Light environment control for reducing energy loss and increasing crop yield in plant factories

Huichuan Zou[a,b], Chunzhe Li[b], Aoyu Zhang[a,b], Xinping Zhang[a,b], Xudong Chen[b],
Fuqiang Wang[a,b*], Yuying Yan[c], Shuai Zhang[c]

[a] *School of Energy Science and Engineering, Harbin Institute of Technology, 92, West Dazhi Street, Harbin 150001, China*

[b] *School of New Energy, Harbin Institute of Technology at Weihai, 2, West Wenhua Road, Weihai 264209, China*

[c] *Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, United Kingdom*

Abstract: Energy utilization for plant lighting is one of the primary constraints of the development of plant factories. Most researchers overlook the impact of energy attenuation during the propagation process on energy efficiency utilization, and the redistribution process of energy lacks corresponding theoretical guidance. Based on the expansion of Bouguer's law, a new strategy of environmental control is proposed to solve this problem by interfering the form of energy propagation and redistributing the energy. Through the method of environment control, we establish two different environments (by changing surface reflectance): high-reflection environment and high-absorption environment (resembling an unbounded space). Near the leaf canopy in the high-reflection environment, the photosynthetic photon flux density (PPFD) and illumination intensity are 116.15 $\mu mol\cdot m^{-2}\cdot s^{-1}$ and 7069 lx, respectively. In contrast, in the high-absorption environment, the values are significantly lower: 30.59 $\mu mol\cdot m^{-2}\cdot s^{-1}$ for the PPFD and 1815 lx for the illumination intensity. The results of further plant growth experiments show that the average weight and leaf number growth of lettuces increased by 4.12 and 3.22 times, respectively, in high-reflection environment. The growing status of plants is also better in the high-reflection environment compared with the high-absorption environment. The strategy of environmental control provides a new direction to reduce energy loss and increase crop yield in plant factories.

Keywords: Plant factory, LED, Photosynthetic photon flux density, Fresh Weight,

Plant growth

1. Introduction

Solar energy, as an abundant and environmentally friendly source of renewable energy, has garnered global attention [1,2]. Nowadays, there is a growing range of applications for solar energy, including solar thermal storage [3,4], solar power generation [5-7], solar heating [8-10], solar thermochemistry [11,12], solar atmospheric science [13], etc. Human’s production [14-19], life [20-22], as well as the growth of plants and animals rely heavily on solar energy. Without sunlight, plants can’t carry out photosynthesis. However, less than fifty percent of solar energy reaches the Earth's surface, resulting in a low utilization rate of sunlight for plant photosynthesis [23,24]. Ineffective energy utilization is also a key obstacle to the development of plant factories [25]. Lighting in artificial light plant factories accounts for around 80% of total energy consumption, encompassing the light source, air conditioning, and nutrient circulation systems [26]. Thus, increasing the energy utilization of artificial light sources can significantly increases crop yield and reduces costs.

Plant factory can enable continuous annual crop production through high-precision environmental control in the facility and fewer constraints imposed by natural conditions. It represents the advanced stage of facility horticulture development [27-30]. Traditional agriculture is highly affected by the natural environment and various types of extreme environments [31,32]. However, Plant factory is completely controlled by humans and not disturbed by the natural environment. Plant factory can not only enable comprehensive coverage of traditional agriculture, but also be applied to all kinds of extreme environments: deserts, extremely cold areas, and outer space (space station, moon base). It breaks traditional farming form, completely by artificial intervention, realizing the efficient use of time and space, and the yield can be tens of times increased [33,34].

Light source is one of the core elements of plant factory [35,36]. Plant factory light sources have evolved from halogen lamps and incandescent lamps to the current LED lights. The research direction has gradually transitioned from focusing solely on light intensity, photoperiod, and light quality for plant growth [37-39], to exploring the synergistic effects of photoperiod, light intensity, and light quality [40,41]. The more challenging spectral conversion and spectral matching for plant growth is now a hot research topic [42,43]. In general, photosynthesis is dominated by chlorophyll and carotenoids [44,45]. Chlorophylls a and b mainly absorb the blue light at 350-480 nm (with main absorption peaks at 430 nm and 460 nm, respectively) and the red light at 580-680 nm (with a main absorption peak at 660 nm), which are the typical blue/red light receptors. Carotenoids, including lutein and carotene, are the primary receptors for blue light, predominantly absorbing light in the range of 400-500 nm [46-48]. In addition to their role in plant photosynthesis in plant photosynthesis, red and blue light can also be used as a light signal to regulate plant growth [49]. Blue light stimulates protein synthesis in plants; and affects the growth of plants and plumule formation. Red light can regulate the photoperiod of plants, accelerate the development of stem, and enhance seed germination [50]. Illuminating with red light at 650 nm and 680 nm, it can significantly promote the growth of plants, resulting in a double light amplification phenomenon. The phenomenon is also known as the Emerson effect [51]. It means that light quality plays a vital role in the growth and development of plants.

The approach of spectral regulation can be divided into two types. The first involves specially designed lamps that emit red, blue, and UV light through nanoparticles [42]. The other utilizes light-converting membranes doped with light-emitting nanoparticles to convert the full-color spectrum of sunlight into the corresponding spectral wavelengths of chlorophyll, carotenoids, and photoreceptors [52]. Currently, photoconverters include rare earth-inorganic complexes, rare earth-organic complexes, and organic fluorescent dyes [53-55]. Yang's group manufactured a spectral-shifting and unidirectional light-extracting film, which is able to convert green light into red light, increasing the yield of lettuce by more than 20% [56]. Hyo and his team produced a spectrum conversion film that converts blue-green light to red light, improving the photosynthesis efficiency of plants [57]. Wan Soo Kim and his group produced a red film that effectively increased lettuce yield [58]. Based on aggregation induced emission effects, Yunpeng Qi and his group explored highly efficient light conversion agents for agricultural film [53]. Furthermore, the films have been studied for the conversion of ultraviolet (UV) light to visible light and the enhancement of red and blue light emission properties by adding carbon dots [59,60].

The efficient utilization of energy is very essential to reduce the cost and promote the development of plant factories. Kota Saito and his team researched the effects of lighting designs in plant factories with artificial light (PFALs) by optical simulations. By appropriately controlling the layout of the lamps and their directionality, they improved the coefficient of utilization for the lighting system [61]. Jaewoo Kim and his group studied light use efficiency in plant factories through the method of combining ray-tracing simulation with plants growth experiments. The research results can provide an effective reference for the design of light environment in plant factories [62]. Li Kun and his team explored an irradiation pattern used LED with zoom lenses (Z-LED) in a plant factory, which saved over half of the light source electricity [63]. Moreover，L. Poulet and his group researched the energy efficiency in different LED lighting systems. Results showed that the LED lighting system with spectral optimization had better biomass conversion efficiency [64]. The efficient utilization of energy and the optimization of the layout of the lighting system also have a positive impact in indoor lighting [65,66].

The literature review demonstrates that there are many researches in spectral conversion and design of lighting system to increase the utilization of energy in plant factory. However, researchers often overlook the impact of the light propagation process. And the distribution process of energy lacks corresponding theoretical guidance. This paper introduces a new concept of environmental control, which is based on and expands upon Bouguer's law. When light travels through the air, it is scattered by gas molecules, resulting in a scattering phenomenon. As the light path increases, both the light intensity and the photosynthetic photon flux density (PPFD) decrease. The scattered light is absorbed by the surroundings, diminishing the plant’s effective utilization of light energy. Therefore, by minimizing absorption and transmittance in the surrounding environment and maximizing surface reflectance, the scattered light energy can be converged back to the plants, thereby enhancing the utilization of light energy by the plant. In this paper, we have successfully regulated the light propagation process through environmental control (by changing surface reflectance). It enhances the effective utilization of light energy by plants and offers a new direction for further reducing energy consumption of lighting in plant light factories.

2. Materials and methods

2.1 Mathematical model

When light travels through a medium, its energy gradually attenuates because of the absorbing and scattering effects of the medium [67-70]. Burger's law describes this phenomenon with mathematical expressions. Bouguer's law states that the radiant intensity of light decays exponentially with the distance of the propagation [71]. Its mathematical expression is shown as:

$$I_L = I_0 \exp(-\varepsilon L) \qquad (1)$$

Where I_0 is the radiation intensity of light source (W·m^{-2}·sr^{-1}), I_L is the radiation intensity after the light has traveled a distance of L meters in the medium (W·m^{-2}·sr^{-1}), ε is the attenuation coefficient of the medium, which can be defined as:

$$\varepsilon = \alpha + \beta \qquad (2)$$

Where α is the absorption coefficient of the medium, β is the scattering coefficient of the medium. In this experiment, the medium is air, and air has an almost negligible absorption rate for visible light (380 - 760 nm), resulting in an absorption coefficient close to 0 [72]. In this case, it is nearly equal to β for α, which means that the attenuation of the light is mainly caused by the scattering of the medium. Since this experiment is carried out in a sealed environment, the air inside can be considered to be homogeneous and stable. Therefore, the scattering coefficient β and attenuation coefficient can be regarded as a constant. Ultimately, the radiation intensity of light only depends on the distances that the light travels in the medium.

In a highly absorptive environment, scattered energy is absorbed by the surroundings with no reflection, resembling an infinite open space. However, in a highly reflective environment, the scattered energy is reflected back by the surroundings, which increases the energy density in the space. For instance, considering a point P beneath a light source, the corresponding radiation intensities of point P in a highly absorptive environment and a highly reflective environment are I_A^P (W·m^{-2}·sr^{-1}) and I_R^P (W·m^{-2}·sr^{-1}), respectively, which are defined as:

$$I_A^P = I_0 \exp(\text{-}\varepsilon L_P) \tag{3}$$

$$I_R^P = I_0 \exp(\text{-}\varepsilon L_{\mathrm{P}}) + I_r^P \tag{4}$$

Where I_r^P (W·m^{-2}·sr^{-1}) represents the radiant energy reflected back from the surroundings, which is defined as:

$$I_r^P = \sum_k \rho^k \sum_{N_k} I_0 \exp(-\varepsilon L_P^{N_k}) \tag{5}$$

Where ρ is the reflectivity of the surroundings, k is the number of reflections, N_k denotes the total amount of energy that can reach point P after k reflections, and $L_P^{N_k}$ (m) represents the distance traveled by the light from the light source to point P after k reflections. On the basis of Burger's law, equation (5) further describes the redistribution of energy by the surrounding environment after energy propagation in a medium. Its specific meaning is that the surrounding environment reflects the energy back to a point in space, and its magnitude reflects the degree of environment on the redistribution of energy.

Radiation intensity of light decrease with the increase of propagation distance and number of reflections. Therefore, when the radiation intensity significantly reduces to 1%, it can be ignored. It is described as:

$$\rho^k \sum_{N_k} \exp(-\frac{L_P^{N_k}}{L_P}) \leq 0.01 \tag{6}$$

Based on the analysis of the above mathematical expressions, it is found that the light propagation process can be intervened by means of regulating the environment (change of ρ) for the purpose of energy redistribution. Therefore, by increasing the surface reflectance of the environment, the authors reduce the absorbance of the surroundings. While the input energy remains constant, it would enhance the energy density in the space and increase the energy utilization of plants. The strategy of environment control is developed by this thought, and some experiments are conducted to prove it.

2.2 Research idea

Plant light factories represent an advanced stage in the development of facility horticulture and are an inevitable trend for future agriculture [27-29]. In this paper, we propose a method of environmental control to improve energy utilization and lower lighting cost in plant factories. Bouguer's law states that light energy weakens as it travels through a medium [71]. It is caused by the absorption and scattering of light by the medium. When visible light travels through air, air absorbs almost no visible light. Instead, the attenuated energy is mainly scattered into and absorbed by the surroundings. Based on this principle, we have extended Burger's law (equation (5)) by introducing the strategy of environmental control. Scattered energy is redistributed to the plant by arranging the surrounding environment of plants as a highly reflective environment.

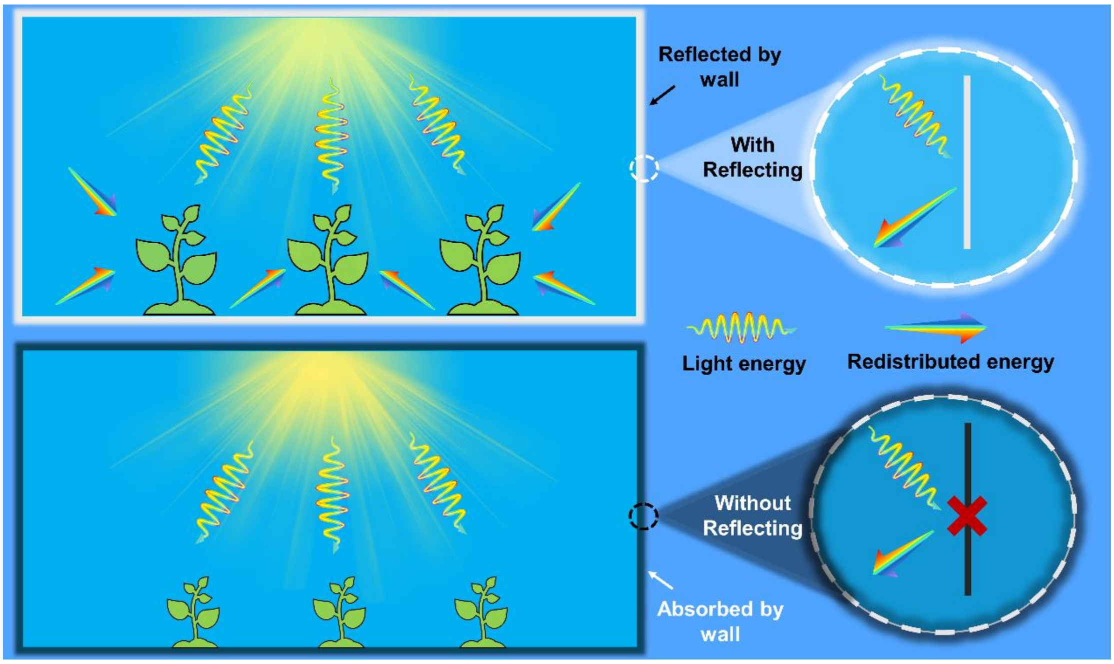

Fig. 1. Schematic diagram of the distribution of energy in high-reflection and high-absorption environments.

As shown in Fig. 1, two different environments are constructed in two square spaces by arranging high-reflection and high-absorption materials on the walls, respectively. These two environments are called the highly reflective and highly absorptive environments, respectively. In the highly reflective environment, the scattered light is redistributed to plants by the reflection of the wall, greatly improving the effective utilization of energy. However, in the highly absorptive environment, scattered light energy is absorbed by the wall, rendering it akin to a boundaryless space. In this space, plant energy absorption relies solely on direct irradiation by light source. Thus, the scattered energy is not efficiently absorbed by the plants, which leads to inefficient energy utilization. Most scattered energy is always not effectively utilized in the plant factory [40,61]. Therefore, the proposed concept of light environment control in this paper aims to reutilize the scattered energy. It will significantly enhance energy utilization and effectively promote plant growth.

2.3 Plant growth experiment

In this experiment, some equipment was used to conduct the experiment and measure relevant data. The detailed information of the equipment used in the experiment was shown in Table 1. Table 2 presented the concrete photometric properties of lamps in different height.

Table 1. The detailed information of the equipment used in the experiment

Equipment	Function	Production address
the plant light analyzer (PLA-30)	used to measure the PPFD and light intensity in different environments	Hangzhou Yuanfang Optoelectronic Information Co. Ltd., China
UV-VIS-NIR spectrophotometer (SolidSpec-3700)	used to measure the reflectivity of materials	Shimadzu, Japan
Plant growth lamps (WEN-8)	used for plant illuminating	WEGA Guixiang, China
precision electronic scale (AX124ZH)	used for weighing	Aarhus Instruments Co., Ltd, China

Table 2. Detailed photometric properties of lamps in different height

Height (cm)	illumination intensity (lx)	PPFD ($\mu mol \cdot m^{-2} \cdot s^{-1}$)
10	13745	229
15	9708	162
20	6775	112
25	5283	88
30	4222	71

Acrylic plates, mirror stickers, and black light-absorbing cloth were materials used to establish different light environments. Both sides of the acrylic plates were covered with mirror stickers. The acrylic plates covered with mirror stickers were assembled together to form a closed rectangular space, which was a highly reflective environment. And the highly absorptive environment was established in the same way, except that the mirror sticker was replaced with a black cloth. 'Italy' lettuces served as the experimental objects and were planted in cylindrical resin pots. The soil was made of universal nutrient soil and fertilized with a universal nutrient solution. Fig. 2 shows the essential properties of the materials and equipment employed in the experiment. Figure 2a depicts the reflectance of two different materials (mirror sticker and black fabric) in the visible range and the absolute spectral values of the plant grow lamp. As can be seen in Figure 2b, the light emitting color of the plant grow lamp tends to be white, which would be much friendly to the humans' eyes. Figure 2c shows the experimental installation for the high-reflection and high-absorption environments. Fig. 2d shows the growth status of lettuce in different environments (from left to right: high-reflection and high-absorption environments, respectively). The growth of lettuce in the high-reflection environment is significantly better than the high-absorption environment.

Two rectangular spaces (40 cm × 80 cm × 80 cm), assembled from acrylic plates, were established for regulating different growth environments of plants and conducting control experiments (Fig. 2c). The key characteristic of artificial light plant factories is that they are not affected by the natural environment and the growth and development of plants are completely controlled by humans. Therefore, the impact of external light should be eliminated. Mirror stickers and black light-absorbing cloth are used for the arrangement of two spaces, which can isolate the impact of the external lighting environment on plant growth and ensure the difference between the two environments. Under same lighting conditions, the two rectangular spaces are applied to prove the influence of surroundings on plant growth by regulating the light-absorption environment.

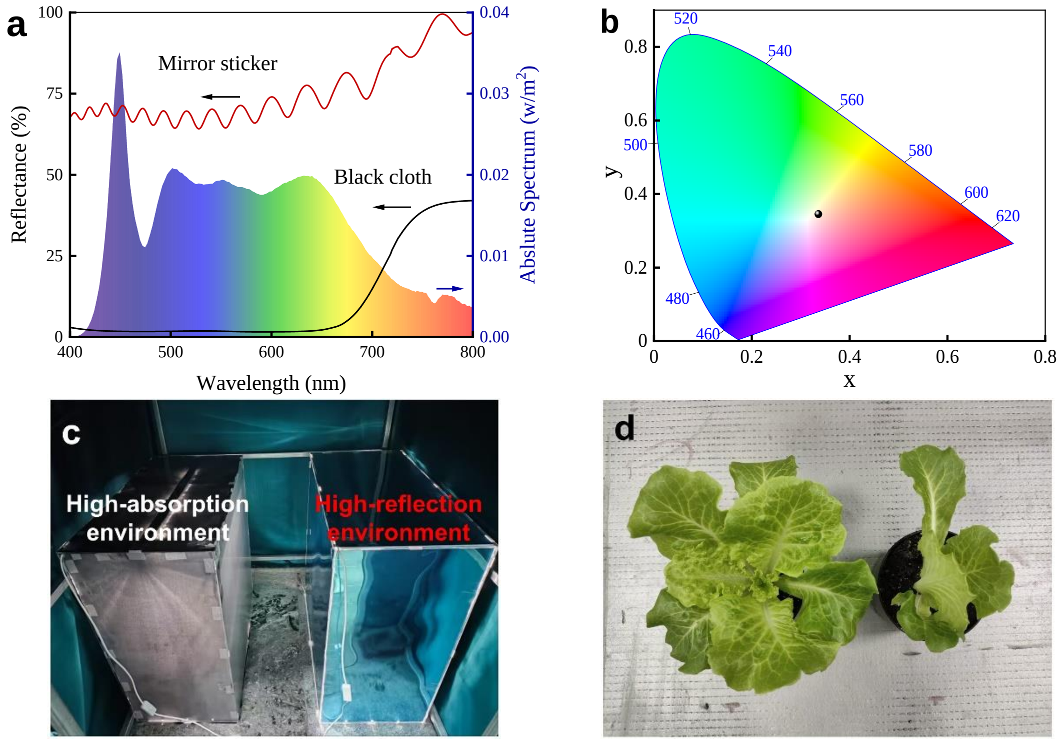

Fig. 2. Plant growth experiments. (a) Reflectance of mirror stickers and black cloths for highly reflective and absorptive environments and absolute spectra of plant growth lamps. (b) Chromaticity diagram of plant grow lamps. (c) Different environments for plant growth experiments. (d) Lettuce growth status in different environments after plant growth experiments (high reflective environment on the left and high absorptive environment on the right).

Different plants have different growth rate and sensitivity on light. Therefore, authors need to choose a valuable, fast-going, and light sensitive plant. As lettuce is a vegetable with high economy and nutrition, it is selected as a model crop. It is one of the most valuable crops grown in the United States. From an experimental perspective, lettuce is also chosen because it is sensitive to the photon spectrum and has a short growth cycle [56]. Lettuces were cultivated in a cylindrical resin pot with a capacity of approximately 0.57 L. The light/ dark photoperiod was 10:12 h. During the growth period, the plants were irrigated as needed (every 2 days) with 50 ml water. Additionally, a water-soluble fertilizer was supplied with the following nutrients (in $mg \cdot L^{-1}$): $N \geq 40$, $K_2O \geq 30$, P_2O_5, ≥ 80, $Zn \geq 0.5$, $B \geq 0.5$, $Fe \geq 0.25$, $Mn \geq 2.5$. The daily illumination time for lettuce plants was 10 hours. In addition to the illumination, the growth status of the plants was recorded and photographed (four times a day at 8:00 am, 12:00 pm, 4:00 pm and 8:00 pm). Every other day, a set of photos was selected to display the growth status of plants in different light environments. Furthermore, lettuce height and number of leaves were measured and recorded every other day. Fresh weight of lettuces was only measured on the first and the last day.

3. Results and discussion

3.1 Experiments on energy utilization under different light environments

Firstly, a blank control experiment was carried out to observe the changes of PPFD in the high reflective and absorptive environments without placing plants. From Fig. 3a, it can be seen that the PPFD in the vertical direction decreases with the decrease in height, and the decreasing trend gradually slows down with the decrease in height. At higher heights, the difference in PPFD between the highly reflective and absorptive environments is minimal. The difference in PPFD between the two increases significantly as the height decreases. The highly reflective environment is significantly larger than the highly absorptive environment. At a height of 60 cm, the PPFD of the highly reflective environment (198.02 $\mu mol \cdot m^{-2} \cdot s^{-1}$) is 1.17 times higher than that in the highly absorptive environment (169.54 $\mu mol \cdot m^{-2} \cdot s^{-1}$), while at a height of 10 cm, it reaches 4.53 times (103.56 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 22.78 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively).

Light scattering is ultimately responsible for this phenomenon. A decrease in height means an increase in distance from the light source, and the light is scattered more strongly by the air. In a highly absorbing environment, scattered light is absorbed by the surroundings, leading to a decrease in PPFD. However, in a highly reflective environment, light is scattered but not absorbed by the surroundings, instead, it is reflected back. Therefore, PPFD will be much higher in a highly reflective environment than an absorbing one. On this basis, the light intensity also shows a law consistent with the PPFD in Fig. 3b. As the lettuce canopy's height of approximately 20 cm, PPFD and light intensity were measured on a horizontal plane at the same height. As shown in Fig. 3c, the PPFD was symmetrically distributed at both sides of the center, and the trend of the whole curve was approximately in the form of an arch-bridge. The PPFD at the center is higher, and with the distance from the center getting farther and farther, the PPFD also gradually decreases (the plus and minus signs in Fig. 3 indicate the direction, the minus sign indicates the left side, and the plus sign indicates the right side). The trend of light intensity is consistent with the PPFD in Fig. 3d.

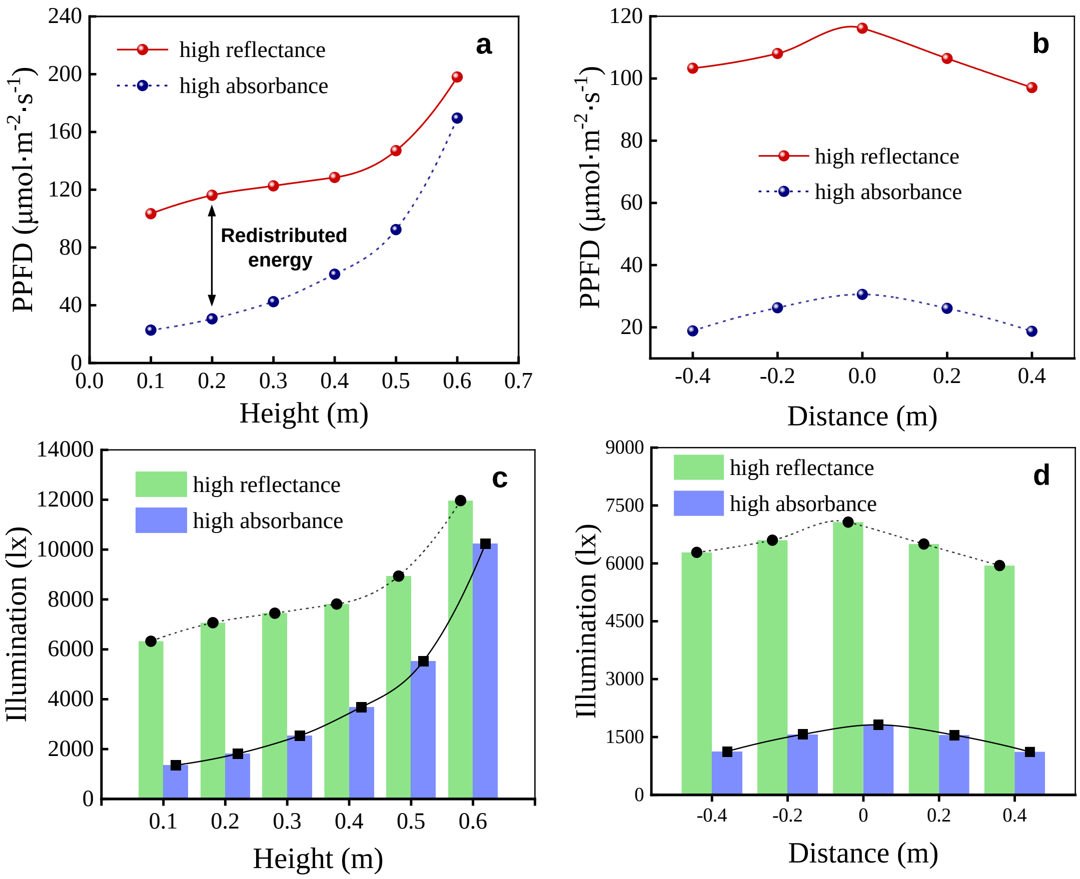

Fig.3. Differences in PPFD and illumination intensity under the high-absorption environment and high-reflection environment. (a) PPFD in vertical direction. (b) PPFD in horizontal direction (Height is 20 cm, near the leaf canopy). (c) illumination intensity in vertical direction. (d) illumination intensity in horizontal direction.

The comparison of PPFD and illumination intensity in high-reflection and high-absorption environments reflected the effectiveness of environmental control. The energy utilization experiments demonstrated the significant impact of the environment on energy utilization. In the highly reflective environment near the lettuce canopy, the PPFD and illumination intensity were 116.15 $\mu mol\cdot m^{-2}\cdot s^{-1}$ and 7069 lx, respectively. In contrast, in the highly absorptive environment, these values were 30.59 $\mu mol\cdot m^{-2}\cdot s^{-1}$ and 1815 lx, respectively. The PPFD in the high-reflection environment was 3.78 times higher than in the high-absorption environment, and illumination intensity was 3.9 times higher. The additional values represent the energy redistributed by the environment. This provides compelling evidence of the pivotal role of environmental regulation in enhancing energy utilization.

3.2 Experiments on lettuce growth under different light environments

As shown in Fig. 4, at the initial moment, there was no significant difference in the size of lettuces between the highly reflective environment and the highly absorptive environment (the front rows of lettuces in the figure are numbered 1-3 from left to right, and the back rows of lettuces are numbered 4-6 from left to right). However, as the duration of light exposure increased, the growth rate of plants in the high-reflection environment was significantly greater than that in the high-absorption environment. With the passage of growing days, the number of leaves and the leaf area increased significantly, the entire plant grew well, and the plants appeared to be more luxuriant from the appearance in the high-reflection environment (Videos 1 and 2 show the growth of lettuce in the high-reflection environment and high-absorption environment, respectively). However, changes in lettuce plants were less pronounced in the high-absorption environment, with slight overall plant growth, but much less than in the highly reflective environment. When comparing lettuce plants in highly reflective and highly absorptive environments, it was found that the leaves of lettuces in highly reflective environments were spread out and open, while the leaves of lettuces in highly absorptive environments were compact and closed.

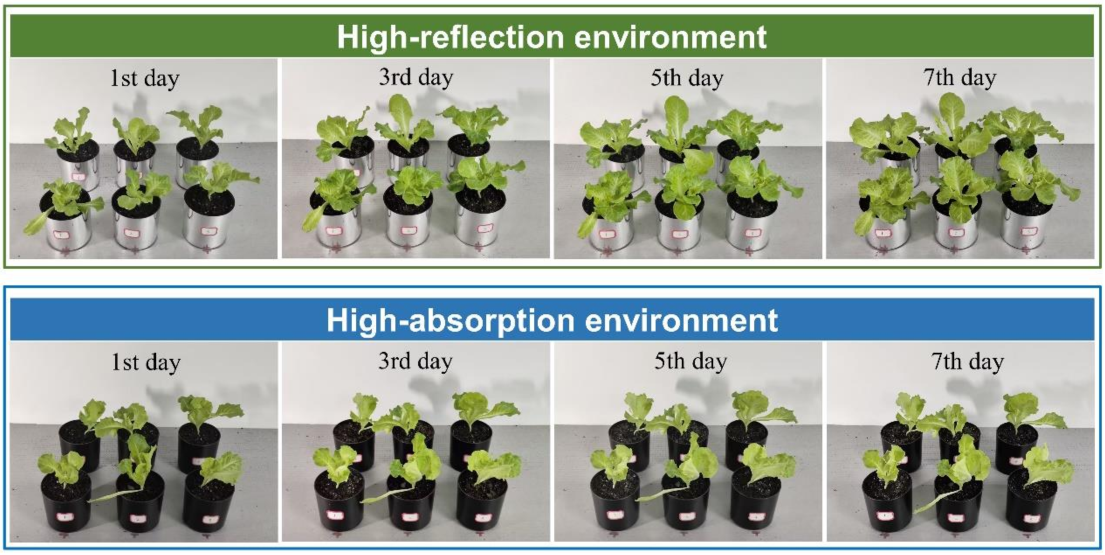

Fig. 4. Morphology of lettuce grown in the high-reflection environment (experiment) and the high-absorption environment (control).

The primary factor affecting the disparity between the two lies in their respective environments. Under the same illumination condition, when light reaches the plant leaves, it needs to pass through an air layer, in which a large amount of light is scattered by the air layer, making the energy reaching the plant leaves much weaker. As shown in Fig. 3a, in a highly absorbing environment, the PPTD at a height of 60 cm is 169.54 $\mu\text{mol}\cdot\text{m}^{2}\cdot\text{s}^{-1}$, while the PPFD at a height of 20 cm is only 30.59 $\mu\text{mol}\cdot\text{m}^{2}\cdot\text{s}^{-1}$, a difference of 5.54 times between them. This proves that the air scatters the majority of light into the surroundings. In highly absorbing environments, nearly all of the scattered light is absorbed, so that the utilization of light energy by the lettuce plant is greatly reduced. Consequently, the lettuces grow in a worse state due to the lack of light. In contrast, lettuces grow better in a highly reflective environment.

Although the PPFD at 60 cm height (198.02 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) is 1.7 times than the height of 20 cm (116.15 $\mu\text{mol}\cdot\text{m}^{2}\cdot\text{s}^{-1}$) according to Fig. 3a. At 20 cm height, the PPFD in a highly reflective environment is 3.8 times higher than that in a highly absorptive environment. In the highly reflective environment, there is a significant difference in PPFD at different heights, which is caused by two factors. One is that the entire space cannot be completely enclosed, allowing some scattered light transmit through the gaps. Another reason is that the reflective wall cannot achieve 100% light reflection. But, the high-reflection environment is still able to utilize energy efficiently. Highly reflective environments reflect scattered light back to the plants, greatly improving the effective utilization of light energy by lettuce plants, thereby effectively saving energy.

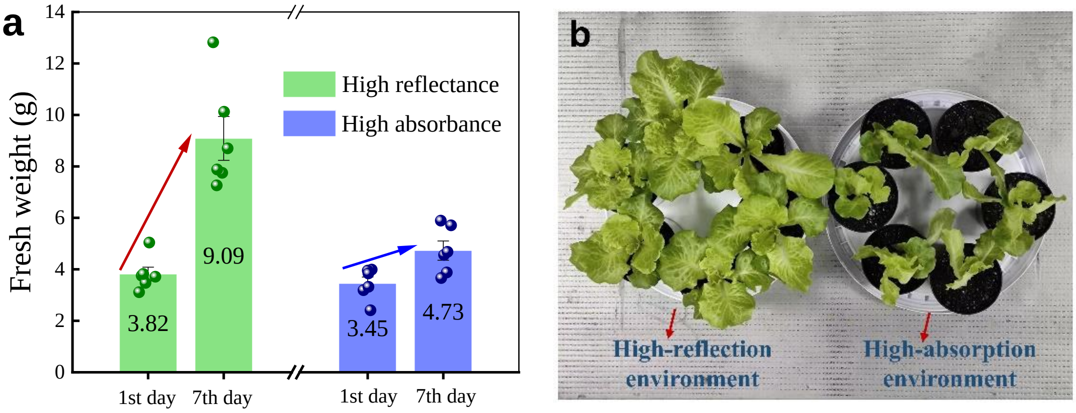

Fig. 5. Growth of weight of lettuces under different light environments. (a) Comparison of lettuces fresh weight growth in highly reflective and absorptive environments. (b) Comparison of lettuces growth conditions in different environments.

Based on the blank experiment, lettuce plants were placed for testing. Twelve plants were tested, divided into two groups of six each. These plants were labeled A1 to A6 and R1 to R6 (A1 and R1 represent plant No.1 in the high absorbing environment and high reflecting environment, respectively). Before the experiment, the plants in both groups were weighed. As shown in Fig. 5, the average weights of the plants in the high-absorption and high-reflection environments were 3.45g and 3.82g, respectively, with a relatively uniform mass distribution.

After one week, the plants were taken out and weighed. The results showed that in the high-absorption environment, the average growth weight of the plants was 1.28 g, with a growth rate of 37.10%. However, in the high-reflection environment, the average growth weight of the plants was 5.27 g, with a growth rate of 137.96%, significantly surpassing the growth rate in the high-absorption environment. In the high-reflection environment, the average growth weight of the plants reached 4.12 times than that in the high-absorption environment. This result suggested that higher energy attenuation in the high-absorption environment resulted in a decrease in biomass conversion efficiency. However, the lower energy attenuation in the high-reflection environment resulted in a significant increase in the biomass conversion efficiency of plants. Hence, the energy can be maximized to be used by lettuce plants for photosynthesis in the high-reflection environment. This maximized energy usage enhances their growth rate and overall energy efficiency.

The number of leaves of lettuces was counted before the start of the experiment. The results showed that in the high-reflection environment, only plant R5 had 7 leaves, and the rest of plants had 6 leaves; in the high-absorption environment, A1 had 5 leaves, A2 had 8 leaves, and the rest of plants had 6 leaves. Afterwards, the number of leaves in the plant were recorded every other day and plotted into a chart corresponding to the change in leaf number, as shown in Fig. 6 and Fig. 7. From the whole trend of changes of leaf number, the increase of leaf quantity in the high-reflection environment is markedly higher than that in the high-absorption environment. In the highly reflective environment, R2, R3 and R5 each grew two new leaves, R1 and R4 grew three new leaves, and the number of new leaves in R6 reached four, bringing the total number of new leaves to 16, with an average of 2.67 new leaves. Conversely, in the highly absorptive environment, only plant A4 grew 2 leaves, A1, A2 and A6 only grew 1 leaf, A3 and A5 did not produce any new leaves. The total number of new leaves was only 5, with an average of merely 0.83 leaves per plant, significantly lower than in the high-reflection environment. This shows that in highly reflective environments, the lettuce absorbs more light energy which promotes growth. As shown in Fig. 2d, in the high-absorption environment, the outer leaves of the plant are closed, preventing the inner new leaves from receiving light, which reduces the growth of the plant and stops the production of new leaves. The heights of all plants were measured before the experiment. Initially, the average height of the plants in the high reflection environment was about 9.16 cm, while the average height of the plants in the high absorption environment was about 9.43 cm. The distribution between the two groups was relatively balanced, with plants in the high-absorption environment being slightly taller than those in the high-reflection environment. Subsequently, plant height was measured every other day and plotted as a corresponding growth curve, as shown in Fig. 8.

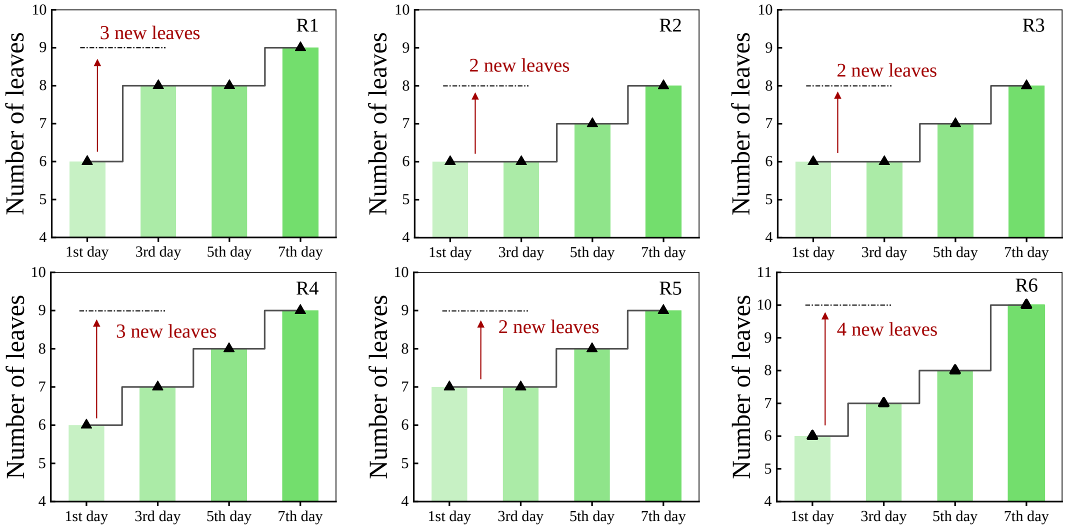

Fig. 6. The growth trend of leaf number in R1~R6 lettuces under high-reflection Environment.

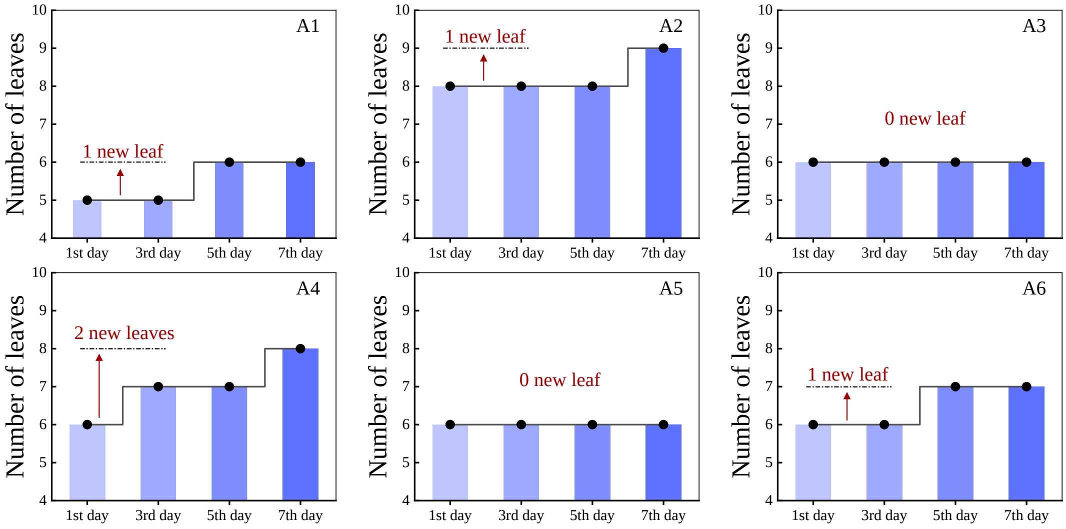

Fig. 7. The growth trend of leaf number in A1~A6 lettuces under high-absorption Environment.

By analyzing the growth change curves of plants in different light environments, it was found that out of 18 groups studied for plant height increase, 8 groups showed that the growth height of plants in the high-absorption environment was higher than that in the high-reflection environment. Conversely, the remaining 10 groups showed that the high-reflection environment was greater than that in the high-absorption environment. Considering the results, it was found that the increase in the height of plants under the high-reflection environment was not significantly distinguished from that under the high-absorption environment. However, in terms of the increase in growth height, the high-reflection environment exhibited a slight superiority over the high-absorption environment. The average height of the plants in the highly reflective environment was 11.07 cm and it was 10.61 cm in the highly absorptive environment. The mean growth heights of the plants were 1.91 cm and 1.18 cm, respectively.

The increase in plant height was less pronounced compared to the increase in plant weight and number of leaves. It may be owing to the fact that in high absorption environments, the light energy absorbed by the lettuce plant decreases due to the absorption of the surroundings. Therefore, to obtain more illumination, the leaves can only grow upwards. Eventually, it showed a small difference in plant height growth between the high absorption and high reflection environments. However, it still showed a more rapid increase of height in the high-reflection environment.

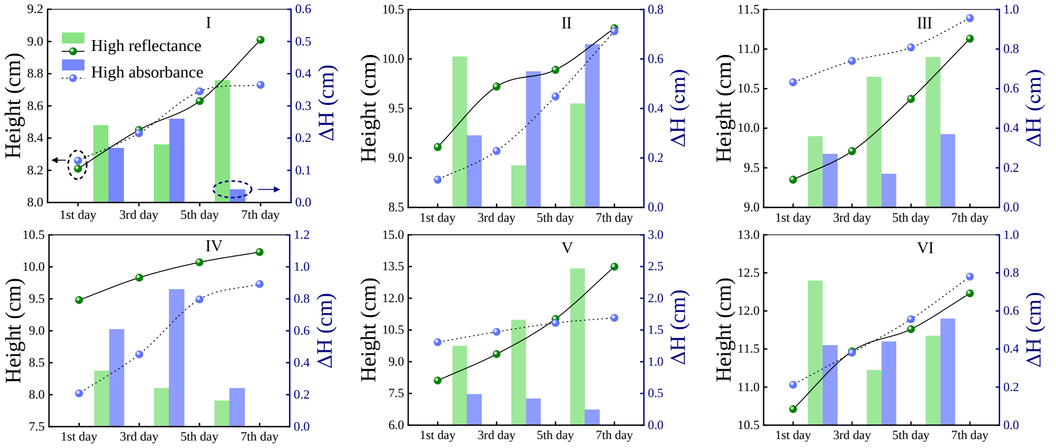

Fig. 8. Height growth of lettuces under different environments (I - VI correspond to plants 1 - 6 in different environments).

4. Conclusion

Lighting in plant factories accounts for the majority of total energy consumption. But energy utilization for plant lighting is poor, which obstacles the development of plant factories. To resolve the issue of energy utilization, this paper proposed a new strategy of regulating light environment. This new strategy (environment control) was based on Bouguer's law and further developed. Two different environments were established to demonstrate the effectiveness of environment control. PPFD and illumination intensity were measured to characterize the energy utilization in different environments. On this basis, further plant growth experiments were conducted. Further plant growth experiments have demonstrated that lettuces exhibit superior weight, height, leaf count, and growth status in high-reflection environment. It implied that interfering energy propagation process through environmental control could result in energy redistribution, thereby significantly increasing the effective utilization of light energy by plants.

(1) In the highly reflective environment, the PPFD and illumination intensity near the lettuce canopy were 116.15 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 7069 lx, respectively. In contrast, in the highly absorptive environment, these values were 30.59 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 1815 lx, respectively.

(2) Further plant growth experiments showed that the initial average weight of lettuces in the high-reflection environment increased from 3.08 g to 9.09 g, with an increase of 6.01 g. However, the average weight of lettuces in the high-absorption environment increased from 3.45 g to 4.73 g, with an increase of only 1.28 g.

(3) In the high-absorption environment, there was a minimal increase of only 0.83 leaves in the average leaf count, whereas in the high-reflection environment, the average number of leaves reached 2.67. In the highly reflective and absorptive environments, the average plant height growth was 1.91 cm and 1.18 cm, respectively.

(4) The growing status of plants was better in the high-reflection environment. the leaves of lettuces in the high-reflection environment were spread out and open, while the leaves of lettuces in highly absorptive environments were compact and closed.

Author contributions:

Huichuan Zou: Methodology, experiment, writing-original draft. Chunzhe Li: Data curation. Aoyu Zhang: Methodology. Xinping Zhang: Material preparation. Xudong Chen: experiment. Fuqiang Wang: Supervision, Writing – review & editing, Funding acquisition. Yuying Yan: review & editing. Shuai Zhang: review & editing.

Acknowledgments:

This work was supported by the National Natural Science Foundation of China (Grant No. 52076064). A very special acknowledgment is made to the editors and peer reviewers who provided important comments that improved this paper.

5.Reference

[1] X. Sun, D. Yang, C.A. Gueymard, J.M. Bright, P. Wang, Effects of spatial scale of atmospheric reanalysis data on clear-sky surface radiation modeling in tropical climates: A case study for Singapore, Solar Energy. 241 (2022) 525-537.

[2] W. Wang, D. Yang, T. Hong, J. Kleissl, An archived dataset from the ECMWF Ensemble Prediction System for probabilistic solar power forecasting, Solar Energy. 248 (2022) 64-75.

[3] A. Sharma, R. Pitchumani, R. Chauhan, Melting and solidification performance investigation of latent heat storage unit designs for low-temperature solar thermal applications, Journal of Energy Storage. 66 (2023) 107323.

[4] A. Sharma, R. Pitchumani, R. Chauhan, Solar air heating systems with latent heat storage - A review of state-of-the-art, Journal of Energy Storage. 48 (2022) 104013.

[5] E. Dai, M. Lin, J. Xia, Y. Dai, Experimental investigation on a GAX based absorption heat pump driven by hybrid liquefied petroleum gas and solar energy, Solar Energy. 169 (2018) 167-178.

[6] A. Bosio, S. Pasini, N. Romeo, The history of photovoltaics with emphasis on cdTe solar cells and modules, Coatings. 10 (4) (2020) 344.

[7] P.D. Myers, D.Y. Goswami, Thermal energy storage using chloride salts and their eutectics, Applied Thermal Engineering. 109 (2016) 889-900.

[8] A. Shahsavar, P. Jha, M. Arici, G. Kefayati, A comparative experimental

investigation of energetic and exergetic performances of water/magnetite nanofluid-based photovoltaic/thermal system equipped with finned and unfinned collectors, Energy. 220 (2021) 119714.

[9] E. Bellos, C. Tzivanidis, A detailed investigation of an evacuated flat plate solar collector, Applied Thermal Engineering. 234 (2023) 121334.

[10] F. Wang, L. Ma, Z. Cheng, J. Tan, X. Huang, L. Liu, Radiative heat transfer in solar thermochemical particle reactor: A comprehensive review, Renewable and Sustainable Energy Reviews. 73 (2017) 935-949.

[11] X. Shi, J. Song, Z. Cheng, H. Liang, Y. Dong, F. Wang, W. Zhang, Radiative intensity regulation to match energy conversion on demand in solar methane dry reforming to improve solar to fuel conversion efficiency, Renewable Energy. 207 (2023) 436-446.

[12] J. Song, Z. Cheng, Y. Fan, F. Wang, X. Shi, J. Xu, H. Yi, Human ear inspired solar thermochemical reactor for steam methane reforming with the consideration of minimum Gibbs free energy principle, Journal of Energy Storage. 72 (2023) 108172.

[13] D. Yang, Correlogram, predictability error growth, and bounds of mean square error of solar irradiance forecasts, Renewable and Sustainable Energy Reviews. 167 (2022) 112736.

[14] Z. Cheng, H. Han, F. Wang, Y. Yan, X. Shi, H. Liang, X. Zhang, Y. Shuai, Efficient radiative cooling coating with biomimetic human skin wrinkle structure, Nano Energy. 89 (2021) 106377.

[15] Y. Dong, X. Zhang, L. Chen, W. Meng, C. Wang, Z. Cheng, H. Liang, F. Wang, Progress in passive daytime radiative cooling: A review from optical mechanism, performance test, and application, Renewable and Sustainable Energy Reviews. 188 (2023) 113801.

[16] H. Liang, F. Wang, D. Zhang, Z. Cheng, C. Zhang, B. Lin, H. Xu, Experimental investigation of cost-effective ZnO nanofluid based spectral splitting CPV/T system, Energy. 194 (2020) 116913.

[17] K. Jiang, X. Du, Q. Zhang, Y. Kong, C. Xu, X. Ju, Review on gas-solid fluidized

bed particle solar receivers applied in concentrated solar applications: Materials, configurations and methodologies, Renewable and Sustainable Energy Reviews. 150 (2021) 111479.

[18] Q. Mao, Y. Zhang, Effect of unsteady heat source condition on thermal performance for cascaded latent heat storage packed bed, Energy. 284 (2023) 129362.

[19] H. Zheng, X. Liu, Y. Xuan, Y. Ding, G. Flamant, Efficient direct solar-driven thermochemical energy storage of (AlMgFeMn)$O_x$$CaCO_3$ pellets in a fluidized bed reactor, Energy Conversion and Management. 285 (2023) 116990.

[20] Y. Dong, W. Meng, F. Wang, H. Han, H. Liang, X. Li, Y. Zou, C. Yang, Z. Xu, Y. Yan, Z. Cheng, "Warm in winter and cool in summer": scalable biochameleon inspired temperature-adaptive coating with easy preparation and construction, Nano Letters. 23(19) (2023) 9034-9041.

[21] J. Yang, T. Xie, Q. Zhu, J. Wang, L. Xu, C. Liu, Boosting the photocatalytic activity of BiOX under solar light via selective crystal facet growth, Journal of Materials Chemistry C. 8(7) (2020) 2579-2588.

[22] X. Zhang, Z. Cheng, D. Yang, Y. Dong, X. Shi, H. Liang, F. Wang, H. Han, W. Meng, Y. Shuai, Y. Yan, Scalable bio-skin-inspired radiative cooling metafabric for breaking trade-off between optical properties and application requirements, ACS Photonics. 10(5) (2023) 1624-1632.

[23] Y. Ji, Y. Yuan, G. Wu, C. Feng, R. Cheng, Q. Ma, X. Chen, Y. Tong, A novel spectral-splitting solar indoor lighting system with reflective direct-absorption cavity: Optical and thermal performance investigating, Energy Conversion and Management. 266 (2022) 115788.

[24] A. Kleidon, What limits photosynthesis? Identifying the thermodynamic constraints of the terrestrial biosphere within the Earth system, Biochimica et Biophysica Acta (BBA) - Bioenergetics. 1862(1) (2021) 148303.

[25] R. Yorifuji, S.Y. Obara, Economic design of artificial light plant factories based on the energy conversion efficiency of biomass, Applied Energy. 305 (2022) 117850.

[26] T. Kozai, G. Niu, M. Takagaki, Plant factory: An indoor vertical farming system

for quality food production, Plant Factory, San Diego: Academic Press. 2016.

[27] O. Hadj Abdelkader, H. Bouzebiba, D. Pena, A.P. Aguiar, Energy-efficient IoT-based light control system in smart indoor agriculture, Sensors. 23(18) (2023) 7670.

[28] X. Liu, Y. Xu, Y. Wang, Q. Yang, Q. Li, Rerouting artificial light for efficient Crops production: a review of lighting strategy in PFALs, Agronomy. 12(5) (2022) 1021.

[29] I. Tsitsimpelis, I. Wolfenden, C.J. Taylor, Development of a grow-cell test facility for research into sustainable controlled-environment agriculture, Biosystems Engineering. 150 (2016) 40-53.

[30] W. Xu, N. Lu, M. Kikuchi, M. Takagaki, Continuous lighting and high daily light integral enhance yield and quality of mass-produced nasturtium (Tropaeolum majus L.) in plant factories, Plants. 10(6) (2021) 1203.

[31] P. Ahmad, M. Prasad, Environmental adaptations and stress tolerance of plants in the era of climate change, New Approaches to Study Metal-Induced Stress in Plants. (Chapter 19) (2012) 413-427.

[32] B. Liu, X. Wang, K. Li, Z. Cai, Spatially resolved metabolomics and lipidomics reveal salinity and drought-tolerant mechanisms of cottonseeds, Journal of Agricultural and Food Chemistry. 69(28) (2021) 8028-8037.

[33] M. Li, X. Zhang, H. Zhang, W. Chen, L. Ma, X. Wang, Y. Liu, B. Lei, Highly efficient and dual broad emitting light convertor: an option for next-generation plant growth LEDs, Journal of Materials Chemistry C. 7(12) (2019) 3617-3622.

[34] M. Arcel, A.F. Yousef, Z.H.. Shen, W.J. Nyimbo, S.H. Zheng, Optimizing lettuce yields and quality by incorporating movable downward lighting with a supplemental adjustable sideward lighting system in a plant factory, PeerJ. 11 (2023) e15401.

[35] R. He, Y. Zhang, S. Song, W. Su, Y. Hao, H. Liu, UV-A and FR irradiation improves growth and nutritional properties of lettuce grown in an artificial light plant factory, Food Chemistry. 345 (2021) 128727.

[36] M. Montes Rivera, N. Escalante-Garcia, J.A. Dena-Aguilar, E. Olvera-Gonzalez, P. Vacas-Jacques, Feature selection to predict LED light energy consumption with

specific light recipes in closed plant production systems, Applied Sciences. 12(12) (2022) 5901.

[37] C. Miao, S. Yang, J. Xu, H. Wang, Y. Zhang, J. Cui, H. Zhang, H. Jin, P. Lu, L. He, J. Yu, Q. Zhou, X. Ding, Effects of light intensity on growth and quality of lettuce and spinach cultivars in a plant factory, Plants. 12(18) (2023) 3337.

[38] M.A. Razzak, M. Asaduzzaman, H. Tanaka, T. Asao, Effects of supplementing green light to red and blue light on the growth and yield of lettuce in plant factories, Scientia Horticulturae. 305 (2022) 111429.

[39] J. Zheng, F. Ji, D. He, G. Niu, Effect of light intensity on rooting and growth of hydroponic strawberry runner plants in a LED plant factory, Agronomy. 9(12) (2019) 875.

[40] H. Shimizu, Y. Saito, H. Nakashima, J. Miyasaka, K. Ohdoi, Light environment optimization for lettuce growth in plant factory, IFAC Proceedings Volumes. 44(1) (2011) 605-609.

[41] T. Zou, C. Huang, P. Wu, L. Ge, Y. Xu, Optimization of artificial light for spinach growth in plant factory based on orthogonal test, Plants. 9(4) (2020) 490.

[42] H.Z. Rihan, M. Aldarkazali, S.J. Mohamed, N.B. Mcmulkin, M.H. Jbara, M.P. Fuller, A novel new light recipe significantly increases the growth and yield of sweet basil (ocimum basilicum) grown in a plant factory system, Agronomy. 10(7) (2020) 934.

[43] A. Thongtip, K. Mosaleeyanon, S. Korinsak, T. Toojinda, C.T. Darwell, P. Chutimanukul, P. Chutimanukul, Promotion of seed germination and early plant growth by KNO_3 and light spectra in Ocimum tenuiflorum using a plant factory, Scientific Reports. 12(1) (2022) 6995.

[44] F. Kuo, Y. Chien, C. Chen, Effects of light sources on growth and carotenoid content of photosynthetic bacteria Rhodopseudomonas palustris, Bioresource Technology. 113 (2012) 315-318.

[45] Z. Zhou, N. Zhang, J. Chen, X. Zhou, M.S. Molokeev, C. Guo, The Vis-NIR multicolor emitting phosphor $Ba_4Gd_3Na_3(PO4)_6F_2$: Eu^{2+}, Pr^{3+} for LED towards plant growth, Journal of Industrial and Engineering Chemistry. 65 (2018) 411-417.

[46] B. Li, G. Annadurai, J. Liang, L. Sun, S. Wang, Q. Sun, X. Huang, Lu^{3+} doping induced photoluminescence enhancement in novel high-efficiency $Ba_3Eu(BO_3)_3$ red phosphors for near-UV-excited warm-white LEDs, RSC Advances. 8(59) (2018) 33710-33716.

[47] K. Li, H. Lian, R. V. Deun, M.G. Brik, A far-red-emitting $NaMgLaTeO_6:Mn^{4+}$ phosphor with perovskite structure for indoor plant growth, Dyes and Pigments. 162 (2019) 214-221.

[48] M. Xia, X. Wu, Y. Zhong, Z. Zhou, W. Wong, A novel $Na_3La(PO_4)_2/LaPO_4:Eu$ blue-red dual-emitting phosphor with high thermal stability for plant growth lighting, Journal of Materials Chemistry C. 7(8) (2019) 2385-2393.

[49] A. Agarwal, S.D. Gupta, Impact of light-emitting diodes (LEDs) and its potential on plant growth and development in controlled-environment plant production system, Current Biotechnology. 5(1) (2016) 28-43.

[50] G.D. Goins, N.C. Yorio, M.M. Sanwo, C.S. Brown, Photomorphogenesis, photosynthesis, and seed yield of wheat plants grown under red light-emitting diodes (LEDs) with and without supplemental blue lighting, Journal of Experimental Botany. 48(7) (1997) 1407-1413.

[51] H. Senger, N.I. Bishop, Emerson enhancement effect in synchronous scenedesmus cultures, Nature. 221(5184) (1969) 975-975.

[52] R. Dong, Y. Li, W. Li, H. Zhang, Y. Liu, L. Ma, X. Wang, B. Lei, Recent developments in luminescent nanoparticles for plant imaging and photosynthesis, Journal of Rare Earths. 37(9) (2019) 903-915.

[53] Y. Qi, Y. Wang, Y. Yu, Z. Liu, Y. Zhang, Y. Qi, C. Zhou, Exploring highly efficient light conversion agents for agricultural film based on aggregation induced emission effects, Journal of Materials Chemistry C. 4(47) (2016) 11291-11297.

[54] W. Wu, Z. Zhang, R. Dong, G. Xie, J. Zhou, K. Wu, H. Zhang, Q. Cai, B. Lei, Characterization and properties of a $Sr_2Si_5N_8:Eu^{2+}$-based light-conversion agricultural film, Journal of Rare Earths. 38(5) (2020) 539-545.

[55] G. Zhao, Y. Feng, Y. Wen, Syntheses, Crystal structures and kinetic mechanisms of thermal decomposition of rare earth complexes with schiff base derived from

o-vanillin and p-toluidine, Journal of Rare Earths. 24(3) (2006) 268-275.

[56] L. Shen, R. Lou, Y. Park, Y. Guo, E.J. Stallknecht, Y. Xiao, D. Rieder, R. Yang, E.S. Runkle, X. Yin, Increasing greenhouse production by spectral-shifting and unidirectional light-extracting photonics, Nature Food. 2(6) (2021) 434-441.

[57] H.I. Yoon, J.H. Kim, K.S. Park, J.W. Namgoong, T.G. Hwang, J.P. Kim, J.E. Son, Quantitative methods for evaluating the conversion performance of spectrum conversion films and testing plant responses under simulated solar conditions, Horticulture, Environment, and Biotechnology. 61(6) (2020) 999-1009.

[58] W.S. Kim, H.I. Yoon, J.M. Lee, T.G. Hwang, H.M. Kim, H.K. Lee, S. Kim, W.J. Choi, J.P. Kim, Substituents effects on properties of perylene dyes for spectrum conversion film, Dyes and Pigments. 209 (2023) 110845.

[59] J. He, Y. He, J. Zhuang, H. Zhang, B. Lei, Y. Liu, Luminescence properties of Eu^{3+}/CDs/PVA composite applied in light conversion film, Optical Materials. 62 (2016) 458-464.

[60] Y. You, H. Zhang, Y. Liu, B. Lei, Transparent sunlight conversion film based on carboxymethyl cellulose and carbon dots, Carbohydrate Polymers. 151 (2016) 245-250.

[61] K. Saito, Y. Ishigami, E. Goto, Evaluation of the light environment of a Plant factory with artificial light by using an optical simulation, Agronomy. 2020, 10(11) (2020) 1663.

[62] J. Kim, W.H. Kang, J.E. Son, Interpretation and evaluation of electrical lighting in plant factories with ray-tracing simulation and 3D plant modeling, Agronomy. 10(10) (2020) 1545.

[63] K. Li, Z. Li, Q. Yang, Improving light distribution by zoom lens for electricity savings in a plant factory with light-emitting diodes, Frontiers in Plant Science, 7 (2016)

[64] L. Poulet, G.D. Massa, R.C. Morrow, C.M. Bourget, R.M. Wheeler, C.A. Mitchell, Significant reduction in energy for plant-growth lighting in space using targeted LED lighting and spectral manipulation, Life Sciences in Space Research. 2 (2014) 43-53.

[65] S. Jin, S.H. Lee, Lighting layout optimization for 3D Indoor scenes, Computer Graphics Forum. 38(7) (2019) 733-743.

[66] Z. Li, L. Yu, M. Okunev, M. Chandraker, Z. Dong, Spatiotemporally consistent HDR indoor lighting estimation, ACM Trans. Graph. 42(3)(2023) Article 34.

[67] A. Zhang, F. Wang, Y. Dong, D. Yang, W. Xie, Dependent scattering criterion modification of disordered dispersed particulate medium with the consideration of particle random distribution and high complex refractive index effects, International Journal of Heat and Mass Transfer. 197 (2022) 123331.

[68] A. Zhang, F. Wang, Z. Cheng, H. Liang, X. Shi, Radiative property investigation of dispersed particulate medium with the consideration of non-uniform particle size distribution and dependent scattering effects, International Journal of Heat and Mass Transfer. 186 (2022) 122488.

[69] M. Li, T. Vu, G. Sankin, B. Winship, K. Boydston, R. Terry, P. Zhong, J. Yao, Internal-Illumination photoacoustic tomography enhanced by a graded-scattering fiber diffuser, IEEE Transactions on Medical Imaging. 40 (1) (2021) 346-356.

[70] J.V. Thompson, B.H. Hokr, W. Kim, C.W. Ballmann, B.E. Applegate, J. Jo, A. Yamilov, H. Cao, M.O. Scully, V.V. Yakovlev, Enhanced coupling of light into a turbid medium through microscopic interface engineering, Proceedings of the National Academy of Sciences. 114 (30) (2017) 7941-7946.

[71] D.R. Malinin, J.H. Yoe, Development of the laws of colorimetry: A historical sketch, Journal of Chemical Education. 38 (3) (1961) 129.

[72] P.E. Ciddor, Refractive index of air: new equations for the visible and near infrared, Applied Optics. 35(9) (1996) 1566-1573.