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Morphology and Leaf Color Changes of Grafted Tomato Plug Seedlings Irradiated by Different Wavelengths of Photosynthetically Active Radiation during Low Light Irradiation Storage

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Abstract. To investigate the effects of different wavelengths of photosynthetically active radiation on the morphology and leaf color changes of a single tomato (*Lycopersicon esculentum*) seedling, we stored the seedling at 10±0.5°C under eight different wavelengths (peak wavelengths; 405, 450, 505, 545, 600, 645, 680, and 700 nm) with a constant photosynthetic photon flux of 3 μmol m^{-2} s^{-1} for 28 d. Under the 405, 450, and 505 nm wavelength conditions, the leaves of the seedlings showed vigorous shape with an upright morphology. Rachis elongation was suppressed and hence compact appearance was observed under the 450 and 505 nm conditions. Although the difference in leaf color between before storage and on 28 days after storage was observed under all wavelength conditions, the 405 and 700 nm irradiations changed the leaf color to light green. Application of light-emitting diode (LED) light irradiated from around 450 to 545 nm can contribute to vigorous shape with an upright morphology of tomato seedlings during low light irradiation-low temperature storage.

Key words : light-emitting diode, *Lycopersicon esculentum*, transplant

Introduction

Use of transplants for the production of high quality horticultural plants has recently increased worldwide. Long-term postharvest storage of seedlings would allow their producers to regulate market supply during surplus production or peak demand. If seedlings can be well preserved for over a month, their off-season production can be encouraged and the utilization in greenhouse facilities can be enhanced. Hence, seedlings storage techniques for maintaining their quality for over a month are required.

To date, many studies on low light irradiation-low temperature storage (LLI-LTS) of seedlings have been reported (Heins et al., 1992; Fujiwara et al., 1999, 2001; Kozai et al., 1996; Kubota and Kozai, 1995). An operational experiment with the automatic photosynthetic photon flux (PPF) control system for maintaining the CO_2 exchange rate at zero was reported (Fujiwara et al., 2005), and it was revealed that addition of a low percentage of blue light along with red light using light-emitting diodes (LEDs) improved the morphological appearance of tomato seedlings and reduced the PPF required to suppress the change in dry weight. Although morphology and leaf color are of great importance for seedlings assessment, the effects of different narrow light wavelengths of photosynthetically active radiation (PAR) on the morphology and leaf color of seedlings during LLI-LTS have not been reported.

Fortuitously, the price of LEDs has been decreasing, irrespective of the peak wavelength, even as their luminous intensity has increased. These advances raise the possibility that LEDs could be practically applied to seedling storage systems. There have been several reports showing the effect of a narrow wavelength (monochromatic) light irradiation on the growth and development of green plants (Fujiwara et al., 1999; Fujiwara et al., 2001; Fujiwara et al., 2005). Under long-term light exposure, an increase in the blue light fraction from <0.1% to 26% decreased internode length, by specifically inhibiting soybean cell division in stems (Dougher and Bugbee, 2004). A brief pulse of green light could preclude blue-light-mediated stomatal opening in *Vicia*

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faba epidermal peels, and an action spectrum revealed 540 nm to be the most effective wavelength for reversal (Frechilla et al., 2000). This band of wavelengths, i.e., 500~600 nm, has negative effects on plant growth (Dougher and Bugbee, 2001; Went 1957). These results suggest that light of different wavelengths from LEDs may have a different effect on seedling storage. Thus, selection and optimization of the light wavelength of PAR could improve the visual quality of seedlings during LLI-LTS. As a preliminary experiment, we examined the effects of eight different wavelengths of PAR on the morphology and leaf color of grafted tomato seedlings during LLI-LTS for 28 days.

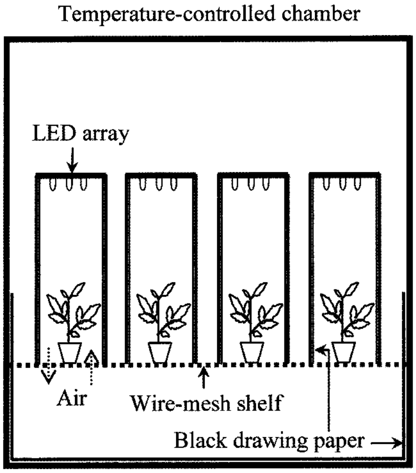

Fig. 1. Schematic diagram of the experimental setup used in the present experiment. Eight cylinders were concentrically placed on a wire-mesh shelf in a temperature-controlled chamber.

Materials and methods

Seedlings and storage conditions

Grafted tomato (*Lycopersicon esculentum* Mill., scion: 'Momotaro Haruka' and rootstock: 'B-barrier' for the first, second, and fifth experiments and 'Block' for the third and fourth experiments) plug seedlings grown in a 128-plug tray filled with peat, vermiculite, bark, and perlite mix (4:4:1:1) were obtained from a commercial seedling supplier (Berg Earth Co., Ltd., Ehime, Japan). They were placed in a chamber (MIR 153, Sanyo Co., Ltd. Tokyo, Japan) at 20±1°C for 1 d prior to storage, under fluorescent lamps (CREA1-FPL55EX-L, Iwasaki Electric Co., Ltd., Tokyo, Japan) that provided 220 (four corners) to 250 (center) μmol m^{-2} s^{-1} PPF at the top of the seedlings. Each of eight groups contained one seedling. This applied to all five experiments. We carefully selected eight out of 128 seedlings that met the criterion of a totally expanded third leaf and had identical stem length. A tomato seedling was placed in a cylinder (125 mm in diameter and 250 mm in height), and covered with a black drawing paper on the lateral side to prevent light leakage from and entrance into the cylinder through the lateral side. This cylinder was placed in a temperature-controlled chamber (MIR 553, Sanyo Co., Ltd. Tokyo, Japan) (Fig. 1). Eight cylinders containing one seedling each were concentrically placed on a wire-mesh shelf, through which air in the cylinder can flow naturally from the inside to the outside of the cylinder (Fig. 1). The inner wall, floor beneath, and the shelf of the chamber were completely covered with black drawing paper to prevent the light reflected from the walls and floor. The seedlings placed in the cylinders were irradiated from the top of the cylinder with eight different wavelengths and stored for 28 days at 10±0.5°C.

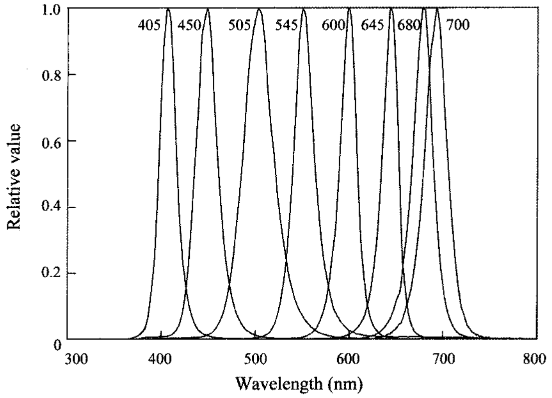

Fig. 2. Relative spectral distribution of light from different light-emitting diodes (LEDs) (405, 450, 505, 545, 600, 645, 680, and 700 nm, respectively) at the top of seedling on applying their standard-rated forward voltages.

LED characteristics and the PPF control system

Peak wavelengths of 405 (L405-36V, Epitex INC., Kyoto, Japan), 450 (L450-36U, Epitex INC., Kyoto, Japan), 505 (L505-36U, Epitex INC., Kyoto, Japan), 545 (L545-04, Epitex INC., Kyoto, Japan), 600 (L600-36V, Epitex INC., Kyoto, Japan), 645 (L645-36V, Epitex

INC., Kyoto, Japan), 680 (L680-36AU, Epitex INC., Kyoto, Japan), or 700 nm (L700-36AU, Epitex INC., Kyoto, Japan) (Fig. 2) were adopted as light sources and six LEDs each arrayed in a hexagon formation on a rectangular universal circuit board (110 × 150 mm). The directional half-value angle of the LEDs was 30°. Each cylinder was placed directly below an LED array. The PPF of 3 μmol m^{-2} s^{-1} at the top of the seedlings in the present experiment was determined by reference to the following reports: the quality of broccoli (*Brassica oleracea* L.) plantlets was best maintained under white light at 2 μmol m^{-2} s^{-1} (Kubota et al., 1996); the light compensation point was reached at a PPF of 3.5 μmol m^{-2} s^{-1} for photoautotrophic seedlings of broccoli (Wilson et al., 1998) and 4-5 μmol m^{-2} s^{-1} for eggplant (*Solanum melongena* L.) plug seedlings (Kozai et al., 1996).

Measurement

Stem length, the number of fully expanded leaves, and the difference in leaf color (ΔE^*ab) were recorded for all the seedlings on 0, 7, 14, 21, and 28 days after storage. The leaf colors of all the seedlings were determined with a color reader (CR-13, Konica Minolta Holdings, Inc., Tokyo, Japan) before storage and every week after storage. A circle of 1 cm diameter on the terminal leaflet of the third leaf was used for leaf color measurements. ΔE^*ab was calculated with the L^*, a^*, and b^* values on the color reader. Photos of the top and lateral views of all the seedlings were captured with a digital camera (E-10, Olympus Corporation, Tokyo, Japan) before storage and every week after storage. The experiment was conducted five times with completely randomized designs. Statistical analysis was subjected to analysis of variance followed by least significant difference (LSD) at $P \leq 0.05$ using the JMP software (JMP, SAS Institute Inc., Cary, NC, USA).

Results and Discussion

Morphology and leaf color

The number of fully expanded leaves of the seedlings irradiated with the eight different wavelengths during storage was not different from that before storage (data not shown). The ratio of stem length at different time points after storage under irradiation to that before storage under the 645 nm irradiation condition had not much increased to a great extent, whereas those under the other radiations except for 645 nm relatively increased during storage (Fig. 3). The ΔE^*ab under all irradiation conditions for the 3rd leaf of the seedlings between day 0 and each measurement day was significantly different (Fig. 4); the ΔE^*ab values under the 405 and 700 nm irradiation conditions were greater than those for the other irradiation conditions at 28 d from the start of storage. In the present experiment the seedlings irradiated with the eight different wavelengths for 28 d did not show a regular change in stem elongation and leaf color.

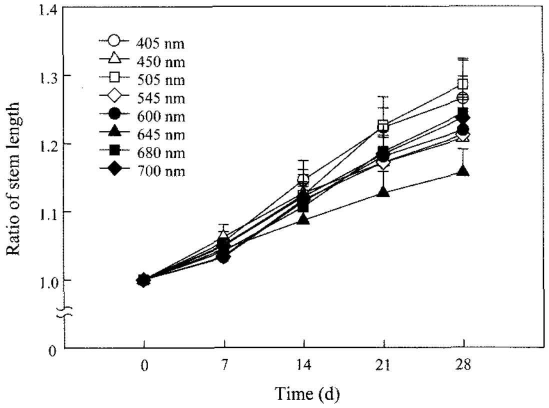

Fig. 3. Time courses of the ratio of stem length at different time points to that before the storage of grafted tomato plug seedlings during low light irradiation, low temperature storage with different wavelengths of photosynthetically active radiation at 10°C. The photosynthetic photon flux at the top of the seedlings was consistent at 3 μmol m^{-2} s^{-1} throughout the duration of storage for all the wavelengths. Data are represented as the means ± SE (n = 5).

In contrast to the leaves of seedlings stored under wavelengths of over 545 nm (Fig. 5), the stored under wavelengths less than 545 nm appeared vigorous with an upright morphology even at 28 d after storage. In addition, the seedlings under the 450 and 505 nm irradiation conditions appeared compact at 28 d after storage due to suppressed rachis elongation (the main axis of the pinnate leaf) during storage, whereas those under the other wavelengths did not appear compact (Fig. 5). Although phyochromes and cryptochromes, which are known as blue and green light receptors (Folta and Maruhnich 2007), would be related with these morphological properties, there is little information on how

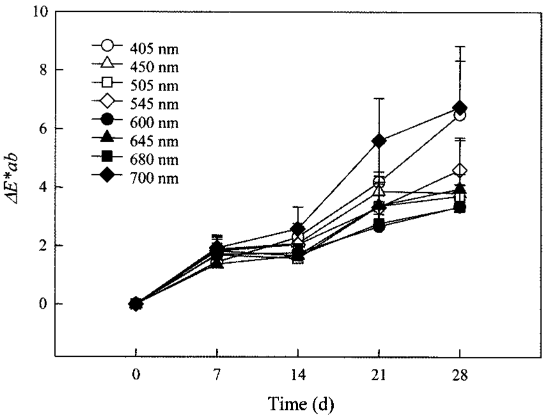

Fig. 4. Time courses of the difference in leaf color of the 3rd leaf between day 0 and each measurement day (*ΔE*ab*) of grafted tomato plug seedlings during low light irradiation, low temperature storage with different wavelengths of photosynthetically active radiation at 10°C. The photosynthetic photon flux at the top of the seedlings was consistent at 3 μmol m^{-2} s^{-1} throughout the duration of storage for all the wavelengths. Data are represented as the means ± SE (n = 5).

the receptors affect the vigorous shape with upright morphology. The addition of blue light to red light irradiation was responsible for the vigorous appearance of the stored tomato seedlings (Fujiwara et al., 2005). The various parameters of seedling quality from the viewpoint of the grower include seedling morphology, leaf color, and location of first flower truss, etc. Deterioration of seedlings quality during long-term storage, i.e., for over 4 weeks, normally occurs in terms of leaf color change and leaf drooping. On the basis of these results, we concluded that light wavelengths within the range of blue to green light (around 450~545 nm) will have a beneficial effect on the morphology of seedlings during LLI-LTS.

Conclusions

The eight wavelengths of PAR did not show a great difference in terms of their effects on the stem length and leaf color of the grafted tomato plug seedlings during LLI-LTS at a constant PPF of 3 μmol m^{-2} s^{-1} for 28 d. However, shorter wavelengths of less than 545 nm induced the vigorous shape with upright morphology of the seedling leaves. The effect of the short wavelengths of PAR on green plant morphology during LLI-LTS can contribute to maintain visual quality and to prolong the

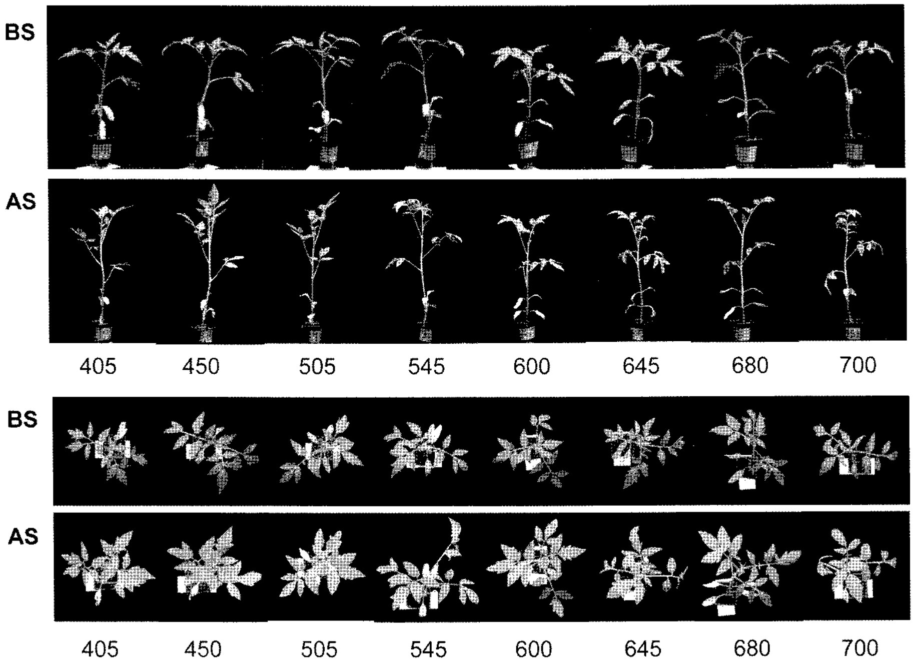

Fig. 5. Tomato plug seedlings before storage (BS) and after storage (AS) irradiated with eight different wavelengths from light-emitting diodes (LEDs) (peak wavelength; 405, 450, 505, 545, 600, 645, 680, and 700 nm, respectively) at the photosynthetic photon flux of 3 μmol m^{-2} s^{-1} during low light irradiation, low temperature storage for 28 d.

storage period of seedlings.

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저광 조사 저온 저장 중 PAR의 각 파장에 의한 토마토 플러그 묘의 형태 및 엽색의 변화

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적 요. 본 연구는 저광 조사 저온 저장 중 광합성유효방사(PAR)내의 각 파장이 토마토 묘의 형태와 엽색 변화에 미치는 영향을 조사하기 위하여 실시되었다. 10±0.5°C의 온도와 피크 파장이 각각 405, 450, 505, 545, 600, 645, 680, 700nm의 발광다이오드로부터 조사된 3μmol m^{-2} s^{-1}의 광합성유효광량자속밀도 조건에서 토마토 접목묘를 28일간 저장하였다. 405, 450, 505nm의 파장에서 저장된 묘의 잎은 다른 파장에서 저장된 잎에 비해 직립하는 경향을 보였으며, 특히 450과 505nm 파장에서 저장된 묘의 경우 엽축 생장이 억제되면서 콤팩트한 형태를 보였다. 파장의 변화에 따른 엽색의 규칙적인 변화는 저장 전후를 비교하여 관찰되지 않았으나, 405와 700nm 파장에서 저장된 묘는 엷은 녹색을 나타내었다. 저광 조사 저온 저장 중, 450~545nm 영역의 광조사는 토마토 묘의 직립을 유도하여 외관상 건강한 묘로 인정 받는데 기여할 것으로 기대된다.

주제어 : 광합성유효방사, 발광다이오드, 육묘, 형태형성