Effects of light intensity and photoperiod on runner plant propagation of hydroponic strawberry transplants under LED lighting

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Abstract: Vegetative propagation of strawberry (*Fragaria* × *ananassa* Duch.) in the plant factory with artificial lighting is considered as an effective approach to produce high-quality transplants. In this study, mother plants of 'Benihoppe' strawberry were grown hydroponically for 50 d under eight LED lighting treatments by combining four levels of light intensity (200, 250, 300 and 350 μmol/(m^2·s)) and two photoperiods (12 h/d and 16 h/d). Runner development, growth of runner plants, photon yield and energy yield in runners and runner plants were investigated to evaluate the strawberry propagation efficiency. Results indicated that length of runners decreased linearly with increasing daily light integral (DLI) under each photoperiod and was significantly shorter under photoperiod of 16 h/d. Runner elongation was inhibited by high DLI. Number of runners and runner plants formed by mother plants increased by 38.9% and 33.7%, when DLI increased from 8.6 to 11.5 mol/(m^2·d), respectively; however, no further increase was observed when DLI was higher than 11.5 mol/(m^2·d). Similar trends were found in crown diameter and biomass of primary and secondary runner plants. Negative impact of high DLI (20.2 mol/(m^2·d)) on photosynthetic capacity of runner plants was observed as a decrease in leaf net photosynthetic rate, potential maximum photochemical efficiency of PSII, and chlorophyll content. Furthermore, photon yield and energy yield in runners and runner plants decreased significantly with increasing DLI. Therefore, DLI in a range of 11.5-17.3 mol/(m^2·d) is beneficial to improve strawberry propagation efficiency and quality of runner plants, and 11.5 mol/(m^2·d) is optimal for the strawberry propagation of runner plants in the LED plant factory because of the higher photon and energy yields.

Keywords: hydroponic strawberry, vegetative propagation, daily light integral, photon yield

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1 Introduction

Commercial strawberry (*Fragaria* × *ananassa* Duch.) transplants are usually propagated vegetatively by runners. The runner plant propagation rate and plant quality are susceptibly influenced by environmental conditions such as temperature, photoperiod, diseases, and so on in the field and low-tech greenhouses[1-3]. An effective approach for vegetative propagation of high quality transplants is to produce in a plant factory with artificial lighting (PFAL) under precisely controlled environment[4,5]. Productivity of strawberry plug transplants in the PFAL was 110-140 times greater than that by using conventional propagation methods[6]. Generally, light-emitting diode (LED) light is used as the sole-source lighting for plant growth in the PFAL. Light intensity and photoperiod determine the daily light integral (DLI), which is closely related to electricity input for LED lighting. The electrical energy consumption of lighting is approximate 70% to 80% of total electricity consumption for year-round production in PFALs[7]. It is necessary to determine the optimal combination of light intensity and photoperiod for efficient production of strawberry transplants under LED lighting in PFAL.

High light intensity generally promotes runner formation and runner plant growth. In air-conditioned glasshouses, more runners were produced by mother plants when suitable light intensity during the day or the light intensity of the supplemental light for extending the photoperiod were increased[8]. In a closed transplant production system using fluorescent light, strawberry mother plants grown under 280 μmol/(m^2·s) produced more runners than those grown under 210 μmol/(m^2·s) and 140 μmol/(m^2·s), and runner plant growth was improved by increasing light intensity during strawberry transplant propagation[9]. Wu et al.[10] compared the effect of different light quality and light intensity on runner plant propagation of 'Toyonoka' strawberry plants under fluorescent light and found that cool white quality in color temperature of 6500 K and 5000 K with high light intensity (110-122 μmol/(m^2·s)) promoted runner formation and runner plant growth compared with warmer color quality in color temperature of 4000 K and 3000 K with lower light intensity (50-55 μmol/(m^2·s)). Furthermore, increasing light intensity for mother plants rather than runner plants was more effective in enhancing the growth of runner plants. Thus, the efficiency of strawberry propagation in a plant factory may be improved by decreasing light intensity for runner plants[11].

Photoperiod affects formation and elongation of runners. Everbearing strawberry 'Natsuakari' plants produced more runners under longer photoperiod than 10 h/d and 12 h/d[12]. The number of runners and runner plants per mother plant increased

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significantly when photoperiod was extended to 15 h/d by using fluorescent light with light intensity of approximately 1 μmol/(m^2·s)[13]. Strawberry runners and petioles differentiated and elongated under short-day had shorter length compared to those growing under long-day, resulting from shorter cell length and fewer number of cells[14,15].

Although the effect of light intensity on runner plant propagation in the plant factory by using fluorescent light has been investigated, the influence of photoperiod or the combined effects of light intensity and photoperiod still needs to be studied further, especially when using LED lights, which are expected to reduce the electricity costs[16,17]. Therefore, purpose of this study was to investigate the effects of light intensity and photoperiod on runner plant propagation of hydroponic strawberry under LED lighting.

2 Materials and methods

2.1 Plant materials and growth conditions

Strawberry 'Benihoppe' transplants, which are widely produced commercially in China, were chosen as plant material in this experiment. The micropropagated strawberry plants were acclimated in hydroponics. A total of 64 acclimated transplants having 3.3±0.5 leaves and 10.7±0.7 mm crown diameters were selected as mother plants for runner plant propagation. The mother plants were planted in two vertical hydroponic transplant propagation systems (Figure 1). Each system consists of four cultivation beds and one solution tank. Each hydroponic cultivation bed (1200 mm × 900 mm × 70 mm) had 117 planting holes (25 mm in diameter). In the central region of the bed, eight mother plants were planted, and the remaining planting holes were plugged with sponges (25 mm × 25 mm × 25 mm). During the experiment, runner plants at one-leaf stage were placed in a waterlogged sponge. Roots of runner plants gradually penetrated through the sponge and touched the nutrient solution in about three days. The runner plants were harvested at 50 days after planting the mother plants when the cultivation beds were fully covered with runner plants. Nutrient solution was prepared according to Yamasaki strawberry formula (N 77, P 15.5, K 117, Ca 40, Mg 12, S 16, Fe 2, Mn 0.2, B 0.2, Zn 0.02, Cu 0.01, Mo 0.005 mg/L) and continuously recirculated (5.5 L/min) among four cultivation beds and the solution tank in each hydroponic system. Electrical conductivity and pH of the nutrient solution were maintained at 0.6-0.8 mS/cm and 6.0-6.5, respectively. The nutrient solution was renewed every 7 days during the experiment. Air temperature in the growth chamber was maintained at (25±1)°C/(20±1)°C during light/dark period. Average daily relative humidity was 75%±10%. CO_2 concentration was enhanced to (800±50) μmol/mol during light period and without control during dark period.

2.2 Lighting treatments

Tube-type LED lights consisting of white chips and red chips (WR-LED5/1-16W, Beijing Lighting Valley Technology Company Ltd., China) were installed at 30 cm above the cultivation bed. The spectral distribution of LED lighting was measured under 15 cm from the lights in wavelength ranging from 300 nm to 800 nm using a fiber spectrometer (AvaField-2, Avantes Inc., The Netherland). The photon flux of lighting was composed of 0.1% ultraviolet (300-399 nm), 24.7% blue (400-499 nm), 43.6% green (500-599 nm), 29.7% red (600-699 nm) and 1.9% far red (700-800 nm) light, respectively. Eight lighting treatments were created by combinations of four levels of light intensity (200, 250, 300 and 350 μmol/(m^2·s)) and two photoperiods (12 h/d and 16 h/d) (Table 1). Each cultivation bed holding eight mother plants was exposed to one lighting treatment. Light intensities were measured at nine evenly distributed points at 15 cm below the LED lights using a portable quantum meter (LI-250A, LI-COR Biosciences Inc., USA). Four light intensity levels, 203±6, 247±10, 298±12, and 347±13 μmol/(m^2·s) were achieved by changing the number and location of LED lights.

Figure 1 Hydroponic strawberry transplant propagation system using LED lighting

Table 1 Lighting treatments created by combinations of four levels of light intensity (L) and two levels of photoperiod (H)

Treatment symbol	Light intensity /μmol·m^{-2}·s^{-1}	Photoperiod /h·d^{-1}	DLI /mol·m^{-2}·d^{-1}	Number of LED lights in each bed	Total power in each bed /W
L200-H12	200	12	8.6	7	106.4
L250-H12	250		10.8	9	136.8
L300-H12	300		13.0	11	167.2
L350-H12	350		15.1	13	197.6
L200-H16	200	16	11.5	7	106.4
L250-H16	250		14.4	9	136.8
L300-H16	300		17.3	11	167.2
L350-H16	350		20.2	13	197.6

Note: DLI represents daily light integral, DLI (mol/(m^2·d)) = light intensity (μmol/(m^2·s))×photoperiod (h/d)×3600 (s/h)×10^{-6}. L200-H12 represents light intensity of 200 μmol/(m^2·s) and photoperiod of 12 h/d.

2.3 Measurements and calculations

2.3.1 Growth characteristics of runners and runner plants

The number of runners formed by mother plants was counted every two days. The length of runners sprouting from the mother plant was measured every day using a ruler. At the end of the experiment, number of primary runner plants formed by mother plants, number of secondary runner plants originating from the primary runner plants, and number of tertiary runner plants formed from the secondary runner plants were counted, and total number of runner plants was calculated. Growth characteristics (crown diameter, leaf number, and dry weight) of the primary runner plants and secondary runner plants were determined. The crown diameter of runner plants was measured using a digital Vernier caliper. Leaf count was based on unfolded trifoliate leaves of runner plants. Runner plants were dried in an oven at a temperature of 105°C for 3 h and then at 70°C until constant weight. Dry weight of runner plants was measured using an electronic analytical balance (AX622ZH, Ohaus Instruments (Shanghai) Co., Ltd, China).

2.3.2 Net photosynthetic rate, chlorophyll fluorescence, and chlorophyll content

The third unfolded leaf from the central leaf of the mother plants and the primary runner plants were selected to measure net photosynthetic rate, chlorophyll fluorescence, and chlorophyll content at day 50. Net photosynthetic rate was measured using a portable photosynthesis system (LI-6400XT, LI-COR Biosciences Inc., USA) with a leaf chamber with red and blue LED light sources. In the leaf chamber, light intensity, air temperature, and CO_2 concentration were set at 400 μmol/(m^2·s), 25°C, and 800 μmol/mol, respectively. Chlorophyll fluorescence was measured using a chlorophyll fluorescence monitoring system (M-PEA, Hansatech Instruments Ltd., UK). Leaf chlorophyll was extracted in 80% acetone and absorbance of extracted solution were measured at 663 nm and 645 nm using a spectrophotometer (UV-3150, Shimadzu Corporation, Japan). Chlorophyll content was calculated according to Arnon's Equations[18].

2.3.3 Photon yield and energy yield in runners and runner plants

Photon yield and energy yield were calculated to assess the efficiency of electric light sources for cultivating crops in a plant factory[19]. Briefly, photon yield in runners is calculated as the number of runners produced per mole photons during the entire propagation period. And energy yield in runners is calculated as the number of runners produced per kilowatt-hour electricity. Similarly, photon yield and energy yield in runner plants are calculated based on the number of runner plants.

2.4 Statistical analysis

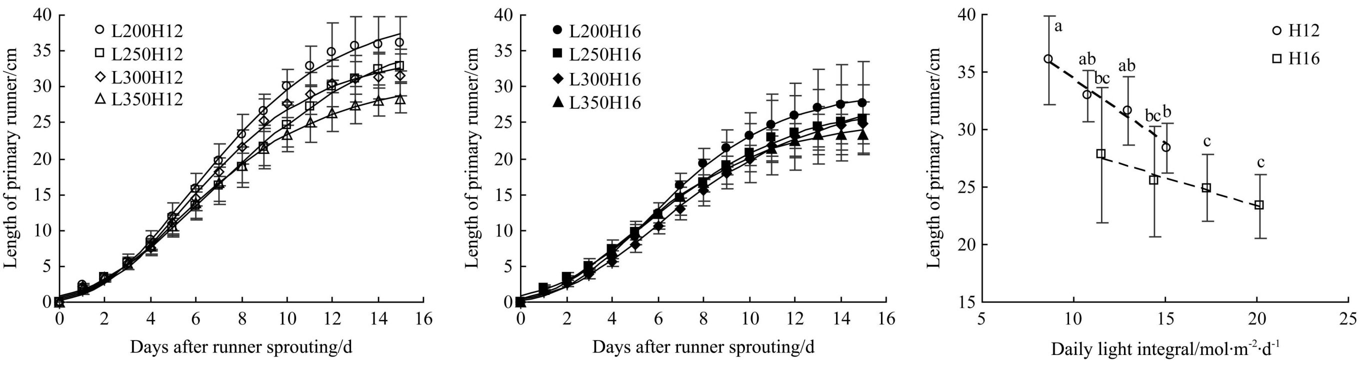
The experiments were repeated independently for three times. The data were shown as mean ± standard deviation (n=6). Statistical analysis was performed using SPSS 21.0 (IBM, Inc., Chicago, IL, USA). All data were analyzed for significance by analysis of variance (ANOVA) followed by the Duncan's multiple range test for mean separation at p≤0.05.

3 Results and discussion

3.1 Effects of light intensity and photoperiod on formation and elongation of runners

Runner length increased with time following the Gompertz growth model (Figures 2a and 2b). Around 15 d after sprouting, the runner length gradually stabilized, which means elongation gradually ceased. The runner tip started to develop into a primary runner plant. The final length of the primary runner, affected by light intensity and photoperiod, was longest (36.0 cm) at 200 μmol/(m^2·s) with photoperiod of 12 h/d and shortest (23.3 cm) at 350 μmol/(m^2·s) with photoperiod of 16 h/d. Length of runners decreased with increasing light intensity regardless of photoperiod. A similar result was reported by Kim et al.[9] that length of primary runner and secondary runner decreased as light intensity increased from 140 μmol/(m^2·s) to 280 μmol/(m^2·s). It is worth noting that the primary runner under 16 h/d had a shorter length than that under 12 h/d when light intensity was same. This result was different from previous studies[13,15] that runners were longer under long-day than short-day owing to the increase in number and length of epidermal cells. The discrepancy may be due to the differences in light intensity during the extended photoperiod. Hasan et al.[13] and Nishizawa[15] created long photoperiod by extending daylength using incandescent or fluorescent light with light intensity of no more than 5 μmol/(m^2·s), which is extremely lower than the light compensation point of strawberry leaves. Mother plants have shorter runner length and increased clonal branching under favorable environments[20]. Extending photoperiod with light intensity below the compensation point might give a signal to the mother plant that it is under light deprivation. The runners would stretch out to let runner plants avoid unfavorable conditions.

Length of primary runners decreased linearly with increasing DLI, and the decreasing slope was smaller under 16 h/d than 12 h/d (Figure 2c). Similar trend was found in the average internode elongation of *Tecoma stans* as DLI increased from 0.75 mol/(m^2·d) to 15.6 mol/(m^2·d)[21]. Height of *Impatiens* and *Salvia* decreased by 27% and 37%, as DLI increased from 4.1 to 14.2 mol/(m^2·d)[22], respectively. Increasing DLI reduced the internode elongation and height of flowers. Our study indicated that runner elongation was inhibited by high DLI. Shorter runners mean a smaller space requirement for mother plants during propagation, thus improving runner plants yield per unit area and using the space more efficiently in a plant factory.



Note: Letters a-c indicate significant differences according to Duncan's multiple range test at p≤0.05 (n=6). Vertical bars represent standard deviations.

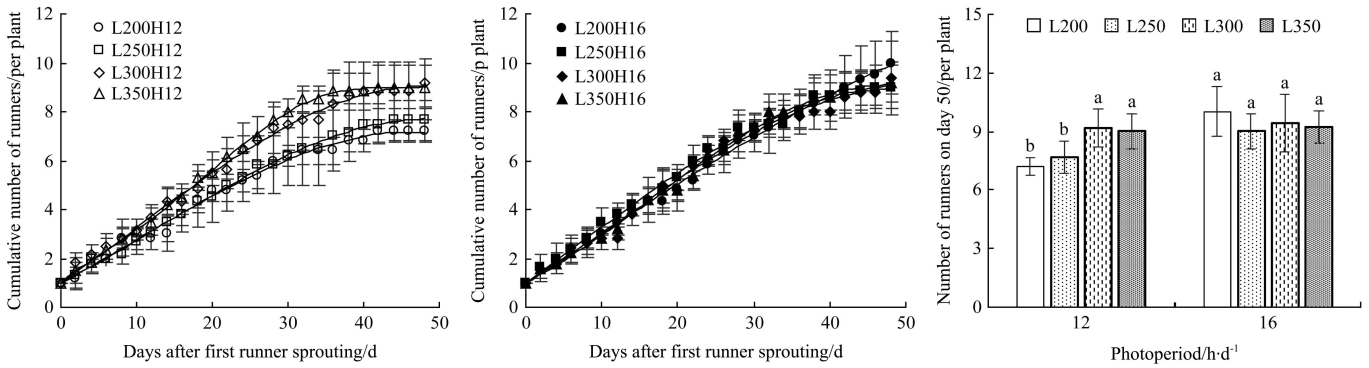
Figure 2 Time courses of length of primary runners as affected by light intensity and photoperiod (a and b) and relationship between the length of primary runners and daily light integral (c)

Number of runners emerged from mother plants increased linearly with time in the first 30-day propagation period and then gradually reached a plateau (Figures 3a and 3b). The final number of runners formed by mother plants at 50 d after planting increased by 27.3% as light intensity increased from 200 μmol/(m^2·s) to 300 μmol/(m^2·s); however, the number was not improved further when light intensity increased to 350 μmol/(m^2·s) under photoperiod of 12 h/d (Figure 3c). Moreover, number of runners did not increase when light intensity increased from 200 μmol/(m^2·s) to 350 μmol/(m^2·s) under photoperiod of 16 h/d. Number of runners can be improved by increasing the photoperiod at light intensity of 200-300 μmol/(m^2·s). Nevertheless, there were no significant difference in number of runners between photoperiods of 12 h/d and 16 h/d when light intensity was at 350 μmol/(m^2·s).

Wu et al.[10] reported that high light intensity (110-122 μmol/(m^2·s)) promoted runner formation of 'Toyonoka' strawberry compared to low light intensity (50-55 μmol/(m^2·s)). Kim et al.[9] reported that strawberry mother plants grown under 280 μmol/(m^2·s) produced more runners than those grown under 210 μmol/(m^2·s) and 140 μmol/(m^2·s). In our hydroponic strawberry transplant propagation system, number of runners formed by mother plants was affected by both light intensity and photoperiod, which was related to DLI. Number of runners increased by 38.9% when DLI increased from 8.6 to 11.5 mol/(m^2·d), but did not change in the range from 11.5 mol/(m^2·d) to 20.2 mol/(m^2·d).

3.2 Effects of light intensity and photoperiod on propagation of runner plants

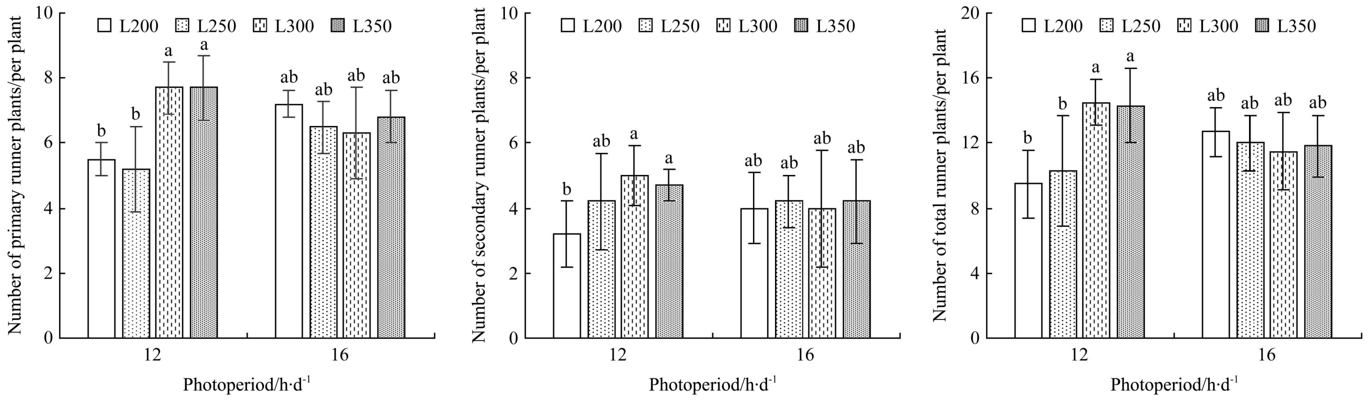
The number of primary runner plants increased by 52.6% when light intensity increased from 200 μmol/(m^2·s) to 300 μmol/(m^2·s) under photoperiod of 12 h/d (Figure 4a). However, there was no significant difference in number of primary runner plants among four levels of light intensity under photoperiod of 16 h/d. Moreover, no significant difference in number of primary runner plants was found between photoperiod of 12 h/d and 16 h/d regardless of light intensity. The same trends were also found in the number of secondary runner plants and total number of runner plants (Figures 4b and 4c). The highest number of runner plants was 14.5 per mother plant under light intensity of 300 μmol/(m^2·s) with photoperiod of 12 h/d in the current study. Kim et al.[9] reported that 'Maehyang' strawberry grown under light intensity of 280 μmol/(m^2·s) with photoperiod of 16 h/d produced highest number (9.4) of runner plants per mother plant during 35 d. If we divide the total number of runner plants by propagation days, the average propagation rate of 'Benihoppe' strawberry was 0.29 plant per day per mother plant, which was slightly higher than that (0.27) for 'Maehyang' strawberry[9].



a. b. c.

Note: Letters a-b indicate significant differences according to Duncan's multiple range test at $p\leq0.05$ (n=6). Vertical bars represent standard deviations.

Figure 3 Time course of cumulative number of runners (a and b) and number of strawberry runners 50 days after planting as affected by light intensity and photoperiod (c)



a. b. c.

Note: Letters a-b indicate significant differences according to Duncan's multiple range test at $p\leq0.05$ (n=6). Vertical bars represent standard deviations.

Figure 4 Number of primary runners (a), secondary runners (b), and total number of runners (c) 50 d after planting as affected by light intensity and photoperiod

Light intensity and photoperiod had interactive effects on crown diameter of primary runner plants and secondary runner plants (Table 2). Crown diameter under photoperiod of 16 h/d was significantly higher than that under 12 h/d, but the difference shrunk with the increase of light intensity. Primary runner plants grown under light intensity of 300 μmol/(m^2·s) with photoperiod of 16 h/d had the highest number (7.0) of leaves, while those under light intensity of 200 μmol/(m^2·s) with photoperiod of 12 h/d had the lowest number (6.0) of leaves. No significant difference in number of leaves was found among secondary runner plants, since they all had about three leaves. When light intensity increased from 200 μmol/(m^2·s) to 300 μmol/(m^2·s), the dry weight of primary runner plants grown under photoperiod of 12 h/d increased by 79.6%, but no significant difference was observed under photoperiod of 16 h/d. Similar trends were found in dry weight of secondary runner plants. For the mother plants, net photosynthetic rate increased by 24.0% when light intensity increased from 200 μmol/(m^2·s) to 350 μmol/(m^2·s) under 12 h/d, but decrease was observed when light intensity increased from 300 μmol/(m^2·s) to 350 μmol/(m^2·s) under 16 h/d (Table 3). Chlorophyll content followed the same trends. However, no significant difference was found in F_v/F_m among the eight treatments. For the primary runner plants, no significant difference was observed in net photosynthetic rate among four levels of light intensity under 12 h/d. However, decrease was observed in net photosynthetic rate, F_v/F_m and chlorophyll content when light intensity increased from 300 μmol/(m^2·s) to 350 μmol/(m^2·s) under 16 h/d.

Table 2 Growth of primary runner plants and secondary runner plants as affected by light intensity and photoperiod

Treatment symbol	Primary runner plants			Secondary runner plants		
	Crown diameter/mm	Leaf number/per plant	Dry weight/g per plant	Crown diameter/mm	Leaf number/per plant	Dry weight/g per plant
L200-H12	8.0±0.6 d	6.0±0.0 b	1.47±0.28 b	5.7±0.4 b	3.2±0.4 NS	0.59±0.06 b
L250-H12	9.0±0.8 c	6.2±0.4 ab	1.92±0.62 b	6.1±0.4 ab	3.3±0.5 NS	0.57±0.13 b
L300-H12	9.8±0.5 b	6.8±0.8 ab	2.64±0.54 a	6.1±0.3 ab	3.7±0.5 NS	0.86±0.16 a
L350-H12	9.6±0.7 b	6.4±0.5 ab	1.87±0.20 b	6.3±0.2 ab	3.5±0.5 NS	0.62±0.10 b
L200-H16	10.7±0.7 a	6.7±0.5 ab	3.02±0.45 a	6.7±0.5 a	3.7±0.5 NS	0.96±0.20 a
L250-H16	10.4±0.9 ab	6.3±0.5 ab	3.04±0.49 a	6.8±0.3 a	3.5±0.5 NS	0.98±0.28 a
L300-H16	10.5±0.6 ab	7.0±0.7 a	3.07±0.61 a	6.5±0.4 ab	3.2±0.4 NS	0.91±0.13 a
L350-H16	10.1±0.7 ab	6.0±0.0 b	3.09±0.23 a	6.2±0.8 ab	3.3±0.5 NS	0.55±0.11 b
ANOVA						
L	NS	*	NS	NS	NS	*
H	*	NS	*	*	NS	*
L×H	*	NS	NS	*	NS	*

Note: The data were expressed as mean ± standard deviation. Different letters in the same column indicate significant differences according to Duncan's multiple range test at $p\leq0.05$ (n=6). NS and * represent nonsignificant or significant differences at $p\leq0.05$ (n=6), respectively.

Table 3 Net photosynthetic rate (Pn), chlorophyll fluorescence (F_v/F_m), and chlorophyll (Chl) content of strawberry leaves as affected by light intensity and photoperiod

Treatment symbol	Mother plants				Primary runner plants			
	Pn /μmol·m^{-2}·s^{-1}	F_v/F_m	Total Chl content /mg·g^{-1}	Chl a/b	Pn /μmol·m^{-2}·s^{-1}	F_v/F_m	Total Chl content /mg·g^{-1}	Chl a/b
L200-H12	14.2±0.8 c	0.832±0.003 NS	2.24±0.23 ab	2.29±0.14 b	17.5±0.7 a	0.835±0.001 a	2.69±0.24 a	2.63±0.07 a
L250-H12	16.3±0.7 b	0.827±0.005 NS	2.15±0.13 ab	2.38±0.08 b	17.4±0.7 a	0.830±0.006 ab	2.34±0.27 b	2.62±0.17 a
L300-H12	16.5±1.0 b	0.830±0.003 NS	2.28±0.24 ab	2.44±0.16 ab	17.5±0.9 a	0.825±0.003 ab	2.40±0.19 ab	2.51±0.08 ab
L350-H12	17.6±0.8 a	0.826±0.004 NS	2.30±0.27 ab	2.50±0.11 ab	17.1±0.2 a	0.822±0.006 b	2.17±0.25 b	2.54±0.09 ab
L200-H16	14.4±0.4 c	0.826±0.005 NS	2.47±0.31 a	2.55±0.21 ab	15.2±0.7 c	0.830±0.006 ab	1.82±0.23 c	2.29±0.14 c
L250-H16	15.8±0.8 b	0.831±0.005 NS	2.24±0.18 ab	2.62±0.19 a	16.1±0.8 b	0.828±0.007 ab	2.29±0.22 b	2.33±0.14 bc
L300-H16	15.9±0.9 b	0.823±0.005 NS	2.01±0.22 ab	2.50±0.17 ab	17.2±0.6 a	0.825±0.008 ab	2.32±0.23 b	2.51±0.21 ab
L350-H16	14.7±0.9 c	0.828±0.007 NS	1.76±0.23 b	2.37±0.21 b	15.2±0.5 c	0.809±0.009 c	1.85±0.16 c	2.46±0.17 b
ANOVA								
L	*	NS	*	NS	*	*	*	NS
H	*	NS	NS	*	*	*	*	*
L×H	*	NS	*	*	*	*	*	*

Note: The data were expressed as mean ± standard deviation. Different letters in the same column indicate significant differences according to Duncan's multiple range test at $p\leq0.05$ (n=6). NS and * represent nonsignificant or significant differences at $p\leq0.05$ (n=6), respectively.

Generally, 1% increase in the amount of light results in a 1% yield increase in greenhouse grown crops, including fruit vegetables, soil grown vegetables, cut flowers, bulb flowers, flowering pot plants, and non-flowering pot plants[23]. However, biomass of primary and secondary runner plants in the current experiment did not completely follow this "rule of thumb". In fact, the biomass of runner plants under highest DLI (20.2 mol/(m^2·d)) had a significant decrease. Obviously, excessive light inhibited growth of runner plants, which was supported by evidences that net photosynthetic rate, F_v/F_m and chlorophyll content of runner plant leaves under highest DLI were at lowest level. Similar results on bedding plants were reported that the total plant dry mass increased at a decreasing rate as DLI increased from 5 mol/(m^2·d) to 43 mol/(m^2·d), and the maximum peak point varied with specific species[24]. However, everbearing strawberry 'HS138' had 1.4-1.5 times greater dry matter accumulation in the plants at a high DLI (29.2 mol/(m^2·d)) than at a low DLI (19.4 mol/(m^2·d)), and no adverse effects on plants were found under high DLI and continuous lighting[25,26]. The discrepancy in results in response to high DLI may be due to different cultivars and different growth stages in these studies. The light saturation point depends on species, cultivar and growth stage.

3.3 Photon yield and energy yield in runners and runner plants under different daily light integral

Photon yield and energy yield in runners decreased with increasing light intensity regardless of photoperiod (Table 4). There were no significant differences of photon yield in runners under photoperiod between 12 and 16 h/d when light intensity was at 200 μmol/(m^2·s) and 250 μmol/(m^2·s), respectively. However, photon yield in runners was significantly lower at light intensity of 300 μmol/(m^2·s) and 350 μmol/(m^2·s) compared with 200 μmol/(m^2·s). Photon yield in runner plants followed the same trends as that of runners. The highest photon yield in runners was 0.14 runner/mol, which was obtained at light intensity of 200 μmol/(m^2·s) and photoperiod of 16 h/d, where photon yield in runner plants was also highest (0.18 runner plant/mol). The lowest photon yield in runners of 0.07 runner/mol was obtained at light intensity of 350 μmol/(m^2·s) and photoperiod of 16 h/d, where photon yield in runner plants was also lowest (0.09 runner plant/mol). Energy yield in runners and runner plants followed the same trends as the photon yield. The higher photon yield value, more runners and runner plants were produced per unit mole photons. Xu[27] reported that the photon yield in 'Albion' runner plants during the first 12 weeks propagation period and additional 9 weeks propagation period were 0.08 and 0.10 runner plant/mol, respectively, when cool white fluorescent light in color temperature of 4100 K was used as the sole light source. In the current experiment, photon yield in runner plants under DLI between 8.6 to 20.2 mol/(m^2·d) was 0.09-0.18 runner plant/mol, which was higher compared with that of 'Albion' strawberry.

Table 4 Photon yield and energy yield in runners and runner plants as affected by light intensity and photoperiod

Treatment symbol	Photon yield		Energy yield	
	Runners /runner·mol^{-1}	Runner plants /runner plant·mol^{-1}	Runners /runner·kWh^{-1}	Runner plants /runner plant·kWh^{-1}
L200-H12	0.13±0.01 a	0.18±0.04 a	0.90±0.05 a	1.19±0.26 a
L250-H12	0.11±0.01 b	0.15±0.05 ab	0.75±0.08 b	1.00±0.33 ab
L300-H12	0.11±0.01 b	0.18±0.02 a	0.73±0.08 b	1.16±0.11 a
L350-H12	0.10±0.01 c	0.15±0.02 ab	0.61±0.06 c	0.97±0.15 ab
L200-H16	0.14±0.02 a	0.18±0.02 a	0.94±0.12 a	1.19±0.14 a
L250-H16	0.10±0.01 bc	0.13±0.02 b	0.66±0.07 bc	0.88±0.12 b
L300-H16	0.09±0.01 c	0.11±0.02 bc	0.56±0.09 c	0.69±0.15 bc
L350-H16	0.07±0.01 d	0.09±0.02 c	0.47±0.05 d	0.60±0.10 c
ANOVA				
L	*	*	*	*
H	*	*	*	*
L×H	*	*	*	*

Note: The data were expressed as mean ± standard deviation. Different letters in the same column indicate significant differences according to Duncan's multiple range test at p≤0.05 (n=6). * significant differences at p≤0.05 (n=6).

4 Conclusions

Light intensity and photoperiod interactively affected the growth of runners and runner plants. Runner elongation can be inhibited by high DLI, which is related to high light intensity and long photoperiod. DLI in a range of 11.5-17.3 mol/(m^2·d) is beneficial to improve propagation efficiency and quality of runner plants, and 11.5 mol/(m^2·d) is optimal for strawberry propagation of runner plants in a plant factory at higher photon and energy yields. Further research is needed to optimize the light quality using different LEDs for more efficient propagation in hydroponic strawberry runner plants propagation.

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