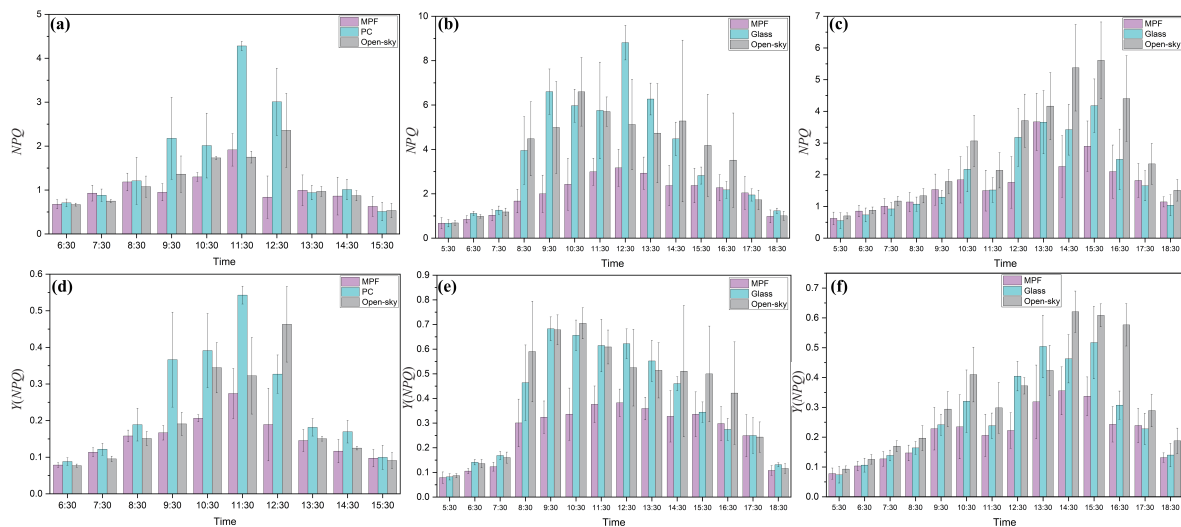


Fig. 7. NPQ values for three full-day fixed-point fluorescence induction tests: (a) September 30, 2022—tobacco; (b) May 14, 2023—lettuce; (c) June 1, 2023—lettuce. $Y(NPQ)$ values for three full-day fixed-point fluorescence induction tests: (d) September 30, 2022—tobacco; (e) May 14, 2023—lettuce; (f) June 1, 2023—lettuce.

became more pronounced. After 8:30 a.m., the NPQ of the other control groups significantly surpassed that of the experimental group under the MPF cover. This observation suggests a relatively minor allocation of energy toward heat dissipation in photosystem II of plants under MPF coverage, implying a predominant utilization of energy for photochemical reactions. This finding aligns with our earlier observation of higher $Y(II)$ values in plants under MPF cover, providing evidence that more absorbed energy is converted into chemical energy while minimizing heat dissipation. Furthermore, when considering the $Y(II)$ value shown in Fig. 6, plants under MPF cover clearly presented greater photosynthetic capacity not only under extreme light intensity but also under weaker light radiation conditions; even during cloudy periods on June 1, when sunlight was blocked for several hours, plants under MPF cover maintained high photosynthetic efficiency and low heat loss ratios compared with those of the other controls. Therefore, it can be concluded from those experiments that MPF not only has advantages under extreme light conditions but also has superior photosynthetic efficiency even in common cloudy environments, as supported by $Y(II)$ data analysis.

3.5 Plant biomass analysis

As shown in Fig. S3, there was no significant disparity in plant growth among the three control groups within the experimental setting. Although the light intensity under MPF was only one-third that under the other two control treatments, it had a minimal effect on plant growth. Furthermore, as depicted in Fig. S3b, plants covered with glass exhibit signs of dehydration due to high temperatures and low humidity at noon. Consequently, the plants in the other two control groups experienced considerable environmental stress, resulting in a decline in photosynthetic efficiency, which aligns with the abovementioned test results.

The growth states of plants in different periods under different experimental environments shown in Fig. S4b12 and c12 also clearly revealed that the plants experienced dehydration at noon, but the MPF experimental group was basically not affected much in Fig. S4a, whereas the dehydration phenomenon of the plants in the glass and open-sky control groups was still very obvious, which proved that the plants in the MPF coverage group experienced relatively light environmental stress at the high-temperature stage at noon and could still maintain high photosynthetic efficiency. This finding also revealed why there was essentially no visual difference in the plants under such a weak light intensity.

In the first lettuce planting experiment conducted in May 2023, two issues requiring further exploration and resolution were identified. First, it was necessary to investigate whether MPF had differential effects on plant biomass at different growth stages. We observed that the plants in the MPF coverage experimental group were significantly larger than those in the other two control groups during the early stage of the experiment, but there was a phenomenon of backward excess in the latter half of the growth period. Second, this planting experiment coincided with Hefei's plum rain season, resulting in more than 60% of the entire planting cycle being characterized by rainy or cloudy days. The prolonged plum rain days

failed in the MPF coverage experimental group to achieve the saturation light intensity required for optimal plant growth. The stress did not result in the inhibition of the other two control groups at noon, potentially resulting in the observed decrease in final MPF biomass. Consequently, a subsequent lettuce planting experiment was conducted in June 2023, denoted as the second trial for lettuce planting in that month. The obtained biomass results are illustrated in Fig. 8.

In the lettuce repeat experiment conducted in June 2023, three distinct growth stages were selected for biomass measurement. With respect to fresh biomass, during the early growth phase of plants, those under the MPF coverage environment presented a relatively high water content due to the protective effect of MPF. This protection resulted in reduced transpiration and soil water evaporation, leading to a higher plant water content than those in the other control groups. However, as the plants grew, on the 19th day, fresh biomass of MPF cover group were lower than the other two control groups. This can be attributed to this stage being crucial for lettuce growth with high light-intensity demand. However, due to the shielding caused by the MPF, the plants were unable to reach saturated light intensity for an extended period. Consequently, the photosynthetic capacity of the plants in the MPF treatment was lower than that of the control plants which had access to high light intensity during this period. However, during the subsequent 10-day growth period, the protective effect of MPF continued to exert a discernible influence, resulting in a higher plant water content and a 10.3%

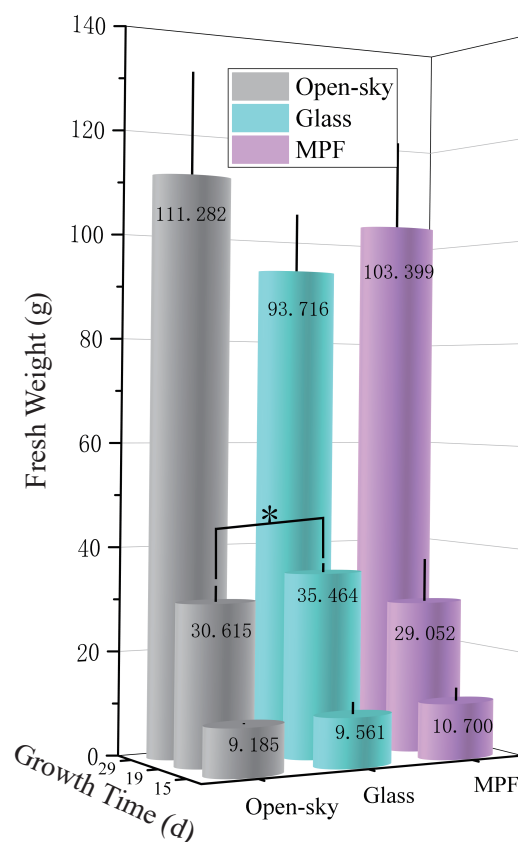


Fig. 8. Comparison of the biomass of lettuce at different growth stages (June 2023).

increase in the fresh biomass of lettuce compared with those under glass. Throughout the entire growth cycle of lettuce, there were no significant differences in the fresh biomass of the plants between the MPF coverage experimental group and the two control groups. However, on day 19 of growth, a significant difference was observed between the glass control group and the open-sky control group ($P = 0.04$), indicating that the limited convection microenvironment provided by glass alleviated the effects of environmental stress on plant physiology.

4 Conclusions

Despite being affected by local plum rain weather and experiencing numerous rainy days, the experimental groups covered by MPF presented remarkable outcomes. Compared with that of the control groups, the photosynthetic efficiency and reduced environmental stress were greater, and the biomass of the MPF group was 10.33% greater than that of glass group, which was not significantly different from the other control groups. These findings validate the feasibility of employing the MPF light separation strategy. Although there was a slight decrease in biomass production, two-thirds of the reflected solar radiation after light separation could still be utilized in other domains, such as photovoltaic power generation, thereby generating additional economic benefits, and the experiments provided valuable data for researchers investigating light separation strategies in agriculture.

Supporting information

The supporting information for this article can be found online at <https://doi.org/10.52396/JUSTC-2025-0021>. This supporting information includes four figures and five tables.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflict of interest

The authors declare that they have no conflict of interest.

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References

- [1] Al Mamun M A, Dargusch P, Wadley D, et al. A review of research on agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, **2022**, *161*: 112351.
- [2] Chen J, Liu Y, Wang L. Research on coupling coordination development for photovoltaic agriculture system in China. *Sustainability*, **2019**, *11*: 1065.
- [3] Xue J. Photovoltaic agriculture—New opportunity for photovoltaic applications in China. *Renewable and Sustainable Energy Reviews*, **2017**, *73*: 1–9.
- [4] Song C, Guo Z, Liu Z, et al. Application of photovoltaics on different types of land in China: Opportunities, status and challenges. *Renewable and Sustainable Energy Reviews*, **2024**, *191*: 114146.
- [5] Cossu M, Yano A, Li Z, 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.
- [6] Yano A, Onoe M, Nakata J. Prototype semi-transparent photovoltaic modules for greenhouse roof applications. *Biosystems Engineering*, **2014**, *122*: 62–73.
- [7] Amaducci S, Yin X, Colauzzi M. Agrivoltaic systems to optimise land use for electric energy production. *Applied Energy*, **2018**, *220*: 545–561.
- [8] Ravishanker E, Charles M, Xiong Y, et al. Balancing crop production and energy harvesting in organic solar-powered greenhouses. *Cell Reports Physical Science*, **2021**, *2*: 100381.
- [9] Liu W, Liu L, Guan C, et al. A novel agricultural photovoltaic system based on solar spectrum separation. *Solar Energy*, **2018**, *162*: 84–94.
- [10] Shi H, Xia R, Zhang G, et al. Spectral engineering of semitransparent polymer solar cells for greenhouse applications. *Advanced Energy Materials*, **2019**, *9*: 1803438.
- [11] Wang D, Liu H, Li Y, et al. High-performance and eco-friendly semitransparent organic solar cells for greenhouse applications. *Joule*, **2021**, *5*: 945–957.
- [12] Weng S, Tamang A, Salleo A, et al. Band-gap-engineered transparent perovskite solar modules to combine photovoltaics with photosynthesis. *ACS Applied Materials & Interfaces*, **2021**, *13*: 39230–39238.
- [13] Zhang F, Li M, Zhang W, et al. Large-scale and cost-efficient agrivoltaics system by spectral separation. *iScience*, **2023**, *26*: 108129.
- [14] Zhu X G, Long S P, Ort D R. What is the maximum efficiency with which photosynthesis can convert solar energy into biomass? *Current Opinion in Biotechnology*, **2008**, *19*: 153–159.
- [15] Delegido J, Fernández G, Gandía S, et al. Retrieval of chlorophyll content and LAI of crops using hyperspectral techniques: Application to PROBA/CHRIS data. *International Journal of Remote Sensing*, **2008**, *29*: 7107–7127.
- [16] Chen M, Blankenship R E. Expanding the solar spectrum used by photosynthesis. *Trends in Plant Science*, **2011**, *16*: 427–431.
- [17] La Notte L, Giordano L, Calabrò E, et al. Hybrid and organic photovoltaics for greenhouse applications. *Applied Energy*, **2020**, *278*: 115582.
- [18] Zhang Z, Chang T, Zhang X, et al. Solar spectral splitting for improved photosynthetic yield and energy polygeneration. *Journal of Cleaner Production*, **2024**, *442*: 140948.
- [19] Murchie E H, Ruban A V. Dynamic non-photochemical quenching in plants: From molecular mechanism to productivity. *The Plant Journal*, **2020**, *101*: 885–896.
- [20] Ort D R. When there is too much light. *Plant Physiology*, **2001**, *125* (1): 29–32.
- [21] Zhang Z, Zhang F, Zhang W, et al. Spectral-splitting concentrator agrivoltaics for higher hybrid solar energy conversion efficiency.

- Energy Conversion and Management*, **2023**, 276: 116567.
- [22] Chen L L, Wang H Y, Gong X C, et al. Transcriptome analysis reveals effects of red and blue light-emitting diodes (LEDs) on the growth, chlorophyll fluorescence and endogenous plant hormones of potato (*Solanum tuberosum* L.) plantlets cultured *in vitro*. *Journal of Integrative Agriculture*, **2021**, 20: 2914–2931.
- [23] Zheng L, Van Labeke M C. Chrysanthemum morphology, photosynthetic efficiency and antioxidant capacity are differentially modified by light quality. *Journal of Plant Physiology*, **2017**, 213: 66–74.
- [24] Kitajima M, Butler W L. Quenching of chlorophyll fluorescence and primary photochemistry in chloroplasts by dibromothymoquinone. *Biochimica et Biophysica Acta (BBA)–Bioenergetics*, **1975**, 376: 105–115.
- [25] van Kooten O, Snel J F H. The use of chlorophyll fluorescence nomenclature in plant stress physiology. *Photosynthesis Research*, **1990**, 25: 147–150.
- [26] Liu Z, Guo C, Yu Q, et al. A SIF-based approach for quantifying canopy photosynthesis by simulating the fraction of open PSII reaction centers (q_L). *Remote Sensing of Environment*, **2024**, 305: 114111.
- [27] Jones R J, Hoegh-Guldberg O, Larkum A W D, et al. Temperature-induced bleaching of corals begins with impairment of the CO₂ fixation mechanism in zooxanthellae. *Plant, Cell & Environment*, **1998**, 21: 1219–1230.
- [28] White A J, Critchley C. Rapid light curves: A new fluorescence method to assess the state of the photosynthetic apparatus. *Photosynthesis Research*, **1999**, 59: 63–72.