Scientia Horticulturae 173 (2014) 92–99

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Growth and morphological response of cucumber seedlings to supplemental red and blue photon flux ratios under varied solar daily light integrals

Ricardo Hernández*, Chieri Kubota

School of Plant Sciences, The University of Arizona, Tucson, AZ 85721-0036, USA

ARTICLE INFO

Article history:
Received 16 December 2013
Received in revised form 23 April 2014
Accepted 28 April 2014
Available online 24 May 2014

Keywords:
DLI
Greenhouse
Light-emitting diode
Cucumis sativus
Spectral quality
B:R ratio

ABSTRACT

High intensity light-emitting diodes (LEDs) have the potential to be used as supplemental lighting technology in greenhouses. However, LED light quality requirements of greenhouse crops grown when supplementing the solar spectrum are unknown. In this study, to find the requirements, cucumber (*Cucumis sativus* L. cv. Cumlaude) seedlings were grown in a greenhouse with and without supplemental LED lighting (PPF: 54 ± 1.1 μmol m^{-2} s^{-1}) at varied blue (400–500 nm with the peak at 455 nm) and red (600–700 nm with the peak at 661 nm) photon flux (PF) ratios (B:R ratios) under different solar daily light integrals (DLI). The treatments were 0B:100R% (54 μmol m^{-2} s^{-1} red PF), 4B:96R% (2.3 and 52 μmol m^{-2} s^{-1} blue and red PF, respectively), 16B:84R% (8.5 and 46.2 μmol m^{-2} s^{-1} blue and red PF, respectively), and a control without supplemental lighting. The solar DLIs during the experiment were 5.2 ± 1.2 and 16.2 ± 5.3 mol m^{-2} d^{-1} created inside a greenhouse using shade screen. Regardless of B:R ratio, morphological and growth parameters of the seedlings were all improved under supplemental LED lighting compared to the no-supplemental-light control. Under high DLI conditions, no significant differences were found for any parameters between the different B:R ratios. Under low DLI, chlorophyll concentration increased with increasing B:R ratio (i.e., increasing blue PF without increasing photosynthetic photon flux, PPF) of the supplemental lighting. Dry mass, leaf number, and leaf area decreased with increasing B:R ratio under low DLI conditions. The reduction in dry mass and leaf number were attributed to the reduction in leaf area. Leaf net photosynthetic rate measured under ambient CO_2, ambient temperature, and 1000 μmol m^{-2} s^{-1} PPF (light source: tungsten halogen lamp) also showed no difference among treatments of B:R ratios, indicating that B:R ratio treatments did not cause any changes in plant photosynthetic apparatus. When used for supplemental lighting in the greenhouse, use of 100% red LED is preferred for cucumber seedlings, and additional blue LED was not beneficial.

1. Introduction

Light is commonly a limiting factor for greenhouse-grown plants. For example, 30–35 mol m^{-2} d^{-1} is reportedly an optimal daily light integral (DLI) to maximize greenhouse tomato production (Spaargaren, 2001), and similarly 13 mol m^{-2} d^{-1} is considered optimal for vegetable-seedling production (Fan et al., 2013). Spaargaren (2001) reported that DLI outside the greenhouse in The Netherlands from September to March was 12 mol m^{-2} d^{-1} on average. Supplemental lighting has been used as an effective tool for promoting plant growth and productivity in greenhouse, especially during the time solar DLI does not meet the optimal levels.

High pressure sodium (HPS) lamps and metal halide lamps are most commonly used for supplemental lighting in greenhouses, whereas LED lamps show potential for future adoption (Bourget, 2008). The efficiency of LEDs has increased very rapidly (Cope and Bugbee, 2013; Philips, 2012) and the light quality can be optimized to match crop-specific light requirements in order to increase plant quantum efficiency, promote growth, and/or improve morphology.

LEDs have been studied extensively as the sole source of light for plant growth (Massa et al., 2008). Research using LEDs as the sole light source generally agree that adding blue (400–500 nm) to red (600–700 nm) light are optimal wavelengths to promote plant growth and maintain normal plant development (Brown et al., 1995; Hogewoning et al., 2010b; Kim et al., 2005; Liu et al., 2011; Massa et al., 2008; Nanya et al., 2012; van Ieperen et al., 2012).

* Corresponding author. Tel.: +1 520 850 4131; fax: +1 520 656 1700.
E-mail addresses: ricahdez@email.arizona.edu, ricahm@gmail.com (R. Hernández).

http://dx.doi.org/10.1016/j.scienta.2014.04.035
0304-4238/

In vegetable seedlings such as pepper, tomato and cucumber, the combination of blue and red wavelengths also promoted growth and improved morphology of plants when grown under artificial light only (Hogewoning et al., 2010b; Liu et al., 2011; Savvides et al., 2012; van Ieperen et al., 2012). Recently, high intensity LEDs were also evaluated as supplemental lighting as alternative to conventional HPS lamps, for greenhouse ornamental crops (Currey and Lopez, 2013) and mature vegetable plants (Gómez et al., 2013; Trouwborst et al., 2010). These research reports employed red and blue LEDs mixed at a selected ratio, typically a value between 5 and 20% blue PF (80–95% red PF), presumably based on previous studies conducted under LEDs as the sole source of light.

Plant responses to blue PF in greenhouses supplemental lighting can be different from those to blue PF in the sole-source artificial lighting, as the background solar radiation has much blue PF, possibly meeting the requirement of blue PF for plant growth. According to ASTM (2003), solar radiation contains approximately 31% blue and 34% red radiation over photosynthetically active radiation (sun-facing, 37° tilted surface, energy basis $W\,m^{-2}$ data representing direct and diffuse light spectrum). However, limited research is available on plant responses to different blue and red percentages of greenhouse supplemental lighting. In a previous study, we examined different percentages of red and blue PF in supplemental lighting to grow tomato seedlings under varied solar DLIs (Hernández and Kubota, 2012). In this study, even under a low solar DLI ($8.9 \pm 0.9\,mol\,m^{-2}\,d^{-1}$), solar radiation seemed to fulfill blue-light requirements of tomato seedlings, and red light alone was sufficient for supplemental lighting of tomato seedlings.

To further investigate the blue PF requirement in supplemental lighting, we conducted a similar experiment using a different plant species, cucumber (*Cucumis sativus* L.). Research under sole-source artificial light suggested that plant responses to light quality are species specific (Cope and Bugbee, 2013; Hogewoning et al., 2010b; Nanya et al., 2012), and this may be also true for supplemental lighting under greenhouse conditions. Cucumbers are known to be more sensitive to light quality and irradiance treatments than other greenhouse crops such as tomato and peppers (Hernández and Kubota, 2012; Trouwborst et al., 2010; Hemming et al., 2008). Our objectives were to find the optimal light quality of supplemental LED light for cucumber transplants, to identify any interactions caused by background solar DLI, and consequently to advance the adoption of LED fixtures with optimal light quality by greenhouse-production areas.

2. Materials and methods

2.1. Plant materials and growing conditions

Greenhouse cucumber 'Cumlaude' seeds (Rijk Zwaan, Bergschenhoek, The Netherlands) were sown in rockwool plugs (plug size: 2.5 cm $L \times$ 2.5 cm $W \times$ 4.0 cm H) (Grodan, Delta, Canada) then covered with a layer of vermiculite. Seeded trays were kept in darkness for 24 h and the substrate temperature was maintained at 28 °C. Plugs were then transferred to rockwool cubes (cube size: 7 cm $L \times$ 7 cm $W \times$ 6.5 cm H) (Grodan, Delta, Canada) and then moved into the greenhouse. The greenhouse (Tucson, AZ, USA) was covered with double-layer acrylic glazing, oriented north to south, and equipped with pad-and-fan cooling system, under-bench misting system for humidification, and natural-gas-forced hot-air heating system. The greenhouse had a floor area of 108 m^2, with 2.5-m gutter height and 4.3-m peak height. When cotyledons of seedlings were expanded, uniform seedlings were selected and subjected to the treatments. 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.

2.2. Environmental conditions: solar DLI, temperature, atmospheric moisture

The greenhouse floor area was divided in two sections from north to south. Inside the greenhouse the top (1.5 m above the bench) and the side of one half (west section) were covered with two layers of shade cloth (XLS55F harmony revolux) with manufacturer specifications of 55% light transmission (Ludvig Svensson Inc., Charlotte, NC, USA). The two layers of shade cloth were placed on top of each other to achieve ~25% radiation transmittance and create low solar DLI conditions. The other half (east section) of the greenhouse was left without shade cloth to create high solar DLI conditions. DLIs were recorded everyday throughout the experiment using a quantum sensor (LI-190, LI-COR Inc., Lincoln, NE) placed at 1.35 m height from the bench in the middle of the each section of greenhouse, in order to avoid contamination by supplemental lighting. In order to maintain similar air temperatures between the two DLIs, a set of fans were placed under the benches inside the greenhouse. Air temperature measured 60 cm above the canopy and air temperature measured directly under the leaves (near-canopy air temperature) were recorded for each treatment with two fine-wire thermocouples (type T, gauge 24, Omega Inc., Stamford, CT, USA) (16 thermocouples in the greenhouse). Atmospheric moisture was measured in the middle of the greenhouse using a humidity probe (HMP110, Vaisala Inc., Helsinki, Finland). Atmospheric moisture was maintained by a misting system (Orbit Irrigation Products Inc., Bountiful, UT, USA) installed on each bench misting to the air (plants were not in contact with misting water). All sensors were connected to a CR-1000 datalogger with a multiplexer (Campbell Scientific, Logan, UT, USA) scanned every minute and recorded at 10-min intervals.

2.3. LED light source

The LED fixtures (CCS Inc., Kyoto, Japan) used in the present study were 35 cm × 34 cm in area and built with 24 blue LEDs (peak wavelength 455 nm, full width at half maximum (FWHM): 15 nm) and 510 red LEDs (peak wavelength 661 nm, FWHM: 20 nm) with a digital controller (ISC-101-4, CCS Inc., Kyoto, Japan) capable of controlling output of blue and red LEDs independently. Six LED fixtures were mounted in the greenhouse at 1.3 m above a bench uniformly irradiating six 0.3-m^2 plant-growth areas. Before starting the experiment, PF and light distribution from all fixtures was measured using a spectroradiometer (PAR-NIR, Apogee Instruments Inc., UT, USA) to ensure light quality and distribution consistencies among the fixtures.

2.4. Supplemental light treatments

Three different B:R ratios (0B:100R%, 4B:96R%, and 16B:84R%) were applied to LED supplemental lighting under two DLI conditions. Blue and red PF were adjusted independently by the input voltage of blue and red LEDs using the controller. The percent blue PF (0, 4, and 16%) were chosen within the range reported on previous literatures (0–20% blue PF). Photon fluxes over the bench surface were measured on five locations in the plant-growth area using a spectroradiometer (PAR-NIR, Apogee Instruments Inc., Logan, UT, USA) (Table 1). Additionally, a no-supplemental light treatment (control) was included under both DLI conditions. In order to have similar shading patterns in the LED treatments and the control treatment, a mock plywood panel of identical size to the LED fixture was installed at the corresponding location above the control treatment. There were a total of four treatments within the high or low DLI sections of the greenhouse, separated approximately 3.3 m each to avoid light contamination between treatments. The location of the light-quality treatments within the