Comparison of LEDs, Fluorescent Lamps and Incandescent Bulbs for Long-day Treatment of Forcing Strawberries as Affected by Respective Color Temperature

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Long day (LD) treatment is frequently applied for horticultural crops, including strawberry, and sufficient effect similar to 4 to 6 hours of day time elongation in the evening can be achieved by 1 to 3 hours of night break in the mid night. Incandescent lamps (IC) have long been an important light source, but the general incandescent lamps are out of production and have been replaced with LED or florescent lamps (FL). Thus, we compared light sources and their color temperature (2,800 K, warm white similar to IC; 6,500 K, daylight) in different lighting programs. The effectiveness of 3 and 4 cycles of alternate intermittent lighting, 30 min on/30 min off, were equal to and larger than 2 hours of night break, respectively. Measured intensity of illumination (lux) at the canopy surface by 2,800 K LED (6.9 W) and FL (12 W) was 1.50 and 0.95 times as large as IC (54 W), but leaf growth under LED and FL was similar to and less vigorous than IC, respectively. On the other hand, intensity values of illumination by 6,500 K LED (6.9 W) and FL (12 W) were both 1.20 times as large as 2,800 K ones, but 6,500 K light sources were much less effective compared to 2,800 K ones. Daylight type LED and FL which have higher luminance efficiency but emit less red light compared to warm white ones, are not suitable as alternative light sources for IC.

Key words : daylight, *Fragaria ×ananassa* Duch., intermittent lighting, luminance efficiency, warm white

Introduction

Winter dormancy of strawberry and also other temperate perennial plants is induced by short-day and low temperature in the autumn. Vegetative growth of forced or semi-forced strawberries can be stimulated by long-day treatment (Fujimoto, 1972). For a long time, incandescent bulbs (IC) have been the major lighting source for long-day treatment of horticultural crops. They contain large red and far-red regions of the spectrum, the active regions for light conversion of phytochrome. However, most governments around the world have passed measures to phase out IC for general lighting in favor of more energy-efficient lighting alternatives, and the production of general incandescent lamps terminated around 2013.

Compact fluorescent lamps (FL) and light emitting diodes (LED) are major alternative light sources (JLMA, 2011a, b). They produce "white" light with irregular spectral distributions, not a continuous range of wavelength. They can provide optical stimuli similar to incandescent bulbs visible to the human eye, but the different spectral distribution from incandescent bulb or daylight (Panasonic, 2014) may result in different physiological responses in strawberry and other horticultural crops (LFC, 2014). For FL and LED, the color of the emitted light can be converted easily and two types of alternative "bulbs" adaptable to the E26 bulb socket are commercially supplied, reddish "warm white" and bluish "daylight", expressed as 2,800 K and 6,500 K color temperature, respectively. The luminance efficiency of LED is almost 10 times higher than IC, and generally the efficiency of daylight type LED is higher than warm white type. Therefore, we compared the effectiveness of these light sources for forcing strawberry plants.

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Materials and Methods

Light Sources

Characteristics of examined light sources are shown in Table 1. The LED and FL are commercially available as alternatives to 60 W normal IC bulb which requires 54 W of power and they fit into the E26 bulb socket. The IC-R bulb and LED lamps spread the light at an angle of 120°, and the downward light flux is stated to be similar to 60 W type IC. The examinations were undertaken in two experiments from 2011 to 2014.

Experiment 1. Comparison of Warm White Alternative Light Sources

On December 1, 2011, 'Hokowase' and 'Fukuoka S6' plants grown in 9 cm plastic pots were planted on annual hills 20 cm apart between and within rows, in a plastic walk in tunnel oriented south to north (6 m × 15 m and five 12 m long beds were furrowed). IC (center of the tunnel), W-FL 12 W (5 m apart to the north) and W-LED (5 m apart to the south) were set 2.2 m above the upper surface of the bed. Horizontal distance from the light sources to the examined plants which were planted on the east and west most beds was around 2 m. Two hours of night break was begun December 10 and continued till March 10, 2012. Intensity of light is expressed in several ways. Table 2 shows the differences in illuminance which indicates brightness stimulating human eyes, irradiance which indicates light energy including far-red and photosynthetic photon flux density (PPFD). Illuminance above the canopy was almost similar for all light sources, but the irradiance was 33% and 57% of IC, for FL and LED, respectively. For PPFD, FL was apparently smaller than IC and LED. When these 3 light sources were lighted simultaneously giving similar conditions as 2 hours of night break treatment, irradiance and PPFD of FL were around 60% of

Table 1　Examined light sources commercially available as alternatives to 60 W type incandescent light bulb.

Light sources[z]	Power (W)	Total flux (lm)	Irradiation angle
Warm white type (2,700～2,800 K)			
IC	54	810	-
IC-R	40	540	120
W-LED	6.9	450	120
W-FL	12	810	-
	22[y]	1520	-
Daylight type (6,700 K)			
D-LED	6.9	570	120
D-FL	12	730	-

[z] IC, normal incandescent bulb; IC-R, reflector type incandescent bulb; LED, light emmiting diode; FL, compact fluorescence lamp; W, warm white type; D, daylight type.

[y] FL 22 W is equivalent to IC 100 W.

Table 2　Differences among warm white (W, 2,800 K) bulbs in illuminance, irradiance and photosynthetic photon flux density (PPFD).

Light sources[z]	Illuminance (lx)	Irradiance ($mW \cdot m^{-2}$)	PPFD ($\mu mol \cdot m^{-2} \cdot s^{-1}$)
Lighted separately			
W-FL 12 W	4.8 (92)[y]	15.0 (33)	0.06 (54)
IC 54 W	5.2 (100)	45.2 (100)	0.12 (100)
W-LED 6.9 W	5.9 (112)	25.9 (57)	0.10 (86)
Lighted simultaneously			
W-FL 12 W	6.3 (97)	25.9 (57)	0.09 (65)
IC 54 W	6.5 (100)	45.5 (100)	0.14 (100)
W-LED 6.9 W	8.0 (124)	35.7 (79)	0.13 (93)

[z] Three light sources were set in the center of greenhouse (6 m × 15 m), 5 m apart within raw (north-south direction) and 2.2 m above ground level. Intensity values at the plant canopy were measured 2 m away from the sources in an east-west direction horizontally.

[y] Values in parenthses are relative to IC 54 W.

IC and for LED 80% and 90%, respectively.

Experiment 2. Effectiveness of Light Sources, Color Temperature and Lighting Programs

Tray grown 'Nyoho' plants were planted in peat bags, 8 plants in a 80 cm bag, on September 30, 2011, 2012 and 2013 and grown practically in a plastic greenhouse having 5 compartments of 6.5 m × 50 m. Two lines of lamps were settled in each compartment 3.3 m and 3 m apart, between and within lines, respectively. Examined plants in peat bags were located on either side of 5 rows in a compartment to minimize the effect of light sources other than the nearest sources. Three compartments were lighted with different night-break programs as follows; (1) 2 hours of night break, 2 lines of bulbs were lighted simultaneously in the midnight; (2) west and east lines were lighted alternately in 30 min intervals for 3 cycles; (3) lighted alternately for 4 cycles. Lighting was conducted from November 10 to mid-February each year. Energy consumption can be reduced to 75% using 3 cycles of 30 min intermittent lighting. In such conditions, more than 2 lamps of each light source (Table 1) were arranged in a row and light distribution and plant growth were measured between the successive 2 lamps. To evaluate the plant vigor, mean canopy width, petiole length and size of terminal leaflet of the 3rd newly expanded leaf and plant height were measured in cm in the 2011, 2012 and 2013 seasons. Mean canopy width in a 2011-12 season was estimated by image analysis of bird's eye picture using a self-created application while the other measurements were conducted with a ruler.

The differences in light distribution among the light sources are shown in Fig. 1. Illuminance was higher in D-FL 12 W than W-FL 12 W or IC-R. FL 22 W emitted almost twice the visible light flux compared to 12 W type. LED 6.9 W emitted much larger light flux than FL 12 W or IC-R but the distribution was not even.

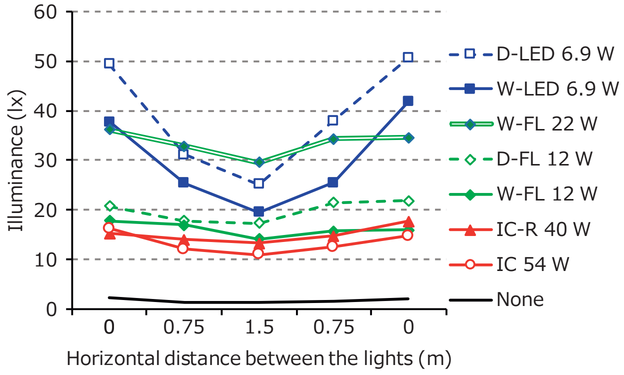

Fig. 1 Differences in illuminance distribution between 2 successive lights of each light source described in Table 1 (experiment 2).

Results and Discussion

Experiment 1. Warm White Alternative Light Sources

Effect of LED on leaf growth was similar to IC, while FL resulted in lower growth than for IC and LED both for petiole length and leaf area of the 3rd newly expanded leaf (Fig. 2). It is well known that dormancy of temperate perennials is induced by short days in late summer, and the plant response to day length includes light conversion of phytochrome. Although there was little difference in color temperature and illuminance sensitivity to the human eye, the spectrum of LED and the FL was largely different from an IC bulb, which emits much red light and also far-red light. However, W-FL emits very little red light and has a large peak of orange and pale green light (Panasonic, 2014). In LED, color temperature is transformed by converting blue light originally emitted by the diode to other wave

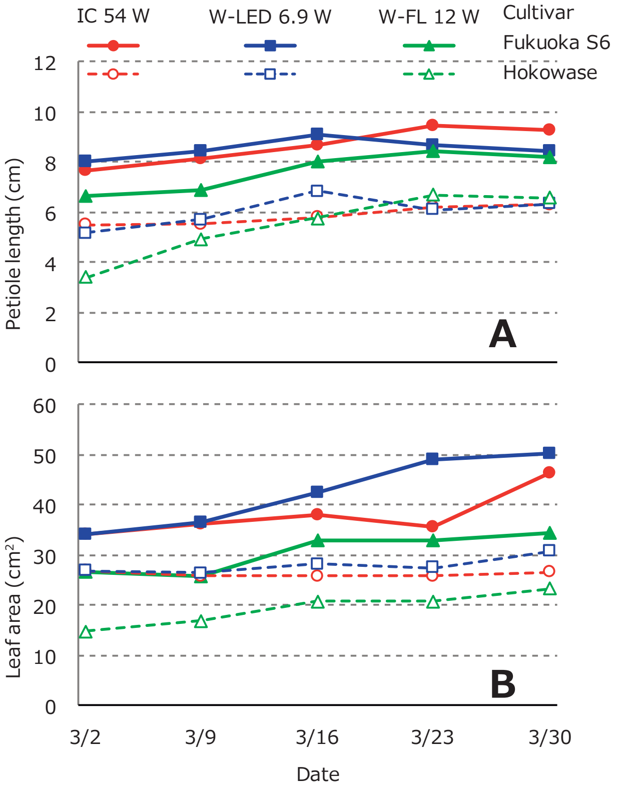

Fig. 2 Effect of light source on changes in the petiole length (A) and leaf area (length × width, B) of central leaflet of the 3rd newly expanded leaf of two strawberry cultivars in March 2012. Two hr of night break treatment was conducted from1 Dec 2011 to 10 Mar 2012.

lengths using fluorescent substance. LEDs emit less yellow to pale green light and much more red and blue light compared to FL (Panasonic, 2014). The smaller growth effect of FL compared to LED, may result from insufficient amount of red light.

Experiment 2. Lighting Programs and Light Sources

In 2011-12, canopy width was a little smaller in plants subjected to 3 cycles of 30 min lighting with IC-R than those subjected to 2 hours of continuous lighting. However, the effect of 4 cycles of 30 min lighting was apparently larger than for the other two (Fig. 3). For leaf area and petiole length, 3 cycles of 30 min lighting was equally effective as continuous 2 hours in 2012-13 and 4 cycles of 30 min lighting was much more effective than 2 hours (Fig. 4).

As shown in Fig. 5, the effects on leaf expansion and also petiole elongation were largest in W-LED compared to other alternative light sources. Although the nominal flux of 450 lm was the smallest (Table 1), actual illuminance of W-LED was nearly twice that of IC-R. The effect of W-FL was smaller than W-LED as in experiment 1 (Fig. 1) and that of D-FL was smallest. However, 22 W type of W-FL, which is stated to emit similar light flux to 100 W type IC, had larger effect than 12 W type. The differences in spectral distribution, mainly deficiency in red light (Panasonic, 2014), may have caused the poor effects of W-FL, but the effect of W-FL could be enhanced by increasing total flux. It is well known that both light intensity and lighting duration affect the effectiveness of long day treatments (Sato, 1981). But leaf area and petiole length were still smaller for W-FL than for IC-R or W-LED in early January. The effect of W-FL 22 W may still have been insufficient in mid-winter, when vegetative growth of strawberry is usually suppressed by dormancy inducing factors, such as reduced photoperiod and total energy of sunlight, decreased temperature, and increased demand for photosynthate by developing berries on primary and secondary inflorescences.

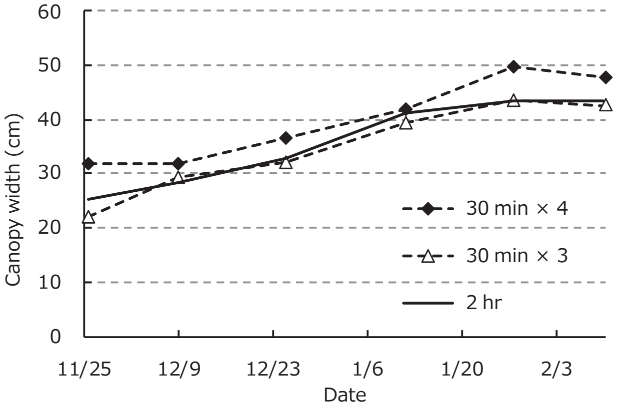

Fig. 3　Changes from 25 Nov 2011 to 8 Feb 2012 in canopy width of strawberry ‘Nyoho’ determined by image analysis of bird’s eye picture, as affected by lighting programs of IC-R executed at midnight.

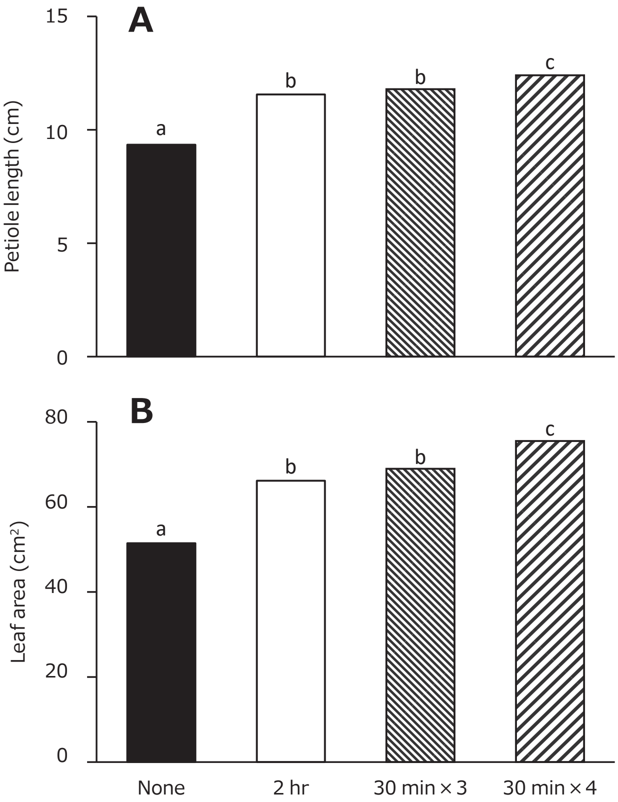

Fig. 4　Effect of lighting programs on petiole length and leaf area of the 3rd newly expanded leaf in strawberry ‘Nyoho’ (Means of 5 light sources and 3 measurements, see Fig. 5). Different letters indicate significant difference by Tukey’s HSD test, P ≦ 0.05.

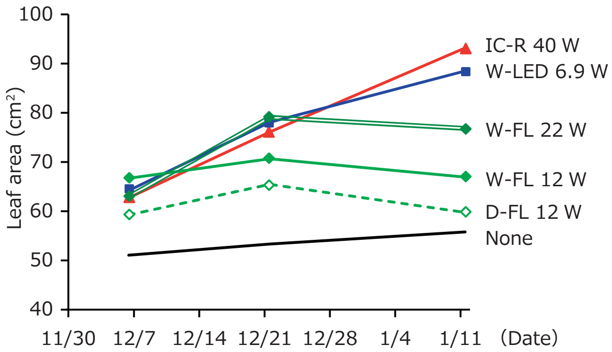

Fig. 5　Changes in leaf area from 6 Dec 2012 to 10 Jan 2013 of the 3rd newly expanded leaf of ‘Nyoho’ strawberry, as affected by six light treatments (Means of 3 lighting programs in 2012-13).

Significant effect of color temperature was also confirmed in LED (Fig. 6). Although daylight type light

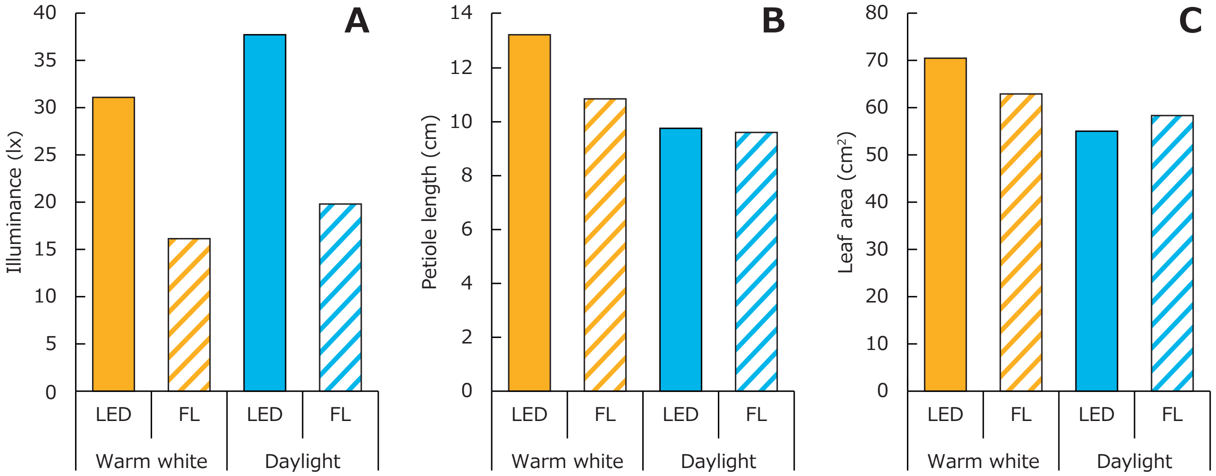

Fig. 6 Differences in illuminance and in petiole length and leaf area of the 3rd newly expanded leaf of 'Nyoho' strawberry, caused by alternative light sources (LED and FL) and color temperature (warm white of 2,800 K and daylight of 6,500 K) (Means of 3 lighting programs and 3 measurements in 2012–13).

sources emit larger light flux than warm white light sources both in FL and LED, but stimulatory effect for vegetative growth was significantly less in daylight sources than in warm white ones. D-LED was less effective than W-LED and also W-FL, which emitted only 82% and 42% of light flux of D-LED, respectively. When spectral distribution is compared, "daylight" sources emitted less red light and much higher levels of blue light than "warm white" ones. Both insufficient stimulus of red light and inhibitive effect of blue light (Masuda et al, 2004) may cause the low growth effect of "daylight" bulbs.

A significant interaction of lighting program and light source was observed in 2014 (Fig. 7). When W-LED 6.9 W and W-FL 22 W were compared, the effect of W-LED for 30 min × 3 times was similar to that for 2 hours of continuous lighting, but only the effect of W-FL for 30 min × 3 times gave lower plant height than the other 3 treatments. Emitted light flux of the FL is rather low just after lighting. It requires several min to reach maximum level especially at low temperatures (JLMA, 2011a). The low effectiveness of FL in an intermittent lighting program may be a partly result of the low performance just after turning on the lamp. Moreover life-span of FL is adversely affected by frequent switching (JLMA, 2011a). FL bulbs may therefore be unsuitable for intermittent lighting.

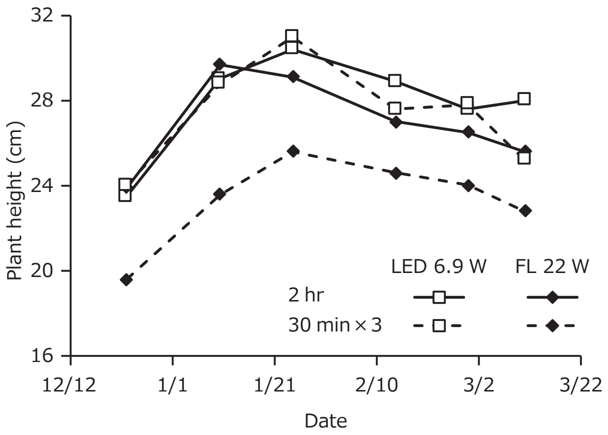

Fig. 7 Changes in plant height of 'Nyoho' strawberry from 12 Dec 2013 to 22 Mar 2014, caused by the interaction of alternative light sources (warm white LED and FL of 2,800 K) and lighting programs (2 hr and 30 min × 3) (2013–14).

Conclusions

Effectiveness of light sources could not be evaluated by illuminance (lx or lm) or irradiance (W/m^2). PPFD, which is a measure similar to but somewhat different from visible light intensity, may be better for estimating the response of strawberry plants. However color temperature of a light source is a quite important factor; "warm white" (2,700–2,800 K) is much more effective than "daylight" (6,500 K). Lower amount of red light and higher amount of blue light may have caused the reduced effectiveness of daylight LED and FL. Both warm white LED and FL can be alternative light sources for strawberry. However, although luminance efficiency was the highest in LED, the cost-performance could not be calculated since it is dependent on the life span of the diodes, which could not be estimated in these experiments.

Literature cited

Fujimoto, K. 1972. Studies on physiological and ecological characteristics of strawberry ‘Hoko-wase’ and development of new cropping type. Special Bull. Nara Agr. Exp. Stn. **1**：1-151.

Japan Lighting Manufacturers Association (JLMA). 2011a. Guidebook for fluorescent lamps.
<https://www.jlma.or.jp/tisiki/pdf/guide_keikou.pdf>

Japan Lighting Manufacturers Association (JLMA). 2011b. Guidebook for LED light bulbs.
<http://www.jlma.or.jp/tisiki/pdf/guide_led.pdf>

Light and Flower Consortium (LFC). 2014. Light source guidance for Chrysanthemum lighting.
<https://www.naro.go.jp/laboratory/nivfs/research/files/light_source_guidance_201403.pdf>

Masuda, M., K. Nakachi, K. Murakami and Y. Yoshida. 2004. Growth and dry matter production of sweet pepper under continuous lighting of fluorescent lamps with different light qualities. J. Soc. High Tech. Agric. **16**：131-136.

Panasonic Corporation. 2014. General catalog of lamps 2014. p. 20 (LED), p. 47 (FL), p.114 (IC).
<http://www2.panasonic.biz/es/catalog/web_catalog/lamp/>

Sato, N. 1982. Studies on the lighting method to the forcing strawberry. II. Effects of lighting conditions and the lighting method by a relay system. Bull. Kanagawa Hortic. Expt. Sta. **29**：39-46.