Paper

Design and Development of a Plant-Response Experimental Light-Source System with LEDs of Five Peak Wavelengths

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Received March 23, 2011, Accepted June 22, 2011
Paper originally presented at the 3rd Lighting Symposium of China, Japan, and Korea on 2010

ABSTRACT
We have designed and developed a light-source system to support advanced experiments for plant light-response studies. The light-source system consists of light-emitting diodes (LEDs) of five types: violet, blue, orange-red, red, and far-red (peak wavelengths, λp: 405, 460, 630, 660, and 735 nm). The light-source system can produce light with different compositions of the five wavelength ranges, and can provide photosynthetic photon flux densities (PPFDs) of 468 μmol m⁻² s⁻¹ for an area of 0.18 m² at a distance of 173 mm below the LEDs. This is sufficient for the cultivation of almost all leafy vegetables and other plants that might be produced under artificial light in commercial plant factories. This report provides a technical description of the light-source system and the results of quantification tests.

KEYWORDS: light-source system, plant light-response, wavelength range

1. Introduction
To produce numerous plants rapidly, or to induce plants to develop the necessary functions before planting, it is necessary to ascertain the most appropriate environment for plants in the production and propagation stages. Environmental factors such as temperature, relative humidity, gas concentrations, irradiance, and photon flux density (PFD) are easily controlled when plants are grown in a plant factory with artificial lighting. However, it is difficult to control spectral irradiance or spectral PFD (SPFD) at the canopy level even with a state-of-the-art plant factory. An LED artificial-light-source system that can produce a spectral power distribution that approximates ground level sunlight within a wavelength range of 380-940 nm has been developed, but the spectral power distribution of this system can be modified arbitrarily by application of different voltages to LEDs with 32 different peak wavelengths. However, the irradiated area is limited to as small as approximately 7 cm².

To date, no existing light-source system has been developed that can control the most important wavelength ranges of light known to produce crucial effects on plant growth and development, and also provide high irradiance at the plant canopy level with a sufficient irradiated area for plant cultivation. Therefore, we have designed and developed a light-source system to support advanced experiments for plant light-response studies. The system has LEDs of five types: it can produce light with different compositions of five wavelength ranges and can provide sufficient PFD for the cultivation of almost all leafy vegetables and other plants that might be produced in commercial plant factories under artificial light. The present paper describes the configuration and specifications of the light-source system and the quantification test results.

We use PFD [mol m⁻² s⁻¹] and SPFD [mol m⁻² s⁻¹ nm⁻¹], respectively, rather than irradiance [W m⁻²] and spectral irradiance [W m⁻² nm⁻¹] in this paper because the number of photon counts in the relevant wavelength range is regarded as a physical quantity to be described in the field of photobiology rather than their energy content.

2. Hardware configuration
The light-source system comprises seven LED arrays, a cooling fan unit, an aluminum supporting structure, six DC power supplies, a resistance circuit for current fine-tuning, and five digital timers. The seven LED arrays and cooling fan unit are supported by the aluminum support structure (Figure 1 and Figure 2).
2.1 LED array

2.1.1 LED types

The LEDs are of five types: violet, blue, orange-red, red, and far-red (peak wavelengths, \( \lambda_p \): 405, 460, 630, 660, and 735 nm). Wavelength ranges including these \( \lambda_p \) values are known to affect plant growth and development. The 405 nm LED provides the shortest wavelength light effective for photosynthesis. Its wavelength range covers a part of ultraviolet-A (UV-A) light, which is known to affect the quantities of functional substances such as antioxidants in some plant species. The wavelength range of around 460 nm covers the \( \lambda_p \) of the action spectra of plant responses through blue-light receptors (phototropin and cryptochrome) and occupies part of the wavelength range that is effective for photosynthesis. The 630 nm LED enhances photosynthesis. The wavelength ranges of around 660 nm and 735 nm cover the \( \lambda_p \) of the action spectra of plant responses such as flowering, morphogenesis, and photoperiodic responses through red/far-red-light receptors (phytochrome). The wavelength range around 660 nm also occupies a primary part of the photosynthetically effective wavelength range. The LEDs were made of clear epoxy resin molds and had an outer dimension of 3 mm (see Table 1 for model codes, manufacturers, and fundamental specifications).

2.1.2 LED arrangement

The LED array (100-mm-wide × 400-mm-long) consists of 2 × 8 basic modules, each of which consists of 25 LEDs. The 400 (2 × 8 × 25) LEDs are arrayed on an aluminum-core glass-epoxy printed circuit board (Figure 2). The 25 LEDs are arrayed in a 5 × 5 square configuration, which occupies 50 mm × 50 mm on the printed circuit board (Figure 3). The lead frames on the reverse side of the printed circuit boards were not trimmed after soldering, thereby allowing the lead frames to act as heat radiators.

The installation of the 25 LEDs was based on a

<table>
<thead>
<tr>
<th>( \lambda_p ) [nm]</th>
<th>Model code</th>
<th>N/25</th>
<th>N/400</th>
<th>SCN</th>
<th>PL</th>
<th>( V_F ) [V]</th>
<th>( I_F ) [A] array</th>
<th>( I_F ) [A] 7 arrays</th>
<th>VHA [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>405</td>
<td>L405R-36*</td>
<td>4</td>
<td>64</td>
<td>16</td>
<td>4</td>
<td>56.0 (3.5)</td>
<td>0.08 (0.02)</td>
<td>0.56</td>
<td>±25</td>
</tr>
<tr>
<td>460</td>
<td>L460-36*</td>
<td>7</td>
<td>122</td>
<td>14</td>
<td>8</td>
<td>44.8 (3.2)</td>
<td>0.16 (0.02)</td>
<td>1.12</td>
<td>±32</td>
</tr>
<tr>
<td>630</td>
<td>L630-36*</td>
<td>6</td>
<td>126</td>
<td>24</td>
<td>4</td>
<td>50.4 (2.1)</td>
<td>0.08 (0.02)</td>
<td>0.56</td>
<td>±33</td>
</tr>
<tr>
<td>660</td>
<td>SRK3-3A80-LE**</td>
<td>4</td>
<td>64</td>
<td>16</td>
<td>4</td>
<td>33.6 (2.1)</td>
<td>0.08 (0.02)</td>
<td>0.56</td>
<td>±33</td>
</tr>
<tr>
<td>735</td>
<td>L735-50AU*</td>
<td>4</td>
<td>64</td>
<td>16</td>
<td>4</td>
<td>28.8 (1.8)</td>
<td>0.20 (0.05)</td>
<td>1.40</td>
<td>±33</td>
</tr>
</tbody>
</table>

* Epitex Inc., Kyoto, Japan; ** Toricon Co., Shimane, Japan
calculation of the proportion of each type of LED so that the spectral photon flux emitted by each type of LED at its $\lambda_p$ would be similar. The spectral photon flux at the rated standard forward currents for each LED type was obtained in advance using an integrating sphere (FOIS-1: Ocean Optics Inc., Dunedin, FL, USA).

The most appropriate arrangement of LEDs was determined as an arrangement such that the curve of the surface SPFD 100 mm from the LED array was of a similar shape for all points at the intersection of the light axes of the 25 LEDs and the irradiated area if the square formation of $5 \times 5$ LEDs was placed at infinity. More specifically, the most appropriate arrangement was determined based on the squared error of the SPFD values at the $\lambda_p$ of each type of LED at the intersection of the light axes of the 25 LEDs and the irradiated area. A dynamic programming technique was used to reduce the computation time. We omit a detailed description of the calculation method developed and used for the decision of the most appropriate arrangement of LEDs because it is fairly complicated and includes numerous operation steps. A detailed description will be presented in a separate paper.

2.2 Connection of LEDs and power supply

Each type of LED installed in an LED array was connected as a combination of series and parallel circuits. For example, 64 LEDs of $\lambda_p$ 405 nm were connected in four parallel circuits, each of which consisted of 16 LEDs connected in series (Table 1). The same five types of LED on the seven LED arrays were then connected in parallel to five DC power supplies (PAS80-4.5: Kikusui Electronics Corp., Yokohama, Japan). The PPFD and SPFD on the irradiated area at a desired distance from LED array were controlled by modulating the output driving current or by applying voltage of each DC power supply.

2.3 Resistance circuit board for current fine-tuning

To make even the irregular distribution on an irradiated area of SPFD at each $\lambda_p$, a resistance circuit board, using 35 adjustable resistors, for current fine-tuning for 35 parallel connections ( = LED of five types × 7 LED arrays) was built into the light-source system. We decided to design and build it into the system because obvious irregular distributions of SPFD at two $\lambda_p$ beneath certain LED arrays were observed without a resistance circuit board. The causes of the obvious irregular distribution beneath certain LED arrays might be installation of LEDs with different lots.

2.4 Cooling fan unit

A cooling fan unit was attached above (i.e., on the reverse side of) the arrays 40 mm from the printed circuit boards. The cooling fan unit consisted of 24 (4 × 6) DC fans (San Ace 80; Sanyo Electric Co., Ltd., Tokyo, Japan) and their supporting frame. The DC fans were powered by a DC power supply (PAS80-4.5: Kikusui Electronics Corp., Yokohama, Japan).

2.5 Digital timer

The lighting cycle for each type of LED is controlled using five digital timers (H5CX-A-N; Omron Corp., Kyoto, Japan), each connected to one of the DC power supplies for the LED arrays. These timers enable irradiation of plants with any combination of LED of different types at any time period, independently.

2.6 Support structure

An aluminum support structure (470 mm wide × 770 mm long × 410 mm high) was constructed to hold and support the seven LED arrays and cooling fan units (Figure 1). The structure had four reflective plates (100 mm wide), arranged in a square, to enclose the seven LED arrays to minimize the reduction in PPFD or irradiance at the periphery of the irradiated area (400 mm × 700 mm). The distance from the surface of the printed circuit boards of the arrays to the bottom of the structure legs was 345 mm, i.e., when 245 mm high plants were placed under the LED arrays, the distances from the surfaces of the printed circuit boards and the LEDs to the plant canopy level were, respectively, 100 mm and 95 mm.

3. Quantification tests

3.1 Spectral photon flux density (SPFD)

The SPFD in the wavelength range of 350–800 nm at the rated standard forward voltage for each type of LED was measured using a spectroradiometer.
(MS-720: Eko Instruments Co., Ltd., Tokyo, Japan) at 91 \((7 \times 13)\) points, which were determined as inner grid points at a grid interval of 50 mm on the irradiated areas at a distance of 173 mm below the LEDs. The SPFD 173 mm below the LEDs showed an acceptable variation both in curve shape and in the SPFD magnitude from point to point (Figure 4).

To express a distribution of PFD for each type of LED on an irradiated area and to enable an intuitive understanding of the distribution, Figure 5 shows the SPFD at the \(\lambda_0\) of each type of LED (405, 460, 630, 660, and 735 nm) at the 91 grid points at distances 173 mm below the LEDs. The graphs show a lack of any discernible irregular distribution of SPFD on any \(\lambda_0\) of each type of LED because a resistance circuit for current fine-tuning was built into the lighting system and because a fine-tuning operation was conducted to minimize the irregular distributions.

**Figure 4** Spectral photon flux density (SPFD) at 91 \((7 \times 13)\) points, which were determined as inner grid points at grid intervals of 50 mm on the irradiated area \((400 \text{ mm} \times 700 \text{ mm})\) at a distance of 173 mm below the LEDs. In all, 91 SPFD curves are shown for the 91 inner grid points.

**Figure 5** Spectral photon flux density (SPFD) at the \(\lambda_0\) of each type of LED (405, 460, 630, 660, and 735 nm) at 91 \((7 \times 13)\) points, which were determined as inner grid points at grid intervals of 50 mm on the irradiated area \((400 \text{ mm} \times 700 \text{ mm})\) at a distance of 173 mm below the LEDs. ‘Distance’ in the figure denotes that from the center of the irradiated area corresponding to \((0, 0).\)

### 3.2 Average photon flux density (PFD) and average photosynthetic photon flux density (PPFD)

The average PFD values of the 91 inner grid points at a distance of 173 mm below the LEDs were 667 \(\mu\text{mol m}^{-2} \text{s}^{-1}\) when the rated forward voltages were applied for LED of each type. The average PPFD values, defined as the PFD within the effective wavelength range for photosynthesis (between 400 nm and 700 nm), of the grid points at distances 173 mm below the LEDs were 488 \(\mu\text{mol m}^{-2} \text{s}^{-1}\).

The 91 inner grid points cover an area of 0.18 \((300 \text{ mm} \times 600 \text{ mm})\) \(\text{m}^2\). These results indicate that the light-source system can provide an average PPFD of 488 \(\mu\text{mol m}^{-2} \text{s}^{-1}\) for an area of 0.18 \(\text{m}^2\) at a distance of 173 mm below the LEDs, which is sufficient for
cultivation of almost all leaf vegetables and other plants that might be produced under artificial light in commercial plant factories.

3.3 Validation of the cooling system

The validity of the cooling system was checked using a combination of a cooling fan unit and untrimmed lead frames as heat radiators. Temperatures were measured at two points on the backside of the printed circuit boards located in the center ($T_{bc}$) and endmost ($T_{bo}$) point of the seven LED arrays, and at five points on the side-surface of LED epoxy resin mold of each type of LED in a $5 \times 5$ basic-module block next to the center point of the LED array located in the center of the seven LED arrays, and the PPFD at the center of the irradiated area 173 mm below the LEDs when the cooling fans were turned off and on at room air temperature (24.5±1.5°C). The cooling fans were off and on each for 30 min. Temperatures were measured using chromel-alumel thermocouple thermometers with wire diameter of 0.1 mm (TCK01-200+VX15-2800: Yamari Industries, Ltd., Osaka, Japan) and monitored using a data logger (MV208: Yokogawa Electric Corp., Tokyo, Japan). PPFD was monitored using the spectroradiometer described above.

The $T_{bc}$ reached 46–47°C when the cooling fans were off; it became stable at around 29°C within a few minutes after the cooling fans were turned on (Figure 6). The $T_{bo}$ was 4–5°C lower than $T_{bc}$, except during the first 5 min, when the cooling fans were off. No large difference was apparent in the temperature time course of the side-surfaces of LED epoxy resin molds among the LEDs with $\lambda_p$ of 405, 460, 630, and 735 nm. The temperature of the side-surface of the LED with $\lambda_p$ of 600 nm was 2–5°C lower than those of the other four LEDs.

The PPFD decreased by 2–3 μmol m$^{-2}$ s$^{-1}$ when the fans were off. It increased by an almost identical degree of PPFD sharply immediately after the fans were turned on and remained almost constant at around 509 μmol m$^{-2}$ s$^{-1}$ when the fans were on.

These results demonstrate that the cooling system with the combination of cooling fan unit and untrimmed lead frames contributes to the suppression of temperature elevation of the printed circuit boards and side-surfaces of LED epoxy resin molds, and to the stabilization of the PPFD by indirectly stabilizing the LED temperatures.

3.4 Next version of a light source system with LEDs of multi-peak wavelengths

The light source system presented here can not provide any green light, as noted from Figure 3. Green light has attracted much attention recently$^{60}$. Therefore, incorporation of green LEDs into the next version of a light source system is apparently of the highest priority. Moreover, epoxy-resin mold type LEDs would be replaced with surface-mounting type LEDs because those are widely used in many fields rather than epoxy-resin mold type LEDs and those are therefore more easily available. Computer-aided control of spectral photon flux (output) from each type of LED on each LED array should be developed for creating SPFD graduation on the irradiated area along its length direction with desired $\lambda_p$ light and facilitating dynamic control of SPFD and PPFD.

4. Conclusions

The qualification test results show that it is possible to achieve the required average PPFD for an area of approximately 0.18 m$^2$, at a distance of 173 mm below the LEDs, and to stabilize the PPFD with the cooling fan unit. Obvious irregular distributions of SPFD at two $\lambda_p$ beneath certain LED arrays have been overcome by building...
resistance circuit boards for current fine-tuning into the light-source system. This light-source system with LEDs of five types presents many possibilities for advanced experiments in plant light-response studies.

Acknowledgments

This work was conducted as a sub-project of the Committed Research Project "Elucidation of biological mechanisms of photo-response and development of advanced technologies using light" by the Ministry of Agriculture, Forestry and Fisheries of Japan.

References


