Scientia Horticulturae 198 (2016) 363–369

Contents lists available at ScienceDirect

Scientia Horticulturae

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

Effects of spectral distribution and photosynthetic photon flux density for overnight LED light irradiation on tomato seedling growth and leaf injury

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ARTICLE INFO

Article history:
Received 5 July 2015
Received in revised form
16 September 2015
Accepted 26 November 2015
Available online 17 December 2015

Keywords:
Continuous light-induced injury
Dry matter production
Growth analysis
Light-emitting diode
Solanum lycopersicum
Supplemental lighting

ABSTRACT

We investigated the effects of spectral distribution and photosynthetic photon flux density (PPFD) for overnight light irradiation supplied by light-emitting diodes (LEDs) on the growth and degree of continuous light (CL)-induced leaf injury of tomato seedlings in a growth-chamber experiment. Over a 14-day treatment period, all plants were irradiated daily for 12 h with white LED light at 300 μmol m^{-2} s^{-1} PPFD. During each 12-h nighttime interval, all plants except for the controls were irradiated with white LED light at 150 or 300 μmol m^{-2} s^{-1}, or alternatively with blue, orange, or red LED light at 150 μmol m^{-2} s^{-1}. Plants irradiated overnight exhibited injuries, with their visually rated severity of injury increased as the PPFD of nighttime white light was increased. In plants irradiated overnight at 150 μmol m^{-2} s^{-1}, a higher degree of injury was experienced under blue light than under orange and red light. Overnight white-light irradiation at 150 μmol m^{-2} s^{-1} PPFD promoted dry matter production compared with the no-irradiation control, but no further increase was observed at a PPFD of 300 μmol m^{-2} s^{-1}. Among different spectra, blue light was less effective than orange light at promoting dry matter production when white light was supplied during the day. Thus, both spectral distribution and PPFD of overnight LED light irradiation were demonstrated to affect tomato seedling growth and degree of injury.

1. Introduction

Dry matter productivity of greenhouse-grown plants can be effectively promoted by photoperiod extension using supplemental assimilation lighting with electric light sources. This technique is especially useful when the daily integral of solar radiation is insufficient for plant growth. Given that such promotion is primarily due to an increase in daily net photosynthetic CO_2 assimilation, productivity might be expected to increase according to the duration of the supplemental lighting. Nevertheless, the use of excessively long photoperiods including CL to create a 24 h d^{-1} photoperiod often causes an interveinal chlorosis-like mottled injury (CL-induced injury; Velez-Ramirez et al., 2011) in leaves of some plant species (Arthur et al., 1930; Hillman, 1956; Hurd and Thornley, 1974; Kristoffersen, 1963; Murage et al., 1996b; Vlahos, 1990; Wheeler and Tibbitts, 1986; Withrow and Withrow, 1949). Tomato (*Solanum lycopersicum*) is highly susceptible to CL-induced injury (Hillman, 1956). A locus involved in tolerance to CL-induced injury has recently been identified in tomato (Velez-Ramirez et al., 2014, 2015), but the detailed mechanism associated with this injury has not yet been fully elucidated. Under greenhouse conditions with supplemental lighting, an optimal photoperiod for tomato growth and yield has been reported to be 14 h d^{-1}, with longer photoperiods of 20 and 24 h d^{-1} causing CL-induced injury and decreased growth and yield (Demers and Gosselin, 2002; Demers et al., 1998).

The degree of injury induced by CL is influenced by other environmental factors besides photoperiod (Velez-Ramirez et al., 2011). In particular, the extent to which PPFD (Arthur et al., 1930; Murage et al., 1997; Withrow and Withrow, 1949) and temperature (Haque et al., 2015; Hillman, 1956; Matsuda et al., 2012, 2014; Ohyama et al., 2005a,b; Shibaeva and Sherudilo, 2015; Sysoeva et al., 2012) affect injury and growth under CL has been well studied. For example, the severity of injury in tomato has been positively correlated with the PPFD for nighttime supplemental lighting (Withrow and Withrow, 1949) or the PPFD of CL throughout the day (Arthur et al., 1930). Spectral distribution is also known to be a factor

Abbreviations: CL, continuous light; DOI, degree of injury; FL, fluorescent lamp; PSS, phytochrome photostationary state; SPD, spectral photon flux density distribution.

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http://dx.doi.org/10.1016/j.scienta.2015.11.045
0304-4238/

influencing CL-induced injury, but few studies of its effect have been reported. In one such study, Globig et al. (1997) grew tomato plants in a growth chamber under CL using cool white fluorescent lamps (FLs) and incandescent lamps with or without supplemental far-red FLs. They found that leaf chlorophyll content was higher and the number of dead leaves was lower under supplemental far-red light irradiation, which indicates that far-red light reduces the degree of CL-induced injury. In a study using eggplant (*Solanum melongena*; Murage et al., 1997), injury was more severe and chlorophyll content was lower in leaves grown under continuous blue or red light from FLs than under continuous white light from FLs. It should be noted, however, that the PPFD of CL in that study differed among light sources. In a greenhouse experiment, overnight supplemental lighting with metal-halide lamps reportedly brought about more severe injury in tomato than did high-pressure sodium lamps (Demers and Gosselin, 2002). This difference in injuries was suggested to be related to the higher energy of the blue-light waveband emitted by the metal-halide lamps. It appears that no conclusive links can yet be made between particular wavelengths and CL-induced injury (Velez-Ramirez et al., 2011).

Exploring the effects of spectral distribution can contribute to the design and development of lighting technology for overnight light irradiation using an appropriate light source. We therefore investigated the effects of spectral distribution on the degree of CL-induced injury and growth of tomato plants in a growth-chamber experiment. In earlier growth-chamber experiments (Globig et al., 1997; Murage et al., 1997), plants were subjected to CL of various spectral distributions that were fixed for 24 h. If supplemental lighting for photoperiod extension is used for greenhouse plant production, however, plants must be grown under common white light during the day and irradiated with light of different spectral distributions at night. LEDs were used as light sources in the present experiment for two reasons: the effects of specific monochromatic wavebands can be distinguished, and LEDs have recently been considered as potentially useful for greenhouse supplemental lighting (Currey and Lopez, 2013; Gómez and Mitchell, 2015; Gómez et al., 2013; Hernández and Kubota, 2014; Lu et al., 2012; Trouwborst et al., 2010). While the main goal of this study was to provide insight into the effects of light spectral distribution on CL-induced injury and growth, we also examined the effects of the PPFD for overnight light irradiation using white LEDs.

2. Materials and methods

2.1. Plant material and growth conditions

Seeds of tomato 'Momotaro Fight' (Takii Co., Ltd., Kyoto, Japan) were sown into plug trays filled with a substrate containing granular rockwool and peat moss (Best Mix No. 3; Nippon Rockwool Corp., Tokyo, Japan) and placed in temperature-controlled growth chambers (MIR-554; Panasonic Healthcare Co., Ltd., Osaka, Japan) equipped with cool white FLs (FPL55EX-N; Iwasaki Electric Co., Ltd., Tokyo, Japan). The trays were kept in darkness at 25 °C for the first 3 days and then exposed to 300 μmol m^{-2} s^{-1} PPFD for 12 h d^{-1} (8:00 to 20:00) at 25/20 °C (day/night). The trays were subirrigated with tap water once daily for 10 to 20 min for the first 7 days and thereafter with a nutrient solution (prescription A; OAT Agrio Co., Ltd., Tokyo, Japan) adjusted to an electrical conductivity of 120 mS m^{-1}. Uniform plug seedlings were selected 10 days after seeding and individually transplanted onto rockwool blocks (Delta 6.5G; ROCKWOOL B.V., Roermond, The Netherlands).

Table 1
Light environmental conditions during daytime (12 h) and nighttime (12 h) treatments.

Treatmentcode	LED[a]		PPFD[b] (μmol m^{-2} s^{-1})		PSS[c]	
	Day	Night	Day	Night	Day	Night
Ctrl	White	–	300	0	0.83	N/A[d]
W150	White	White	300	150	0.83	0.83
B150	White	Blue	300	150	0.83	0.53
O150	White	Orange	300	150	0.83	0.91
R150	White	Red	300	150	0.83	0.89
W300	White	White	300	300	0.83	0.83

[a] Light-emitting diode. See Fig. 1 for spectral photon flux density distributions.
[b] Photosynthetic photon flux density.
[c] Phytochrome photostationary state calculated according to Sager et al. (1998).
[d] Not available because PPFD = 0 μmol m^2 s^{-1}.

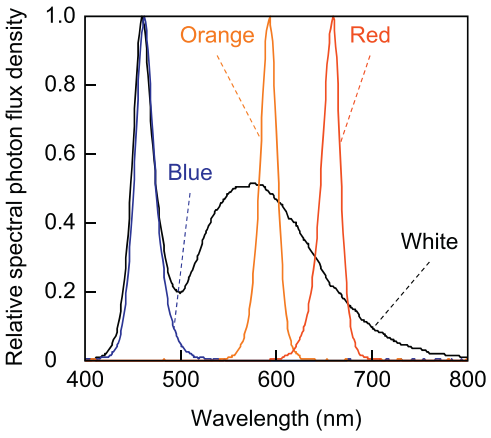

Fig. 1. Relative spectral photon flux density distributions of white, blue, orange, and red LED light.

2.2. Treatments and LED arrays

Ten days after seeding, plants were transferred to and grown in temperature-controlled growth chambers (MIR-553; SANYO Electric Co., Ltd., Osaka, Japan) equipped with LED arrays as described below. The plants were irradiated with white LED light (NSPW310DS [b2w], Nichia Corp., Tokushima, Japan) during the 12-h daytime period and subjected to various 12-h nighttime light environments: without irradiation as a control (Ctrl), with irradiation from white LEDs at 150 (W150) or 300 (W300) μmol m^{-2} s^{-1} PPFD, or with irradiation from blue (B150; HBL3-3S55-LE, Toricon, Shimane, Japan), orange (O150; OS5YAA3131P, OptoSupply Ltd., Hong Kong, China), or red (R150; SRK3-3A80-LE, Toricon) LEDs at 150 μmol m^{-2} s^{-1} PPFD (Table 1). PPFDs were measured with a quantum sensor (LI-190SA connected to LI-250; LI-COR Inc., Lincoln, NE, USA) and adjusted at the top of plants. The distance between the LEDs and the top of plants was approximately 10 cm. Spectral photon flux density distributions (SPDs) of LED light were measured using a spectroradiometer (MS-720; EKO Instruments, Co., Ltd., Tokyo, Japan) (Fig. 1). Peak wavelengths measured for blue, orange, and red LEDs were 462, 593, and 659 nm, respectively. Phytochrome photostationary state (PSS), corresponding to the fraction of active phytochrome (P_{fr}) in total phytochrome ($P_{fr} + P_r$), was cal-