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RESEARCH REPORT

Protected Horticulture

Effects of light quality, light intensity, and photoperiod on growth and yield of cherry radish grown under red plus blue LEDs

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Abstract
For more plant species to be suitable for plant factory production, their optimal light regimes need to be optimized. We evaluated the effects of light quality, light intensity, and photoperiod on the growth and yield of cherry radish grown under red plus blue LEDs in a controlled environment. Radish plants were cultivated under two light qualities with different red:blue ratios (1R:1B, 2R:1B) at three light intensities (180, 240, 300 μmol m^{-2} s^{-1}) or two photoperiods (12 h/12 h, 16 h/8 h), respectively. The light quality 2R:1B increased root diameter, root volume, and the biomass of shoot and root compared to light quality 1R:1B under a light intensity of 240 and 300 μmol m^{-2} s^{-1}, but the growth differences between 1R:1B and 2R:1B were significant when the light intensity was 240 μmol m^{-2} s^{-1}. New leaf chlorophyll content, root growth indices and the root-shoot ratio increased with light intensity. Cherry radish only formed storage roots with commercial value when light intensity was equal to or over 240 μmol m^{-2} s^{-1}. The root diameter, root volume, root-shoot ratio, and the biomass of shoot and root of plants grown in the 2R:1B treatment was significantly higher than those in the 1R:1B treatment under the 16 h/8 h photoperiod. However, no significant difference was observed in the 12 h/12 h photoperiod. These results indicated that light regime in combination with a light intensity between 240 and 300 μmol m^{-2} s^{-1}, the light quality 2R:1B, and a 16 h/8 h photoperiod produced appropriate growth of cherry radish in plant factory settings using an LED light source. In conclusion, the production of commercial storage roots in cherry radish is primarily dependent on light intensity, followed by light quality and photoperiod. Furthermore, the effectiveness of light quality regulation of storage roots was highly depended on light intensity and photoperiod.

Keywords LED · Light intensity · Photoperiod · Plant factory · Ratio of red and blue light · Root vegetable

1 Introduction

Plant factory has potential to produce higher quality and yield of crop plants in a short time and with less resource compared to conventional greenhouse systems (Kang et al. 2013). Light emitting diodes (LEDs) were commercially introduced to plant factories in the 2000s as a more efficient light source compared to traditional light sources (Watanabe 2011), due to their small volume, longevity, low energy consumption, low thermal energy output, wavelength specificity and adjustable light intensity/quality (Bula et al. 1991). Generally, precise control of the light environment (i.e. light quality, light intensity, and photoperiod) according to specific plant requirements can improve the yield and quality of the plant and its production efficiency; therefore, plant factories that use LED light sources have a high productivity potential because of the ability to specifically regulate the light environment. In practice, small plants such as leaf vegetables, small-sized root vegetables, and some medicinal plants are more appropriate for plant factories that use LEDs,. At present, plant species cultivated in plant factories are unitary, mainly leaf vegetables, such as lettuce and spinach. (Shiina et al. 2011; Goto 2012; Kang et al. 2013). Previous studies of light environmental control in plant factories also mostly used leaf vegetables as research subjects

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(Hogewoning et al. 2010; Kang et al. 2013; Kozai 2013). Root vegetables were rarely planted in plant factories, and there are only a few published scientific reports on the effect of light conditions on root vegetable production (Drozdova et al. 2001; Yorio et al. 2001; Samuoliene et al. 2011). Furthermore, traditional light sources were used as experimental lights such as fluorescent and high-pressure sodium lamps, in these reports. Cherry radish is a popular small root vegetable with a short growth cycle, good taste, compact morphology, and high nutritional value, which make it suitable to be grown and commercially produced in plant factories using artificial light.

It is well known that light quality, light intensity, and photoperiod are key regulatory components for high plant productivity under controlled environments that use artificial light sources, particularly LEDs. Optimal light quality, especially the red to blue light ratio, was extensively investigated for many plant species, including radish, to establish suitable light conditions for plant growth. Previous studies show that certain proportional red light plus blue light conditions were necessary and sufficient to complete the life cycles of many kinds of plants (Bula and Tibbitts 1992; Goins et al. 1997; Yorio et al. 2001; Samuoliene et al. 2011). As reported, radish growth and morphology were significantly dependent on light quality (Drozdova et al. 1987; Yorio et al. 2001; Kara et al. 1997); radish grown under 170 µmol m^{-2} s^{-1} red light alone lacked significant storage root development, and shoot growth was also affected (Bukhov et al. 1996; Kara et al. 1997). However, Drozdova et al. (2001) found that radish accumulated a lot of dry storage root biomass at later stages of growth under 170 µmol m^{-2} s^{-1} red light alone compared to blue light. It seems that red light did not prevent storage root formation, but delayed tuberization. Samuoliene et al. (2011) reported supplemental blue light was necessary for non-structural carbohydrate distribution between radish storage organs and leaves, which resulted in hypocotyl thickening. Moreover, significant increases in storage root dry weight was observed when red LEDs were supplemented with 10% blue light (Yorio et al. 2001). However, the high blue light ratio does not always have positive effects on the growth of several species, including radish (Cope et al. 2014). Studies have shown that light intensity is a vital factor for the growth and development of storage roots in root vegetables (Ikeda et al. 1988; Inada and Yasumoto 1989; Hall 1990; Cope et al. 2014). Storage root weight in radish, red beet, and carrot was markedly reduced as light intensity decreased from 445 to 125 µmol m^{-2} s^{-1}; while the leaf area and shoot fresh and dry weights of red beet and carrot remained constant at a range of light intensity (Hole and Dearman 1993). It is well known that a prolonged photoperiod can increase the duration of photosynthesis and promote the accumulation of dry matter in many plant species (Adams and Langton 2005), including radish (Soffe et al. 1977). Long photoperiods promoted the growth of radish including its leaf area, leaf chlorophyll content, fresh weight, and dry weight; whereas, this effect was reduced when photoperiod extended to 24 h (Craker et al. 1983; Warrington and Norton 1991; Sirtautas et al. 2011).

Light quality, light intensity, and photoperiod are not independent of each other; therefore radish plants can be regulated by these three elements together. There was no difference in lettuce dry weight among different blue light to red light ratios under a light intensity of 100 µmol m^{-2} s^{-1}, while the total dry weight was significantly influenced by the blue to red light ratio when the light intensity was 300 µmol m^{-2} s^{-1} (Furuyama et al. 2014). Inada and Yasumoto (1989) used metal halide and high-pressure sodium lamps to study the effect of light quality and light intensity on radish growth; their results showed that the biomass of radishes grown under lamps with higher red to blue ratio, and lower red to far red light ratio was enhanced more apparently by improved light intensity.

Few reports on the effect of multiple light factors on the growth and yield of radishes have been conducted and the light sources applied in previous studies cannot accurately control for light intensity and light quality. Based on previous reports, the present study was conducted to investigate the effects of light quality, light intensity, and photoperiod on growth and yield of cherry radishes grown under red plus blue LEDs. The objectives of this study were to evaluate the effectiveness of multiple light factors on the growth and yield of cherry radish, and to optimize suitable light conditions for cherry radish production in plant factories using LEDs. We hope these results can be used to inform light regulation strategies for the establishment for high productivity of plant factory frown cherry radishes.

2 Materials and methods

2.1 Plant material and experimental conditions

Two separate experiments were performed in a trail plant factory under a controlled environment at the Institute of Environment and Sustainable Development in Agriculture. The 'Changfeng' cultivar used in the experiments was bought from a Chinese company (Qing Xian Changfeng Seed Co., Ltd.). Cherry radish (*Raphanus sativus* L.) seeds were sown in cultivation plastic pots (38 cm × 18 cm × 10 cm) on July 4 and 9 2016 for experiments 1 and 2, respectively. The cultivation pots were filled with horticultural grade soilless media (1:1 peat: vermiculite by volume). Ten radish seedlings were established in each pot 5 d after cotyledon emergence. Radishes were watered every day with 200 mL during the experiments. Each pot sprayed 200 ml nutrient solution every 5 d after plantlet establishment. The nutrient solution was composed of 0.75 mM K_2SO_4, 0.5 mM KH_2PO_4, 0.1 mM KCl, 0.65 $MgSO_4 \cdot 7H_2O$, 1.0×10^{-3} mM H_3BO_3, 1.0×10^{-3} mM $MnSO_4 \cdot H_2O$, 1.0×10^{-4} mM $CuSO_4 \cdot 5H_2O$, 1.0×10^{-3} mM $ZnSO_4 \cdot 7H_2O$, 0.1 mM EDTA-Fe, 5×10^{-6} mM $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$, and 4.0 mM Ca $(NO_3)_2 \cdot 4H_2O$ (pH: 6.3;EC: 1.228 dS m^{-1}). The ambient temperature conditions for the experiments were constant at 25–29 °C and 26–29 °C, respectively. Relative humidity was maintained in the range of 65–75%.

2.2 Lighting regimes

Radish plants were grown under red–blue LED panels (50 cm × 50 cm, Shenzhen Huihao Optoelectronic Co. Ltd., Shenzhen, P. R. China) with peak wavelengths of 660 nm and 430 nm. Based on previous reports of light intensity (Hole and Dearman 1993;Drozdova et al. 2001), red to blue light ratio (Bula and Tibbitts 1992; Goins et al. 1997; Yorio et al. 2001; Samuoliene et al. 2011; Cope et al. 2014) and photoperiod (Warrington and Norton 1991) for radish and other plants, we designed two red to blue light ratios (1R:1B, 2R:1B) that we could use with three light intensities (180, 240, 300 μmol m^{-2} s^{-1}) in experiment 1, and two red to blue light ratios (1R:1B, 2R:1B) with two photoperiods (12 h/12 h, 16 h/8 h) in experiment 2. The photoperiod of experiment 1and light intensity of experiment 2 were 16 h/8 h and 240 μmol m^{-2} s^{-1}, respectively. Red and blue LED lamps were distributed uniformly on panels. Light was measured with a quantum meter (3415F, LightScout, CO, USA) to adjust to the light intensity and quality to the experimental set values. For example, in the 1R:1B and 180 μmol m^{-2} s^{-1} treatment, blue light was gradually increased to 90 ± 6 μmol m^{-2} s^{-1} first, and then the red light was adjusted until the total light intensity was 180 ± 6 μmol m^{-2} s^{-1}.

2.3 Harvest and measurement

Radishes in both experiment1 and experiment 2 were harvested and measured 30 d after sowing. Three radish plants from each treatment were randomly harvested for measurements. Leaf chlorophyll content was measured using a chlorophyll meter (SPAD-502, Konica Minolta Sensing Inc., Osaka, Japan). Vernier calipers were used to measure root length and diameter. Shoots and roots were separated and weighed separately. Finally, the shoots and roots were incubated at 105 °C for half an hour and then dried at 80 °C for 48 h. We then recorded shoot and root dry weights.

2.4 Statistical analysis

The statistical software SPSS 16.0 (International Business Machines Corporation) was used to evaluate the variation in parameter data among the treatments. Data analysis was subjected to two-way analysis of using variance (ANOVA), and significant differences between the means were tested using Duncan's multiple range tests at 95% confidence.

3 Results

3.1 Effects of light quality and intensity on shoot growth and biomass in cherry radish

The data regarding shoot growth is presented in Table 1. Radish plants did not exhibit a significant difference in true leaf number when grown under varied light treatments. The leaf chlorophyll content of new leaves increased with light intensity under both 1R:1B and 2R:1B treatments. However, the difference in chlorophyll content in old leaves was not significant in the different treatments. The greatest shoot fresh and dry weights were measured in plants grown

Table 1 Effects of light quality and light intensity on leaf number, chlorophyll content, and shoot fresh and dry weight in cherry radish

Treatments	True leaf number	Leaf chlorophyll content (SPAD value)		Shoot fresh weight (g)	Shoot dry weight (g)
		Old leaf	New leaf		
1R:1B (180)	4.0a	35.8a	38.5c	3.8abc	0.31b
2R:1B (180)	4.0a	35.9a	39.4bc	3.2c	0.26b
1R:1B (240)	3.7a	36.5a	40.1bc	3.7bc	0.30b
2R:1B (240)	3.3a	39.4a	44.6abc	4.7a	0.40a
1R:1B (300)	3.7a	42.3a	49.4a	3.1c	0.31b
2R:1B (300)	4.0a	40.7a	47.4ab	4.2ab	0.39a
$F_{(Light\ quality)}$	0.1^{NS}	0.1^{NS}	0.3^{NS}	4.6*	4.1^{NS}
$F_{(Light\ intensity)}$	1.2^{NS}	3.2^{NS}	7.6**	3.2^{NS}	5.1*
$F_{(Light\ quality \times light\ intensity)}$	0.5^{NS}	0.5^{NS}	0.9^{NS}	5.8**	6.1*

NS, * and ** indicate nonsignificant or significant at $p \le 0.05$ or 0.01 respectively

Different letters in the same column indicate a significant difference among treatments at $p < 0.05$

under 2R:1B light quality in combination with light intensity 240 μmol m^{-2} s^{-1}. Compared to 1R:1B, shoot fresh and dry weights were significantly higher under a red:blue light ratio of 2R:1B when light intensities were 240 μmol m^{-2} s^{-1} and 300 μmol m^{-2} s^{-1}, while no significant difference of two red:blue light ratio was observed under 180 μmol m^{-2} s^{-1} light conditions. Furthermore, the differences in true leaf number, leaf chlorophyll content, shoot fresh weight and dry weight between light quality 1R:1B and 2R:1B at 240 μmol m^{-2} s^{-1} were greater than that measured at 180 and 300 μmol m^{-2} s^{-1}. Leaf chlorophyll content in new leaves and the shoot dry weight was significantly affected by light intensity and interaction between light quality and light intensity, respectively.

3.2 Effects of light quality and intensity on storage root morphology and biomass in cherry radish

The data presented in Table 2 demonstrates that radish root growth was significantly affected by light and light quality intensity; however, no significant difference was observed in the root length of plants grown in the different light treatments. The root volume, root fresh weight and root dry weight of radish grown under 2R:1B (240), 2R:1B (300), and 1R:1B (300) treatments were significantly higher than those measured in radish plants grown under other three treatments. These root growth parameters increased with light intensity under the same red:blue ratio, and increased with red:blue ratios under the same light intensity. Light quality 2R:1B significantly increased the root diameter, root volume, root fresh weight, and root dry weight compared to 1R:1B when light intensity was 240 μmol m^{-2} s^{-1}. However, no significant difference was observed between light quality treatments when the light intensity was 180 and 300 μmol m^{-2} s^{-1}. Among the light treatments, the storage root growth parameters except root length were all highest in 2R:1B (300) and lowest in 1R:1B (180) conditions. As indicated by ANOVA (Table 2), the light intensity was the main factor that significantly influenced root diameter, root volume, root fresh weight, and root dry weight.

3.3 Effects of light quality and light intensity on cherry radish root-shoot ratios

Figure 1 demonstrates that 2R:1B (240), 2R:1B (300) and 1R:1B (300) treatments significantly increased the shoot root ratio more than twice that of the other three treatments. In the 2R:1B (240), 2R:1B (300) and 1R:1B (300) treatments, the root-shoot ratio calculated from dry weight measurements was lower than that of the fresh weight. The root-shoot ratios from fresh weight and dry weight both increased as light intensity increased with the same light quality. Root-shoot ratios of fresh weight and dry weight were significantly increased in the 2R:1B treatment compared to 1R:1B when light intensity was set at 240 μmol m^{-2} s^{-1}. However,

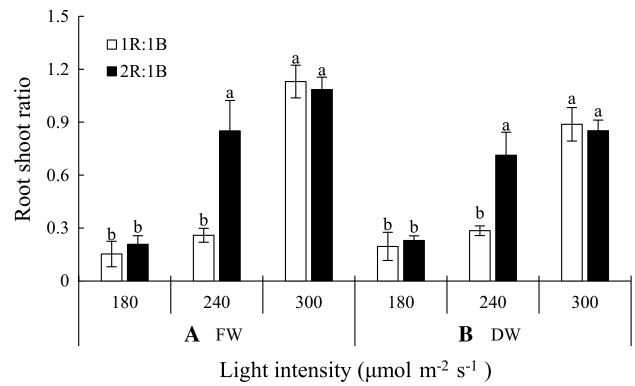

Fig. 1 Effect of light quality and light intensity on the fresh weight (FW) root-shoot ratio (**a**) and day weight (DW) root-shoot ratio (**b**) in cherry radish. Vertical bars indicate standard error ($n=3$). Different letters represent the significant difference at $p<0.05$ among treatments by the Duncan's multiple range test

Table 2 Effects of the red:blue light ratio and light intensity on root length, diameter, volume, and fresh and dry weight in cherry radish storage roots

Treatments	Root length (cm)	Root diameter (mm)	Root volume (cm^3)	Root fresh weight (g)	Root dry weight (g)
1R:1B (180)	4.1a	5.6b	0.6b	0.6b	0.06b
2R:1B (180)	4.2a	6.3b	0.8b	0.7b	0.06b
1R:1B (240)	3.1a	9.04b	0.9b	1.0b	0.09b
2R:1B (240)	4.2a	17.2a	4.0a	4.0a	0.28a
1R:1B (300)	3.4a	16.02a	3.4a	3.5a	0.28a
2R:1B (300)	3.7a	19.56a	4.6a	4.5a	0.33a
$F_{(Light\ quality)}$	3.4^{NS}	18.0**	12.4**	8.2*	5.8*
$F_{(Light\ intensity)}$	1.8^{NS}	50.0**	20.2**	17.5**	17.1**
$F_{(Light\ quality \times light\ intensity)}$	1.1^{NS}	4.9*	4.3*	3.4^{NS}	2.8*

NS, * and ** indicate nonsignificant or significant at $p \leq 0.05$ or 0.01 respectively

Different letters in the same column indicate a significant difference among treatments at $p<0.05$

no significant difference was observed for these values between 2R:1B and 1R:1B under 180 and 300 μmol m^{-2} s^{-1}.

3.4 Effects of light quality and photoperiod on shoot growth and biomass in cherry radish

As shown in Table 3, there was no significant difference of true leaf number between light treatments that had different light quality and photoperiods. A long photoperiod (16 h/8 h) increased the leaf chlorophyll content compared to a short photoperiod (12 h/12 h), and this phenomenon was more significant in new leaves. Neither shoot fresh weight nor dry weight was significantly influenced by light quality or photoperiod. Shoot fresh weight was the greatest under 1R:1B light conditions in a short photoperiod (12 h/12 h) and 2R:1B in a long photoperiod (16 h/8 h); the dry weight of the latter treatment was the highest among all treatments at the same time. Photoperiod alone had a significant effect on leaf chlorophyll content, while light quality, photoperiod and their interaction had no significant effect on other indices of shoot growth.

3.5 Effects of light quality and photoperiod on storage root morphology and biomass in cherry radish

There was no significant difference in root length among the light treatments (Table 4). Among the four treatments, the highest root diameter, root volume, root fresh weight, and dry weight were observed in the 2R:1B light quality treatment in a long photoperiod (16 h/8 h), and lowest values were measured in 1R:1B in a long photoperiod (16 h/8 h). Furthermore, these indices in former treatment were significantly higher than the other treatments tested. No significant difference was observed between light quality 1R:1B and 2R:1B conditions in a 12 h/12 h photoperiod, whereas the root diameter, root volume, root fresh weight, and dry weight were significantly increased in 2R:1B compared to 1R:1B under the 16 h/8 h photoperiod. Photoperiod alone was found to have no significant effect on morphology and biomass of storage root. The interaction of light quality and photoperiod was the main factor that significantly affected the storage root morphology and biomass, excluding root length.

Table 3 Effect of light quality and photoperiod on true leaf number, chlorophyll content and shoot fresh and dry weight in cherry radish

Treatments	True leaf number	Leaf chlorophyll content (SPAD value)		Shoot fresh weight (g)	Shoot dry weight (g)
		Old leaf	New leaf		
1R:1B (12 h/12 h)	3.7a	33.8b	37.8c	3.9a	0.27a
2R:1B (12 h/12 h)	3.7a	34.5ab	38.6bc	3.3a	0.25a
1R:1B (16 h/8 h)	3.3a	40.6a	42.5ab	3.1a	0.27a
2R:1B (16 h/8 h)	4.3a	37.1ab	43.3a	3.9a	0.35a
$F_{(\text{Light quality})}$	2.3^{NS}	0.5^{NS}	0.3^{NS}	0.0^{NS}	0.8^{NS}
$F_{(\text{Photoperiod})}$	0.3^{NS}	5.9*	11.7**	0.1^{NS}	2.2^{NS}
$F_{(\text{Light quality} \times \text{photoperiod})}$	2.3^{NS}	1.2^{NS}	0.0^{NS}	2.2^{NS}	2.6^{NS}

NS, * and ** indicate nonsignificant or significant at $p \leq 0.05$ or 0.01 respectively

Different letters in the same column indicate a significant difference among treatments at $p < 0.05$

Table 4 The effects of light quality and photoperiod on root length, diameter, volume, and fresh and dry weight in cherry radish storage roots

Treatments	Root length (cm)	Root diameter (mm)	Root volume (cm^3)	Root fresh weight (g)	Root dry weight (g)
1R:1B (12 h/12 h)	4.6a	10.0b	1.5b	1.5b	0.11b
2R:1B (12 h/12 h)	4.9a	8.5bc	1.2b	1.1b	0.10b
1R:1B (16 h/8 h)	4.2a	5.7c	1.0b	0.8b	0.08b
2R:1B (16 h/8 h)	4.9a	15.7a	2.8a	2.8a	0.23a
$F_{(\text{Light quality})}$	1.7*	15.8*	5.2^{NS}	6.1*	7.7*
$F_{(\text{Photoperiod})}$	0.3^{NS}	1.8^{NS}	2.7^{NS}	2.5^{NS}	3.9^{NS}
$F_{(\text{Light quality} \times \text{photoperiod})}$	0.3^{NS}	29.0**	11.3*	15.0**	11.9*

NS, * and ** indicate nonsignificant or significant at $p \leq 0.05$ or 0.01 respectively

Different letters in the same column indicate a significant difference among treatments at $p < 0.05$

3.6 Effects of light quality and photoperiod on root shoot ratio in cherry radish

Root shoot ratio of both fresh weight and dry weight of plants grown in 2R:1B combined with a 16 h/8 h photoperiod were significantly higher than those measured in the other three treatments (Fig. 2). The lowest root-shoot ratio from fresh weight and dry weight were both observed in 1R:1B conditions combined with a 16 h/8 h photoperiod. There was no significant difference in the root-shoot ratios between 1R:1B and 2R:1B treatments in a 12 h/12 h photoperiod. Nevertheless, in a photoperiod of 16 h/8 h, the root-shoot ratios from fresh weight and dry weight were significantly different between the light quality treatments.

4 Discussion

Previous studies have confirmed that radishes grown under red light alone could complete their life cycle, but the formation of the storage root was limited (Samuolienė et al. 2011). Drozdova et al. (1987) found that red light prevented and blue light promoted the formation of the storage organ in radish. The supplemented blue light was necessary for the non-structural carbohydrate distribution between the radish storage organs and leaves, which resulted in hypocotyl thickening (Samuolienė et al. 2011). However, a high blue light ratio was also shown to have negative effects on the growth of several plant species, including radish (Cope et al. 2014). According to our data, the shoot fresh weight and dry weight of plants grown in 2R:1B light quality conditions were significantly greater than those grown in 1R:1B conditions when the light intensity of 240 and 300 μmol m^{-2} s^{-1}. Whereas, no significant different true leaf number and leaf chlorophyll content were observed between light quality 2R:1B and 1R:1B under any light intensity. These results are consistent with earlier works that showed leaf chlorophyll content and dry mass in radish increased at first and then decreased with an increasing of blue light percentage. Also, the maximum leaf chlorophyll content and dry mass appeared when blue light are 15–25 percent of total light intensity (Cope et al. 2014). Indeed, our results demonstrate that the red:blue light ratio had a greater impact on root growth than shoot growth. Root length, root diameter, root volume, root fresh weight and dry weight were improved by a 2R:1B light quality condition compared to light quality 1R:1B under any light intensity. Our results showed that red light supplemented with an appropriate proportion of blue light (e.g. 2R:1B) was conducive to promoting the growth and enlargement of the storage root in radishes. The specific responses of radish plants to different light qualities closely correlated with the distribution of various phytohormones between the aboveground and underground parts of the plants (Drozdova et al. 2001). Red light can increase the content of gibberellins in the aboveground parts of radish, whereas blue light stimulates the synthesis of cytokinins and heteroauxin in the hypocotyl; thus, creating a higher sink demands between the roots and leaves (Drozdova et al. 2001). Cytokinin can also stimulate tuber formation of potato (Palmer and Smith 1969), but it is not clear how phytohormones distribute when plants are grown in light conditions with different red:blue ratios. Additionally, the ability for plants grown under light with different spectral quality to form a storage organ might be affected by the photosynthetic activity in the leaves (Bukhov et al. 1995).

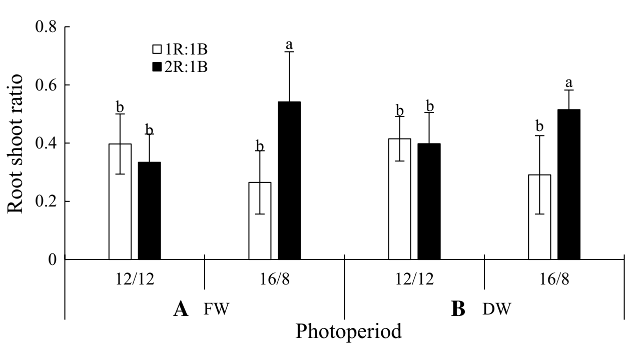

Fig. 2 Effect of light quality and photoperiod on the fresh weight (FW) root-shoot ratio (**a**) and dry weight (DW) root-shoot ratio (**b**) in cherry radish. Vertical bars indicate standard error ($n=3$). Different letters represent significant difference at $p<0.05$ among treatments by the Duncan's multiple range test

A sufficient dose of photosynthetically active radiation is crucial for the formation of assimilates and the accumulation of biomass (Lee et al. 2007; Samuolienė et al. 2011). Our data confirm that the radish biomass is strongly dependent on light intensity, especially for the formation and biomass of the storage root. Significantly increased root diameter, root volume, and root fresh and dry weight were observed with increasing light intensity of any light quality, which could be related to photosynthesis. It is well known that the net photosynthetic rate of plant increases with an increase of light intensity within a certain range; whereas, only the chlorophyll content in new leaves increased with an increase in light intensity. Numerous experiments had indicated that the biomass of both shoots and storage roots of radishes decrease as light intensity decreases, but that the storage organ is affected to a greater extent (Hole and Dearman 1993; Marcelis et al. 1997). Using ^{14}C distribution analysis, Hole and Dearman (1993) found that a greater proportion of fixed ^{14}C was retained in the petioles, which indicated that resources were preferentially allocated to leaf extension at low light intensity. Moreover, contrary to root diameter, the light intensity did not influence the length of the storage root. This result is consistent with Hall (1990), who found that the increased biomass of the storage root was mainly due to increased root diameter.

Radish growth increased with light intensity but also depended on light quality. When light intensity was 180 and 300 μmol m^{-2} s^{-1}, no significant differences in leaf chlorophyll content, shoot fresh and dry weight, root diameter, root volume, root fresh and dry weight, or root-shoot ratio were observed between light quality 2R:1B and 1R:1B conditions. However, these indices were significantly higher under 2R:1B compared to 1R:1B when the light intensity was 240 μmol m^{-2} s^{-1}. Similarly, Cope et al. (2014) grew radishes under 200 and 500 PPF with different blue light fractions between 0.3 and 92%. The fluctuation in leaf area, leaf chlorophyll concentration, and dry biomass varied when the blue light percentage was greater at 500 PPF than 200 PPF. On the basis of these results, we can conclude that light intensity is the foremost factor influencing the radish growth. Meanwhile, light quality influences the effectiveness of light intensity on radish growth to a certain extent. In addition, high red:blue light ratios had positive effects on radish growth when light intensity was 240 μmol m^{-2} s^{-1}. Therefore, adjusting light quality might be a more energy-saving way to increase radish yield compared to light intensity increments during factory production. Adams and Langton (2005) summarized studies on photoperiod and suggested that a long photoperiod could promote growth in a variety of plants, including radish. According to our data, a long photoperiod (16 h/8 h) significantly increased the leaf chlorophyll content in cherry radishes compared to a short photoperiod (12 h/12 h). This result was in agreement with Inada and Yasumoto (1989), who stated that leaf length, area, and chlorophyll content in radishes increased with extending photoperiods. Our data indicated a significant difference in root biomass between light quality treatments when the photoperiod was 16 h/8 h. Moreover, the greatest shoot and storage root biomass was observed under 2R:1B light quality conditions during a long photoperiod (16 h/8 h). Liu and Jiang (2016) also reported that a high red–blue ratio with a long photoperiod facilitated root development in radish seedlings. These results indicate that the interaction between light quality and photoperiod is the main factor that influences storage root biomass. More importantly, light quality only had a significant effect on radish growth when coupled with a relatively longer photoperiod (16 h/8 h), indicating a simultaneous influence on plant growth. Light condition with 2R:1B light quality, 240–300 μmol m^{-2} s^{-1} light intensity, and a photoperiod of 16 h/8 h would therefore be appropriate for the production of cherry radish in a plant factory setting.

5 Conclusions

When compared with a low red–blue light ratio (1R:1B), a high red–blue light ratio (2R:1B) was more effective at improving cherry radish growth, and had a significant positive effect when the light intensity was 240 μmol m^{-2} s^{-1}. Light quality and photoperiod jointly affected the growth of cherry radish. A high red–blue light ratio (2R:1B) in combination with a long photoperiod (16 h/8 h) facilitated shoot and root development in the cherry radish. Cherry radish formed commercially valuable storage roots when the light intensity was equal to or more than 240 μmol m^{-2} s^{-1}. Moreover, the effects of the light quality on storage root formation were more obvious when the light intensity was higher than a critical value (240 μmol m^{-2} s^{-1}) or when the photoperiod was relatively long (16 h/8 h). In conclusion, the effect of light condition was more significant on storage roots than on shoots. Radishes only formed commercially viable storage roots in supercritical light intensity conditions, and the ability of light quality to regulate storage root development was highly dependent on light intensity and photoperiod.

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