Effect of Frequency and Duty Cycle of a Full-Spectrum Pulsed LED Light Source on Plant Photosynthetic Rate

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Abstract: In this study, we reviewed the research progress on the use of pulsed lighting for plants and presented the concept of a full-spectrum pulsed LED light source panel. The changes in photosynthetic photon flux density (PPFD) at 25 cm below the lamp plate in response to changing light source frequency and duty cycle were measured. Furthermore, changes in photosynthetic rate with frequency were studied under a fixed duty cycle of the light source. The photosynthetic rate was greatest at 100 Hz. Additionally, the photosynthetic rate with a fixed light source frequency was highest at a duty cycle of 40%. Since PPFD cannot be maintained at a fixed frequency or duty cycle alongside a change in duty cycle or frequency, the concept of photo carbon ability is proposed here (photo carbon ability = photosynthetic rate/PPFD, which refers to the number of carbon dioxide molecules that can be induced into photosynthesis by a photon). The changes in the optical carbon ability with varying frequency were studied under a fixed duty cycle of the light source. The optical carbon ability was greatest at 100 Hz. Compared with traditional continuous light sources, this pulse frequency is expected to save 40% energy.

1 INTRODUCTION

The market scale of plant lighting is huge, and there is large potential for specific uses in the field. The total global area of greenhouses was equivalent to 2.835 million hectares, of which China accounts for approximately 86% (Qichang et al., 2009). Furthermore, it was estimated that a 200 kW high-pressure sodium lamp is required on average per hectare, although it is also estimated that 50–60% of the energy used could be saved by switching to LEDs instead. The market scale for LEDs purposed for plant lighting was approximately 283 billion watts, and considering this, appropriate plant lighting conditions can be adjusted to reduce energy waste while also promoting production (Haishan et al., 2021; Jianzhao et al., 2022; Runa et al., 2021; Wang et al., 2021; Zheng et al., 2022). The efficiency of light energy utilization was generally low, at approximately 1% for plants in the field, and can reach as high as 3% for rice (Haxeltine et al., 1996; Ma et al., 2020; Middleton et al. 2009; Nichol et al., 2002; Yao et al., 2017). Various reasons contributed toward the challenges pertaining to this efficiency, including nutrient composition, light parameters, temperature, and humidity (Angmo P et al., 2021; Nomura K et al., 2011; Qichang, 2008, 2011a, 2011b, 2011c; Qichang et al., 2011; Zhang et al., 2011, 2021). One important challenge with light parameters is that the solar lighting is continuous, and not pulsed.

Currently, the majority of plant lighting fixtures utilize continuous lighting, including LEDs, incandescent lamps, fluorescent lamps, and high-pressure sodium lamps. However, plant pulse lighting optimizes the efficiency of photosynthesis and improves the utilization of light by adjusting the frequency and duty cycle of the pulse light source, thereby improving the output while simultaneously saving energy.

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Previous studies have investigated the impacts of pulsed LED lights on plants and found that this can lead to an improved photosynthetic rate (Cinq-Mars M et al., 2021; Kanechi M et al., 2011; Kozai et al., 1999; Miliauskienė J et al., 2021; Shimada et al., 2016). For example, Kozai et al. (1999) in their study on the effects of LED pulse lighting on photosynthesis and growth in lettuces, found that at the pulse lighting period shorter than 100 μs, the growth of lettuce was 20% higher than that under continuous lighting. In addition, Shimada et al. (2011) showed that pulse light improved the levels of a few plant indicators by more than 30% when studying plant cultivation under a 180° phase difference between red and blue light.

These studies have used plants for long-term verification, with lengthy experimental periods, high costs, several uncertain variables, and small optimized pulsed light parameter conditions. To solve these problems, the present study proposes optimizing the parameters of the pulsed light source through rapid measurements using a photosynthesis instrument, LI-6400.

The experimental temperature was 23 °C, CO_2 concentration was 600 PPM, and the atmospheric pressure was 1 atm. The LED lamps used consisted of 2835 lamp beads of red, white, and yellow light mixed into a full spectrum with a power supply that had an adjustable frequency and duty cycle power supply. The light spectral structure of the lamps after mixing is shown in Figure 1, while the solar spectrum is shown in Figure 2. It was found that the spectrum after LED mixing highlighted the blue and red wavelengths absorbed by chlorophyll, which can promote the absorption of light by chlorophyll to a certain extent.

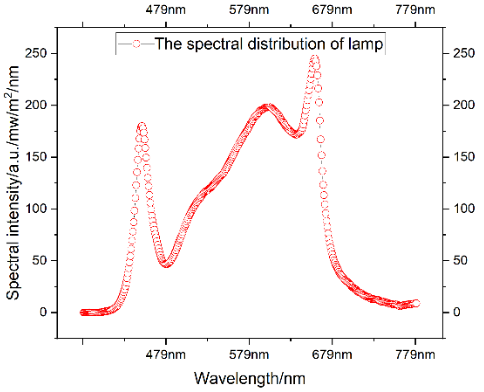

Figure 1: Light spectral structure of full-spectrum LED beads.

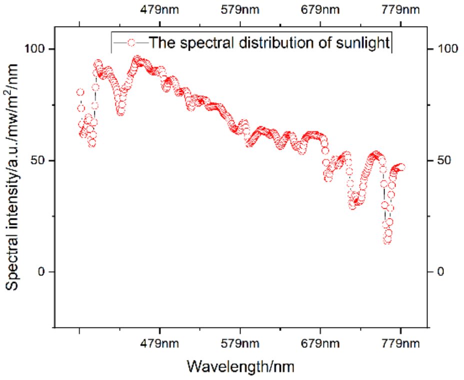

Figure 2: The light spectral structureof sunlight.

Figures 3–5 show the variation curves for photosynthetic photon flux density (PPFD) 25 cm under the lamp panel at varying frequencies. Figure 3 shows that in the range of 0–2000 Hz, PPFD increased with increasing frequency, and Figure 4 shows that between 2000–20000 Hz, PPFD remained relatively stable. Furthermore, Figure 5 revealed that in the range of 2000–100000 Hz, PPFD decreased as frequency increased.

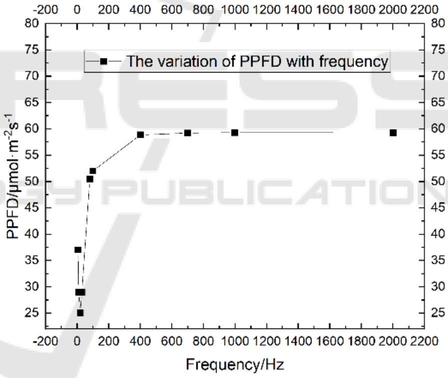

Figure 3: Variation curve for PPFD data 25 cm below the light plate with frequency 0–2000 Hz

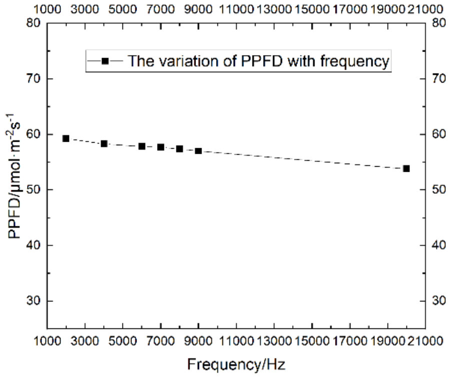

Figure 4: Variation curve for PPFD data 25 cm below the light plate with frequency 2000–20000 Hz.

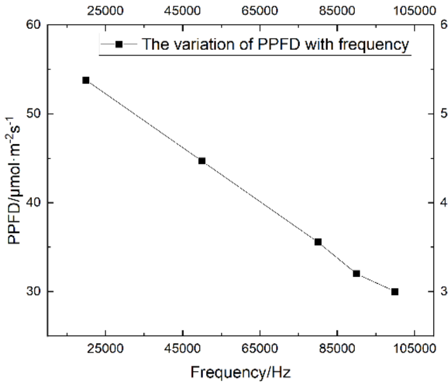

Figure 5: The variation curve for PPFD data 25 cm below the light plate with frequency 20000–100000 Hz.

For the experimental procedure, the appropriate frequency and duty cycle were first selected, before turning on the light for 30 min to allow both the LED lamp and plant to stabilize. Then, the photosynthetic rate of the plant was measured using LI-6400.

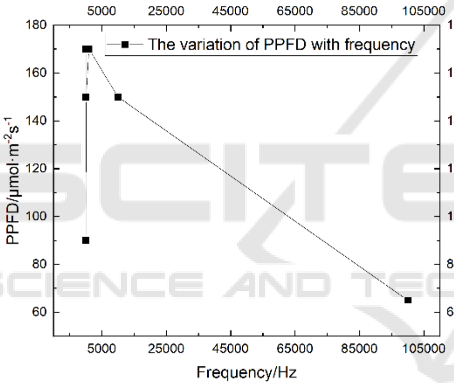

Figure 6: Variation curve for PPFD data and frequency at 25 cm below the lamp panel.

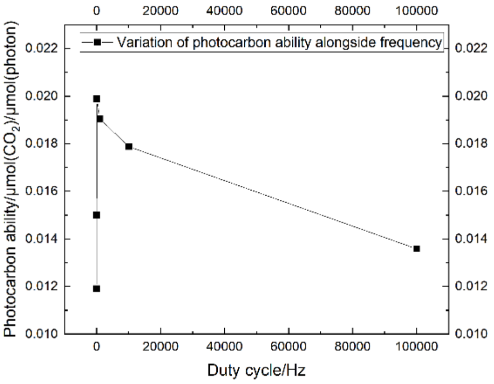

Figure 7: Variation curve for photosynthetic ability data and frequency at 25 cm below the lamp panel.

In total, 150 full-spectrum LED beads composed of 2835 patch mixed beads were used. The experiments were divided into two groups. The first group was for the fixed duty cycle and frequency conversion and the second group was for a fixed frequency with a conversion duty cycle. Finally, the optimized optical parameters were obtained.

Frequency was varied from 1 Hz, 10 Hz, 100 Hz, 1000 Hz, 10000 Hz, and 100000 Hz, with a duty cycle of 50%. Owing to the use of pulse width modulation (PWM) pulse light, the photosynthetic photon illuminance of the pulse light at different frequencies and the same duty cycle both changed because of the non-zero opening voltage. The PPFD data corresponding to the above frequencies were 170 µmol·m^{-2}s^{-1}, 90 µmol·m^{-2}s^{-1}, 150 µmol·m^{-2}s^{-1}, 170 µmol·m^{-2}s^{-1}, 150 µmol·m^{-2}s^{-1}, and 65 µmol·m^{-2}s^{-1}, respectively. It can be seen from Figure 7 that with the variation in pulse light frequency, the resultant photosynthetic rates were 2.55 µmol(CO_2)·m^{-2}s^{-1}, 1.07 µmol(CO_2)·m^{-2}s^{-1}, 2.98 µmol(CO_2)·m^{-2}s^{-1}, 3.24 µmol(CO_2)·m^{-2}s^{-1}, 2.68 µmol(CO_2)·m^{-2}s^{-1}, 0.88 µmol(CO_2)·m^{-2}s^{-1}, respectively. It can also be seen from the figure that the highest photosynthetic rate for plants was recorded at 1000 Hz.

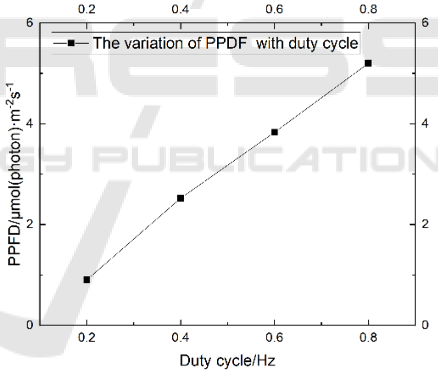

Figure 8 Variation curve for PPFD data alongside duty cycle at 25 cm below the lamp panel.

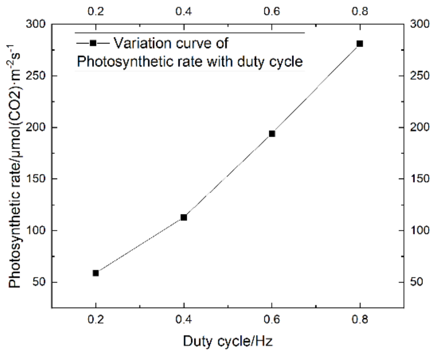

Figure 9 Variation curve for photosynthetic rate data alongside duty cycle at 25 cm below the lamp panel.

Next, we studied the effects of pulse lighting with varying duty cycles on plant photosynthetic rate under a fixed frequency of 100 Hz. Figure 9 shows that for these conditions the PPFD results associated with the above frequencies were 59 μmol·m^{-2}s^{-1}, 113 μmol·m^{-2}s^{-1}, 194 μmol·m^{-2}s^{-1}, and 281 μmol·m^{-2}s^{-1}, respectively. For pulse lighting with a duty cycle of 20%, 40%, 60%, and 80%, the respective photosynthetic rates of plants were 0.90 μmol(CO_2)·m^{-2}s^{-1}, 2.52 μmol(CO_2)·m^{-2}s^{-1}, 3.83 μmol(CO_2)·m^{-2}s^{-1}, and 5.20 μmol(CO_2)·m^{-2}s^{-1}. When frequency was 100 Hz, the photosynthetic rate of the plants was highest at a duty cycle of 60%.

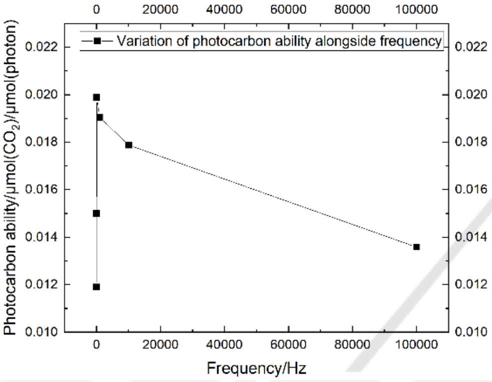

Figure 10 Variation of photocarbon ability alongside frequency at 25 cm below the light plate.

To better measure the photosynthetic rate under the unit PPFD, we propose a new concept here: Photocarbon ability = (photosynthetic rate)/PPFD, that is, the normalized treatment of photon illuminance by photosynthetic rate (i.e., how many carbon dioxide molecules a photon can convert).

Frequencies of 1 Hz, 10 Hz, 100 Hz, 1000 Hz, 10000 Hz, and 100000 Hz were applied, with a duty cycle of 50%. Considering that PWM pulse light was used, the photosynthetic photon illuminance of pulse light with different frequencies and the same duty cycle changed as a result of the non-zero switching on voltage. Therefore, the plant photosynthetic rate was normalized by the same amount of photosynthetic photon illuminance, and the plant utilization rate of light was measured using the normalized treatment of photosynthetic rate on photon illuminance, that is, the light carbon ability. It can be seen from the figure that, with the changes in pulse light frequency to 1 Hz, 10 Hz, 100 Hz, 1000 Hz, 10000 Hz, and 100000 Hz, the respective optical carbon ability was 0.015 μmol(CO_2) μmol^{-1}(photon), 0.012 μmol(CO_2) μmol^{-1}(photon), 0.020 μmol(CO_2) μmol^{-1}(photon), 0.019 μmol(CO_2) μmol^{-1}(photon), 0.018 μmol(CO_2) μmol^{-1}(photon), and 0.014 μmol(CO_2) μmol^{-1}(photon). Figure 10 also shows that the optical carbon ability was highest with a pulse frequency of 100 Hz.

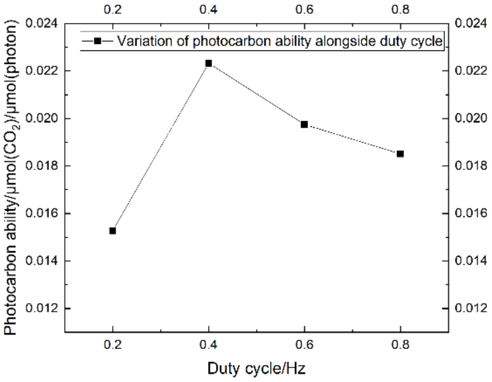

Figure 11 Variation of photocarbon ability alongside duty cycle at 25 cm below the light plate.

Subsequently, we investigated the effects of pulse lighting with a varying duty cycle on plant photosynthetic rate under a fixed light pulse frequency of 100 Hz. Figure 11 shows that under these conditions, the light carbon ability of plants were 0.015 μmol(CO_2) μmol^{-1}(photon), 0.022 μmol(CO_2) μmol^{-1}(photon), 0.020 μmol(CO_2) μmol^{-1}(photon), 0.019 μmol(CO_2) μmol^{-1}(photon) with respective duty cycles of 20 %, 40 %, 60 %, and 80 %.

3 CONCLUSIONS

To conclude, by first fixing the duty cycles and varying the frequencies, we found that the photosynthetic rate of plants was greatest at a frequency of 1000 Hz. Furthermore, at a fixed pulse frequency of 1000 Hz, the highest photosynthetic rate of plants was observed at a duty cycle of 40%. To better measure the ability of photons to convert CO_2, a new concept of optical carbon ability is proposed here. That is to say, under the same conditions, varying the pulse light frequency to 1 Hz, 10 Hz, 100 Hz, 1000 Hz, 10000 Hz, 100000 Hz. This study showed that the light carbon ability of plants was greatest when frequency was 100 Hz. Then, at a fixed pulse frequency of 100 Hz, the light carbon rate of plants was optimal at a duty cycle of 60%. Compared with traditional continuous light sources, this pulse frequency is expected to save 40% energy.

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