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Effect of green light wavelength and intensity on photomorphogenesis and photosynthesis in *Lactuca sativa*

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ABSTRACT

In this study, the effects of green light-emitting diodes (LEDs) with different peak wavelengths and light intensities on lettuce growth and photosynthesis were evaluated. The green LEDs used were G510 (peak wavelength: 510 nm; band width at half peak height: 18 nm), G520 (524 nm; 30 nm) and G530 (532 nm; 36 nm) at a photosynthetic photon flux (PPF) of 100, 200 and 300 μmol m^{-2} s^{-1}, respectively (maximum output of G530 was PPF 260). Shoot and root growth in lettuce plants irradiated with green LED light at PPF 100 decreased compared with white fluorescent light, but root growth of plants irradiated with green LED light at PPF 200 increased, and shoot growth of plants grown under G510 at PPF 300 was the highest of all light sources. Leaf photosynthetic rate (Pn) of plants irradiated with green LED light at PPF 200 was dramatically higher than that at PPF 100, and the Pn of plants irradiated with G510 was the highest of all light sources. These results indicated that high-intensity green LED light was effective to promote plant growth and, in particular, short-wavelength green light was available for active plant growth.

1. Introduction

Plants appear green because green light is reflected by the plant. Therefore, green light has been thought to be of no use for plant growth, particularly for photomorphogenesis and photosynthesis. Plants grow normally under sunlight or combined artificial red and blue light (Kim et al., 2004a; Ohasi-Kaneko et al., 2007), but irradiation with green light induces stem elongation (Folta, 2004) and decreased biomass production (Folta and Maruhnich, 2007). Green light is absorbed only weakly by chlorophylls and pigments extracted from green leaves (Terashima et al., 2009). However, Terashima et al. (2009) indicated that green light mixed with strong white light drove photosynthesis more effectively than red light in sunflower leaves. Thus, green light is often held to be unavailable for plant growth, but might be available for plant growth under strong light intensity.

Green higher plants utilize chlorophylls a and b and a variety of carotenoids to capture light for photosynthesis (Nishio, 2000). The percentage absorption of blue or red light by plant leaves is about 90% and that of green light is about 70–80% (Terashima et al., 2009). Thus, plant development and physiology are strongly influenced by blue or red light. Blue light suppresses hypocotyl elongation and induces biomass production, and red light induces hypocotyl elongation and expansion in leaf area (McNellis and Deng, 1995; Johkan et al., 2010). Green light also affects plant morphology and physiology, including leaf growth, stomatal conductance and early stem elongation (Folta, 2004; Kim et al., 2004a,b).

Plant growth under the combination of blue and red light has been studied in lettuce, spinach, komatsuna (Japanese mustard spinach) and radish (Yorio et al., 2001; Hanyu and Shoji, 2002; Ohasi-Kaneko et al., 2007). The combination of red and blue light was an effective lighting source to produce plant biomass, and the addition of green light with blue and red light was also effective (Kim et al., 2004a,b). Green light can penetrate into the plant canopy better than blue or red light (Klein, 1992). Leaves in the lower canopy would be able to use the transmitted green light in photosynthesis (Nishio, 2000), so plant growth is promoted by the addition of green light with blue and red light (Kim et al., 2004a,b). However, the growth of plants irradiated with green light decreases as the proportion of green light increases (Kim et al., 2004a,b).

Plant physiological reactions to green light and the effects of green light on plant growth have been investigated, but there is no report of plants being cultivated under green light only. Hence, the question arises whether the plants could be grown under green light only. Major previous reports showed that green light was not active for plant growth (Van et al., 1977; Kim et al., 2004a,b), and some previous reports showed that green light was active for plant growth when the proportion of green light to photosynthetic

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photon flux (PPF) was low (Kim et al., 2004a,b; Terashima et al., 2009). Terashima et al. (2009) reported that sufficient blue or red lights were strongly absorbed near the adaxial side of leaf, but sufficient green light, which chloroplasts are hard to absorb, penetrated and was absorbed by the chloroplasts in the abaxial side. However, typical values of absorptance at 550 nm range from 50% in lettuce (Inada, 1976). We thought that low activation of plant growth with the green light due to the lower PPF of light source in the previous works. Therefore, previous reports raise the hypothesis that the green light with higher PPF would penetrate into the plant leaves, be absorbed in chloroplast and drive the photosynthesis enough to growth. Moreover, the green light region is between 500 and 600 nm, but it is unknown which particular wavelengths of green light promote plant growth. In this study, three types of green light-emitting diode (LED) lights with different peak wavelengths and light intensities were used to investigate the effect of green light on lettuce growth and photosynthesis, and the availability of green light for plant growth is discussed.

2. Materials and methods

2.1. Plant growth

Germinated seeds of red leaf lettuce (*Lactuca sativa* L. cv Banchu Red Fire; Takii Seed Co., Kyoto, Japan) were sown in urethane cubes (W2.4 cm × D2.4 cm × H2.8 cm) filled with water. The seedlings were grown at 23 ± 2 °C under 100 μmol m^{-2} s^{-1} PPF for 14 h with white fluorescent lamps (FL; FLR110H-W1A, Mitsubishi/Osram Co., Kyoto, Japan). The seedlings were supplied with a nutrient solution (pH 5.8), containing 9.2 N, 2.6 P, 4.4 K, 2.2 Ca, and 0.8 Mg (in mmol L^{-1}) 7 d after sowing (DAS). The seedlings were transplanted to cultivated panels, supplied with 1 L nutrient solution until the end of experiments, and cultivated at 25 °C, relative humidity (RH) 60% and 900 μmol mol^{-1} CO_2 in a growth chamber (VB1514, W200 cm × D75 cm × H140 cm; Vötsch, Germany). The plants were irradiated with different light spectra from the green LEDs, namely G510 (peak wavelength: 510 nm; band width at half peak height: 18 nm; ISL-305X302-GGGG505, CCS Co., Kyoto, Japan), G520 (peak wavelength: 524 nm; band width at half peak height: 30 nm; ISL-305X302-GGGG525, CCS) and G530 (peak wavelength: 532 nm; band width at half peak height: 36 nm; ISL-305X302-GGGG525, CCS) 10 DAS. All seedlings were irradiated for 24 h at PPF 100, 200 or 300 μmol m^{-2} s^{-1}, but maximum output of G530 was PPF 260 μmol m^{-2} s^{-1}. The wavelength of the light source was determined with a USB2000 spectrometer (Ocean Optics, Dunedin, FL, USA) (Fig. 1). At 17 DAS, leaf number, third-leaf dimensions (leaf length, leaf width, petiole length, and petiole width), leaf area, fresh weight (FW) and dry weight (DW) were measured.

2.2. Leaf gas exchange

At 17 DAS, photosynthetic rate (Pn) and transpiration rate were determined on the second fully expanded leaf with an Arabidopsis leaf chamber (6400-15 Arabidopsis Chamber, 0.785 cm^2, LI-COR, Lincoln, NE, USA) mounted on an infrared CO_2/H_2O analyzer (LI-6400 Portable Photosynthesis System, LI-COR). The conditions in the measurement chamber were controlled as follows: flow rate, 300 μmol s^{-1}; CO_2 concentration in the sample chamber, 900 μmol mol^{-1}; RH, 60%; air temperature, 25 °C. To measure photosynthetic CO_2 fixation under different light conditions, gas exchange characteristics of the second leaf were determined under the FL, G510, G520 and G530 light sources at PPF 100, 200 and 300 μmol m^{-2} s^{-1}.

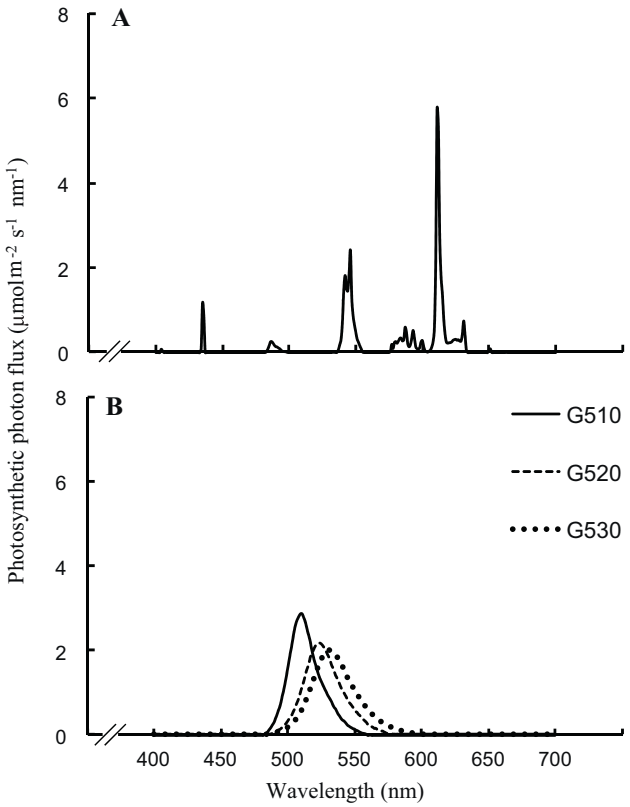

Fig. 1. Spectral photon flux distributions for the lighting treatments. (A) White fluorescent lamp (FL); (B) green light-emitting diodes (LEDs); G510: peak wavelength 510 nm, G520: peak wavelength 524 nm, G530: peak wavelength 532 nm. Total photosynthetic photon flux was 100 μmol m^{-2} s^{-1} in each treatment. Spectral scans of LED light were recorded 20 cm below the panel of LEDs and 45 cm below the FL.

2.3. Statistical analysis

Tukey's multiple range test was used to test the difference between more than two means at the 0.05 significance level using XLSTAT software (Esmi Co., Tokyo, Japan).

3. Results

3.1. Plant growth and morphology

Among plants grown under the FL, the plants irradiated at PPF 100 and 200 showed normal photomorphogenesis, but at PPF 300 the plants were severely dwarfed (Fig. 2). Under green LED light, the plants irradiated at PPF 100 showed succulent growth in contrast to the FL treatment and, moreover, the plants irradiated with G530 at PPF 100 showed remarkably succulent growth. At PPF 200, the plants irradiated with G510 and G520 did not exhibit succulent growth. At PPF 300, the plants irradiated with G510 and G520 were of normal appearance, similar to the plants irradiated with FL at PPF 100. However, the plants irradiated with G530 at PPF 200 and 300 were slightly succulent.

No difference was observed in leaf number irrespective of the wavelength at PPF 100 and 200, but the leaf number of plants irradiated with G510 was significantly increased at PPF 300 (Table 1). The leaf area and FW of plants treated with green LED light were lower than those irradiated with FL at PPF 100, and those grown under the FL at PPF 200 showed maximum leaf area and FW of 65.8 cm^2 and 1738 mg, respectively. However, the leaf area and FW of plants irradiated with G510 at PPF 300 were significantly increased by 71% and 59%, respectively, compared to that at PPF 200. The shoot DW