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Physiological responses of cucumber seedlings under different blue and red photon flux ratios using LEDs

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ABSTRACT

Light emitting diodes (LEDs) are frequently regarded as a new light source for the production of horticultural crops under closed-type conditions. However, before use of LEDs as the sole source of light can be advanced, plant responses to light quality have to be investigated for important horticultural plants. The objective of the present study was to evaluate cucumber (*Cucumis sativus*) seedlings physiological responses to different blue (B) and red (R) photon flux (PF) ratios using LEDs. Cucumber seedlings (cv. Cumlaude) were grown in a growth chamber until the second true leaf stage (17 days) with LED lighting and 18-h photoperiod. The treatments consisted of 100 μmol m^{-2} s^{-1} photosynthetic photon flux (PPF) with B:R PF ratios of 0B:100R%, 10B:90R%, 30B:70R%, 50B:50R%, 75B:25R%, 100B:0R%. Another treatment consisted of B, green (G) and R PF ratio of 20B:28G:52R%. Peak wavelengths of LEDs were 455 nm (B) and 661 nm (R) for the in the B:R treatments and 473 nm (B), 532 nm (G), 660 nm (R) in the B:G:R treatment. Hypocotyl length decreased with the increase of B PF up to the 75B:25R% treatment. Hypocotyl length in the 0B:100R% treatment was 164% greater than in the 75B:25R treatment. Plants under the 100B:0R% treatment had unexpected greater plant height, hypocotyl, and epicotyl length than plants under all other treatments. For example, the hypocotyl length under the 100B:0R% was 69% greater than in the 0B:100R treatment and 346% greater than in the 75B:25R% treatment. Leaf area decreased with the increase of B PF when plants were irradiated with the combination of B and R PF. The response of leaf area under the 100B:0R% treatment was unexpected since plants in the 100B:0R% treatment had 48% greater leaf area than plants in the 75B:25R% treatment. Chlorophyll content per leaf area, net photosynthetic rate, and stomatal conductance increased with the increase of B PF. Shoot dry and fresh mass decreased with the increase of B PF when plants were irradiated with the combination of B and R PF. Plants under 0B:100R% had the lowest dry and fresh mass from all the treatments and plants under 100B:0R% showed the greatest fresh mass from all the treatments and equal dry mass as the plants under 10B:90R% treatment. The addition of G PF to the spectrum did not have any influence in cucumber plant responses. For cucumber seedlings, morphological responses influenced plant growth since B PF responses in growth parameters (i.e., dry mass) closely matched those in morphological parameter (i.e., leaf area). More research is needed to find the optimal spectrum for the growth and development of horticultural crops under sole source electrical lighting such as LEDs.

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1. Introduction

Among environmental factors, light is one of the most important variables affecting plant growth and morphology (Kendrick and Kronenberg, 1994; Mc Donald, 2003). While effects of light intensity on plant physiological responses have received ample attention (Acock et al., 1971; Björkman, 1981; Corré, 1983; Gislerød et al., 1989), research on effects of light quality on plant physiological responses is deficient. Early research evaluating red LEDs in combination with blue fluorescent lamps showed the importance of supplementing R light with B light for plant growth and development. For example, Yorio et al. (1998) summarized work done by NASA life support program on blue light requirements of lettuce, potato, radish, spinach, and wheat, and concluded that a minimum of 35 μmol m^{-2} s^{-1} of B light (in an otherwise R light regime) is necessary for normal plant growth and development. Also, Brown et al. (1995) showed that pepper seedlings, when grown under 100R% light (660 nm peak wavelength), had longer stem length and lower plant dry mass than when grown under the combination of R LED and B fluorescent light (PPF:

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300 μmol m^{-2} s^{-1}, photoperiod: 12 h). After the development of high intensity LEDs, research continued to focus on plant growth and morphological responses to B, green (G) and R PF ratios (Massa et al., 2008). In vegetable transplants, such as tomato, lettuce, pepper and cucumber, different R:G:B PF ratios have been tested. In tomato, under sole source electrical lighting, studies agree that higher B:R ratios decrease tomato plant height (Liu et al., 2011; Nanya et al., 2012; Wollaeger and Runkle, 2014). However, conflicting results are reported on tomato growth rate. For example, Nanya et al. (2012) showed that tomato dry mass was greater under the 10B:90R% treatment than under 50B:50R% or 30B:70R%. Wollaeger and Runkle (2014) showed greater dry mass in tomato seedlings grown under monochromatic R than those grown under G:R, B:G:R, B:G, B:R and monochromatic B. Liu et al. (2011) showed that cherry tomato seedlings grown under monochromatic B LEDs had greater dry mass than plants grown under B:R, B:G:R and R LEDs.

Cope et al. (2014) tested different B:G:R PF ratios in the growth and development of lettuce and peppers using broad spectrum and monochromatic LED lights. They found higher stem length in lettuce and hypocotyl length in peppers under the 0.3B% treatment compared to the 92B% treatment.

In cucumbers, under sole-source lighting, Hogewoning et al. (2010b) tested B:R PF ratios of 0B:100R%, 7B:93R%, 15B:85R%, 22B:78R%, 30B:70R%, 50B:50R% and 100B:0R%, (the total PPF of 100 μmol m^{-2} s^{-1}, photoperiod: 16 h) and showed that cucumber had higher leaf photosynthetic capacity (A_{max}), net photosynthetic rate (Pn), stomatal conductance (g_s), and chlorophyll concentration with the increase of B PF until 50B:50R% treatment. Similarly, Savvides et al. (2012) showed lower g_s, hydraulic conductance, and Pn in cucumbers grown under 0B:100R% compared to those under 100B:0R% and 30B:70R%. The two aforementioned cucumber studies did not present any results on cucumber growth parameters (dry mass, fresh mass, and number of leaves). Under supplemental lighting, Hernández and Kubota (2014a) grew cucumber transplants under different percentages of B and R PF using LEDs (0B:100R%, 4B:96R% and 16B:84R%) and found that under low background solar radiation (5.2 mol m^{-2} day^{-1}) cucumber transplants growth rate decreased with the increase of B PF in the supplemental lighting. The reduction of growth rate was attributed to the reduction of leaf area also caused by the increase B PF.

From the aforementioned studies it is fair to conclude that vegetable transplants responses to light quality are species specific and more research in the responses of individual species to light quality is justified. In the present study cucumber was chosen as the model crop for three reasons: (1) cucumber is known to be more sensitive to light quality treatments than other vegetable transplants (Hemming et al., 2008; Hernández and Kubota, 2012, 2014a; Trouwborst et al., 2010b). (2) Cucumbers are the second-most produced vegetable in greenhouses in the USA (Nanfelt, 2011). (3) To our knowledge limited information is available on growth and morphological-related responses to a broad range of B:R PF ratios.

The objective of the present study is to build upon the existing research conducted under supplemental LED lighting (Hernández and Kubota, 2014a; Hernández and Kubota, 2014b) and sole-source electrical lighting (Hogewoning et al., 2010b; Savvides et al., 2012) by evaluating physiological and morphological responses of cucumber transplants to a broad range of B:R PF ratios under sole-source electrical LED lighting.

2. Materials and methods

2.1. Plant material and growing conditions

Greenhouse cucumber 'Cumlaude' seeds (Rijk Zwaan, Bergschenhoek, The Netherlands) were sown in rockwool cubes (cube size: 7 cm $L \times$ 7 cm $W \times$ 6.5 cm H) (Grodan, Delta, Canada) then covered with a layer of vermiculite. Seeded cubes were kept in darkness for 24 h and the substrate temperature was maintained at 28 °C. Cubes were then transferred to a growth chamber (14.8 m^2). A total of 12 experimental plants were subjected to each light treatment described below. Additional 18 plants per light treatment were positioned around the experimental plants in order to prevent any boundary effects on experimental plants. The plants were sub-irrigated as needed with nutrient solution containing (mg L^{-1}) 90 N, 47 P, 144 K, 160 Ca, 60 Mg, 113 S, 105 Cl, as well as micro-nutrients. The temperature set point in the growth chamber was 25 °C. Air temperature measured directly under the leaves was recorded for each treatment with fine-wire thermocouples (type T, gauge 24, Omega Inc., Stamford, CT, USA) (8 thermocouples in the growth chamber) (Table 1). Atmospheric moisture and air temperature were measured in the middle of the growth chamber using a humidity/temperature probe (HMP110, Vaisala Inc., Helsinki, Finland) (Table 1). Atmospheric CO_2 concentration was measured in the middle of the growth chamber using a CO_2 analyzer (LI-800, LI-COR Biosciences, Lincoln, NE, USA). All sensors were connected to a CR-23X data-logger (Campbell Scientific, Logan, UT, USA) (Table 1) scanned every 5 s and recorded at 5-min intervals.

2.2. Light treatments

Six of the fixtures used in the B:R treatments were built with B LEDs (peak wavelength 455 nm, full width at half maximum (FWHM): 15 nm) and R LEDs (peak wavelength 661 nm, FWHM:

Table 1
Light treatments with different blue (B), green (G) and red (R) PF ratios, average PPF per treatment, phytochrome photostationary state (P_{fr}/P_{total}), and growing environmental conditions.

Parameter	Units	Treatments						
		0B:100R%	10B:90R%	20B:28G:52R%	30B:70R%	50B:50R%	75B:50R%	100B:0R%
PPF[a] (400–700 nm)	μmol m^{-2} s^{-1}	98.3 ± 1.9	97.9 ± 3.4	96.5 ± 4.2	96.4 ± 5.1	97.6 ± 5.9	98.1 ± 4.7	100 ± 1.8
P_{fr}/P_{total}[b]		0.888	0.886	0.878	0.879	0.868	0.831	0.506
R:FR		125.5	127.7	80.5	118.6	114.1	95.0	1.19
Air canopy T	°C	24.9 ± 0.6	24.4 ± 0.8	24.8 ± 0.6	24.3 ± 0.8	24.5 ± 0.7	24.2 ± 0.7	24.5 ± 0.6
Photoperiod	h	18						
Air T above canopy	°C	24.7 ± 0.6						
Relative humidity	%	55.4 ± 9.1						
CO_2 concentration	μmol mol^{-1}	512 ± 159						
Nutrient solution pH		6.0						
Nutrient solution EC	dS m^{-1}	2.2						

[a] Average and standard deviation of five measurements, two measurements per repetition per treatment at the beginning and end of experiment.
[b] Phytochrome photostationary state (Sager et al., 1988).