Chapter 13
Usefulness of Broad-Spectrum White LEDs to Envision Future Plant Factory

Hatsumi Nozue and Masao Gomi

Abstract The effect of the spectrum of a light source on plant growth and the importance of the control of color quality of light-emitting diodes (LEDs) are described. Plant growth is greatly facilitated by the addition of far-red light to conventional blue-red monochromatic LEDs, and a good yield of whole plants is promoted by the addition of green light. This knowledge suggests the usefulness of broad-spectrum white LEDs. Tremendous progress in blue light source phosphor-conversion technology has made the color control of white LEDs possible. Spectral features favorable for plant growth are characterized by a systematic survey of commercially available white LEDs. It is suggested that the balance among blue, red, and far-red colors that constitute white-emitting LEDs is a key factor in determining a suitable LED spectrum. The color temperature (CCT) and the color rendering index (CRI) can serve as a rough and limited indicator for the choice of a white LED. In addition to the benefits of using white LEDs in a plant factory, the accompanying complications and potential strategies are discussed.

Keywords White LED · Spectral PFD · Far-red light · Green light · Correlation color temperature · Color rendering index

13.1 Introduction

Plants on earth have been evolutionally adapted to sunlight. The complexity of plant photosystems is regarded as a tuning system to maintain photosynthetic efficiency under fluctuating sunlight. The plants protect photosystems by the loss of excess energy through heat dissipation (Horton et al. 1996). In plant factories with artificial

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lighting (PFAL), it is expected that the absolute maximum input energy will be put to use for photosynthetic reactions. To achieve progress with efficient lighting, the two primary factors that must be considered are the quality of the illumination system itself and the energy-use efficiency of plants. The desirable LEDs for general use in residences and offices are not always good for plant growth because plant growth is greatly dependent on the spectral features of the LEDs (Chap. 11 in this book). It is generally understood that one of the merits of LEDs is their high electricity-to-light energy conversion, which results in less heat released, and long lifetime. An additional merit of LEDs is their technical capability to create various kinds of spectra (Kozai et al. 2016). Closely related concepts have been recently proposed for mainstream agricultural LED applications, including the importance of the choice of the LED spectrum (Cocetta et al. 2017) and the technological possibility of spectrum control using LEDs (Pattison et al. 2016; Ahlman et al. 2016).

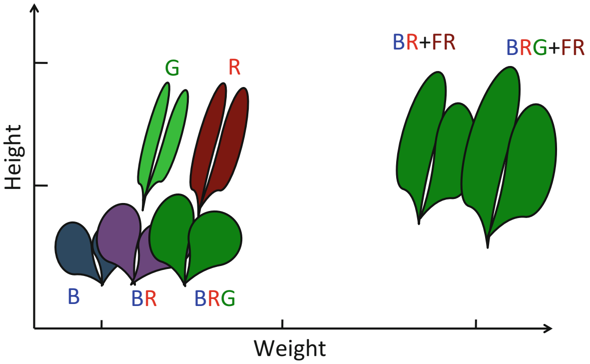
Plant responses to various light spectra have been of great interest to researchers as signaling systems; however, activity by agricultural interests regarding the practical benefits has only just begun. LED applications in horticulture began with monochromatic red and blue. The control of the red-to-blue ratio to improve photosynthetic reactions and plant growth has been one of the considerations for LED use (Matsuda et al. 2004; Hogewoning et al. 2010; Naznin et al. 2016a; Naznin et al. 2016b). Additionally, the visual merits of white light for lettuce and the enhancement of growth were noted (Kim et al. 2004). The usefulness of far-red light for photosynthesis and production has also been tested using an LED light (Park and Runkle 2016; Zhen and Iersel 2017). In addition to the red/blue (R/B) and red/far-red (R/FR) ratios, green light is also an important factor for the lighting of PFALs (Chap. 11 in this book). A possible reason that horticultural LEDs were not transitioned to white may be the low luminous efficiency and high cost of green LEDs. On the other hand, progress in luminescent phosphor techniques has led to the commercial availability of LED lighting equipment with high-color rendering properties that cover the PAR (400–700 nm) region and beyond (Xavier et al. 2017). This chapter describes how LED spectra contribute to plant growth and the usefulness of white LEDs with broadband spectra for horticulture. In addition, the difficulties arising during the research and potential strategies for resolving them are described.

13.2 A Combination of Monochromatic LEDs Facilitates Plant Growth

13.2.1 Characteristic Features of Growth Under Monochromatic LEDs

Plants utilize visible light (380–780 nm) as an energy source for growth. The irradiation in this range can be fully used for photosynthesis, although its efficiency is dependent on the wavelength (Chap. 11 in this book). Recent experimental data

Fig. 13.1 Growth features of lettuce under monochromatic and combination LEDs. The leaf color indicates color vision under each LED lighting. B, 445 nm; G, 540 nm; R, 660 nm; FR, 730 nm



with monochromatic LEDs have more clearly revealed the differences in the effectiveness on plant growth due to wavelength (Naznin et al. 2016a; Naznin et al. 2016b; Park and Runkle 2016). The characteristic aspect of the lettuce grown under monochromatic LEDs and their combination is summarized in Fig. 13.1. Under blue light, the leaves open facing the light. The plants appear healthy but are of modest size. Under red and green light, leaves are little holding with longer shape. The plants are fragile-looking but relatively heavier. Plants grow better under a blue and red combination with normally shaped leaves. However, the morphology of the whole plant is not the same as in sunlight. The plant height is apparently limited. Regarding the effect of the ratio of red to blue (R/B) on the rapidity of growth and plant morphology, a higher R/B promotes growth but leads to a long, spindly form. Under lights that do not contain green wavelengths, the leaves are not green in color, but rather dark. Therefore, it is difficult to notice abnormal changes in the leaves.

13.2.2 Effect of Far-Red Light

The additive far-red effects of R and B LED radiation on leaf and root growth associated with stem elongation and leaf expansion is clearly shown in the early growth stages of snapdragon seedlings (Park and Runkle 2016). The supplemental effect of far-red to RB and RGB LEDs on lettuce production is obvious as well. The phenotype under far-red-supplemented LED is very similar; the stems and leaves are elongated, and leaves are apparently enlarged, which increase the reception of light energy and accelerate the rate of growth. R/FR becomes important for the effective application of far-red light, because R/FR is responsible for the most effective light signaling related to phytochromes.

13.2.3 Effect of Green Light

In contrast to the distinct effect of warm color lights, the effect of blue and green on the growth of an individual plant varies among species and the irradiance photon flux density (PFD) level (Bugbee 2016). Still, the effect of green light on plants is generally understood as positive. Lettuce growth was significantly enhanced by the addition of 24% green fluorescence to RB LEDs (Kim et al. 2004). However, under our cultivation conditions, the effect of green light on lettuce growth is found to be much less than the far-red effect. Optimization of the green level to B or R will be a future subject of research. Such positive effects of green on yields are clearer when the plants are cultivated under higher irradiation doses.

13.3 Usefulness of Broad-Spectrum White LEDs

13.3.1 Technical Principles for Visually Creating a White Color with an LED

Two types of white LED lights that use technically different methods exist in principle. For the creation of lights that seem white to the eye, a mixture of RGB primary colors with monochromatic LEDs (Fig. 13.2a) or a mixture of monochromatic blue and phosphor emitting complement yellow colors (Fig. 13.2b) is generally used. The cost of production and electricity consumption of the former is ordinarily higher than for the latter type. The conventional phosphor white LEDs contain a yellow peak (at approximately 580 nm) with a broad base. As a result, their spectra are continuous from blue to the beginning of red and include enough green but little red. It is noteworthy that recent progress in phosphor technology makes possible the emission of longer wavelengths of red to far-red lights (Fig. 13.3). The white LEDs with a wide variety of spectra are created by such a wavelength conversion technique. Some of those are supplied for the special needs of high-color rendering to display clearly. Intelligent control of the chromaticity of solid-state lighting has been proposed for horticultural lighting (Pattison et al. 2016). As a next step, the theoretical and experimental elucidation of the relationship between the LED spectrum and its potency is expected shortly. Special techniques for designing spectra are helpful in providing ideal LEDs for horticultural needs.

13.3.2 Influence of Spectral Differences on Vegetable Production

In terms of the effects of lighting systems on plant development, many factors are involved other than the properties of the light source itself. To verify how spectral

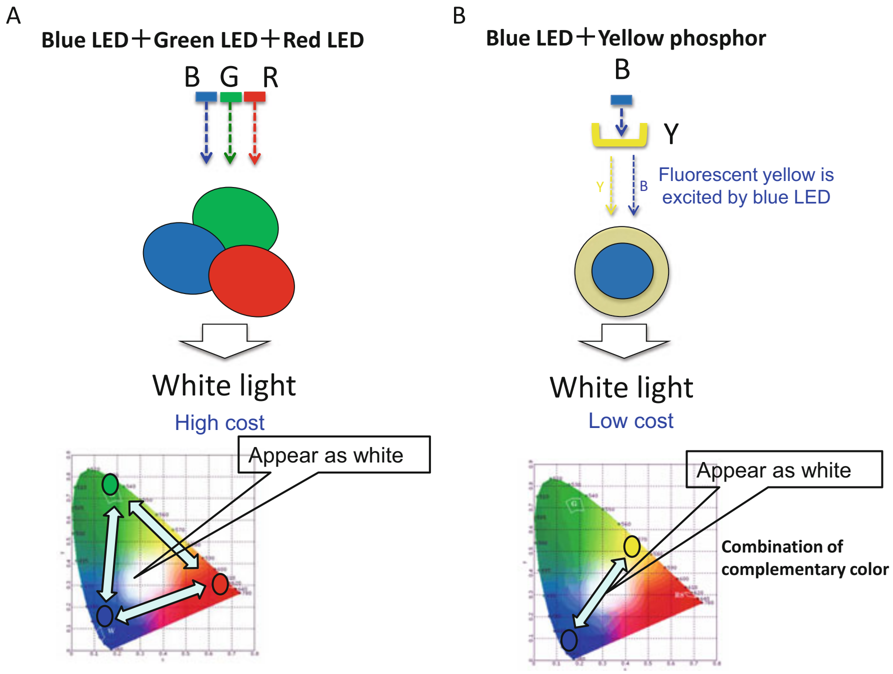


Fig. 13.2 Principles of the color emission of white-appearing LEDs. Combination of monochromatic three light primary color LEDs (**a**) and a blue basal color LED supplemented with complementary phosphor-conversion yellow (**b**)

differences of LEDs affect plant production, uniformity of the culture equipment and the structure and lighting control systems is required. A systematic survey on the production efficiency of 18 phosphor white LEDs has been used to collect useful information about the choice of the spectrum (Nozue et al. 2017a).

The spectral dependency of the yield is clearly shown among white LEDs with a variety of fluorescence emission spectra as well as LED lighting that consists of monochromatic colors. Examples of LED spectra that produce lower and higher fresh weight of lettuce are shown in Fig. 13.4. Conventional white LEDs that have lower-color rendering properties (Fig. 13.4a, LP-1 and Lp-2) and LEDs drastically unbalanced between blue and longer wavelength fluorescent colors (Fig. 13.4a, LP-3 and LP-4) had almost the same or less productivity than the FL. White LEDs that have more balanced spectra had an average 1.3-fold higher than the FL. In terms of the spectral continuity of white LEDs, it is difficult to distinguish the difference between good and poor yields. The ratio of the integrated PFD values of the R/B and the R/FR help to distinguish LEDs for both good and poor yields. When the R/B (x-axis) and R/FR (y-axis) values of each LED spectrum are plotted, the good-yield LEDs are clustered in a range of approximately 1.5–4.5 for R/B and 2.5–7.5 for R/FR (Fig. 13.5). Neither higher nor lower values beyond these ranges resulted in a good yield.

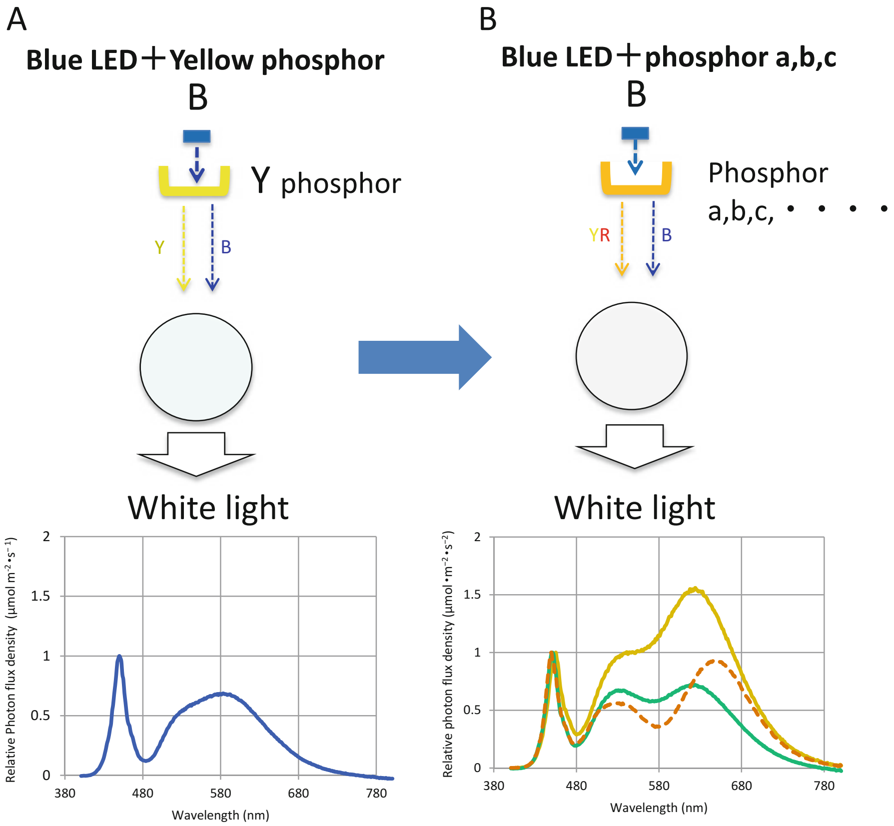


Fig. 13.3 Creation of a variety spectra using new technology. Advanced fluorescent material technology has made possible the creation of white LEDs with a variety of spectra. The recent red conversion approach extended the spectral area to longer wavelengths. Wavelength spectra show the altered examples from an original low-color rendering white LED (**a**) to broad-spectrum white LEDs (**b**). Spectral arrangement to suit a desired form is possible with this technique

13.3.3 Relationship of R/B Ratio to Plant Height and Yield and R/FR Ratio to Plant Height and Yield

Linear relationships are obtained between the R/B ratio, the height, and the yield in a limited range of R/B from 1 to 5 (Table 13.1). The positive correlations are modest, and a large variation among experiments is found in the correlations between R/B and height. The R/FR ratio is inversely associated with the height and the yield in a limited range of R/FR from 1 to 7. Correlation to the height is strong and to the yield is modest (Table 13.1). A statistical analysis suggests that contribution of tall morphology to productivity is limited, and the enhancement of plant production due to R and RF occurs within defined spectral conditions. It is indicated that there is a good balance among B, R, and FR of white LEDs. The spectral choice for better

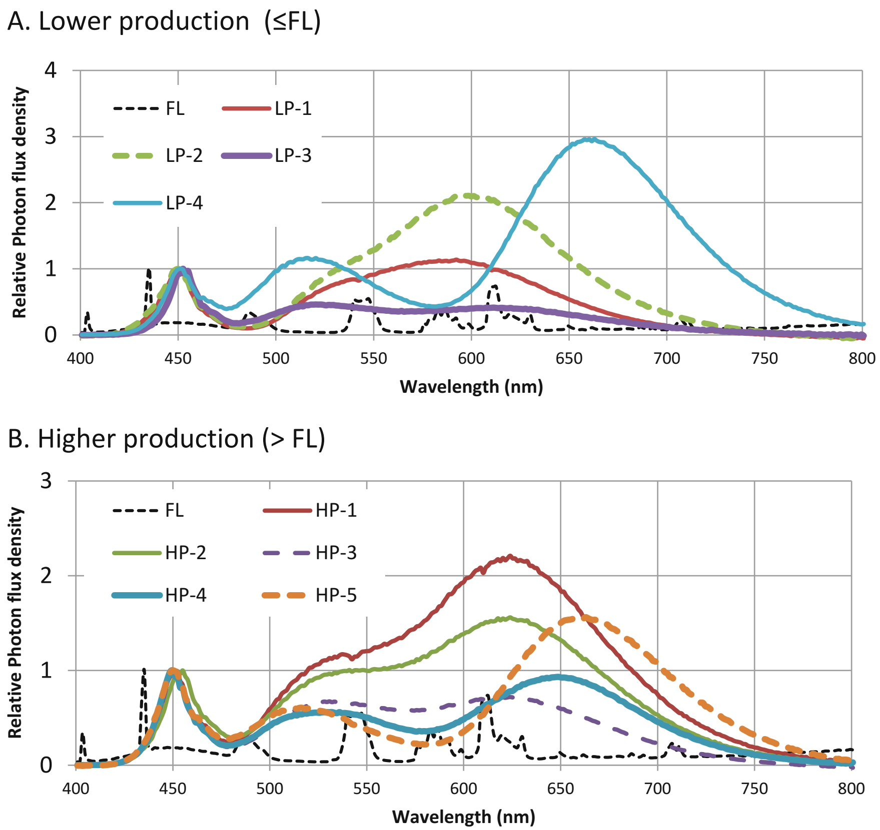


Fig. 13.4 Examples of a variety of white LED spectra distinguished by their capacity for plant production. LEDs whose spectra contain apparently less or excessive 620–780 nm light (R-FR) stimulated less production (**a**). LEDs whose spectra contain R and FR in balance stimulate higher production (**b**). FL, fluorescent light; LP, lower production; HP, higher production

plant production could be guided by optimizing the R/B and R/FR values. However, it should be noted that these values vary depending on the measurement and calculation methods. Still, they are useful as a tool for comparative analysis. The unit of light intensity should be a photon-based PFD instead of the energy-based $\mathrm{Wm}^{-2}\,\mathrm{s}^{-1}$.

13.3.4 CCT and CRI

To characterize a light source, the color temperature expressed in Kelvin (K) is often used. CRI shows the effect of an illuminant on the color appearance of objects in comparison with a natural light source. The parameter Ra (i.e., the average of the

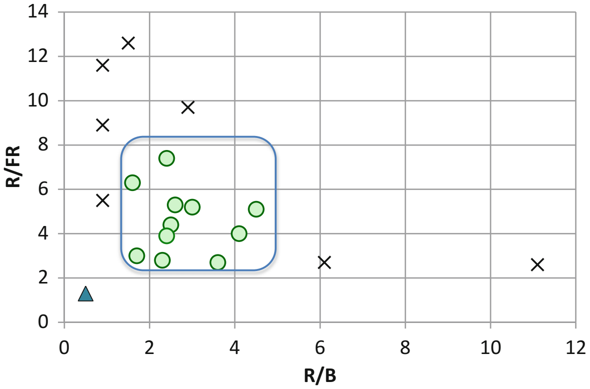


Fig. 13.5 Effect of balancing the R/B and R/FR values of white LEDs on plant growth. △, FL; ○, better production than FL; ×, less production than FL. A square shows approximate area for good production. R, integrated PFD values of 620–700 nm; B, integrated PFD values of 400–490 nm; FR, integrated PFD values of 700–780 nm

Table 13.1 Correlation coefficients of the R/B and the R/FR ratios with the plant height and yield

	R/B	R/FR
Height	(+) 0.54 ± 0.25	(−) 0.81 ± 0.13
Fresh weight	(+) 0.48 ± 0.09	(−) 0.53 ± 0.17

The data are expressed as the average of three independent experiments and the variation (SD) between them. (+) indicates a positive correlation, and (−) indicates a negative correlation

Table 13.2 Relative lettuce fresh weight among white LEDs that have different K or Ra

Ra K	3000	3500	4000	5000	6500
80	–	–	–	1.00	–
90	1.45	1.31	1.23	1.20	1.11
95	–	–	–	1.28	–

rendering index) is often used as the index value**.** The K and CRI (Ra) are indispensable light characteristic traits generally in use for every lighting application. Along with the extension of LED applications to general illumination, horticultural lighting has emerged as a next-generation LED application (Pattison et al. 2016; Han et al. 2017; Carney et al. 2016). Still, there is little information about whether the CCT and CRI of a white LED can be useful indexes for horticultural use. An example of systematic assays with white LEDs that have the same K or Ra value indicate that a relatively higher yield is achieved with a lower K and a higher Ra (Table 13.2).

The percentage of fluorescence emission with a longer wavelength than blue (400–490 nm) in total PFD decreases in an inverse proportion to K. For example, the rate of the integrated PFD value to that of B of 5000 K is less than half of 3000 K (Table 13.3, Fig. 13.6a). The percentage of red area light designated R plus FR

Table 13.3 Integrated PFD of fluorescent emission light relative to blue light

	3000 K	3500 K	4000 K	5000 K	6500 K
F/B	13.9	9.3	8.9	5.6	4.0

F, fluorescence emission with a wavelength of 490–780 nm; B, blue light with a wavelength of 400–490 nm

Table 13.4 Integrated PFD of R + FR light relative to blue light

	Ra80	Ra90	Ra95
(R + FR)/B	0.24	1.08	1.61

(R + FR), light with a wavelength of 620–780 nm; B, blue light with a wavelength of 400–490 nm

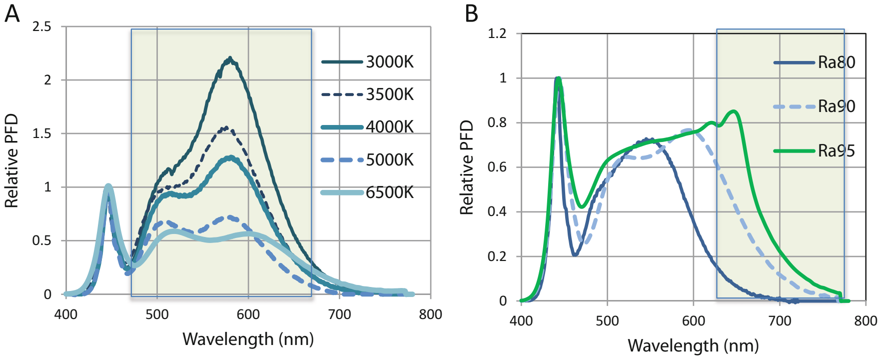


Fig. 13.6 Examples of spectral differences among white LEDs arising from the difference in K or Ra. LED spectra with Ra90 but different K (**a**) and with 5000 K but different Ra (**b**). The squares show comparison ranges of fluorescence emission and red to far-red area light

(620–780 nm) increases in proportion to Ra. For 5000 K LEDs, calculation indicates that the rate of R plus FR to B of Ra90 is 4.5 folds of that of Ra80 (Table 13.4, Fig. 13.6b).

Taken together, the difference in the productivity observed with these white LEDs that are arranged by K and Ra values is thought to reflect the differences in the color distributions. A few white LEDs that are not included in this line are commercially available. Basically, the spectral features of LEDs must be assessed.

13.3.5 Power Consumption of White LEDs

The beneficial aspects of the lower electrical energy of phosphor white LEDs are generally well known. Our results indicate a potential benefit in plant growth, too. Significant difference in their light-use efficiency between conventional lighting systems is found. When the irradiance PFD level is low, the difference is clear. The electrical power consumptions for producing 1 g of marketable aerial part of

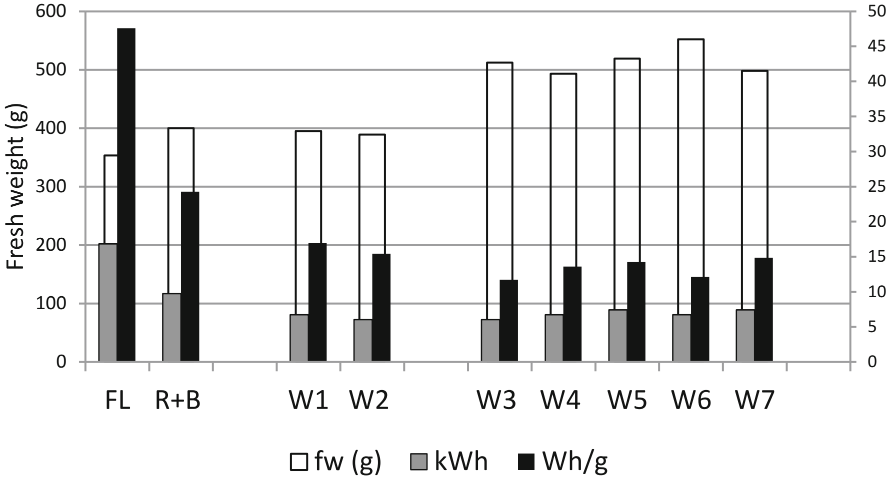


Fig. 13.7 Comparison of electrical power consumption for production of marketable aerial part of lettuce plants. Six plants were cultivated under each lightings at 130 μmol m^{-2} s^{-1}. Integrated power consumption during cultivation (kWh) is divided by the fresh weight (g). Wattages of each lightings are obtained from measured values. Total productions of edible parts of lettuce are used as the fresh weight. FL and R + B indicate fluorescent light and combined red and blue (2.5:1) monochromatic LEDs, respectively. W1-2 are low-color rendering, and W3-7 are high-color rendering types of white LEDs

lettuce plants were less than those of RB LEDs and nearly one-third those of fluorescent light (Fig. 13.7). The energy consumption values are affected by high irradiance. The values obtained under 180–200 μmol m^{-2} s^{-1} were 1.3–1.5-folds of those under 110–130 μmol m^{-2} s^{-1}. Disappearing of wavelength dependency to photosynthetic characteristics can in principle be understood. If a grower choses higher PFD more than 200 μmol m^{-2} s^{-1}, the difference energy would be reduced. It is still apparent that the use of white LEDs can promote energy savings.

13.4 Notes on LED Use for Plant Cultivation

13.4.1 Adequate PFD Dose for a Light Source

The effective radiation dose varied due to spectrum-related factors. The growth rate is accelerated with an increase of PFD until photosynthesis reactions become saturated. However, the light curve of each LED is different because of the differences of the capacity of each light source to contribute to photosynthesis. In some cases, light saturation occurs early, and the supply of higher PFD is merely wasted. In other cases, greater irradiation promotes growth (Fig. 13.8).

Under close-set conditions, plants are sometimes extremely sensitive to LED irradiation. The risk of injury is dependent on the quantity and quality of the light and

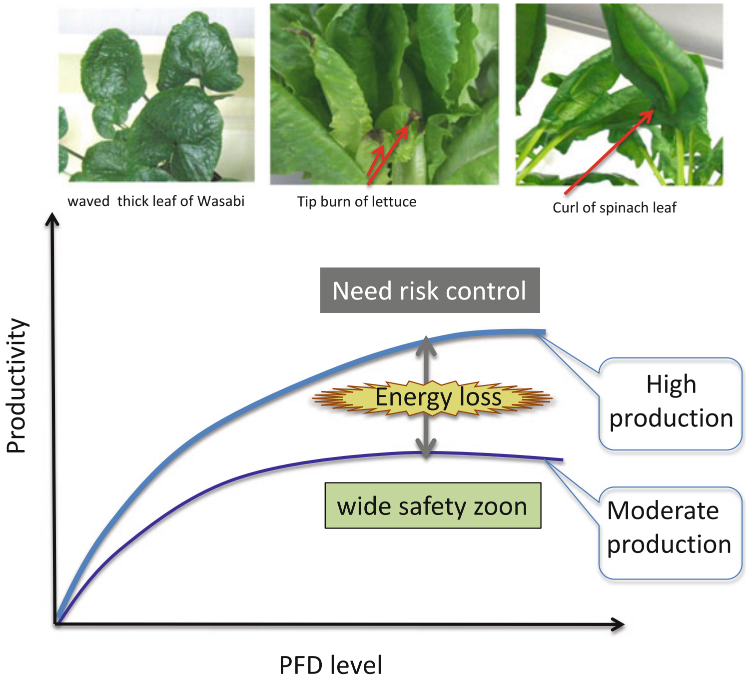


Fig. 13.8 Conceptual image supporting the necessity of controlling light quality and quantity in a plant factory. Excess energy that does not support photosynthesis causes an increase in the risk of product damage

the botanical variety and additionally influenced by other culture conditions such as temperature, humidity, ventilation, and possibly the CO_2 concentration and nutrition. The situations that are unfavorable to plants seem extremely complicated. PFD dose control of plants is an effective means to avoid damage. What little is known about actual methods for PFD control from experiment has resulted from work in indoor plant factories in Japan. The color temperature (K) seems to be ordinarily associated with the frequency of damage during production. As previously described, a lower K and higher PFD engender rapid growth but increase the risk of quality deterioration and result in considerable damage in the productivity. It should be noted that the response of cultured plants is variable among cultivars and growth age.

13.4.2 Damages Controllable by Choice of LED Spectrum

Red light is well known to facilitate plant growth via the promotion of photosynthetic activity. However, if plants are grown under a single monochromatic red LED that has an emission peak at 660 nm, the plants cannot sense excess light that causes photodamage to the leaves because of the mechanistic specificity of plant photosystems. The plants sense excess energy by means of blue light absorbance, which stimulates damage avoidance reactions in the photosystems and cellular functions (Gruszecki et al. 2010). The question “Is a combination of red and blue enough?” might arise. To answer this question, we must understand photosynthetic function in three dimensions. Blue and red lights are thought to be absorbed on the surface mainly by the palisade tissue of the leaves; in contrast, green and far-red lights penetrate beneath the leaf surface deeply into the foliage (Sun et al. 1998; Terashima et al. 2009; Broadersen and Volgelmann 2010). Therefore, the application of white LEDs with a broad wavelength spectrum covering the visible light area (380–780 nm) is a reasonable approach to achieve highly efficient conditions in a plant factory. In other words, broad-spectrum LEDs are safer and more easily employed tools for agricultural use.

13.4.3 Growth Phase and Troubles

During the early growth stages, horticultural plants are easy to cultivate under LEDs in a disease- and pest-free plant factory. Most nursery plants grow under any type of LED, possibly because young leaves respond to light conditions in a more flexible fashion than mature leaves (Nozue et al. 2017b). Trouble in the presence of LED lights usually occurs at later growth stages, or sometimes just before harvest. A few signs that seem directly or indirectly related to unfavorable light conditions are tip burn of lettuce leaves, curing of spinach leaves, and the thickness and shrinking of wasabi leaves (Fig. 13.8).

13.5 Steps on the Path to the Future of PFALs

Many studies on the influence of the spectral quality of LEDs on plants have been carried out. However, less attention has been paid to white LEDs. With the appearance of commercially available broad-spectrum white LEDs at a reasonable cost, PFALs have become more realistic systems for horticulture. The white LED has already spread throughout the world; therefore, it is expected that LEDs with good usability in agricultural systems can soon be provided. The benefits of phosphor white LEDs, other than overall good usability, include familiar natural color, low cost, and ease of replacement, all of which will help to establish a realistic expectation for PFALs. In addition, the optimization of LED lighting as an instrument for horticulture, in other words, a structural adjustment for improving the usage efficiency of plants, will be needed. It is hoped that PFALs will play a broad and important role as a tool for solving real-world problems such as food insecurity, natural disasters, demands for medical treatment, and nutrient fortification. To cope with such difficult situations, low-cost facilities and running costs are necessary. A better selection of LEDs and the appropriate application of lighting systems could be a critical requirement of future plant factories.

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