Effects of daily light integral on tomato (*Solanum lycopersicon* L.) grafting and quality in a controlled environment

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Abstract: As the source of energy and biological signals, light can influence the healing process of grafted seedlings by regulating the synthesis of the endogenous hormone, regeneration of wound-healing tissue, and connection of vascular tissue in grafted seedlings. The effect of daily light integral (DLI) on the healing process and seedling quality of tomato (*Solanum lycopersicum* L.) was analyzed in this study, with the comparison of grafted seedlings treated in dark for 7 d after grafting. The results showed that the height increment of scion and rootstock, adhesion of graft union, stem flow, total chlorophyll content, and net photosynthesis rate increased gradually with increasing light intensity, and no longer increased significantly when the DLI was higher than 5.04 mol/m^2 d. The contents of auxin (IAA) and gibberellin (GA) in tomato leaves increased and abscisic acid (ABA) decreased with the increase of DLI. However, there was no significant difference between the treatments with DLI higher than 6.48 mol/m^2 d. Both the biomass and energy use efficiency (EUE) of grafted seedlings increased with DLI in a certain range and then decreased. The biomass was the largest when DLI was 5.04 mol/m^2 d. However, EUE was highest when DLI was 7.46 mol/m^2 d. In conclusion, a suitable DLI is beneficial to cultivate high-quality grafted tomato seedlings, and increasing DLI within a certain range can promote biomass accumulation, connection of vascular tissue, and endogenous hormone biosynthesis in tomato grafted seedlings during the healing period. The lighting environment with DLI of 5.04 mol/m^2 d (light intensity of 100 μmol/m^2 s and light time of 14 h/d) is recommended for the healing treatment in high-quality production, which also improves EUE during the healing period of tomato grafted seedlings.

Keywords: stress resistance, endogenous hormones, stem flow, energy use efficiency, seedling index
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1 Introduction

Grafting can effectively enhance stress resistance, and improve the yield and quality of vegetables in later cultivation. It has been widely used in the production of vegetable seedlings in recent years[1,2]. In the Netherlands, where protected agriculture is developed, the quantity of tomato (*Solanum Lycopersicon* L.) grafted seedlings accounts for more than 98% of seedlings, while the quantity of tomato grafted seedlings accounts for only 1% in China in 2018. In the healing process of grafted seedlings, a suitable healing environment can effectively improve the healing rate and shorten the healing domestication period[3,4]. A great deal of research has shown that the time required for the connection of vascular tissue in tomato grafted seedlings can be shortened by more than 30% in a controlled environment[5-7]. As the source of energy and biological signals, light can influence the healing process by regulating the synthesis of the endogenous hormone, regeneration of wound-healing tissue, and connection of vascular tissue in grafted seedlings[8,9]. However, in actual production, darkness or shading environment are often used during the healing period to reduce the water transpiration from leaves and grafted cut surfaces[10], which prolongs the healing time.

When the light is insufficient, the differentiation and growth of wound-healing tissue are slow, and the net photosynthetic rate of leaves is low, which prolongs the healing time of the grafted seedlings; high light intensity easily causes water loss and wilting of scion leaves and graft union. Within a certain range of light intensity, the study shows the physiological activity of grafted seedlings will be raised with the increase of light intensity[11]. At the light intensity of 77 μmol/m^2 s, tomato leaves have low stomatal opening and low transpiration, which is beneficial to the healing of grafted cut surfaces[12]. But the accumulation of dry matter in grafted seedlings is low. The light intensity of 100 μmol/m^2 s can enhance the regulation of gene transcription factors in watermelon leaves, increase the expression of amino acid metabolic proteins, and promote the connection of vascular tissue[13]. Leaf CO_2 exchange of cucumber grafted seedlings increased by 1.5 times under the light intensity of 237 μmol/m^2 s compared to the cucumber grafted seedlings under the light intensity of 142 μmol/m^2 s[14]. However, excessive light will increase the activity of polyphenol oxidase (PPO), leading to the excessive oxidation of

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phenolics into quinones, which in turn causes browning and necrosis of the grafted cut surface[15,16]. At the same time, short-time illumination during the healing period can effectively improve the photosynthesis and the survival rate of grafted seedlings[17]. Therefore, prolonging the light time within a certain range can promote the dry matter accumulation of grafted seedlings, but neither continuous light nor long darkness is conducive to the regeneration of wound-healing tissue[18].

Although the effect of light intensity on the healing process of grafted seedlings has been studied by many scholars, there is no clear conclusion on the regulation mechanism of light intensity during the healing period of humongous grafted seedlings[12-14,19]. Light time is an important factor affecting the differentiation of the wound-healing tissue, but there are few reports on the effects of the photoperiod and lighting supplementation time on the healing process of grafted seedlings[9,20,21]. At present, the regulatory impact of light intensity and light time on the healing process of grafted seedlings is not very clear. In addition, single light variables (light intensity or light time) do not fully reflect the response of grafted seedlings to light[22]. Daily light integral (multiplication of light intensity and light time in 24 h, DLI) represents the total amount of light that plants receive for photosynthesis within a day[23]. DLI can accurately express the photosynthetic intensity and light response mechanism of grafted seedlings. Suitable DLI can not only improve the growth and shorten the healing time of grafted seedlings, but also promote the light use efficiency of seedlings. Many studies have involved the effects of DLI on seed germination[24], root growth[25], plant morphology[26,27], biomass accumulation[26,28], and energy consumption[29], but fewer the studies on the healing of grafted seedlings. Therefore, the effect of DLI on the healing and physiological characteristics of grafted seedlings using tomato as the material was analyzed in this study, and suitable parameters for regulating the lighting environment of tomato grafted seedlings were proposed, which could provide technical support for cultivating high-quality and strong tomato seedlings, shortening the healing and domestication period, and reducing energy consumption in a controlled environment.

2 Materials and methods

2.1 Sample cultivation

Tomato was used as the experimental material. "Zhongza No.105" was selected as the scion and "Zhezhen No.1" was selected as the rootstock. Tomato seedlings were grown in an artificial lighting plant factory with a mixed culture substrate of peat, vermiculite, and perlite (3V: V: V) in trays. Before grafting, tomato seeds were sprouted, sown, and cultured by conventional methods, and scion seeds were sown about one week later than rootstock seeds. The temperature in the plant factory was (24±1) ℃/(18±1) ℃ (day/night, same below), relative humidity was (60±5)%/(70±5)%, Fluorescent lamp (FL) with red-blue ratio (R: B) of 1.8 was used as the light source (Figure 1). The light intensity was 250 μmol/m^2 s, and the light time was 14 h/d, CO_2 concentration was controlled within (400±50) μmol/mol. Tomato seedlings were irrigated every two days with Japanese Yamasaki tomato nutrient solution.

2.2 Experimental design

Grafting was performed when the stem diameter of the rootstock reached about 2.0 mm, and casing pipe grafting was used as the grafting method. The temperature in the healing chamber was (22±1) ℃/(16±1) ℃, relative humidity was (80±5)%/(90±5)%, CO_2 concentration was (800±50) μmol/mol. After Grafting, all the tomato grafted seedlings were placed in darkness for 1 d. The grafted seedlings treated in darkness for 7 d after grafting were used as the control group (CK). Fluorescent lamps (FL) with R: B of 1.8 were used in the lighting environment treatment for 7 d (Table 1), with four levels of light intensity (50, 100, 150, and 200 μmol/m^2 s) and two levels of light time (12 and 14 h/d) on the canopy. After the treatments, grafted seedlings were continuously cultured in the lighting environment before grafting until they became mature seedlings.

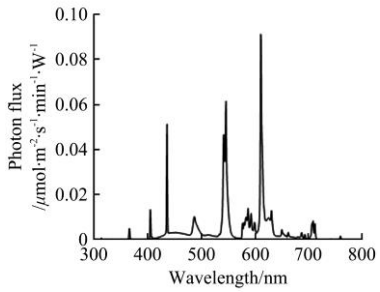


Figure 1 Spectral distribution of fluorescent lamp with red-blue ratio of 1.8

Table 1 Treatments of different DLI on tomato grafted seedlings during the healing period

Light source	Light intensity /μmol m^{-2} s^{-1}	Light time /h d^{-1}	DLI /mol m^{-2} d^{-1}
CK	0	0	0
FL	50	12	2.16
	100		4.32
	150		6.48
	200		8.64
	50	14	2.52
	100		5.04
	150		7.56
	200		10.08

Note: CK indicates the control group, and FL indicates the fluorescent light source.

2.3 Measurement index

2.3.1 Growth morphology

Eight grafted seedlings were taken out from each treatment by different lighting environments (same below), and the height increment of the scion (the increment of the graft union to the growing point), the height increment of the rootstock (the increment of the substrate surface to the graft union), the stem diameter of the scion (the stem diameter at 1 cm above the graft union), the stem diameter of the rootstock (the stem diameter at 1 cm below the graft union) were measured.

2.3.2 Endogenous hormone content

The root activity of grafted seedlings was measured by the 2,3,5-triphenyl tetrazolium chloride (TTC) method using the spectrophotometer (UV5500, Shjingmi Co., China). The contents of auxin (IAA), gibberellin (GA), and abscisic acid (ABA) in leaves of grafted seedlings were measured by high-performance liquid chromatography (SPD-10AVP and VP-ODS, Shimadzu co. Ltd., Japan)[30,31].

2.3.3 Healing effect

The 3 cm long stem near the graft union was taken out and fixed in a digital mechanical force gauge (HF-30, SDCH co. Ltd., China), and the maximum pulling force when the rootstock and scion were separated was the adhesive force of the graft union. The stem of the grafted seedlings was cut off and placed into the 1% acidic fuchsin aqueous solution for 3 h. All the scions were

ground into homogenate, and the supernatant was taken out after centrifugation. The stem flow of the graft union was calculated after measuring by spectrophotometer.

2.3.4 Photosynthetic characteristics

Fresh leaves of about 0.08 g were taken out, crushed, and put into a 10 mL solution with 80% acetone. After dark storage for 48 h, the absorbance of extracting solution at 663 nm, 645 nm, and 470 nm was measured using a spectrophotometer to calculate the total chlorophyll content and chlorophyll a/b of the grafted seedling leaves. The photosynthetic parameters of the grafted leaves were measured using a portable photosynthetic measuring system (LI-6400XT, LI-COR Inc., USA), with the light intensity of 300 μmol/m^2 s, leaf temperature of 25 ℃, CO_2 concentration of 800 μmol/mol, the airflow of 500 μmol/s.

2.3.5 Biomass

The underground section of rootstock (root), the aboveground section of rootstock, and the scions were taken out to measure the fresh weight, and then the plant samples were placed into the oven. After being deactivated at 105 ℃ for 2 h, the plant samples were dried to a constant weight at 85 ℃, and the dry weight of each section was weighed. The seedling index was calculated as Equation (1):

$$S_I = \frac{D_S \times W_{pd}}{H_p} \quad (1)$$

where, S_I is the seedling index; D_S is the stem diameter of the scions, mm; W_{pd} is the total dry weight of grafted seedling (including the scion and rootstock), g/plant; H_p is the seedling height, cm.

2.3.6 Energy consumption

The energy consumption parameters of grafted seedlings during the healing period include light use efficiency (LUE) and energy use efficiency (EUE). LUE and EUE were calculated as Equations (2) and (3):

$$\mathrm{LUE} = \frac{k \times W_D}{PAR} \quad (2)$$

$$\mathrm{EUE} = \frac{k \times W_D}{E_t} \quad (3)$$

where, k is the chemical energy per unit dry weight of grafted seedlings, generally taking 20 MJ/kg; W_D is the dry weight increment of grafted seedlings per unit area, kg/m; PAR is photosynthetically active radiation during the healing period, W/m^2; E_t is the total power consumed by the light source, kW ħ.

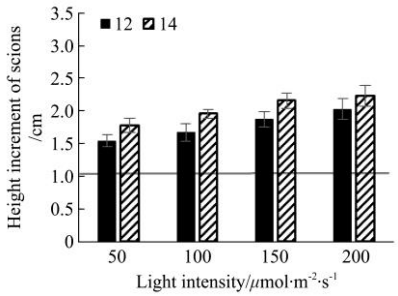
2.4 Data processing

All data were represented by the mean values of eight plants in each treatment. Microsoft Excel 2019 software was used for data summarization and statistics; SPSS 18.0 software was used for data difference significance by an analysis of variance (ANOVA) followed by the LSD test at the $p \leq 0.05$ level; Origin 2018 software was used for the chart and graphic drawing.

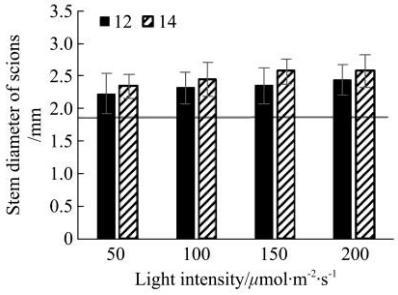
3 Results and analysis

3.1 Differences in growth morphology of tomato grafted seedlings under different DLI

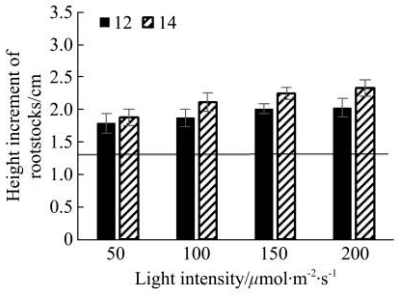
After 8 d of grafting, the survival rate of tomato grafted seedlings cultured under different lighting environments were all above 95%, and there was no significant difference among the treatments. The difference in growth morphology of grafted seedlings under the lighting environment with different DLI was analyzed. The results showed that the height increment of scions, the height increment of rootstocks, and the stem diameter of rootstocks increased with increasing light intensity, which was significantly higher than those of tomato grafted seedlings of CK (Figure 2, $p<0.05$). There was no significant difference in the stem diameter of scions cultured under the fluorescent lighting environment. According to the analysis results of tomato grafted seedlings in Figure 2, it was found that the growth morphology of tomato grafted seedlings under the lighting environment with DLI of 5.04 mol/m^2 d (the light intensity of 100 μmol/m^2 s and the light time of 14 h/d) was significantly better than that of grafted seedlings under the lighting environment with DLI less than 5.04 mol/m^2 d. And there was no significant difference between tomato grafted seedlings with DLI exceeding 5.04 mol/m^2 d. The height increment of the scions, the stem diameter of the scions, the height increment of rootstocks, and the stem diameter of the rootstocks of tomato grafted seedlings under the lighting environment with DLI of 5.04 mol/m^2 d were 89.3%, 30.3%, 57.5%, and 42.1% higher than those of CK, respectively.



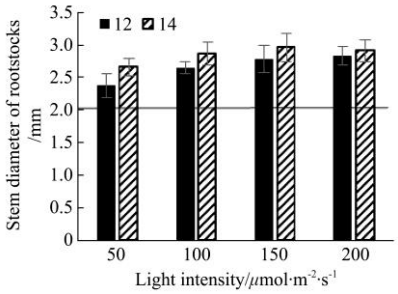
a. Height increment of scions



b. Stem diameter of scions



c. Height increment of rootstocks



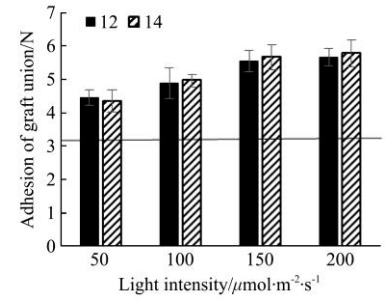
d. Stem diameter of rootstocks

Note: The horizontal line in graphs indicates the level of CK, same below.

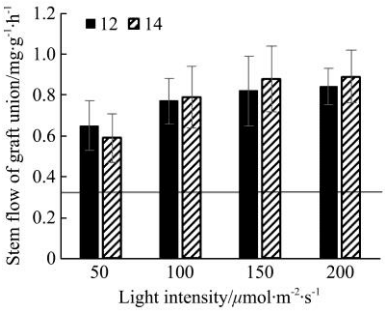
Figure 2 Effects of light intensity and light time on the growth morphology of tomato grafted seedlings

3.2 Differences in the healing effect of tomato grafted seedlings under different DLI

The adhesion and stem flow of graft union of grafted seedlings are remarkable symbols of the healing effect of grafted seedlings. There were significant differences in the adhesion and the stem flow of graft union of tomato grafted seedlings under the lighting environment with different DLI (Figure 3). After grafting for 8 d, the healing effect of tomato grafted seedlings under different lighting environments was significantly higher than those of CK. Among them, the adhesion of graft union under the lighting environment with DLI of 6.48 mol/m^2 d (the light intensity of 150 μmol/m^2 s and the light time of 12 h/d) was 5.54 N, which was 72.1% higher than that of CK. It was found that the adhesion of graft union under the lighting environment with DLI of 6.48 mol/m^2 d was significantly better than that of grafted seedlings under the lighting environment with DLI less than 6.48 mol/m^2 d. And there was no significant difference in adhesion of graft union between tomato grafted seedlings with DLI exceeding 6.48 mol/m^2 d.



a. Adhesion of graft union



b. Stem flow of graft union

Figure 3 Effects of light intensity and light time on the healing effect of tomato grafted seedlings

The stem flow of tomato grafted seedlings under the lighting environment with DLI of 5.04 mol/m^2 d was 0.79 mg/g h, which was 132.3% higher than that of CK. And the stem flow of tomato grafted seedlings in this treatment was significantly higher than that of grafted seedlings under the lighting environment with DLI less than 5.04 mol/m^2 d, while it was not significantly different from that of grafted seedlings under the lighting environment with DLI higher than 5.04 mol/m^2 d.

3.3 Differences in endogenous hormone content in leaves of tomato grafted seedlings under different DLI

As shown in Table 2, the root activity of rootstocks, IAA content, and GA content in scion leaves increased significantly with the increase of DLI, while ABA content in scion leaves decreased. When DLI was 7.56 mol/m^2 d (the light intensity of 150 μmol/m^2 s and the light time of 14 h/d), the root activity of rootstocks, IAA content, and GA content in scion leaves of tomato grafted seedlings under the lighting environment with DLI of 7.56 mol/m^2 d were significantly better than those of grafted seedlings under the lighting environment with DLI less than 7.56 mol/m^2 d. At the same time, there was no significant difference between tomato grafted seedlings with DLI exceeding 7.56 mol/m^2 d.

The IAA content in scion leaves of grafted seedlings under the lighting environment with DLI of 6.48 mol/m^2 d was significantly higher than those of grafted seedlings under the lighting environment with DLI less than 6.48 mol/m^2 d.

Table 2 Effect of DLI on the endogenous hormone content in leaves of tomato grafted seedlings

DLI /mol m^{-2} d^{-1}	Root activity /μg g^{-1}	IAA content /μg kg^{-1}	GA content /μg kg^{-1}	ABA content /μg kg^{-1}
0.00	77.3±8.6 c	34.1±2.1 d	12.3±2.2 d	320±21 a
2.16	103.4±10.3 b	44.5±3.6 bc	18.2±3.4 c	231±14 b
2.52	123.6±14.6 ab	45.2±2.7 c	22.4±1.4 bc	228±14 b
4.32	137.3±11.2 ab	56.9±3.9 b	25.6±1.9 b	234±16 b
5.04	140.6±12.3 ab	49.5±5.4 b	27.9±1.8 ab	198±32 bc
6.48	124.3±10.0 ab	56.9±4.6 a	28.5±2.5 ab	213±12 bc
7.56	145.7±10.9 a	63.2±5.0 a	30.5±2.3 a	153±12 d
8.64	153.2±12.5 a	66.3±4.2 a	31.4±2.7 a	176±22 c
10.08	149.3±9.3 a	59.8±3.5 a	32.2±3.5 a	148±17 d

Note: The letters after data in the table above indicate the results of variance analysis and NS indicates no significant difference, and different letters represent the significant difference ($p \leq 0.05$).

3.4 Differences in photosynthetic characteristics of tomato grafted seedling leaves under different DLI

The leaf chlorophyll content of tomato grafted seedlings showed that the total chlorophyll content and chlorophyll a/b gradually increased with the increase of DLI (Table 3). In particular, the total chlorophyll content was 3.02 mg/g and the chlorophyll a/b was 3.26 in leaves of tomato grafted seedlings under DLI of 5.04 mol/m^2 d, which were better than those grafted seedlings with DLI less than 5.04 mol/m^2 d, and were not significantly different from those grafted seedlings with DLI greater than 5.04 mol/m^2 d.

Table 3 Effects of DLI on the photosynthetic characteristics of tomato grafted seedlings

DLI/ mol m^{-2} d^{-1}	Total chlorophyll content/mg g^{-1}	Chlorophyll a/b	*Pn*/μmol m^{-2} s^{-1}	*Gs*/mol m^{-2} s^{-1}	*Ci*/μmol mol^{-1}	*Tr*/mmol m^{-2} s^{-1}
0.00	2.48±0.15 c	2.86±0.03 c	9.5±0.4 d	0.233±0.032 b	742±21 a	2.12±0.23 NS
2.16	2.73±0.14 b	2.92±0.06 b	11.8±0.7 c	0.342±0.046 a	722±16 b	2.45±0.42 NS
2.52	2.89±0.28 ab	3.11±0.11 ab	13.5±0.6 b	0.342±0.047 a	714±24 b	2.47±0.44 NS
4.32	2.89±0.23 ab	3.10±0.07 ab	13.4±0.8 b	0.356±0.043 a	712±21 b	2.49±0.32 NS
5.04	3.02±0.22 a	3.26±0.07 a	15.3±0.9 ab	0.412±0.066 a	693±31 bc	2.47±0.65 NS
6.48	3.00±0.17 a	3.19±0.04 a	15.5±1.2 ab	0.423±0.058 a	695±23 bc	2.53±0.56 NS
7.56	3.09±0.25 a	3.20±0.08 a	16.7±1.1 a	0.435±0.076 a	683±28 c	2.56±0.54 NS
8.64	3.14±0.14 a	3.12±0.05 ab	16.8±0.9 a	0.456±0.065 a	682±19 c	2.66±0.34 NS
10.08	3.17±0.19 a	3.23±0.12 a	17.2±1.5 a	0.446±0.058 a	677±17 c	2.68±0.77 NS

Light intensity and light time have a significant effect on the photosynthetic characteristics of the leaves of tomato grafted seedlings (Table 3). The net photosynthetic rate (*Pn*) of leaves gradually increased with increasing DLI and was significantly

higher than that of CK. Adversely, the intercellular CO_2 concentration (*Ci*) of leaves gradually decreased with increasing DLI. The effects of DLI on stomatal conductance (*Gs*) and transpiration rate (*Tr*) of leaves were not significant. As shown in Table 3, the net photosynthetic rate of leaves under DLI of 5.04 mol/m^2 d was 15.3 μmol/m^2 s and the intercellular CO_2 concentration was 693 μmol/mol, which was better than those with DLI less than 5.04 mol/m^2 d, and was not significantly different from those with DLI greater than 5.04 mol/m^2 d.

3.5 Differences in biomass and energy consumption of tomato grafted seedlings under different DLI

As shown in Figure 4, the shoot dry weight and root dry weight of tomato grafted seedlings increased firstly and then decrease with increasing DLI. When DLI was 5.04 mol/m^2 d, the shoot dry weight and root dry weight were the largest, 123.7% and 225.6% higher than those of CK, respectively.

The analysis results of LUE and EUE of tomato grafted seedlings during the healing period showed that LUE and EUE of tomato grafted seedlings indicated a trend of increasing firstly and then decreasing with the increase of DLI (Figure 5). Both LUE and seedling index were the largest under the lighting environment with DLI of 7.56 mol/m^2 d, and did not increase significantly thereafter. While EUE reached its maximum lighting environment with DLI of 5.04 mol/m^2 d (Figures 5 and 6).

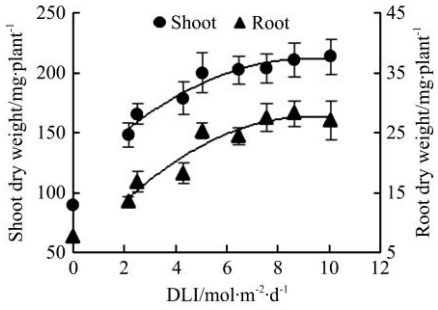


Figure 4 Relationship between DLI and biomass of tomato grafted seedlings

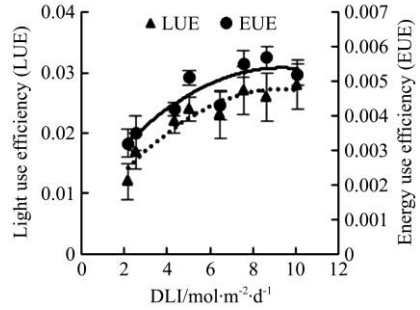


Figure 5 Relationships between DLI and LUE, EUE of tomato grafted seedlings

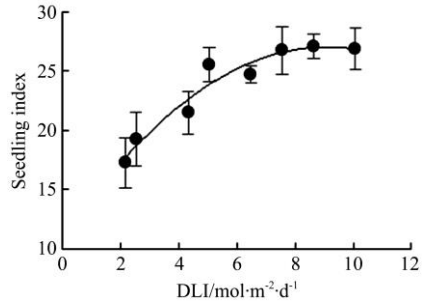


Figure 6 Relationship between DLI and seedling index of tomato grafted seedlings

4 Discussion

The healing process of grafted seedlings can usually be divided into three stages: the appearance of the isolation layer between rootstock and scion, the formation and differentiation of the wound-healing tissue, and the connection of vascular tissue[21,32]. It has been found that the differentiation of the wound-healing tissue of tomato grafted seedlings in greenhouse appeared on the 6th day after grafting; the isolation layer between rootstock and scion disappeared on the 12th day; the vascular tissue started to connect on the 21st day[33]. In a controlled environment, the isolated layer appeared on the 3rd day after tomato grafting; the wound-healing tissue started to differentiate on the 5th day; the vascular tissue started to connect on the 11th day, and the isolated layer disappeared; the vascular tissue formed on the 14th day[5]. It follows that the healing time of grafted seedlings in a controlled environment was significantly reduced, which is important for improving the grafting efficiency of seedlings. However, in order to reduce the water transpiration of the scion leaves and grafted cut surface, the grafted seedlings during the healing period are often in a dark or low-lighting environment in actual production, which prolongs the healing time of grafted seedlings. With the deepening research on the regulation of the lighting environment, a large number of research results showed that light intensity and light time play crucial regulatory roles in the healing process of grafted seedlings[34].

The growth morphology is the primary indicator of the healing effect of grafted seedlings. The results in these experiments showed that supplemental lightening after tomato seedlings grafting significantly increased the increment of scions and rootstocks, while the stem diameter of rootstocks also increased. Therefore, lighting is beneficial to promote the healing of grafted seedlings and the accumulation of nutrients in the grafted cut surface, which is similar to the findings of Zheng et al.[35] and Song et al.[36] Meanwhile, under the lighting environment with the same light intensity, prolonging light time can significantly increase the growth of scions and rootstocks of tomato grafted seedlings, which is in agreement with the experimental results of most researchers[37-39], but different from the findings of Sun et al[20]. This may be due to the fact that prolonging light time can increase the efficiency of photosynthetic carbon assimilation, regulate the activity of key photosynthetic enzymes, and increase the content of plant growth regulating substances that can promote nutrient uptake by seedlings[40,41]. In addition, after the light signal is sensed by the HY5 (elongated hypocotyl 5), a leucine zippers (bZIP) transcription factor, the transportation of photosynthate from graft union to root and the absorption of nitrate are promoted[42].

The formations of adhesion and the stem flow of graft union are signs of grafting survival and vascular tissue connection of seedlings. The results of these experiments showed that the adhesion and stem flow of graft union increased significantly when DLI was less than 6.48 mol/m^2 d, while no significant difference when DLI was greater than 6.48 mol/m^2 d. This may be because too high light intensity will destroy enzyme activity in the healing process, leading to the browning of the wound-healing tissue and inhibiting the connection of vascular tissue[15]. Therefore, increasing DLI within a certain range promotes water transport in the stem by affecting the regeneration of wound-healing tissue and the connection of vascular tissue.

The healing process of grafted seedlings also relates to the

synthesis of endogenous hormones in grafted seedlings. And endogenous hormones are the main control factors in regulating the healing of grafted cut surface in grafted seedlings[43]. IAA in the grafted cut surface of grafted seedlings can promote the formation of wound-healing tissue and the connection of vascular tissue[44]. GA affects the gene expression of vascular proteins and promotes cell elongation and expansion[45]. ABA is associated with plant resistance and affects the survival rate of grafted seedlings[44,46]. The results of these experiments showed that supplemental lightening during the healing period significantly increased the content of endogenous hormones and decreased ABA content in grafted seedlings, which was consistent with most studies[44,45,47,48]. With the increase of DLI, the increase of IAA and GA content in the leaves of tomato grafted seedlings contributed to the formation of healing and vascular tissues, which enhanced the exchange of nutrients and mineral elements, and improve the signal transduction between the shoot and root. Finally, the increase of endogenous hormones promotes the biomass accumulation of grafted seedlings. In contrast, graft union reconnection of the phloem and xylem will delay in a dark or low-lighting environment after grafting[44,49]. It may result from the decrease in ABA content due to excessive light, which reduces the inhibitory effect of ABA on leaf growth and root elongation.

Light intensity affects the photosynthetic carbon assimilation by changing the light compensation point or the light saturation point of grafted seedlings during the healing period, affecting the leaf photosynthesis. Yellowing symptoms of scion are a clear sign of improper healing and acclimatization. Instead, chlorophyll is the most important pigment for photosynthesis[50]. In this study, the total chlorophyll content and chlorophyll a/b of tomato grafted seedlings were significantly higher than those of CK. And the total chlorophyll content and chlorophyll a/b of the leaves gradually increased with increasing DLI. This is due to the decreased uptake of nutrients (especially nitrogen) by the roots of grafted seedlings when the light is too weak, which in turn interrupts the chlorophyll synthesis and decreases sucrose synthase activity in leaves[42]. The experimental results are consistent with the findings of Xiao et al.[51] The effect of DLI on the net photosynthetic rate of grafted seedling leaves was the same as that of total chlorophyll content in leaves.

5 Conclusions

The carbohydrate accumulation in grafted seedlings can be promoted by increasing photosynthetic capacity during the healing period. The results of biomass and seedling index of tomato grafted seedlings in this study showed that the biomass and strong seedling index gradually increased with increasing DLI, which was consistent with the increment of scion and rootstock, water transport capacity of the graft union, and total chlorophyll content. These results fully indicated the importance of DLI in improving the quality of grafted seedlings within a certain range. Meanwhile, LUE and EUE of grafted seedlings increased with DLI less than 7.56 mol/m^2 d.

In summary, increasing DLI within a certain range can promote biomass accumulation, the connection of vascular tissue, and endogenous hormone biosynthesis in tomato grafted seedlings during the healing period, to shorten the healing time and produce high-quality seedlings. In order to develop high-quality grafted tomato seedlings and improve the economic benefits during the healing period, the lighting environment with DLI of 5.04 mol/m^2 d (the light intensity of 100 μmol/m^2 s and the light time of 14 h/d) can be used for the production of tomato grafted seedling.

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