Enhancing transplant quality by optimizing LED light spectrum to advance post-transplant runner plant propagation in strawberry

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Abstract: Light quality is a critical determinant in controlling the quality of strawberry transplants in plant factories with artificial lighting (PFALs). However, the impact of full-spectrum LEDs with varying red-to-blue ratios on the growth and biomass accumulation of strawberry transplants remains inadequately explored. Moreover, the influence of the strawberry transplants obtained on runner plant propagation in greenhouses post-transplanting is unclear. For this reason, this study utilized full-spectrum LEDs (white LEDs and white and red LEDs) with red-to-blue ratios of 0.9 (W0.9), 1.5 (WR1.5), 2.0 (W2.0), and 2.9 (WR2.9) for producing strawberry transplants in the PFAL over a period of 39 d. Subsequently, ten randomly selected transplants from each above treatment were planted as mother plants in a Chinese solar greenhouse for runner plant propagation, continuing for 98 d. These treatments were named as M-W0.9, M-WR1.5, M-W2.0, and M-WR2.9, respectively. Results indicated that the total leaf area of transplants in W2.0 was 1.2 times greater than those in W0.9 and WR2.9, exceeding 300 cm². Conversely, the net photosynthetic rate and F_v/F_m of strawberry transplant leaves were significantly higher in W0.9 compared with other treatments, declining with increasing red-to-blue ratio. In terms of biomass and morphological attributes, transplants in W2.0 exhibited higher fresh mass (17.2 g), leaf count (7 per plant), crown diameter (9.9 mm), and crown dry mass (0.27 g) than other treatments. Therefore, the strawberry transplant quality in W2.0 was significantly better than that of the other treatments. Moreover, shoot dry mass of strawberry mother plants in M-W2.0 was 1.4 and 1.3 times greater than those in M-W0.9 and M-WR2.9, respectively. The number of total runner plants and three-leafed runner plants produced in M-W2.0 were 1.9 times higher than those in M-W0.9, averaging 21 and 18 per plant, respectively. And mother plants in M-W2.0 produced 7 runners per plant, resulting in increased runner plant numbers. In conclusion, full-spectrum LEDs with a red-to-blue ratio of 2.0 enhanced the quality of strawberry transplants and significantly promoted runner plant propagation in greenhouses post-transplanting, and can be recommended as effective light sources for strawberry transplant production in PFALs.

Keywords: strawberry, LED light quality, transplant quality, runner plant propagation

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1 Introduction

Strawberry (*Fragaria×ananassa* Duch.) is a globally significant cash crop, widely cultivated across various regions. The total strawberry production in China has exceeded 4.2 million tons in 2023, accounting for 40.2% of the global output, while the yield per unit area was only 49.6% of that of the United States[1]. In recent years, the annual harvested area in China has surpassed 120 000 hm², with a demand for approximately 14.4 billion transplants each year, indicating substantial market potential[2]. The transplant and cultivation phases of strawberry production are distinctly separated in practice, with the transplant period playing a crucial role in determining transplant quality, survival rates, and the ultimate quality of the harvested fruit[3]. Enhancing transplant quality is therefore essential for advancing the strawberry industry. One effective approach to achieve this is through the application of LED lighting technology during the transplant phase, which allows precise control of environmental conditions, ultimately improving both fruit yield and the propagation of runner plants.

Since the early 21st century, plant factories have been commercially utilized for the production of fruit, vegetable transplants, flowers, and ornamental plants[4]. LEDs have become increasingly favored in these settings due to their high electro-optical conversion efficiency, low energy consumption, and the ability to precisely control the light spectrum[5]. Early LED systems primarily employed red and blue light combinations, given that these wavelengths have a photon efficacy of up to 4.1 μmol/J, significantly higher than other spectrum combinations[6]. Additionally, red and blue light are predominantly absorbed by chlorophyll, which is crucial for photosynthesis[7]. Studies have shown that specific red-to-blue light ratios, such as R7:B3[8]and R2:B1[9], can significantly enhance leaf area, dry mass, and compactness of tomato seedlings. However, plant responses to light quality are complex and vary among species. Full-spectrum LEDs, which include a broader range of wavelengths, have increasingly replaced narrow-spectrum LEDs in crop production in PFALs. Full-spectrum LEDs, rich in green light, play an important role in plant physiological activities, particularly in enhancing canopy productivity[10]. Research has demonstrated that full-spectrum white

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light, as well as combinations of white and red light, can effectively increase the dry mass of entire plants in species such as chili pepper[11] and snapdragon[12]. Furthermore, full-spectrum LEDs are better suited for visual diagnostics of plant health, making them increasingly popular in transplant production[12]. Despite this progress, there remains a need for further research into the effects of full-spectrum LEDs on the growth and development of fruit and vegetable transplants, particularly strawberries.

Vegetative propagation via runners is the primary method of asexual propagation for strawberries, which produces offspring with the desirable traits of the mother plants[13]. The primary goal of this process is to produce a sufficient number of runner plants. The quality of strawberry transplants is a critical factor in achieving this goal. High-quality transplants are characterized by attributes such as high biomass, large crown diameter, expansive leaf area, and a short production cycle[14]. Thus, transplant production and runner plant propagation are both indispensable steps in meeting the rising demand for strawberry transplants. Although considerable research has been conducted on the impact of LED light quality on strawberry plant growth and development, most studies have focused on runner plant propagation[15,16]. Additionally, the crown diameter of transplants has been shown to significantly influence the yield and quality of strawberry fruits post-transplantation[17,18], with a minimum standard of 8 mm being suggested for transplant crown diameter. However, the specific impact of transplant quality on runner plant propagation in greenhouse conditions remains unclear.

Therefore, this study employed white LEDs and white and red LED combinations with varying red-to-blue ratios to influence biomass accumulation and morphological development during the strawberry transplant stage. The subsequent impact of these transplants on runner plant propagation effectiveness in greenhouse cultivation was then assessed. The aim of this research is to identify the optimal LED light qualities for producing high-quality strawberry transplants and to elucidate the key indicators that influence post-transplant growth and runner plant propagation. These findings will provide valuable guidance for optimizing light environments in PFALs to enhance strawberry transplant production.

2 Materials and methods

2.1 Plant materials and environmental conditions

The experiment was conducted in the LED plant factory experimental room and Chinese solar greenhouse of China Agricultural University (116.3E, 40.0N). The strawberry variety used was 'Akihime'. Eighty unrooted runner plants (crown diameter: 6.2±0.4 mm; fresh mass: 3.48±0.42 g/plant; dry mass: 1.08±0.18 g per plant) were uniformly inserted into 32-hole standard cavity trays (L×W×H 540 mm×280 mm×60 mm) filled with a mixture of vermiculite and perlite (1 V:1 V) to obtain transplants. The photosynthetic photon flux density (PPFD) at the canopy of the transplants in each experiment was adjusted to about 90 μmol/(m^2·s) from day 1 to day 8 after the start of the experiment. During the above period, the irrigation was fresh water to water through the substrate every day; and on day 9, the LED lighting treatments were set up as listed in Table 1. The irrigation nutrient solution was prepared using the Japanese Yamazaki formula (Table 2), and EC and pH were maintained in the ranges of 0.6 to 0.8 mS/cm and 6.0 to 6.5, respectively, to water through the substrate every day. The environmental parameters were set as follows: air temperature was controlled at 25°C±1°C in the light period and 20°C±1°C in the dark period; relative humidity was 75%±10%; and CO_2 concentration was controlled at 800±50 μmol/mol in the light period and not in the dark period. The experimental period was 39 d.

Table 1 LED lighting treatment settings

LED lighting treatment	Red-to-blue ratio	PPFD/μmol·m^{-2}·s^{-1}	Photoperiod/h·d^{-1}
W0.9	0.9	270	16
WR1.5	1.5		
W2.0	2.0		
WR2.9	2.9		

Table 2 Yamazaki strawberry formulation

Reagents	Mass concentration/ mg·L^{-1}	Reagents	Mass concentration/ mg·L^{-1}
KNO_3	303.0	H_3BO_3	1.13
$Ca(NO_3)_2·4H_2O$	236.0	$MnSO_4·H_2O$	0.61
$MgSO_4·7H_2O$	123.0	$ZnSO_4·7H_2O$	0.09
$NH_4H_2PO_4$	57.5	$CuSO_4·5H_2O$	0.04
DTPA-Fe-7	28.6	$(NH_4)_6 Mo_7O_{24}·4H_2O$	0.01

Strawberry transplants obtained under each of the above treatments were planted in the Chinese solar greenhouse and used as mother plants for runner plant propagation. In one treatment, ten strawberry transplants (about 7 leaves per plant, crown diameter of 10 mm) were planted in two plastic pots (L×W×H 520 mm×260 mm×180 mm), respectively, with a substrate ratio of charcoal: vermiculite:perlite=1 V:1 V:1 V at a spacing of 15 cm, and irrigated with drip arrows using the same nutrient solution formulation as in the above experiments, at a rate of 150 mL/d per plant. The pots were placed on a cultivation stand 1.0 m above the ground. During the experiment, diseased leaves, old leaves, and flower buds were removed from the strawberry plants. The temperature and humidity changes in the greenhouse during the experiment are shown in Figure 1. The experimental period was 98 d.

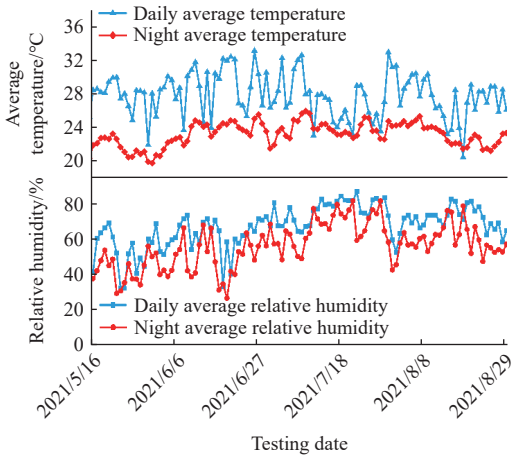


Figure 1 Temperature and relative humidity changes in the greenhouse during the experiment

2.2 LED lighting treatments

White LEDs and white and red LEDs with red-to-blue ratios of 0.9 (W0.9), 1.5 (WR1.5), 2.0 (W2.0), and 2.9 (WR2.9), respectively, mounted 15 cm above the plant canopy were used for the artificial light lamps, and the information of the lamps used is listed in Table 3. The spectrum distribution of LEDs in the range of 300-800 nm was measured at the canopy of the transplants in each treatment using a fiber optic spectrometer (AvaField-2, Avates, Apeldoorn, the Netherlands). According to the spectrum

distributions, the photon flux densities of ultraviolet light (UV, wavelength 300-399 nm), blue light (B, wavelength 400-499 nm), green light (G, wavelength 500-599 nm), red light (R, wavelength 600-699 nm), and far-red light (FR, wavelength 700-800 nm) were calculated separately (Figure 2; Table 4). Subsequently, nine measurement points were selected at the canopy and their PPFD were measured using the quantum meter (LI-250A, LI-COR Inc., US) and were 272±17, 264±18, 277±11, and 269±20 μmol/(m^2·s), respectively. Six transplants planted in the PFAL were randomly selected from each treatment for index measurements. Five strawberry plants planted in the greenhouse were selected for measurements during and after the experiment. The treatments here were named M-W0.9, M-WR1.5, M-W2.0, and M-WR2.9, respectively.

Table 3 Information of LED plant growth lamps

Name	Model	Characteristics	Manufacturer
White LEDs (W0.9)	W-LED-18W-6500K	6500 K white LED, 1.2 m T5 tube	Beijing Lighting Valley Technology Co.
White and red LEDs (WR1.5)	WR-LED5/1-16W	6500 K white LED+660 nm red LED for 5: 1 ratio, 1.2 m T5 tube	
White LEDs (W2.0)	W-LED-18W-4000K	4000 K white LED, 1.2 m T5 tube	
White and red LEDs (WR2.9)	WR-LED5/1-16W	4000 K white LED+660 nm red LED for 5: 1 ratio, 1.2 m T5 tube	

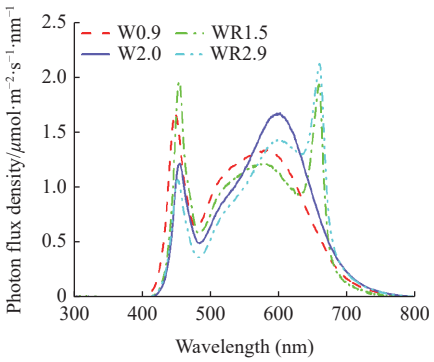


Figure 2 Spectrum distribution in LED lighting treatments with a PPFD of 270 μmol/(m^2·s)

Table 4 Spectrum characteristics in LED lighting treatments with a PPFD of 270 μmol/(m^2·s)

Wavelength/nm		Spectrum composition/%			
		W0.9	WR1.5	W2.0	WR2.9
300-800 nm		100.0	100.0	100.0	100.0
UV light	(300-399 nm)	0.0	0.0	0.0	0.0
Blue light	(400-499 nm)	27.5	23.2	17.9	15.3
Green light	(500-599 nm)	45.5	39.3	44.2	38.2
Red light	(600-699 nm)	24.8	35.4	35.1	43.9
Far-red light	(700-800 nm)	2.2	2.1	2.7	2.6
R:B		0.9	1.5	2.0	2.9
R:Fr		11.3	16.9	12.8	16.7

Note: W0.9, WR1.5, W2.0, and WR2.9 indicate the red-to-blue ratio of 0.9, 1.5, 2.0, and 2.9, respectively.

2.3 Measurement parameters

2.3.1 Growth characteristics of strawberry transplants and mother plants

The related growth index measurements of strawberry transplants in PFALs and mother plants in the greenhouse were referred to in this section. The number of strawberry transplant leaves was counted at the end of the experiment. For strawberry mother plants in the greenhouse, the number of leaves and runners were counted every other week, and the total number of runner plants produced by the mother plants as well as the number of three-leafed runner plants were counted. At the end of the experiment, the crown diameter was measured using vernier calipers. All leaves of plants were scanned using a scanner (LiDE 110, Canon Inc., Beijing, China) for calculating the leaf area through image processing. The shoots and roots of the plants were separated, where the shoots were separated into parts such as leaves, petioles, and crown. The crown, as a shortened stem, is the part of a strawberry plant that connects the roots and shoots. In this experiment, the remaining cylindrical part after removing the roots, leaves, and runners in sequence is called the crown. Then its fresh and dry mass were measured according to the operation. The fresh mass of each part was measured separately using a centesimal balance. The shoots were dried at 105°C for 3 h, then dried at 80°C to constant mass, and the dry mass was measured by an electronic analytical balance (FA1204B, Bioon Group, Shanghai, China).

2.3.2 Measurement of leaf chlorophyll content

Two small round leaves (approximately 0.05 g) were taken from within the third unfolded leaf from the central leaf of the plant using a punch. The leaves tested were placed in a 15 mL test tube and fully macerated by adding a 10 mL acetone solution with a volume ratio of 80%. The absorbance of the chlorophyll extract at 663 nm and 645 nm was measured using a spectrophotometer (UV-3150, Shimadzu Manufacturing, Japan), and the chlorophyll content was calculated according to Arnon's equations[19].

$$\text{Chlorophyll a content}\,(\text{mg}\cdot\text{g}^{-1}) = \frac{(12.72A_{663} - 2.59A_{645})\cdot V}{W} \quad (1)$$

$$\text{Chlorophyll b content}\,(\text{mg}\cdot\text{g}^{-1}) = \frac{(22.88A_{645} - 4.67A_{663})\cdot V}{W} \quad (2)$$

where, A_{663} and A_{645} are the absorbance of chlorophyll solution at wavelengths 663 nm and 645 nm, respectively; V is the volume of the extract, mL; W is the fresh mass of leaves weighed at the time of extraction, g.

2.3.3 Photosynthetic and chlorophyll fluorescence characteristics of plant leaves

The net photosynthetic rate and chlorophyll fluorescence were measured in the third unfolded leaf from the central leaf of the plants at the end of the experiment. The net photosynthetic rate was measured using a portable photosynthesis system (LI-6400XT, LI-COR Biosciences, Lincoln, NE, USA) with the following parameters set in the leaf chamber. For strawberry transplants, the leaf chamber parameters were set at 270 μmol/(m^2·s) for PPFD and 800 μmol/mol for CO_2 concentration, and for strawberry mother plants in the greenhouse, the leaf chamber parameters were set at 400 μmol/(m^2·s) for PPFD and 400 μmol/mol for CO_2 concentration. The rest of the parameters in the leaf chamber were kept the same, with the leaf temperature at 25°C and the air flow rate at 500 μmol/mol. A chlorophyll fluorescence monitoring system (PEA, Hansatech Instruments Ltd., Norfolk, UK) was used to measure the chlorophyll fluorescence of the leaves dark-adapted for more than half an hour.

2.3.4 Statistics and analysis of data

Statistical analysis and graphing of data were done using SPSS 23.0 software and Microsoft Excel 2016, respectively. The ANOVA of the data was based on Duncan's multiple comparison method for comparison of means (p<0.05). The results were expressed in the form of "mean±standard deviation".

3 Results

3.1 Morphology and biomass of strawberry transplants

Full-spectrum LEDs with different red-to-blue ratios significantly affected crown diameter and leaf morphology of strawberry transplants (Table 5). The number of leaves and petiole length of transplants were not significantly affected by different LED light qualities, and the number of leaves could reach about 7 per plant. The crown diameter in W2.0 was significantly higher than that in W0.9 and WR1.5, at 9.9 mm. The single leaf area showed a trend of increasing and then decreasing with the red-to-blue ratio, and the total leaf area showed the same trend. The total leaf area in W2.0 exceeded 300 cm^2, which was 1.2 times higher than that in W0.9 and WR2.9, respectively. LED light quality had a greater effect on the shoot biomass of transplants, while there was no significant effect on the accumulation of biomass in the roots (Table 6). Both shoots and total plant biomass of transplants showed an increasing and then decreasing trend with the increase of the red-to-blue ratio. The shoot fresh mass and total plant dry mass of transplants in W2.0 were significantly higher than other treatments, at 13.1 g and 4.2 g, respectively. It is worth noting that the dry mass of the transplant crown in W2.0 increased by 23% compared with that of W0.9, whereas it was not significantly different from that of WR2.9 (Figure 3). The morphology and biomass of transplants in W2.0 were optimal.

Table 5 Effect of LED light quality on the morphology of strawberry transplants

LED lighting treatment	Leaf number per plant	Petiole length/cm	Crown diameter/mm	Single leaf area/cm^2	Total leaf area/cm^2
W0.9	7.2±0.8^{ns}	15.9±1.1^{ns}	9.2±0.5^{b}	36.4±2.3^{b}	258.4±22.5^{b}
WR1.5	6.7±0.6^{ns}	17.3±0.5^{ns}	9.2±0.5^{b}	37.4±4.7^{ab}	279.1±9.4^{ab}
W2.0	7.3±1.2^{ns}	16.4±0.9^{ns}	9.9±0.3^{a}	42.0±1.4^{a}	301.9±27.5^{a}
WR2.9	6.8±0.4^{ns}	17.0±1.5^{ns}	9.7±0.2^{ab}	41.4±1.4^{ab}	259.5±19.6^{b}

Note: Different letters in the same column indicate significant differences (p<0.05). ns represents no significant difference in the same column. All values are "mean ± standard deviation". Same as below.

Table 6 Effect of LED light quality on shoot and root biomass of strawberry transplants

LED lighting treatment	Shoot fresh mass/g	Root fresh mass/g	Total fresh mass/g	Shoot dry mass/g	Root dry mass/g	Total dry mass/g
W0.9	10.73±1.38^{b}	3.20±0.70^{ns}	14.14±2.44^{b}	2.78±0.40^{b}	0.50±0.12^{ns}	3.28±0.50^{b}
WR1.5	12.22±0.27^{ab}	4.21±0.67^{ns}	16.44±0.83^{ab}	2.97±0.34^{ab}	0.54±0.12^{ns}	3.52±0.45^{ab}
W2.0	13.13±1.07^{a}	4.08±1.05^{ns}	17.21±1.89^{a}	3.51±0.41^{a}	0.67±0.15^{ns}	4.18±0.55^{a}
WR2.9	11.78±0.49^{ab}	4.42±0.63^{ns}	16.20±0.49^{ab}	2.98±0.33^{ab}	0.67±0.26^{ns}	3.65±0.58^{ab}

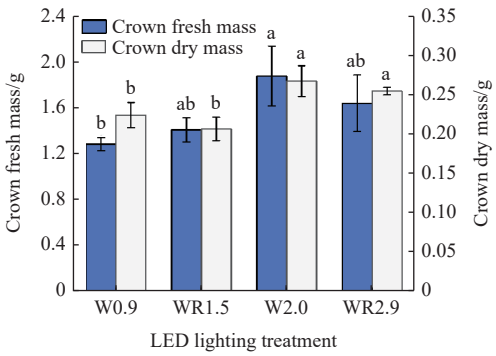


Figure 3 Effect of LED light quality on crown biomass of strawberry transplants

3.2 Effects of LED light quality on chlorophyll content, photosynthesis, and chlorophyll fluorescence of strawberry transplant leaves

The LEDs with a low red-to-blue ratio favored the increase in leaf chlorophyll content and net photosynthetic rate (Figure 4). The chlorophyll *a* content of strawberry transplant leaves in W0.9 was significantly higher than the rest of the treatments, whereas there was no significant difference in the chlorophyll *b* content among the treatments. W0.9 increased the total chlorophyll content by increasing the chlorophyll *a* content in order to increase the light harvesting ability of leaves. Consistently, the net photosynthetic rate of leaves in W0.9 was significantly higher than the rest of the treatments. The net photosynthetic rate of leaves in W0.9 was increased by 14% to 9.9 μmol/(m^2·s) compared with WR2.9. The F_v/F_m of the transplant leaves in different treatments were around 0.83 with no significant difference. PI_{abs} was the more sensitive chlorophyll fluorescence index; its value tended to decrease with the increase of red-to-blue ratios. The PI_{abs} in WR2.9 was only 69% of that of WR1.5. This suggests that LEDs with a low red-to-blue ratio can improve the net photosynthetic rate of leaves by increasing chlorophyll content while favoring the operation of the photosynthetic system.

3.3 Changes in biomass and leaf photosynthesis of strawberry transplants after transplanting

Strawberry transplants were planted in the greenhouse and then used as mother plants for runner plant propagation. The shoot dry mass of strawberry mother plants in M-W2.0 were 1.4 and 1.3 times higher than those in M-W0.9 and M-WR2.9, respectively (Table 7). There was no significant difference in the root biomass of mother plants among the treatments. The shoot biomass of mother plants increased and then decreased with the increase of the red-to-blue ratio, which was in line with the trend of biomass change of transplants. The crown diameter of strawberry mother plants exceeded 10 mm in M-W2.0 and M-WR2.9, which was significantly higher than that of the treatments with low red-to-blue ratios (Table 8). Meanwhile, the fresh mass of crowns of mother plants reached the extreme value of 5.7 g in M-W2.0. The dry mass of crowns in M-W2.0 and M-WR2.9 were not significantly different, but both were significantly higher than the remaining two treatments (Table 8). During the experiment, the light environment in the greenhouse was more homogeneous, and there was no significant difference in the net photosynthetic rate of the strawberry mother plant leaves, and F_v/F_m remained above 0.82 (Figure 5). This indicated that the high biomass accumulation of strawberry mother plants in M-W2.0 treatment was due to their high-quality transplants.

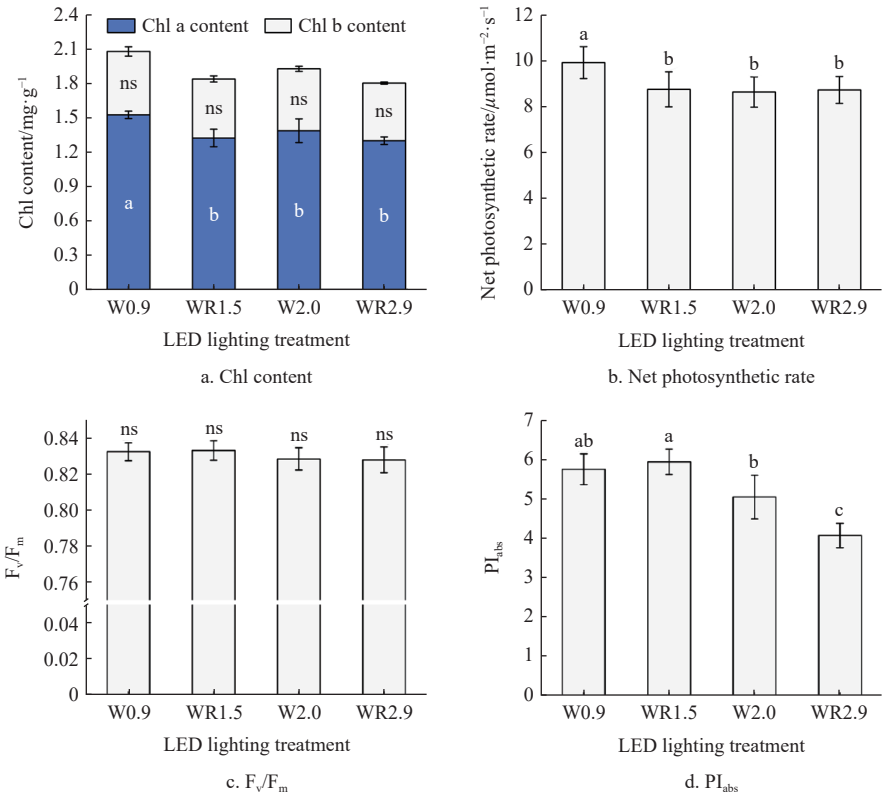


Figure 4 Effect of LED light quality on chlorophyll (a), photosynthesis (b), and chlorophyll fluorescence (c, d) in leaves of strawberry transplants

Table 7 Changes in shoot and root biomass of strawberry mother plants in different LED lighting treatments

LED lighting treatment	Shoot fresh mass/g	Root fresh mass/g	Shoot dry mass/g	Root dry mass/g
M-W0.9	35.33±0.51^{b}	4.80±0.62^{ns}	6.48±0.93^{b}	0.90±0.11^{ns}
M-WR1.5	35.78±3.03^{b}	4.57±0.90^{ns}	6.72±0.53^{b}	0.93±0.09^{ns}
M-W2.0	46.32±8.19^{a}	4.86±0.73^{ns}	9.08±1.49^{a}	1.03±0.16^{ns}
M-WR2.9	37.04±4.56^{b}	5.41±0. 98^{ns}	7.22±0.88^{b}	0.78±0.35^{ns}

Table 8 Changes in crown diameter and crown biomass of strawberry mother plants

LED lighting treatment	Crown diameter/mm	Crown fresh mass/g	Crown dry mass/g
M-W0.9	9.8±0.6^{b}	3.07±0.34^{c}	0.65±0.03^{b}
M-WR1.5	9.9±0.2^{b}	3.15±0.16^{c}	0.63±0.04^{b}
M-W2.0	10.3±0.3^{a}	5.74±0.87^{a}	0.89±0.07^{a}
M-WR2.9	10.5±0.8^{a}	4.45±0.58^{b}	0.87±0.06^{a}

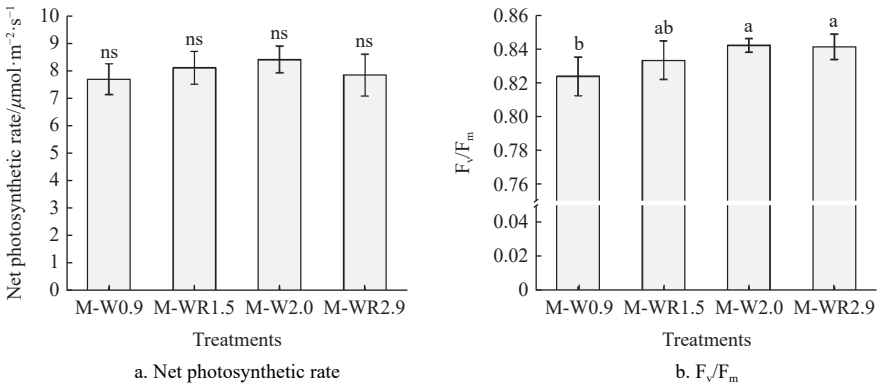
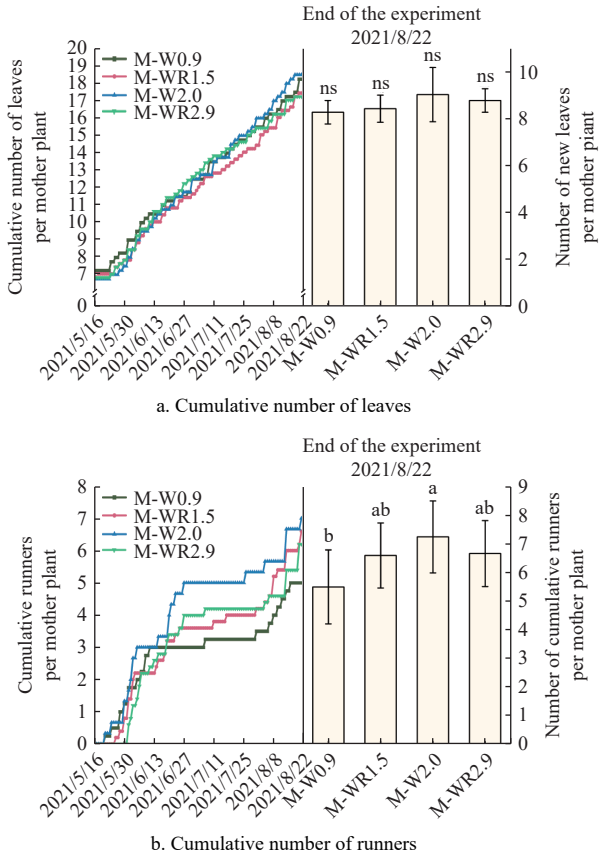


Figure 5 Effect of photosynthesis (a) and chlorophyll fluorescence (b) in leaves of strawberry mother plants

3.4 Runner plant propagation of strawberry mother plants

The cumulative number of unfolded leaves of strawberry mother plants in different LED lighting treatments tended to increase linearly with time during runner plant propagation. Finally, the number of new leaves of strawberry mother plants remained around 9, with no significant difference (Figure 6). However, it can be seen that in mid-July, the rate of leaf emergence of strawberry mother plants in M-W2.0 was slightly higher than that of other treatments. The number of runners that emerged from M-W2.0 was significantly higher than that in M-W0.9, amounting to 7 per plant, which was not significantly different from other treatments. However, the number of runners produced by strawberry mother plants in M-W2.0 was significantly higher than other treatments after the beginning of June. Early runner production helped to produce more runner plants (Figure 6). The number of three-leafed runner plants produced by mother plants in M-W2.0 was significantly higher than that under other treatments, with an increase of 94% and 22% over the M-W0.9 and M-WR2.9, respectively. In addition, the number of total runner plants in M-W2.0 was not significantly higher than that of M-WR2.9, reaching

21 per plant (Figure 7). Thus, strawberry mother plants in M-W2.0 promoted runner plant propagation by producing runners earlier and more frequently.



a. Cumulative number of leaves

b. Cumulative number of runners

Figure 6 Trends of leaves (a) and runners (b) extracted from strawberry mother plants in LED lighting treatments over time

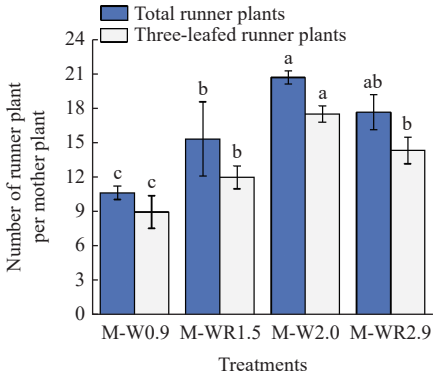


Figure 7 Number of runner plants produced by strawberry mother plants in different LED lighting treatments

4 Discussion

4.1 Full-spectrum LEDs with a higher red-to-blue ratio favor strawberry transplant biomass accumulation

Plant biomass[20], crown diameter[18], and leaf number[21] are the primary indicators used to assess the quality of strawberry transplants. In plant factories, where LEDs serve as the exclusive light source, the spectrum composition of the LEDs plays a critical role in modulating the quality of transplants. The findings from this study indicate that the total dry mass of strawberry transplants in white LEDs with a red-to-blue ratio of 2.0 (W2.0) was significantly higher than that in other treatments, reaching 4.2 g (Table 5). The accumulation of biomass in plants is primarily determined by the net photosynthetic rate of the leaves and the total leaf area influencing the plant's light interception capacity[22]. Compared with monochromatic blue light, red light has been shown to decrease photosynthetic system activity by inhibiting the linear electron transfer essential for the functioning of PS II and PS I, which are crucial for photosynthesis[23]. However, the addition of an appropriate amount of blue light can mitigate this inhibitory effect on PS II[24]. This process is further influenced by the expression of photosynthesis-related genes; specifically, blue light upregulates the expression of CP47 and CP43, which are involved in the repair of PS II [25]. Wu et al.[26] demonstrated that white light with a lower percentage of red light (23%) significantly increased the net photosynthetic rate and maintained higher stomatal conductance in strawberry leaves compared with white light with higher red light proportions (43% and 59% red light, respectively). Similarly, the present study found that white LEDs (W0.9) with 24.8% red light significantly enhanced the net photosynthetic rate of strawberry transplant leaves, leading to a 41% increase in PI_{abs} compared with WR2.9 (Figure 4). Additionally, chlorophyll content in leaves is another factor that affects the photosynthetic rate of plant leaves, and the blue light promoted chlorophyll accumulation in plant leaves[7]. Consequently, full-spectrum LEDs with a lower proportion of red light are more conducive to enhancing photosynthesis in strawberry leaves.

Red light promotes stem elongation and stimulates key morphological changes in plants, including hypocotyl elongation, increased plant height, and expanded leaf area[27]. In the present study, it was observed that increasing the red-to-blue ratio in full-spectrum LEDs effectively enhanced the leaf area of strawberry transplants. Specifically, the leaf area in W2.0 was 1.2 times greater than that in W0.9 and WR2.9 (Table 5). He et al.[28] highlighted that the impact of LED light quality on plant productivity may be more closely associated with induced changes in leaf morphology rather than direct alterations in photosynthetic performance. Consequently, leaf area expansion is critical for optimizing light interception, which in turn drives biomass accumulation. In this experiment, compared with the net photosynthetic rate, the contribution of leaf area to the increase of total plant biomass occupied the main position. The increase in leaf area in W2.0 compensated for the adverse effects caused by the decrease in net photosynthetic rate on total biomass. Notably, the proportion of biomass allocated to the crown in strawberry transplants remained consistent across the different LED lighting treatments, averaging around 6%. However, the substantial increase in total biomass in W2.0 also led to a corresponding increase in crown dry mass (Figure 3). Given that a crown diameter exceeding 8 mm is the internationally recognized minimum standard for strawberry transplants, the crown diameters in this study, which reached approximately 10 mm after 39 d under each LED lighting treatment, represent a significant improvement in transplant quality. Therefore, full-spectrum LEDs with a higher red-to-blue ratio (W2.0) not only promoted biomass accumulation but also optimized overall transplant quality, making them highly effective for strawberry transplant production.

4.2 Transplant quality significantly affects the runner plant propagation of strawberry mother plants after transplanting

High-quality transplants form the foundation for enhanced crop performance and increased profitability post-transplanting[18]. In the current study, it was observed that transplants produced in W2.0 exhibited superior performance compared with other treatments when subsequently planted in the greenhouse for runner plant propagation. Specifically, mother plants in W2.0 produced a total of

21 runner plants, including 18 three-leafed runner plants (Figure 7), significantly higher than that observed in other treatments. Moreover, the final count of runners generated by mother plants in M-W2.0 was markedly greater than those in M-W0.9 (Figure 6). The W2.0 also induced an earlier onset of runner production, which, combined with the increased runner number, substantially boosted the total number of runner plants produced by strawberry mother plants in M-W2.0. Strawberry plant vigor is influenced by numerous factors, with the crown diameter of transplants at the time of planting playing a critical role in determining subsequent production performance[29]. Crown diameter is a clear indicator of transplant quality, while biomass provides a more comprehensive measure of their overall vigor. The crown of a strawberry plant serves as a vital reservoir for carbohydrates, with the transport of fructose, glucose, and sucrose being integral to plant development[30]. A crown with a large diameter and high biomass has a greater capacity to mobilize these reserves, promoting the emergence of leaves and axillary buds, while temporarily increasing sugar content[31]. Notably, a positive correlation has been found between soluble sugar content in the crown and the number of runners produced, as elevated sugar levels facilitate the breaking of dormancy in axillary buds, thereby enhancing runner production[32]. In this study, the biomass of the strawberry transplant crowns in W2.0 was significantly higher than that of other treatments (Figure 3). This increased crown biomass is a key factor contributing to the earlier and more prolific runner production observed in M-W2.0, thereby improving the overall efficiency of runner plant propagation in this experiment.

In practical agricultural production, the use of frozen transplants is a common practice, particularly for optimizing the storage and management of strawberry transplants. This method is vital for ensuring flexible production schedules, especially in environments like PFALs that are capable of producing strawberry transplants year-round. The success of strawberry transplants in cold storage is largely dependent on the high content of assimilated products, particularly starch, stored within the phragmoplasts[33]. These reserves are crucial for the transplants' ability to rapidly resume growth post-transplanting. Given this context, the importance of crown biomass cannot be overstated. The findings of this study underscore that LED light quality has a profound impact on the morphology and biomass of strawberry transplants, with particular emphasis on crown diameter and crown biomass. These factors not only facilitate the successful cryopreservation of transplants but also provide a solid foundation for the efficient propagation of runner plants following transplantation.

5 Conclusions

Full-spectrum LEDs with a red-to-blue ratio of 2.0 were found to significantly enhance the quality of strawberry transplants, thereby promoting subsequent plant growth and runner plant propagation post-transplanting. The increase in the red-to-blue ratio within full-spectrum LEDs notably expanded the leaf area of strawberry transplants, a critical factor contributing to the observed increase in transplant biomass in this study. The production of high-quality transplants under these conditions played a pivotal role in facilitating efficient runner plant propagation after transplanting. Specifically, strawberry transplants grown in M-W2.0 produced a total of 21 runner plants in the greenhouse, representing a 94% increase compared with those grown in M-W0.9. This substantial increase in runner production was primarily attributed to the high biomass and robust crown development, which not only promoted earlier runner emergence but also increased the overall number of runners produced. Therefore, full-spectrum LEDs with a red-to-blue ratio of 2.0 are recommended as an artificial light source for optimizing strawberry transplant production in PFALs. In practical production, strawberry fruit production demands higher quality transplants, with key indicators including thick crowns and early flowering. Future research should delve into various LED light qualities to boost the biomass and crown diameter of strawberry transplants, while simultaneously inducing flower bud differentiation, to advance the time to market of strawberry fruits after transplant planting. Hence, leveraging LEDs with tailored spectrum compositions to selectively and strategically enhance transplant quality, based on production objectives or applications of strawberry or other crops, exemplifies the advantage of controllable environmental agricultural technologies like plant factories, poised to make a greater impact in actual production scenarios.

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