Analyses of multi-color plant-growth light sources in achieving maximum photosynthesis efficiencies with enhanced color qualities

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Abstract: An optimal design of light-emitting diode (LED) lighting that benefits both the photosynthesis performance for plants and the visual health for human eyes has drawn considerable attention. In the present study, we have developed a multi-color driving algorithm that serves as a liaison between desired spectral power distributions and pulse-width-modulation duty cycles. With the aid of this algorithm, our multi-color plant-growth light sources can optimize correlated-color temperature (CCT) and color rendering index (CRI) such that photosynthetic luminous efficacy of radiation (PLER) is maximized regardless of the number of LEDs and the type of photosynthetic action spectrum (PAS). In order to illustrate the accuracies of the proposed algorithm and the practicalities of our plant-growth light sources, we choose six color LEDs and German PAS for experiments. Finally, our study can help provide a useful guide to improve light qualities in plant factories, in which long-term co-inhabitance of plants and human beings is required.

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1. Introduction

The light quality is regarded as one of most important factors for plant growth. Although artificial lights such as torches were utilized to trigger an early blossom approximately a thousand years ago in ancient China, there were no wide applications of plant factories until 1980s, primarily because of the high energy consumption of artificial light sources [1]. It is well known that the photosynthesis is fueled by the power in the incident light, and that the relationship between wavelengths of incident lights and photosynthetic sensitivity of plants can be described via photosynthetic action spectrum (PAS) [2]. Spectral power distributions (SPDs) of incident light should coordinate with the PAS to achieve high degrees of photosynthesis at low power consumption. Due to biological differences among species as well as shifts in measuring conditions, various PASs have been proposed [3,4]. As a result, an ideal plant-growth light source requires a tunable SPD that adapts to different PASs, in order to develop the sustainable agriculture. Unfortunately, we can hardly change SPDs of common traditional light sources (e.g., high pressure sodium lamps, incandescent lamps, and metal halide lamps) [5]. The wide spectral range of these lamps suggests that a large amount of power falls beyond the photosynthesis sensitive range, leading to major energy waste, and limiting the application of artificial light sources for growing plants [6].

Recent developments of solid-state lighting broaden new perspectives for sustainable and highly efficient light sources for plant factories on the basis of light-emitting diodes (LEDs) [7]. LEDs produce narrow spectra and enjoy potential benefits over traditional lighting systems because of specific wavelengths, smaller sizes, durabilities, long lifetimes, and cool...
emitting surfaces [8]. The peak wavelength of LEDs can be tuned continuously from near infrared to ultraviolet regions, greatly facilitating the design of SPDs [7]. By combining a series of LEDs with different peak wavelengths and driving them respectively with independent currents, we can readily tailor any desirable overall SPDs [9]. In addition, since LEDs can be integrated into digital control systems, the light intensity of each individual LED as well as the whole light source can be adjusted programmatically [10]. For example, the light intensity or even the shape of overall SPDs can be changed periodically over a course of plant developmental stages, according to a preset script [11].

In a prototype of our plant-growth light sources, we generate a broad-band spectrum which can closely match the PAS at the highest efficacy, by employing six-color LEDs (423nm, 457nm, 521nm, 597nm, 633nm and 663nm). Two sensitive spectral regions of chlorophylls exist in the majority of plants, with one located in blue while the other located in red [12, 13]. Hence, in lack of the green light, the color of previous plant-growth light sources tends to look pink and purple, causing discomfort for human eyes [14]. It will be inconvenient for workers who need to work routinely under such purple lights. On the other hand, people who keep plants at home or offices usually complain about the abnormal plant growth even under excellent lighting qualities for human eyes. Therefore, because of different spectral sensitivities between plants and human beings, spectra of plant-growth light sources should be carefully designed when both plants and human beings co-inhabit [15].

In this article, we propose a solution to design the multi-color plant-growth light source, which has taken into account both photosynthesis performance and vision-related parameters. Moreover, we especially focus on the simulation of our proposed design, and the multi-color driving algorithm which is the key part of our simulation operates as a liaison between desired SPDs and pulse-width-modulation (PWM) duty cycles. With the aid of the algorithm, we can optimize the photosynthesis performance and vision-related parameters for plant-growth light sources, e.g. photosynthetic luminous efficacy of radiation (PLER), correlated-color temperature (CCT) and color rendering index (CRI), regardless how many LEDs with different colors are adopted and which PAS is selected. In addition, we choose six color LEDs and the German PAS for experiments, and experimental results demonstrate high accuracies of the algorithm and practicalities of the plant-growth light source.

2. Theory

2.1 PAS and key parameters

![Fig. 1. Normalized spectra of the photosynthetic action spectrum curve $P(\lambda)$ and the photopic sensitivity curve $V(\lambda)$.](image)

The PAS can be selected from curves proposed by different researchers, and in this article we choose the PAS curve adopted by the German Institute for Standardization, number DIN 5031-10 [4, 16], to evaluate the photosynthesis performance (Fig. 1). In the same figure, we also present photopic sensitivity function that gauges spectral resolved sensitivities of human eyes under bright cases. Because of the major mismatch of these two curves, we should
carefully design spectra of plant-growth light sources and develop an approach to acquire these spectra as well as the whole light source when both plants and human beings co-inhabit.

By employing six colors that are typically required for the growth of plants, we generate broad-band spectra which can closely match the PAS at the highest efficacy. Blue light encourage vegetative growth by strong root growth and intense photosynthetic activity while red light encourages stem growth, flowering, and fruit production [17, 18]. Mixing red and blue LEDs are very effective to improve photosynthetic activity to support plant production and regulate morphogenesis [19]. Besides, recent researches disclose that plants also absorb and utilize some light of green (525nm) and yellow (590nm) in their photosynthetic processes [20]. In addition, because of narrow-band spectra of blue and red LEDs, the combination light of monochromatic blue and red LED light cannot closely cover blue and red bands in the PAS. Therefore, we utilize two blue LEDs (423nm, 457nm), two red LEDs (633nm, 663nm), one green LED (521nm) and one yellow LED (597nm) to create the plant-growth light source.

Three-color or four-color light sources can also provide good photosynthesis performance via careful designs [2, 16]. However, increasing the number of colors to six can greatly improve spectral flexibility of plant-growth light sources. SPDs of six-color light sources can be readily designed to match different PAS curves and to meet requirements of different plants. Although employing more colors will theoretically lead to better performances, too many colors also increase complexities and costs of plant-growth light sources. Therefore, considering the balance between the performance and costs, we use six-color LEDs to develop plant-growth light sources in this study.

Table 1. Key parameters for the vision and photosynthesis performance

| Vision Performance | LER (lm/W) | \( \text{LER} = \frac{\int \text{V(}\lambda\text{)S(}\lambda\text{)d}\lambda}{\int \text{S(}\lambda\text{)d}\lambda} \) |
|-------------------|-----------|--------------------------------------------------|
| VIL (lx)          |           | \( \text{VIL} = \frac{\int \text{V(}\lambda\text{)S(}\lambda\text{)d}\lambda}{\text{Area(m}^2\text{)}} \) |

| Photosynthesis Performance | PLER (plm/W) | \( \text{PLER} = \frac{\int \text{P(}\lambda\text{)S(}\lambda\text{)d}\lambda}{\int \text{S(}\lambda\text{)d}\lambda} \) |
|----------------------------|--------------|--------------------------------------------------|
| PAF (plm/lm)               | \( \text{PAF} = \frac{\text{PLER(plm/W)}}{\text{LER(lm/W)}} \) |
| PIL (plx)                  | \( \text{PIL} = \text{VIL(lx)} \times \text{PAF(plm/lm)} \) |

Definitions of key parameters associated with the vision and photosynthesis performance are summarized in Table 1. Resembling luminous efficacy of radiation (LER), PLER is defined as the ratio of the photosynthesis luminous flux to the radian flux. As one of the most important parameters to directly evaluate the photosynthesis efficiency, PLER explains how photosynthetically bright the radiation of the spectrum is as perceived by the photoreceptor system of average plants [21]. The photosynthesis action factor (PAF) is defined as the ratio of PLER to LER [4] while the photosynthetic illuminance (PIL) is defined as the product of visual illuminance (VIL) and PAF [21]. Higher PAF means higher PIL under the same value of VIL that can be measured conveniently, and indicates more light energy concentrating on the photosynthesis-sensitive spectral region [16].
2.2 Optimization goals

In this article, CCT, CRI and PLER are selected as target parameters to achieve excellent vision and photosynthesis performance, and principles of decent parameters diversify with different requirements. We set up three kinds of cases according to different requirement of CRI, and all these cases prefer maximum PLER for high photosynthesis performance in plant factories. In case I (basic lighting), no CRI performance is required when people just need basic white lighting. In case II (advanced lighting) and case III (accurate lighting), farmers or workers need to carry out some regular and skilled jobs in plant factories from germination to seed production, such as precisely observing the color of leaves to monitor the growth.

Typically, the value of CRI is recommended to surpass 80 for advanced lighting in case II [22] and to exceed 90 for accurate lighting in case III [23]. Additionally, PLERs of incandescent lamps, high pressure sodium lamps, and metal halide lamps are about 410 plm/W, 370 plm/W, and 260 plm/W, respectively [16]. Therefore, in order to have a better photosynthesis performance than traditional light sources, PLER of our six-color plant-growth lighting sources should exceed 410 plm/W at least.

Finally, we establish optimization goals for three different cases in Table 2. Case I requires maximum PLER but no specific CRI; case II needs maximum PLER basing on CRI ≥ 80; and case III demands maximum PLER basing on maximum CRI.

| Applications | CCT(K) | CRI | PLER |
|--------------|-------|-----|------|
| Case I       | 2700-15000, (|Duv| ≤ 0.005) | - | Maximum (at least 410 plm/W) |
| Case II      | 2700-15000, (|Duv| ≤ 0.005) | ≥ 80 | Maximum (at least 410 plm/W) |
| Case III     | 2700-15000, (|Duv| ≤ 0.005) | Maximum (at least 90) | Maximum (at least 410 plm/W) |

3. Methodology and algorithm

We propose a methodology named multi-color driving algorithm for obtaining overall SPDs of plant-growth light source [24]. For a multi-color LED, the overall SPD consists of SPDs of each individual LED chips that are driven by PWM currents. Therefore, the relative overall SPD can be indicated as

\[ R_i = \frac{P_i}{P_1 + P_2 + \cdots + P_n}, \quad (i = 1, 2, \cdots, n), \tag{1} \]

\[ E_n(\lambda) = R_1E_1(\lambda) + R_2E_2(\lambda) + \cdots + R_nE_n(\lambda), \tag{2} \]

where \( R, P \) and \( E(\lambda) \) denote the optical power ratio, optical power, and relative SPD which is normalized to the area under curves; subscripts ‘o’ denotes overall while ‘n’ denotes the number of colors. Because we utilize six-color LEDs to develop a plant-growth light source, the value of \( n \) equals six in this article. With the aid of Eq. (1) and Eq. (2), an overall SPD can be resolved into six SPDs from these individual chips by one unique power-ratio set, which corresponds to one unique duty-cycle set of PWM signals, and vice versa. Likewise, a bijective relationship is established between duty cycles and overall SPDs. Therefore, by enumerating all possible optical power ratios, we can sweep the whole design space and simulate all relative overall-SPDs of six-color LEDs, select those that possess highest PLER as well as proper CRI at different CCTs, and finally drive six-color LEDs by the corresponding PWM duty cycles.
Generally, we can divide the specific optimization process into six steps in Fig. 2.

Step I: Choose an appropriate PAS curve for a certain plant species. In this study, we select PAS curve adopted by the German Institute for Standardization (Fig. 1).

Step II: Set optimization goals according to different cases in advance (Table 2).

Step III: Measure emission spectra of multi-color LEDs respectively. In this article, we choose six-color LEDs.

Step IV: Change the optical power ratio of each chip to enumerate all available relative overall SPDs.

Step V: Compute chromaticity coordinates for each overall SPD. If the chromaticity coordinate is accepted, then we calculate other target parameters, such as CRI and PLER. Afterwards, we select the relative overall SPD that has highest PLER as well as proper CRI for each CCT, and store all sets of duty cycles within the required CCT range.

Step VI: Drive the RGBW LED with PWM duty cycle corresponding to a certain case.

4. Hardware

Plants need an environment where they can receive different wavelengths of light for a certain period of time because specific color wavelengths can exert significant impacts on the development of plants. In this article, we employ a system to create six-color lighting environment for plants and to realize both decent photosynthesis and vision performance. The system consists of the controller, the current driver, and the commercially-available six-color LEDs [Fig. 3(a)].

The controller can receive commands from a cell phone and individually generate six PWM voltage signals to control the following current drivers that can create PWM currents to...
drive each color LED with the same duty cycles as the PWM voltage signals generated by the
controller.

Figure 3(b) presents instruments for the experiment. Each LED chip is driven by the 20 mA current (duty cycle equals 100%), and the temperature of the heat sink on which the six-color LED is fixed is maintained at 50 °C. Measured by an integrating sphere (ISP-500) and an optical spectrometer (Spectro 320, Instrument Systems, Germany), Spectra and parameters of six LED chips are shown in Fig. 4(a) and Table 3. The yellow LED commonly suffers from low efficiencies, and the optical power of yellow is much lower than other colors as presented in Table 3.

Then, we change duty cycles of each chip via a cell phone and set up the relationship between duty cycles and optical powers for individual chip respectively [Fig. 4(b)]. In the equations, \( D \) indicates duty cycle of individual chips.

**Table 3. Parameters of the six-color LEDs at 20 mA**

|            | CIE x | CIE y | Luminous Flux (lm) | Optical Power (mW) | Peak Wavelength (nm) |
|------------|-------|-------|--------------------|--------------------|----------------------|
| Blue 1 (B1) | 0.1689 | 0.0144 | 0.20               | 17.06              | 423.4                |
| Blue 2 (B3) | 0.1482 | 0.0396 | 0.93               | 18.24              | 456.5                |
| Green (G)   | 0.1749 | 0.7332 | 5.19               | 10.32              | 521.2                |
| Yellow (Y)  | 0.5913 | 0.4081 | 1.59               | 3.33               | 597.0                |
| Red 1 (R1)  | 0.6955 | 0.3043 | 2.35               | 11.96              | 633.4                |
| Red 2 (R2)  | 0.7196 | 0.2803 | 0.82               | 13.83              | 662.7                |

**5. Results and discussion**

**5.1 Case I**

According to the multi-color driving algorithm we proposed, we change the optical power ratio \( R \) of six-color LEDs to simulate all possible relative SPDs. Then, we select the combinations that possess the maximum PLER with CCT from 2700K to 15000K and use corresponding PWM currents to drive each LEDs. Experimental data in Table 4 exhibit satisfactory agreements between set and measured values.
The considerable similarity between set and measured values of PLER is also showed in Fig. 5(a). In addition, the PLER and the CCT are positively correlated, and the maximum PLER increases from 507 plm/W to 527 plm/W when CCT is changed from 2700 K to 15000 K. Figure 5(b) indicates the duty cycles of each LED chip to obtain the maximum PLER at different CCT. The $D_{R2}$ is always kept in high levels because the spectrum of R2 (663nm) can efficiently improve the PLER when no requirement on CRI. Additionally, 2D and 3D images of the optimal SPDs with PLER $\geq$ 507 plm/W at CCTs from 2700 K to 15000 K for case I are showed in Fig. 6.

In case I, the six-color light source can generate white lights at different CCT as well as the superb photosynthesis performance (PLER > 500 plm/W) for plant growth. Therefore, under PWM currents generated by the proposed multi-color driving algorithm, the six-color light source not only can meet the basic requirement of people who works in plant factories with little demand of CRI, but also can maximize the photosynthesis for plants.

### 5.2 Case II and case III

For case II and case III, optimization goals are to maximize PLER when CRI is not less than 80 and CRI is maximum with CCT from 2700 K to 15000 K. After changing the optical power ratio R of six-color LEDs to simulate all available relative SPDs, we select two SPDs for each CCT that best meet the goals for both cases respectively. Experimental results of case II and case III, listed in Tables 5 and 6, are remarkably consistent with simulation values.
Using the data in Tables 5 and 6, we compare measured and set values of PLER and CRI and then draw plots of duty cycle versus CCT for both case II and case III respectively in Figs. 7 and 8.

![Fig. 7. Measured and set values of PLER and CRI for (a) Case II; (b) Case III.](image)

It is presented in Fig. 7 that the measured PLER and CRI can match set values quite well, which demonstrates high accuracies and practicalities of the multi-color driving algorithm. The maximum PLER ranges from 481 plm/W to 505 plm/W with CRI \( \geq 80 \) for case II, while the optimized PLER has a range from 466 plm/W to 495 plm/W with the maximum CRI (optimized CRI larger than 90) for case III. Generally speaking, the PLER and the CCT also exhibit positive correlation as the case I because of the rising proportion of blue light. Growing values of CCT is caused by the increasing proportion of blue light, and more blue light will also enlarge PLER because one peak of PAS curve locates in the blue region.

![Fig. 8. PWM duty cycles versus CCT for (a) Case II; (b) Case III.](image)

The saturation of \( D_Y \) in Fig. 8 is attributed to the low luminous efficacy of the yellow chip. The yellow LED plays a key role to improve CRI, but it commonly suffers from low efficiencies. As presented in Table 3, the optical power of yellow LED is much lower than other colors. Therefore, to accurately render colors for case II and case III, \( D_Y \) is always maintained at high levels.
Fig. 9. 2D images of overall SPDs for (a) case II; (b) case III.

Fig. 10. 3D images of overall SPDs for (a) case II; (b) case III.

Additionally, 2D and 3D images of the optimal SPDs with CRI ≥ 80 and PLER ≥ 481 plm/W at CCTs from 2700 K to 15000 K for plant-growth lighting in case II are shown in Figs. 9(a) and 10(a), respectively. Meanwhile, 2D and 3D images of the optimal SPDs with CRI ≥ 90 and PLER ≥ 465 plm/W at CCTs from 2700 K to 15000 K for plant-growth lighting in case III are shown in Figs. 9(b) and 10(b), respectively.

In summary, according to these experimental results, under PWM currents generated by the proposed multi-color driving algorithm, our six-color light source not only can meet the advanced requirement of human beings working in plant factories with high demand of CRI, but also can maximize the photosynthesis for plants.

5.3 Discussion

We compare trends of PLER and CRI with respect to CCT of three different cases in Fig. 11. From case I to case III, solid lines of maximum PLER drop noticeably in Fig. 11(a) while corresponding curves of CRI increase markedly in Fig. 11(b), which illustrates the trade-off relationship between PLER and CRI among three different cases. Because high CRI requires the continuity of SPDs while large PLER mainly focuses on blue and red lights. In order to improve CRI, the proportion of green and yellow lights is required to be appropriately increased. However, more green and yellow lights will cause the decrease of PLER.
Fig. 11. (a) PLER versus CCT of three different cases as well as three commercialized white LEDs (with SPDs); (b) CRI and $R_f$ versus CCT of three different cases.

In Fig. 11(a), we also plot SPDs and performances of three different commercialized white LEDs. Because of the benefits of utilizing six-color LEDs to realize our plant-growth light source, optimized results for photosynthesis and vision performance greatly surpass common commercialized white LEDs. For example, PLER, CRI and CCT performance of three white LEDs are ($419$ plm/W, 82, 2688K), ($436$ plm/W, 85, 4030K) and ($362$ plm/W, 65, 6333K) respectively while our six-color light source can reach ($465$ plm/W, 90, 2858K), ($466$ plm/W, 92, 4225K) and ($488$ plm/W, 82, 6101K). Under similar CCTs, PLERs of our light sources are 11.0%, 6.9%, and 34.8% higher than commercialized white LEDs respectively. Even our CRI performance is better than they are.

Moreover, photosynthesis and vision performance of our six-color light source can also be better than some previous studies. For example, the result of a previous paper reports that the maximum PLER equals to 469 plm/W and CRI reaches 86 at 10000 K [16], while the PLER is equal to 484 plm/W and CRI gets to 93 at 10130 K according to our optimization for case III. Major limitations for our six-color plant-growth light sources are the added systemic complexities and high capital costs for the first time installation. However, considering the excellent performance and the long lifetime of six-color LED light sources, these limitations can be accepted.

In order to readily obtain relationships between CCT and other key parameters as well as readily compare performances of our plant-growth light source with others, we tune values of CCT from 2700K to 15000K. However, sometimes people may feel uncomfortable about the lighting with excessively large values of CCT. Additionally, CCTs ranging from 2700 K to 6500 K are suggested for long-time lighting of human beings [24].

Because CRI do not usually correlate well with visual evaluation, a new color rendering index called CIE 2017 Color Fidelity Index $R_f$ was released as a TC report CIE 224 on April 2017 for accurate scientific use [25]. In Fig. 11(b), we also plot $R_f$ curves for three cases to better reflect the color rendering ability of our six-color plant-growth light source. It is apparent from the figure that $R_f$ curve is located above CRI obviously for case I while $R_f$ curves lies below CRI slightly for case II and case III.

6. Conclusions

In this article, we propose the multi-color driving algorithm to drive the six-color plant-growth light source for different application cases. Under PWM currents generated by the proposed algorithm, the light source not only maximizes the photosynthesis performance, but also creates decent vision-related parameters. Satisfactory agreements between measured and simulated values of PLER and CRI indicate high accuracies and practicalities of the plant-growth light source. This study can be regarded as a model for practitioners who desire to improve light qualities in plant factories, in which long-time co-inhabitance of plants and human beings is required.
## Appendix

For the purpose of condensing the article, experimental results of the three cases are listed in Table 4-6, respectively.

### Table 4. Experimental results of six-color plant-growth light source for Case I

| Number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| CCT (K) |     |     |     |     |     |     |     |     |
| Measured | 2697 | 3992 | 5009 | 6003 | 8009 | 10002 | 12005 | 14995 |
| Error (%) | 6.90 | 3.63 | 2.99 | 1.18 | 0.41 | 1.89 | 0.27 | −3.55 |
| CIE x |     |     |     |     |     |     |     |     |
| Measured | 0.4631 | 0.3805 | 0.3441 | 0.3224 | 0.2968 | 0.2825 | 0.2725 | 0.2665 |
| Error (%) | −1.51 | −1.18 | −0.96 | −0.50 | −0.44 | −0.60 | −0.29 | 0.15 |
| CIE y |     |     |     |     |     |     |     |     |
| Measured | 0.4160 | 0.3758 | 0.3429 | 0.3261 | 0.2995 | 0.2846 | 0.2764 | 0.2639 |
| Error (%) | 2.79 | 0.77 | 1.52 | 0.95 | 0.93 | 0.33 | 0.87 |     |
| LER (lm/W) |     |     |     |     |     |     |     |     |
| Measured | 148 | 148 | 151 | 159 | 152 | 155 | 152 | 146 |
| Error (%) | 4.24 | 3.95 | 2.73 | 2.00 | 1.71 | 1.01 | 0.64 | 1.21 |
| PAF |     |     |     |     |     |     |     |     |
| Measured | 3.605 | 3.605 | 3.510 | 3.304 | 3.489 | 3.395 | 3.463 | 3.656 |
| Error (%) | −5.07 | −3.82 | −3.21 | −2.18 | −1.80 | −0.75 | −0.80 | −1.07 |
| PAF (plm/W) |     |     |     |     |     |     |     |     |
| Measured | 512 | 512 | 516 | 515 | 520 | 519 | 523 | 526 |
| Error (%) | −0.14 | −0.03 | −0.57 | −0.22 | −0.12 | −0.16 | 0.13 |     |

### Table 5. Experimental results of six-color plant-growth light source for case II

| Number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| CCT (K) |     |     |     |     |     |     |     |     |
| Measured | 2704 | 3991 | 4990 | 5995 | 6990 | 7990 | 8990 | 9990 |
| Error (%) | 5.25 | 4.59 | 4.13 | 1.77 | 0.72 | −1.41 | 1.77 | 1.79 |
| CRI |     |     |     |     |     |     |     |     |
| Measured | 82 | 80 | 80 | 80 | 80 | 81 | 81 | 80 |
| Error (%) | −2.44 | 0.00 | 0.00 | 1.25 | 1.25 | 1.23 | 0.00 | 1.25 |
| CIE x |     |     |     |     |     |     |     |     |
| Measured | 0.4544 | 0.3786 | 0.3448 | 0.3226 | 0.2974 | 0.2831 | 0.2705 | 0.2659 |
| Error (%) | −1.72 | −1.61 | −1.45 | −0.68 | −0.54 | −0.14 | −0.33 | −0.86 |
| CIE y |     |     |     |     |     |     |     |     |
| Measured | 0.4012 | 0.3689 | 0.3547 | 0.3231 | 0.2979 | 0.2834 | 0.2795 | 0.2646 |
| Error (%) | 0.77 | 0.19 | 0.55 | 0.71 | 0.87 | 1.13 | −0.25 | 0.60 |
| LER (lm/W) |     |     |     |     |     |     |     |     |
| Measured | 218 | 232 | 234 | 230 | 223 | 219 | 215 | 220 |
| Error (%) | 2.79 | 1.39 | 1.72 | 1.32 | 1.59 | 1.37 | 0.11 | 1.32 |
| PAF |     |     |     |     |     |     |     |     |
| Measured | 2.219 | 2.076 | 2.074 | 2.122 | 2.220 | 2.283 | 2.333 | 2.294 |
| Error (%) | −2.75 | −1.59 | −1.93 | −1.38 | −1.68 | −1.64 | 0.04 | −1.28 |
| PAF (plm/W) |     |     |     |     |     |     |     |     |
| Measured | 484 | 482 | 485 | 488 | 495 | 498 | 502 | 505 |
| Error (%) | −0.04 | −0.23 | −0.25 | −0.08 | −0.12 | −0.29 | 0.15 | 0.02 |
Table 6. Experimental results of six-color plant-growth light source for case III

|  | Number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|---|--------|-----|-----|-----|-----|-----|-----|-----|-----|
|  | Set    | 2695| 4008| 4990| 5996| 8010| 9998| 11997| 14994|
| CCT (K) | Measured | 2858| 4225| 5262| 6165| 8066| 10130| 12012| 15749|
|  | Error (%) | 6.05| 5.41| 5.45| 2.82| 0.70| 1.32| 0.13| 5.04|
|  | Set    | 89  | 90  | 91  | 91  | 92  | 92  | 91  | 91  |
| CRI | Measured | 90  | 92  | 91  | 92  | 93  | 93  | 92  | 91  |
|  | Error (%) | 1.12| 2.22| 0.00| 1.10| 2.20| 1.09| 0.00| 0.00|
|  | Set    | 0.4683| 0.3806| 0.3463| 0.3217| 0.2939| 0.2787| 0.2691| 0.2690|
| CIE x | Measured | 0.4591| 0.3735| 0.3389| 0.3177| 0.2919| 0.2764| 0.2671| 0.2589|
|  | Error (%) | −1.96| −1.87| −2.14| −1.24| −0.68| −0.83| −0.74| −1.18|
|  | Set    | 0.4250| 0.3785| 0.3623| 0.3392| 0.3084| 0.2921| 0.2816| 0.2694|
| CIE y | Measured | 0.4299| 0.3817| 0.3630| 0.3443| 0.3120| 0.2941| 0.2845| 0.2694|
|  | Error (%) | 1.15| 0.85| 0.19| 1.50| 1.17| 0.68| 1.03| 0.00|
|  | Set    | 254| 260| 267| 272| 252| 247| 257| 241|
| LER (lm/W) | Measured | 262| 266| 275| 281| 257| 251| 261| 243|
|  | Error (%) | 3.13| 2.25| 3.11| 3.35| 1.95| 1.76| 1.69| 0.64|
|  | Set    | 1.841| 1.799| 1.751| 1.728| 1.914| 1.972| 1.888| 2.056|
| PAF | Measured | 1.773| 1.751| 1.693| 1.659| 1.863| 1.927| 1.852| 2.038|
|  | Error (%) | −3.69| −2.66| −3.27| −4.00| −2.66| −2.26| −1.89| −0.84|
|  | Set    | 468| 466| 467| 470| 482| 487| 485| 495|
| PLER (plm/W) | Measured | 465| 466| 466| 466| 479| 484| 484| 494|
|  | Error (%) | −0.68| −0.47| −0.26| −0.78| −0.76| −0.53| −0.22| −0.20|

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