LED supplementary strategy based on hourly light integral for improving the yield and quality of greenhouse strawberries

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Abstract: Supplemental lighting is critical to the growth of greenhouse crops under the environmental conditions of low temperatures combined with weak radiation during the winter and spring seasons. To achieve the essential daily light integral (DLI) for greenhouse crop growth, a supplemental light strategy was proposed based on hourly light integral (HLI). The target HLI was calculated by dividing the target DLI by the duration of light exposure, while the actual HLI was obtained by accumulating the Photosynthetic Photon Flux Density (PPFD) based on real-time monitoring. Subsequently, the supplemental lighting duration for the next hour was determined by the difference between the target HLI and the actual HLI from all previous periods. Furthermore, the supplementary lighting strategy incorporated maximum values for both PPFD and temperature, and the supplemental light was withheld whenever the actual PPFD or temperature exceeded these values. An experiment was conducted on strawberries in a commercial greenhouse, targeting a DLI of 12.6 mol/(m^2·d), with no supplemental lighting as the control. The results indicated that LED supplemental lighting based on HLI increased the DLI to approximately10 mol/(m^2·d) and raised the strawberry canopy temperature by 1°C-2°C. Compared to the control treatment, the LED supplemental lighting based on HLI significantly improved the net photosynthetic rate, stem thickness, number of leaves, leaf length, and leaf width of the strawberry plants. Additionally, the fruit yield per plant, soluble solids content, and sugar-acid ratio in the supplemental lighting treatment increased by 32%, 21%, and 33%, respectively. Thus, LED supplemental lighting based on HLI is an effective strategy for improving the yield and quality of greenhouse crop production.

Keywords: daily light integral, hourly light integral, greenhouse strawberry, LED supplementary strategy, temperature coupling control
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1 Introduction

Light and temperature are the primary factors affecting plant growth and development. Light is crucial for regulating photosynthesis, morphogenesis, material metabolism, and overall growth and development in plants[1-4], while temperature directly affects photosynthesis, respiration, transpiration, nutrient uptake, and material transportation of plants[5,6]. In controlled environments for horticultural crop production during winter and early spring, the prevalent low temperatures and inadequate light conditions significantly hinder the growth and development of these crops, directly limiting both yield and economic viability[7,8].

In recent years, supplementary lighting has become an indispensable environmental control strategy in high-efficiency controlled horticulture, extensively applied in the cultivation of floricultural crops[9], fruit and vegetable crops[10], berries[11], and medicinal plants[12]. Artificial light sources, such as high-pressure sodium lamps and metal halide lamps, have rapidly advanced in controlled agriculture[13,14]. However, they have limitations such as high energy consumption, low light efficiency, and short lifespan[15,16]. Conversely, LED lighting has increasingly become favored due to its reduced cost[17], high energy conversion efficiency[18], broad spectral range[19], and superior durability and water resistance. The dimmability of LED lights has made it possible to develop lighting control strategies beyond simple on/off control[20]. Dynamic supplemental lighting control is primarily achieved by adjusting light intensity, increasing supplementation under low Photosynthetic Photon Flux Density (PPFD) conditions, and deactivating supplemental lighting when natural light intensity exceeds preset thresholds[21]. Researchers established daily photochemical integral with crop growth needs and optimized supplemental lighting intensity to reduce energy consumption[22]. Furthermore, the dynamic calculation of ideal light intensity, adjusted based on the difference between actual and expected PPFD values, enhances the efficiency and effectiveness of supplemental lighting[23].

However, light intensity is only a single influencing factor that cannot comprehensively reflect the plant's light demand. Daily light integral (DLI) represents the total amount of photosynthetic photons received by the plant's surface in a single day, and it could be used to represent the accumulation of assimilates[24]. Current

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recommendations for greenhouse supplemental lighting are based on achieving target DLI levels, which typically exhibit a linear relationship with crop growth. The increase in DLI to levels requisite for plant growth through supplemental lighting can improve fruit yield and quality at different plant growth stages[25]. Previous studies have demonstrated that a 1.0% increase in light can boost yield by 0.5% to 1.0%[26]. Strawberries' yield more than doubled with 12 h of daytime supplemental light compared to greenhouse plants without supplemental light. Yet, at already high DLI levels, yield gains were marginal, resulting in inefficiency[27].

Albright et al.[28] implemented control over supplemental lighting and shading based on real-time electricity prices, weather conditions, and greenhouse location to achieve a consistent target DLI. However, they did not account for the influence of temperature on supplemental lighting, as excessive temperatures during supplemental lighting periods can negatively affect crop growth. Integrating the effects of light and temperature is crucial for optimizing greenhouse crop production efficiency[29]. Xu et al.[8] developed models for coupled net photosynthesis rate and cooling-supplemental lighting energy consumption to achieve optimal control of net photosynthesis rate and energy consumption. Wang et al.[30] established a model of coupled photosynthetic rates with light and temperature and utilized the NSGA-II algorithm to obtain optimal supplemental lighting solutions for enhancing crop yield while reducing energy consumption. However, the practical efficacy of these models in boosting crop productivity has yet to be confirmed.

Therefore, this study aimed to propose a greenhouse LED supplemental lighting strategy based on hourly light integral (HLI), targeting the DLI required for strawberry growth and integrating temperature for coupled control. The effectiveness of this strategy was evaluated in greenhouse strawberry cultivation. The experimental procedure involved monitoring temperature and light intensity in both treatment groups, calculating the HLI and DLI, and measuring the growth parameters, yield, and quality of the strawberries. This study aims to provide technical support for improving the yield and quality of strawberries through LED supplemental lighting in greenhouses.

2 Materials and methods

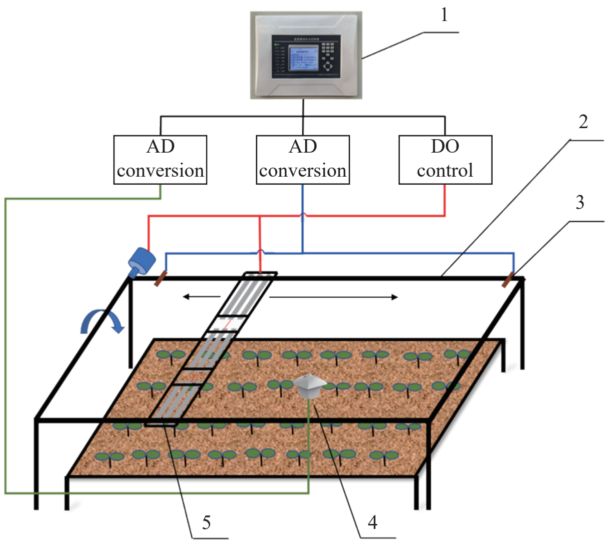
2.1 Plant materials and growth conditions

The experiment was conducted in a multi-span film greenhouse situated in the eastern section of the National Modern Agricultural Science and Technology Demonstration Park in Xiaotangshan, Changping District, Beijing (116°26′E, 44°9′N). The experiment spanned from February 6 to April 6, 2021. The greenhouse, oriented north-south, has a shoulder height of 5.2 m, a ridge height of 3.7 m, 8.0 m spans, and 5.0 m wide bays, comprising 10 spans and 25 bays across a 10 000 m^2 area. It is covered with a 0.15 mm thick, high-transparency, anti-fog polyethylene film and features ventilation systems on the roof and sidewalls.

The strawberries (*Fragaria*×*ananassa* Duch. cv. *Sachinoka*) were planted in staggered rows within H-shaped troughs (30 cm in width and 15 cm in depth), elevated with a spacing of 20 cm between plants. Yamazaki strawberry nutrient solution formula was applied with an electrical conductivity of 0.8-1.4 mS/cm and pH value of 6.0-6.5 with the following components (mg/L): $Ca(NO_3)_2\cdot 4H_2O$, 236; KNO_3, 303; $MgSO_4\cdot 7H_2O$, 123; $NH_4H_2PO_4$, 57; Na_2Fe-EDTA, 15; H_3BO_3, 1.13; $MnSO_4\cdot H_2O$, 0.61; $CuSO_4\cdot 5H_2O$, 0.04; $ZnSO_4\cdot 7H_2O$, 0.09; and $(NH_4)6Mo_6O_{24}\cdot 4H_2O$, 0.01. Irrigation was scheduled once daily at 9 a.m., delivering around 80 mL of nutrient solution per plant during the vegetative growth phase. During the flowering and fruit-bearing stages, an additional afternoon irrigation at 2 p.m. was implemented, with each plant receiving approximately 120-150 mL of water, subject to adjustments based on prevailing weather conditions.

2.2 LED supplementary lighting system for greenhouses

To minimize construction costs and reduce plant shading effects, the LED supplementary lighting system was designed with a gear and rack mechanism for efficient movement. The system was composed of an integrated sensor module, a supplemental lighting controller, a gear-rack transmission mechanism, and LED supplemental lighting fixtures (Figure 1). Positioned at canopy level, the sensor module horizontally aligns with the plant canopy to accurately collect data on PPFD, temperature, relative humidity, and CO_2 concentration.



1. Supplemental lighting controller; 2. Gear-rack transmission mechanism; 3. Limit switch; 4. An integrated sensor module; 5. LED supplemental lighting fixtures

Note: AD conversion: Analog-to-digital conversion; DO control: Digital output control.

Figure 1 Schematic diagram of the greenhouse's movable LED supplementary lighting system based on the HLI

The supplemental lighting controller orchestrated the operations and issued instructions across the entire supplemental lighting system, ensuring real-time monitoring of environmental conditions within the greenhouse, including PPFD, temperature, and relative humidity. Additionally, it was programmed to calculate the DLI and HLI, which are critical for optimizing plant growth conditions. Employing a gear-rack transmission mechanism, the controller facilitated precise management of the LED supplemental lighting fixtures' movement. This mechanism adeptly transformed the deceleration motor's rotational motion into a linear motion along the rack, thereby enabling the fixtures to traverse above the plant canopy to deliver targeted supplemental lighting.

The integrated sensor module encompassed several key components: a quantum light sensor, temperature and humidity sensor (SHT11, Sensirion AG, Switzerland), a CO_2 sensor (S8, SenseAir, Sweden), a mini fan, and a radiation-shielding case. The quantum light sensor employed an ARM (STM32F103, STMicroelectronics, Switzerland) core processor for light transmission. This process involved light correction by a cosine shield, filtration through a sheet, and capture by a silicon photodiode. The light underwent photoelectric conversion, subsequently transformed into a digital signal by an A/D converter for data transmission. The accuracy of the environmental measurements provided by the sensors was as follows: the temperature and humidity sensor offered a precision of ±0.4°C for temperature and ±3% for relative humidity, while the CO_2 sensor maintained an accuracy of ±40 μmol/mol for CO_2 concentration.

The LED supplementary lighting controller was composed of a microcontroller module, a communication module, an LCD module, a power module, and a data storage module. The microcontroller utilized the STM32F407ZG control chip. The communication module extended the serial port and used the SP485 chip for RS-485 communication, enabling point-to-multipoint communication. An LCD320240 screen was used to interface with the microcontroller's I/O ports, and data was stored on an 8 GB SanDisk memory card for real-time display.

2.3 Experimental design

The greenhouse is located in the north-south direction, with a shoulder height of 5.2 m, a ridge height of 3.7 m, a bay of 5.0 m and a span of 8.0 m, a total of 10 spans and 25 bays. The experimental design included two spans: one was treated with supplemental lighting based on HLI, while the other served as the control without supplemental lighting. The area of the supplementary light area is 40 m^2. The continuous greenhouse structure was equipped with a gear rack and pinion transmission mechanism, with a single stroke of 5 m (Figure 2). The light requirement for greenhouse strawberries is 12.6 mol/(m^2·d), with an optimal photoperiod of 14 h/d. The supplemental lighting intensity was set at 250 μmol/(m^2·s). Full-spectrum white LED fixtures, 1.2 m in length and with a color temperature of 4000K (W-LED-36W, Beijing Lighting Valley Technology Co., Ltd., China), were chosen as the supplemental lighting fixtures for the elevated cultivation of strawberries in the greenhouse. The spectral distribution of the supplemental lighting was measured by an optical fiber optic spectrometer (AvaSpec-ULS2048, Avantes Inc., Netherlands) at the wavelength of 300 to 800 nm on the plane 70 cm below the lamps, as recorded in Table 1. The system was designed to allow for adjustable PPFD values, ranging from a minimum of 20 μmol/(m^2·s) to a maximum of 350 μmol/(m^2·s).

a. Production site installation diagram

b. Rack and pinion mechanism

Figure 2 Installation of a movable LED supplementary lighting system in greenhouse strawberry production

Table 1 Spectral distribution of LED supplemental light with PPFD of 250 μmol/(m^2·s) at 70 cm below the LED lamps

Wavelength/nm	PPFD/μmol·m^{-2}·s^{-1}	Spectral fraction of light source/%
Light Intensity (300-800)	250	100.0
UV light (300-399)	0	0.0
Blue light (400-499)	42	16.9
Green light (500-599)	112	44.7
Red light (600-699)	88	35.0
Far-red Light (700-800)	8	3.4
R: B	2.1	
R: FR	10.3	

The amount of supplemental light was determined based on the target supplemental light intensity received by the plant canopy, the length of supplemental lighting, the area of the supplemental lighting area, and the luminous intensity of the luminaires. The area designated for supplemental lighting was outfitted with 48 total LEDs, consisting of 6 sets of LEDs, 8 lamps per set, each lamp with a mass of approximately 0.8 kg, arranged in an east-west orientation. These fixtures were affixed to stainless steel frames and welded for stability, with each frame weighing about 60 kg. Consequently, the total mass of the supplemental lighting setup, including fixtures and frames, amounted to roughly 100 kg. To quantify the system's operational parameters, we applied Newton's second law. The motor, facilitating the movement of the lighting system, operated at a rotation speed of 3.3 r/min, completing a single stroke in 14 min. This configuration resulted in a movement speed of the supplemental lighting system of 0.36 m/min.

2.4 Measurements

2.4.1 Environmental parameters

PPFD levels in both the supplemental lighting and control treatments were monitored every 5 min using a light and temperature-humidity data logger (RS-13L, ESPEC MIC Inc., Japan). Initially measured in lux (lx), PPFD values were converted to the standard unit of μmol/(m^2·s) using a conversion factor of 63.9 lx per 1 μmol/(m^2·s). The HLI and DLI were calculated using the trapezoidal integration method. Solar radiation data, essential for understanding external light conditions, were sourced hourly from NASA based on the greenhouse's coordinates (116°4 ′E, 40°2 ′N). The temperature inside and outside the greenhouse was recorded using sensors integrated into the Galileo Wex agricultural automated control system.

2.4.2 Morphology parameters of strawberry

Leaf length (cm) and width (cm) were measured with a ruler, while stem thickness was determined using a vernier caliper (mm). Measurements were carried out every two weeks, selecting six strawberry plants at the same growth stage for each assessment.

2.4.3 Fruit yield and quality of strawberry

Two months after LED supplemental lighting, the yield and quality of the first batch of strawberries were measured, selecting six plants with similar growth under different treatments for the assessment. Fruit weight was precisely measured using an electronic balance with a resolution of 0.01 g (Model YP402N, Jingke, Shanghai, China). The soluble solids content was assessed using a portable digital refractometer (Model PAL-1, Atago Corporation, Japan). Soluble sugar content was quantified via the anthrone colorimetric method, while total acid content was determined through acid-base titration employing the pH potentiometric technique. The sugar-acid ratio was calculated by dividing the soluble sugar content by the total acid content.

2.4.4 Net photosynthetic rate of strawberry

Leaf net photosynthetic rates [μmol/(m^2·s)] were measured by a portable gas exchange system (LI-6400, LI-COR Inc., USA). The third leaf (from the heart leaf outward) was selected as the target, and the measurement was started at around 10:00 a.m. on a sunny day. The leaf chamber of the portable gas exchange system was set at a light intensity of 400 μmol/(m^2·s), a temperature of 20°C, an airflow rate of 500 μmol/s, and a CO_2 concentration of 400 μmol/mol. Measurements were carried out every 2 weeks, with 6 strawberry plants at identical growth stages selected for each assessment.

2.5 Statistical analysis

The data analysis was performed using Microsoft Excel 2019.

The data was analyzed using SPSS statistics 25 (IBM, Inc., Chicago, IL, USA). The analysis of variance was performed using Duncan's new multiple range test at the significance level of α=0.05.

3 LED supplementary strategy based on HLI

3.1 Description of LED supplementary light strategy based on HLI

Taking 1 h as a period time, the target cumulative hourly light intensity I_{ha} [mmol/(m^2·h)] was calculated from the essential DLI I_d [mol/(m^2·d)] for plant growth and the photoperiod duration H (h/d), according to the following equation:

$$I_{\mathrm{ha}} = \frac{I_d}{H} \times 10^3 \tag{1}$$

During the supplemental lighting photoperiod, the light intensity at the plant canopy, $P_{(t)}$, μmol/(m^2·s), was continuously monitored via a sensor module. This enabled the calculation of the actual HLI received per hour, represented as I_{hi}, mmol/(m^2·h). The calculation is as follows:

$$I_{\mathrm{hi}} = \int P_{(t)} \mathrm{d(t)} \times 10^6 \tag{2}$$

Subsequently, the cumulative actual HLI from all preceding intervals was compared to the cumulative target HLI for those intervals. Based on this comparison, the system assessed the need for supplemental lighting and calculated the required duration of supplemental lighting, denoted as t, s:

If

$$\sum_{i=1}^{n} I_{\mathrm{hi}} < n \times I_{\mathrm{ha}} \tag{3}$$

Then,

$$t = \frac{\left(n \times I_{\mathrm{ha}} - \sum_{i=1}^{n} I_{\mathrm{hi}}\right)}{P} \times 10^6 \tag{4}$$

To mitigate the adverse effects of excessive temperature and light intensity on plant growth, the system dynamically adjusts the supplemental lighting based on real-time temperature $T_{(t)}$, and light intensity, $P_{(t)}$. If the temperature exceeds the predetermined maximum value, $T_{\max}$, or the light intensity surpasses the established maximum, $P_{\max}$, the system temporarily ceases supplemental lighting. This precautionary step ensures the optimal growth and development of strawberries by preventing stress conditions induced by excessive heat and light.

3.2 Control logic of the LED supplementary lighting strategy based on HLI

Prior to operation, the supplemental lighting system's controller was programmed with several key parameters: the DLI (I_d), light duration (H), and supplemental lighting intensity (P) required for optimal greenhouse crop growth, maximum intensity ($P_{\max}$), and maximum temperature ($T_{\max}$). Upon activation, the controller operates the lighting fixtures and engages a deceleration motor that transforms spiral motion into linear motion along a gear rack, with a limit switch governing the reciprocal movement. Throughout the operation, the system calculates the discrepancy between the targeted and actual HLI, based on real-time PPFD measurements, to adjust the duration of supplemental lighting. The system deactivates supplemental lighting if PPFD levels exceed $P_{\max}$ or if greenhouse temperatures surpass $T_{\max}$. After the supplemental lighting period ends, the apparatus retracts to a concealed position beneath the inner shading net and insulation curtain, thereby minimizing any shading impact on the crops. Figure 3 shows the detailed operational logic of the system. In this study, $P_{\max}$ is 350 μmol/(m^2·s), $T_{\max}$ is 20°C.

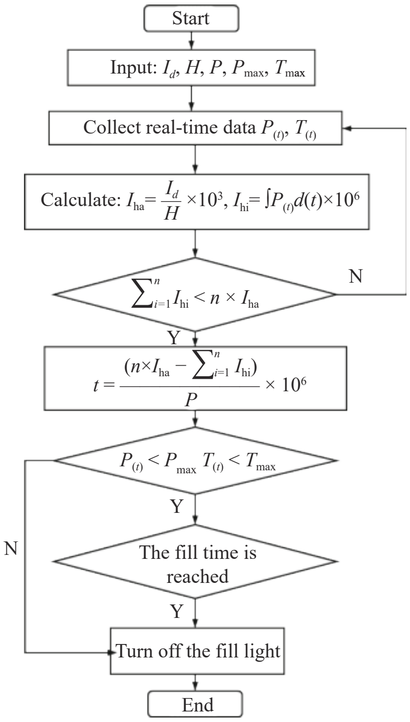


Figure 3 The flowchart of LED supplementary strategy based on HLI

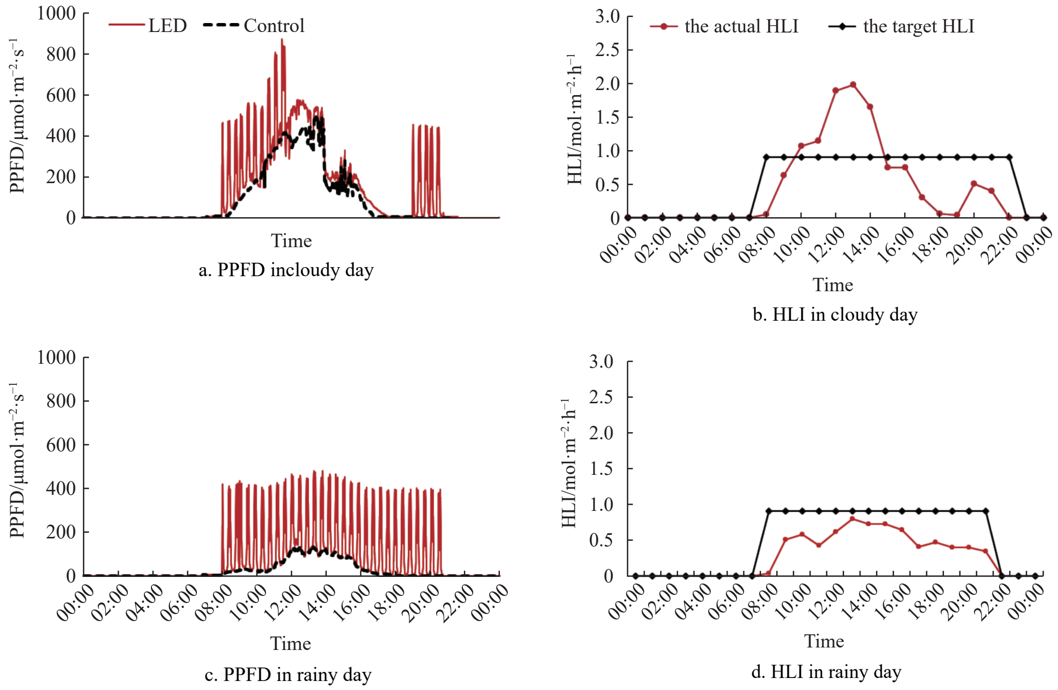
4 Results

4.1 Variations in PPFD, HLI, and DLI

To assess the impact of supplemental lighting in varying weather conditions, Figure 4 shows that under cloudy conditions, supplemental lighting was mainly used from 8:00-10:00 a.m. and after 8:00 p.m. Although the light intensity was weaker between 5:00-8:00 p.m., the supplemental lighting system was not activated because the actual cumulative HLI before 6:00 p.m. exceeded the theoretical cumulative HLI. However, after 8:00 p.m., when the actual cumulative HLI fell below the target cumulative HLI, the LED supplemental lighting system was turned on. On rainy days, the Peak PPFD only reached 120 μmol/(m^2·s) between 12:00 to 3:00 p.m., accompanied by weak light at other periods. This necessitated the continuous operation of the LED supplemental lighting system throughout the day to maintain normal photosynthesis in strawberry plants under low-light conditions.

Analysis of outdoor solar radiation and DLI over a month (Figure 5) demonstrated that during the supplemental lighting phase, solar radiation reached a maximum of 7.0 MJ/m^2 and a minimum of 2.9 MJ/m^2. In the period from February to March, solar radiation frequently remained below 6.0 MJ/m^2. Meanwhile, the DLI under the control treatment without supplemental light showed large fluctuations under the influence of solar radiation. A total of eight days occurred when the DLI was lower than 6.0 mol/(m^2·d), and the lowest DLI was only about 2.0 mol/(m^2·d). In contrast, the LED supplemental lighting treatment maintained DLI around 10 mol/(m^2·d), achieving 1 to 3 mol/(m^2·d) higher than the control under normal weather conditions and providing vital support during periods of cloudy, rainy, and snowy weather. On February 14, for example, supplemental lighting increased the DLI from 3.8 to 8.8 mol/(m^2·d). Therefore, the application of an LED supplemental lighting strategy, guided by HLI, is effective in maintaining a consistently elevated DLI in greenhouse crops.

During the supplemental lighting period, the total photosynthetically active radiation (PAR) in the LED supplemental light and control treatments was calculated to be 300.3 mol/m² and 233.1 mol/m², respectively. The PAR in the LED supplemental lighting treatment was 28.8% higher than that in the control treatment.



a. PPFD incloudy day

b. HLI in cloudy day

c. PPFD in rainy day

d. HLI in rainy day

Note: PPFD: Photosynthetic Photon Flux Density; HLI: Hourly light integral. Same below.

Figure 4 Comparison of PPFD and HLI in the LED supplementary light and control treatments

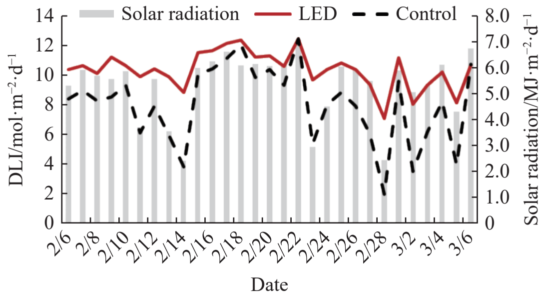


Figure 5 The variations of daily light integral between the supplementary light treatment and control treatments

4.2 The photothermal coupling analysis

During the two-month period of supplemental lighting, external daytime temperatures around the greenhouse fluctuated between 0°C and 20°C, while inside the greenhouse, daytime temperatures remained predominantly stable within the range of 15°C-25°C (Figure 6). However, on overcast and rainy days, indoor temperatures dropped below 15°C. Outdoor nighttime temperatures fluctuated within the range of –5°C-10°C, while indoor nighttime temperatures varied between 10°C and 20°C.

Under cloudy conditions, the temperature was below 20°C for the whole day except for a higher temperature at 3:00 p.m., and the LED supplemental lighting system was operational throughout the day. Post-supplementation, the temperature at the canopy of plants in the supplemented treatment was 1°C-2°C higher than that in the control treatment, as shown in Figure 7. The average temperature remained above 15°C, ensuring normal growth of the strawberry plants. Over the 2 months of supplemental lighting, the cumulative temperature in the LED supplementary treatment was estimated to exceed that of the control treatment by more than 720°C.

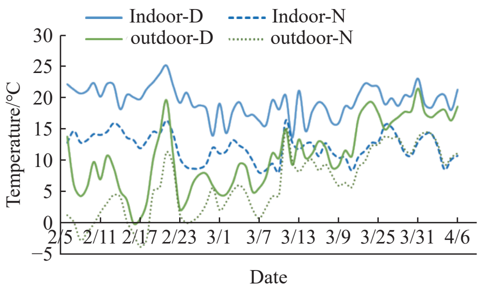
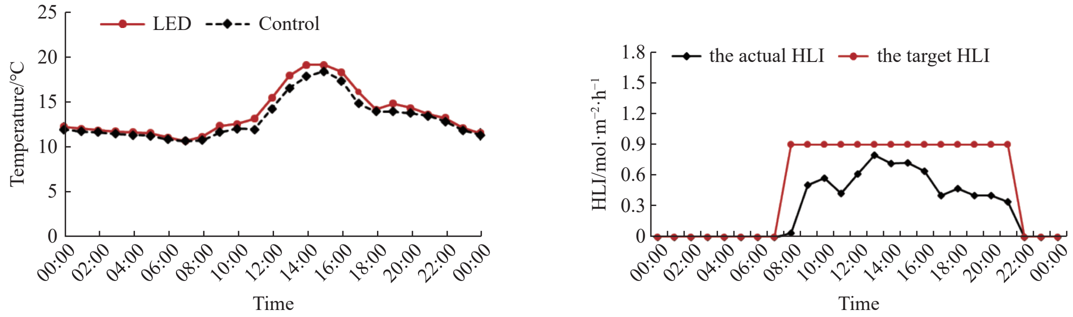


Figure 6 Variations in indoor and outdoor daytime and nighttime temperatures between the supplementary light treatment and control treatments

Under sunny conditions (Figure 7), the light intensity was relatively weak from 7:00 to 8:00 a.m., resulting in the actual DLI not meeting the theoretical requirements. However, the supplemental lights were not activated since the temperature had already reached 20°C before 8 a.m. After 10:00 a.m., the actual HLI was observed to fall below the theoretical HLI, attributed to the operational adjustments within the connected greenhouses. Supplemental lighting was not provided until temperatures moderated to 20°C, at which point it was activated.

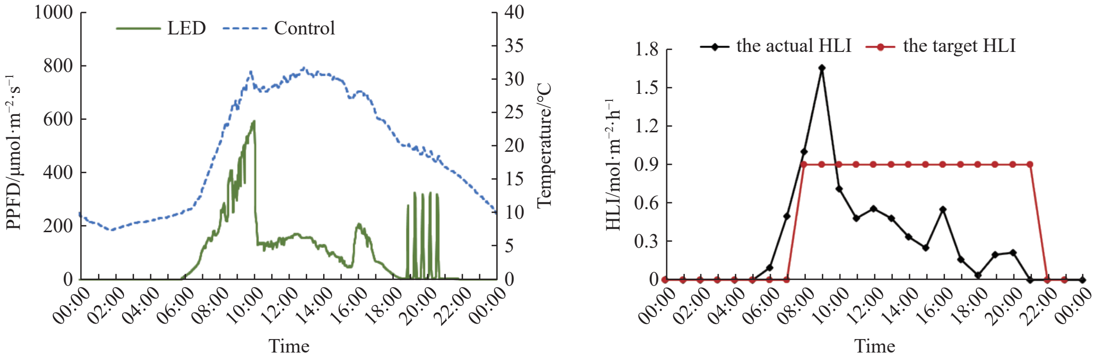
4.3 Morphology of strawberry plants

LED supplemental lighting based on HLI significantly impacted the morphological development of strawberry plants. As shown in Figure 8, 2 weeks after the initiation of LED supplemental lighting, the leaf length, leaf width, and number of leaves of the elevated cultivation strawberry plants were significantly greater than those in the control treatment. Additionally, a discernible increase in stem thickness was observed after 1 month of LED supplemental lighting initiation, with stem thickness reaching its



a. Temperature in the rainy day

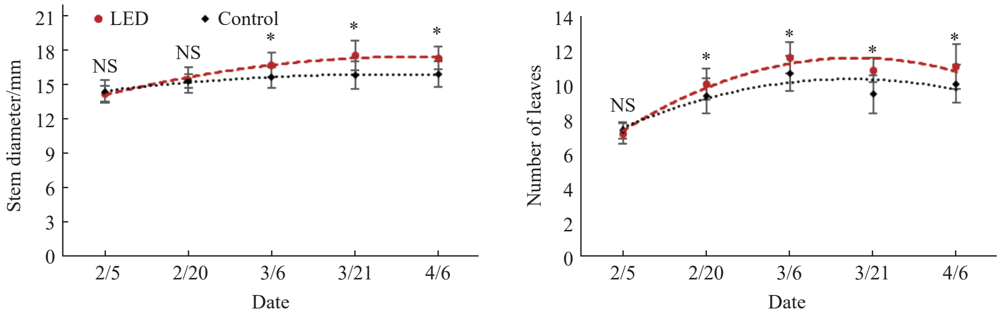
b. HLI in the rainy day



c. PPFD and temperature in the sunny day

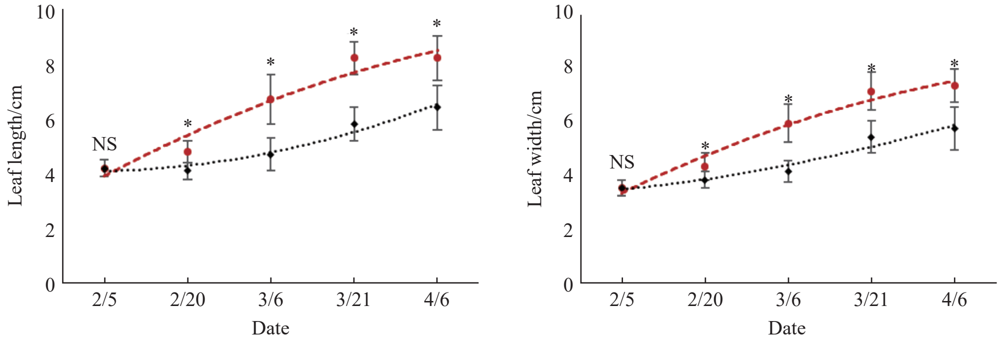
d. HLI in the sunny day

Figure 7 The variations of temperature and HLI in the light-filling treatment under rainy and sunny conditions



a. Stem diameter

b.Number of leaves



c.Leaf length

d. Leaf width

Note: “*” indicates a significant difference between experimental treatments, while “NS” indicates no significant difference. Same as below.

Figure 8 Effects of LED supplementary lighting on the growth of greenhouse strawberry crops

peak at 17.5 mm and leaf length at 8.2 cm in the supplemental light treatment. Subsequently, after 2 months, the leaf width and number of leaves in the LED supplemental light treatment peaked at 7.4 cm and 11.1 leaves, compared to 5.8 cm and 10.1 leaves in the control treatment. This indicates that LED supplemental lighting increased the DLI at the strawberry canopy, effectively promoting the above-ground growth of the strawberry plants.

4.4 Net photosynthetic rate of strawberry plants

The LED supplemental lighting based on HLI significantly increased the net photosynthetic rate of strawberries. As shown in Figure 9, there was no significant difference between the leaf net photosynthetic rate of strawberry plants in the LED supplemental light treatment and the control treatment at the beginning of supplemental lighting. However, after 2 weeks of LED supplemental light, the leaf net photosynthetic rate of strawberry plants in the supplemental light treatment was significantly higher than that in the control treatment. These results indicate that light supplementation could significantly promote photosynthesis in strawberry plants. Furthermore, a gradual decline in the net photosynthetic rate of strawberries was observed throughout the cultivation period.

4.5 Yield and quality of strawberry fruit

The LED supplemental lighting based on HLI significantly enhanced the yield of greenhouse strawberries. The yield of individual plants in the first crop under the supplemental lighting treatment increased by 32% compared to the control treatment, which had a yield of 87.6 g (Table 2). Moreover, the LED supplemental lighting treatment resulted in a 28.8% increase in light intensity, leading to a 31.8% increase in yield. In this experiment, the increase in yield attributable to LED supplemental lighting surpassed the increase in light intensity, indicating that the production efficiency of LED supplemental lighting is 1.1 times higher than that of natural light.

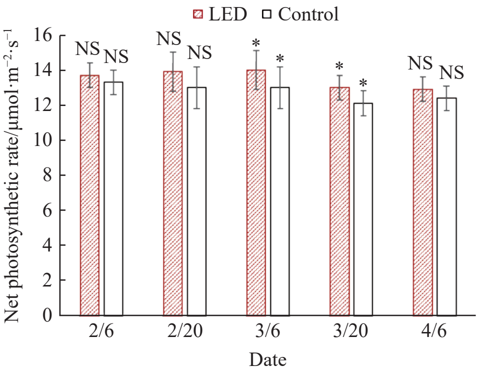


Figure 9 Effect of LED supplementary lighting on the net photosynthetic rate of strawberry plants

Table 2 Effect of movable LED supplementary lighting on yield and quality of greenhouse strawberry

Experimental treatment	Number of fruit per plant		Yield per plant/g		Firmness/kg·cm^{-2}		Soluble solids content/%		Sugar-acid ratio		Vitamin C content /mg·100 g^{-1}	
LED	6.8±0.8	*	115.5±11.4	*	1.7±0.1	NS	11.9±0.9	*	11.3±2.2	*	67.9±16.7	*
Control	5.8±1.0		87.6±9.2		1.8±0.3		9.8±1.1		8.5±1.8		61.6±17.4	

Note: "*" indicates a significant difference between experimental treatments, while "NS" indicates no significant difference.

The LED supplemental lighting based on HLI significantly influenced the soluble solids content and sugar-acid ratio of greenhouse strawberries. The fruits from the LED supplemental lighting treatment exhibited a 21% increase in soluble solids content and a 33% increase in the sugar-acid ratio, compared to the control treatment. However, this treatment did not improve fruit firmness or vitamin C content (Table 2).

5 Discussion

5.1 Photosynthesis characteristics

The LED supplemental lighting strategy based on HLI fully accounted for weather conditions and significantly promoted photosynthesis in strawberry plants by supplementing light intensity during low light conditions. In the experiment, LED supplemental lighting was typically applied between 7:00-10:00 a.m. and 6:00-9:00 p.m. on sunny days, or during periods of weak light on cloudy and rainy days. The results indicated that 2 weeks after the initiation of LED supplemental lighting, the net photosynthetic rate of the strawberry leaves in the supplemented treatment was significantly higher than in the control treatment. Morning and evening supplemental lighting significantly enhanced the photosynthesis of plants. Wang et al.[31] provided 3 h of supplemental lighting to tomato plants in the morning and evening in a greenhouse and measured photosynthetic pigments and Rubisco activity. Their study found that morning supplemental lighting with red and blue light increased light absorption and utilization, promoting the production of photosynthetic pigments and increasing the activity of key enzymes in the Calvin cycle, thereby enhancing leaf photosynthesis. Wei et al.[1] investigated the effect of supplemental lighting after sunrise on the stomata of strawberry plants. They found that the stomata were almost closed under low light conditions at low temperatures in the morning. In contrast, providing supplemental light for 2 h at a light intensity of 100 μmol/(m^2·s) significantly increased the opening of the stomata, indirectly promoting the photosynthetic capacity of strawberry plants. Furthermore, the employment of LEDs in the study was more beneficial in promoting the photosynthesis of strawberries. It was found that, in comparison to high-pressure sodium lamps and metal halide lamps, mixed LEDs substantially elevated the expression of genes related to photosynthesis, thereby ameliorating the quality of grafted tomato seedlings[32]. When contrasted with fluorescent lamps, LED supplemental lighting notably augmented the net photosynthetic rate of strawberry plant leaves[33]. The net photosynthetic rate of strawberry plants is influenced by leaf age, exhibiting a "low-high-low" pattern. In this study, strawberries were planted in September, and the supplementary light experiment was carried out from February to April, marking the late stage of strawberry growth. During this period, leaves gradually aged, leading to a gradual decline in the net photosynthetic rate. Moreover, analogous studies have indicated a decrease in photosynthetic capacity with leaf senescence[34,35].

5.2 Morphological indicators

The LED supplementation based on HLI significantly affected the morphology of strawberry plants. 1 month after supplementation, the stem thickness, leaf length, leaf width, and number of leaves of the strawberry plants were all markedly higher than those in the control treatment. Previous research indicated that under low light conditions, plant branches and leaves tend to be thin. However, with increased DLI, the main stem thickens, leaves broaden, etiolation is mitigated, and the plant structure becomes more compact. Elevating the DLI within a certain range under low light conditions was shown to foster leaf growth and morphological development[36,37]. This effect was also observed in tomatoes, where an increase in supplemental light intensity from 30 μmol/(m^2·s) to 90 μmol/(m^2·s) significantly boosted the number of leaves and leaf area[37]. In addition, applying LED lights with a wide spectral range also promoted plant growth. In greenhouses, supplementing with white LED light significantly increased the leaf length and width of lettuce[38,39]. For *Adenophora triphylla* (Thunb) seedlings, using LEDs with a red-to-blue light ratio of 4:1 for supplemental lighting led to a significant increase in stem thickness and enhanced seedling quality[40], with the analysis attributing these results to the high proportion of red and blue light in LEDs being conducive to stomatal development and photosynthesis.

5.3 Fruit yield and quality

Appropriate temperatures significantly enhanced strawberry growth and yield. In this study, the LED supplemental lighting strategy increased the canopy temperature of strawberries by 1°C-2°C under low-temperature conditions. Conversely, light supplementation was avoided under high temperature and light intensity conditions to minimize potential heat stress damage. The study found that low temperatures altered cell permeability, reduced photosynthesis, and potentially affected pollen quality, leading to fruit malformation[41]. Additionally, high-temperature environments likely caused a reduction in the flowering period of strawberries and a decrease in another dehiscence time, thereby adversely affecting yield[42]. The optimal growth temperature for strawberries was around 15°C-25°C[43]. During periods of LED supplemental lighting, especially in overcast and rainy conditions, the average daytime temperature often fell below 15°C. At such times, supplemental lighting raised the environmental temperature to a range conducive to strawberry growth. The elevation of canopy temperature promoted the accumulation of growing degree days in strawberry plants, which was crucial for the plants to complete specific growth stages or reach certain developmental phases. An increase in effective growing degree days generally led to an increase in yield[44]. Generally, a 1% increase in light input led to a 1% increase in yield. In this study, the light intensity in the LED supplemental lighting treatment was increased by 28.8%, which correspondingly resulted in a 31.8% increase in yield, suggesting a direct relationship between yield increase and accumulated temperature.

LED supplemental lighting extended the light duration during the low-light conditions of spring and winter, enhancing the yield and quality of strawberries. In Beijing, the duration of sunshine from February to April ranges from 9 to 11 h. In this study, the photoperiod was extended to 14 h, thereby prolonging the photosynthesis duration. 2 months after implementing supplemental lighting, strawberries exhibited significant increases in yield, soluble solids content, and sugar-acid ratio. A study conducted in a greenhouse on watermelon seedlings found that 12 and 16 h of supplemental lighting resulted in increased biomass and higher soluble sugar content compared to 8 h of lighting and the absence of supplemental lighting[45]. In an experiment with tomatoes, 16 h of LED lighting per day improved leaf gas exchange, increasing individual tomato weight and yield, with a 16% rise in soluble solids content[16]. For lettuce grown in greenhouses, extending the supplemental lighting period from 12 to 21 h resulted in a 28% increase in dry weight[46]. These studies indicate that extending light duration significantly boosts crop yield. The extension of lighting primarily occurred between 18:00 and 21:00. Researchers found that compared to 3 h of morning supplemental lighting, 3 h of evening lighting significantly increased soluble sugars and decreased organic acids in tomato fruits, improving flavor quality[47], consistent with the sugar-acid ratio increase in our study. Morning supplemental light may have promoted sucrose breakdown, accelerating its conversion to fructose and glucose[48].

6 Conclusions

This study proposed an hourly light integral (HLI)-based LED supplementary light strategy to the necessary daily light integral (DLI) for plant growth, while maintaining optimal light intensity and temperature under varying weather conditions. In the greenhouse strawberry experiment, the DLI in the supplemental lighting treatment was stabilized at an appropriate level compared to the control treatment. The canopy temperature of strawberry plants increased by 1°C to 2°C under supplemental lighting, and there was a significant enhancement in stem thickness, leaf count, leaf length, and leaf width. The yield of strawberries in the supplemental lighting treatment reached 115.5 g per plant, representing a 32% increase compared to the control. Additionally, the soluble solids content and the sugar-acid ratio of the fruits increased by 21% and 33%, respectively. The comprehensive assessment suggested that the greenhouse LED supplemental lighting strategy based on HLI offers a novel solution for regulating supplemental lighting in greenhouses during the winter and spring seasons.

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