

Chapter 2

LED Supplementary Lighting

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2.1 Introduction

Recently, the use of light-emitting diode (LED) lighting systems has rapidly spread to various fields due to the improved luminous efficacy and reduced production cost and market price of LED lamps. LEDs have also begun to be used in plant production due to various advantages such as flexibility in controlling lighting conditions, including the wavelength, irradiated portion, and timing. LEDs are used not only for plant production under a controlled environment such as a plant factory but also as light sources for supplementary lighting. During plant production, supplementary lighting, defined as irradiation that is additional to sunlight, is used to improve the light environment. Supplementary lighting is used to improve plant growth, i.e., to compensate for a shortage of sunlight for photosynthesis; to control plant morphogenesis, including flowering; to protect the plants from diseases; and to improve plant quality. LED technology has several merits for use in supplementary lighting systems. In this chapter, the advantages of using LEDs in supplementary lighting systems are discussed along with their applications for several purposes in plant production. The methods adopted for evaluating the efficiency of supplementary lighting have also been illustrated.

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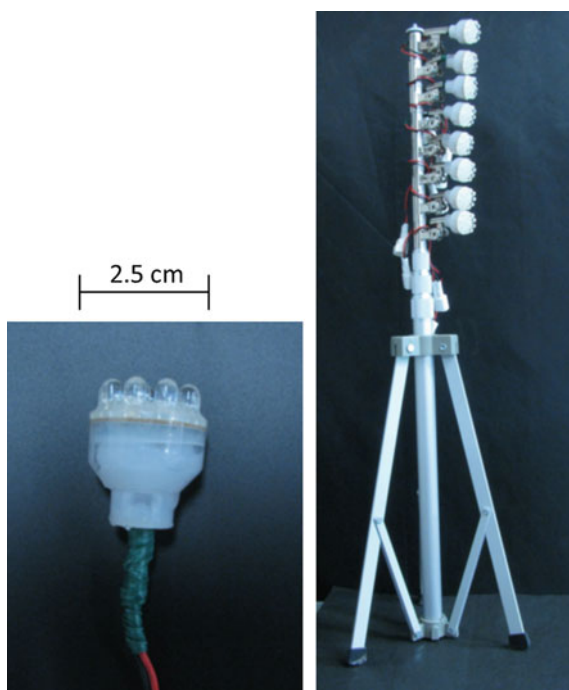
2.2 Advantages of LED for Supplementary Lighting Systems

The advantages of using LEDs as a light source in plant production include their potential for miniaturization and reduction of weight, low radiant heat emittance, and flexibility in wavelength, intensity, light distribution. The primary advantage of using LEDs in supplementary lighting systems is their small size. Small lighting devices can minimize the interception of sunlight, i.e., shading, thereby maximizing the sunlight received by plants and in turn the production efficiency. In addition, the small size of LEDs contributes to enhanced portability, which is one of the desirable features of supplementary lighting devices because the requirement of supplementary lighting depends on the stage of plant growth and development, and the lighting devices may be moved to avoid a reduction in the lighting efficiency with plant growth (Ibaraki 2016). In addition, LED supplementary lighting systems can be set close to plants due to the low emittance of heat; therefore, they are suitable for intracanopy lighting, in which lighting devices are set inside the plant canopy. For example, LEDs have previously been set inside the canopy of tomato plants being grown in a greenhouse (Tokuno et al. 2012; Deram et al. 2014; Tewolde et al. 2016).

Research into the spectral effects of light on plant growth and development has progressed due to the use of LEDs, which can provide light of a narrow bandwidth at a relatively high intensity. LEDs can be used in supplementary lighting systems with light of a specific wavelength. For example, blue-violet LED supplementary lighting systems have been used for protecting plants from diseases (Tokuno et al. 2012) and red LEDs have been applied for controlling flowering (Liao et al. 2014). The intensity of light in LEDs can be easily controlled by regulating the electrical current or duty ratio. This would be helpful for a dynamic control of supplementary lighting according to the variation in solar radiation. Moreover, LEDs with high directivity may be useful for controlling the lighting direction or site, which may be effective in improving the lighting efficiency. Thus, LEDs provide flexibility in controlling the light environment and are suitable for supplementary lighting.

Several types of LED lighting devices for supplementary lighting have been developed. One type can be installed in existing general lighting equipment as an alternative to fluorescent lights and electric lamps. Another type is specially designed for plant production. These include line (bar), flat (plate), and small unit types. The flat-type LED lighting system is easy to handle and provides uniform irradiation but more shading. The line-type LED lighting system is equipped with LED lamps arrayed in a linear fashion and is easy to handle and can be used not only for downward lighting but also for sideward lighting. In addition, tape-type systems consisting of a flexible material also exist. The small unit LED lighting system consists of multiple small units equipped with one or several LED lamps (Fig. 2.1). This type of lighting system can be used as a line type or flat type depending on the arrangement of units. Moreover, light intensity is controlled by regulating the distance between the units.

Fig. 2.1 Example of a small unit LED supplementary lighting system (*left*) consisting of a small LED unit (*right*)



2.3 Supplementary Lighting for Photosynthesis

One of the main purposes of supplementary lighting is to compensate for a shortage of light for photosynthesis under conditions of low sunlight. LED supplementary lighting has reportedly been used for this purpose in tomatoes (Deram et al. 2014; Tewolde et al. 2016), lettuces (Wojciechowska et al. 2015), cucumbers (Trouwborst et al. 2010), strawberries (Hidaka et al. 2013), and peppers (Li et al. 2016). Supplementary lighting is used for irradiation during the daytime to improve the light intensity or for nighttime irradiation to prolong the photoperiod.

It should be noted that the spectral properties of LEDs are very important, even for supplementary lighting for photosynthesis. White light with a spectrum similar to that of sunlight is suitable for this purpose. However, there are several types of white LEDs with different spectral properties. Their effects on photosynthesis depend on the spectral properties. Although the ratio of red and blue lights is one of the indices used for evaluating the spectral properties of light for plant growth, absolute blue light intensity was also reported to be important, affecting the photosynthetic rate (Cope and Bugbee 2013).

The irradiated portion is also important because the photosynthetic properties depend on the leaf age and/or position, and light intensity distribution exists inside the canopy. The effect of supplementary lighting depends on the position of the leaves to be irradiated. For example, the degree of improvement of photosynthetic

rates by increasing the photosynthetic photon flux density (PPFD) may differ between the upper leaves that have already received light with a high PPFD and lower leaves that receive light with a low PPFD.

2.4 Supplementary Lighting for Controlling Morphogenesis

In some species of plants, flowering can be controlled by regulating the photoperiod with supplementary lighting, allowing flower growers to control flowering according to market demand. In general, night breaking with supplementary lighting inhibits floral differentiation in short-day plants and promotes flower bud formation in long-day plants. This photoperiodism is thought to be caused by the photoreceptor phytochrome, which has two forms that mainly absorb red and far-red light, respectively, and so red and/or far-red light irradiation is important for controlling flowering. Incandescence lamps with a relatively high proportion of red and far-red light have previously been used for this purpose, but their use has been limited in recent years due to their low luminous efficacy and high electricity consumption. Consequently, the use of LED lamps has been now tested for controlling flowering.

The use of LEDs with a narrow range of wavelengths has revealed that the response of plants to the quality of light during the night break varies between species and that light other than red light may also affect flowering. For example, the optimal spectral properties of supplementary lighting for controlling flowering in chrysanthemum differ between varieties (Liao et al. 2014; Ochiai et al. 2015). In addition, the light quality supplied during the daily photoperiod might affect the light quality required for effective night break (Higuchi et al. 2012). Plants may be roughly divided into four groups based on their flowering response to different spectra of irradiation during night: inhibition mainly by red light, promotion mainly by red light, promotion mainly by far-red light, and no effect (Hisamatsu 2012).

Plant growth retardants are commonly used to regulate morphogenesis, but it is preferable to limit their use due to their potential negative effects on human health and the environment (Islam et al. 2015). Therefore, environmental control is a promising alternate method for controlling morphogenesis, which includes controlling the temperature difference between the daytime and nighttime (the DIF) and manipulating supplementary lighting regimes. Blue, red, and far-red lights are generally effective for controlling morphogenesis, associating with different photoreceptors (phototropins and cryptochromes for blue, and phytochromes for red and far red), and LED lamps can be used to control these spectral properties of light being irradiated on plants.

2.5 Supplementary Lighting for Other Purposes

2.5.1 *Protection from Plant Disease*

It has recently been reported that irradiation with specific wavelengths of light has the potential for suppressing plant disease. For example, irradiation with ultraviolet B (UV-B) light could suppress disease in strawberry (Kanto et al. 2009) and in rose (Kobayashi et al. 2013) and supplementary lighting devices using fluorescent lamps that provide UV-B irradiation are now commercially available (“Tahunarei,” Panasonic). Green light irradiation during the nighttime has also been reported to have suppressive effects on plant disease (Kudo et al. 2011), and supplementary blue-violet LED lighting, which has an emission peak at around 405 nm, has been used to suppress disease in house-grown tomato (Tokuno et al. 2012). It is believed that blue-violet LED lighting induces resistance to plant disease (Ito et al. 2013), as well as having direct suppressive effects (Imada et al. 2014). It has also been reported that red light induces resistance to plant disease (Wang et al. 2010; Suthaparan and Torre 2010), although there are no reports of supplementary red LED lighting being used for this purpose. The protection of plants from disease through the use of lights is an emerging technology and so some issues remain to be resolved, including the dependence of different plant species and optimization of the lighting conditions.

2.5.2 *Improving the Concentration of Functional Components*

Light irradiation can induce the production of some secondary metabolites and so supplementary lighting has the potential for improving their contents as functional ingredients. Many studies have reported on the spectral effects of light on secondary metabolites, including phenolic acid and flavonoids, which are used as defense mechanisms under stressful conditions (Shetty et al. 2011). Furthermore, control of light quality has often been reported as enhancing antioxidant capacity (e.g., Ebisawa et al. 2008; Li and Kubota 2009; Shiga et al. 2009; Samuoliene et al. 2012; Carvalho et al. 2016) as a result of increasing the concentration of metabolites that serve as antioxidants, such as ascorbic acid and flavonoids. In an investigation on the effects of the proportion of blue/red light on rose, chrysanthemum, and campanula, Ouzounis et al. (2014) found that a high blue light ratio increased the concentrations of phenolic acid and flavonoids, although the effects differed between species.

LED supplementary lighting is effective for controlling the spectral properties of light being irradiated on plants. Furthermore, LEDs with various peak wavelengths are now available, which can be used to modify the light spectrum during the daytime and to irradiate plants with specific wavelengths of light during the night time.

2.6 Evaluation of the Efficiency of Supplementary Lighting

2.6.1 *Methods for Evaluation of the Efficiency of Supplementary Lighting*

Although the use of artificial lighting in plant production has increased, little attention has been paid to the efficiency of lighting (Ibaraki and Shigemoto 2013). As artificial lighting, including supplementary lighting, consumes energy, thereby increasing the cost of production, it is critical that plant growers improve the efficiency of their lighting systems (Ibaraki 2016). An adequate evaluation of lighting efficiency is essential for determining methods of improving it.

As previously described, supplementary lighting is implemented for various purposes. The direct evaluation of supplementary lighting involves estimating the benefit/return corresponding to the objectives of an endeavor. This could be obtained by calculating the supplementary lighting per unit cost or per unit energy consumption required for the lighting. For example, a method to evaluate the efficiency of supplementary lighting for photosynthesis is to estimate the amount of biomass produced per unit of energy used to irradiate the plants (Ibaraki 2016). The possible benefits of supplementary lighting depend on the purposes of the lighting, e.g., increase in the concentration of the target component or control of period of flowering.

These parameters can be estimated by comparing results of a cultivation utilizing supplementary lighting with that not utilizing supplementary lighting. However, this approach may not be realistic as it requires cultivation without supplementary lighting for every comparison. Moreover, comparison or quantification of the results might be difficult in some cases, such as supplementary lighting for controlling morphogenesis or protection from plant disease. Alternatively, a possible important index is determining to what degree the distribution of light intensity is changed by the supplementary lighting. Thus, lighting efficiency can also be evaluated by interpreting the extent of light intensity that can be improved on leaf surfaces.

A method of evaluating the efficiency of supplementary lighting based on light intensity distribution on a canopy surface, expressed as a PPFD histogram, was previously developed (Ibaraki and Shigemoto 2013). This is based on the method developed by Ibaraki et al. (2012a, b), wherein the reflection images of plant canopy surfaces at specific ranges of wavelength acquired with a digital camera are used for the estimation of PPFD on leaf surfaces. The pixel value of the image is converted into a PPFD by a regression model determined from the PPFD measured at one point on the canopy with simultaneous imaging, following which a PPFD histogram is constructed. To characterize the PPFD distribution, an average PPFD, a median PPFD, and the coefficient of variance of the PPFD over the illuminated canopy surface can be calculated from the PPFD histogram. In addition, the fraction of leaf area with a PPFD value greater than a certain threshold can be calculated. This method has been applied for analyzing PPFD distribution on the canopy surface in tomatoes grown in a greenhouse (Ibaraki et al. 2012a) and lettuces

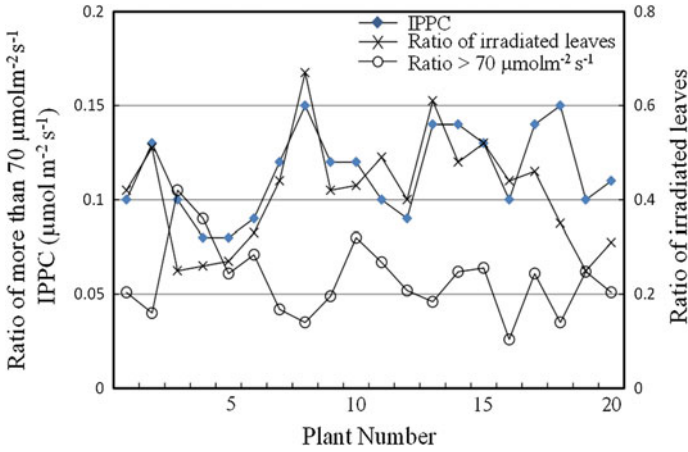


Fig. 2.2 Example of the variation of efficiency of supplementary lighting with line-type LED lighting systems for tomato plants. Parameters were estimated for evaluating the efficiency in each plant ($n = 20$)

cultivated under artificial lighting (Miyoshi et al. 2016). Integrated PPFD over all illuminated leaves per unit power consumption (IPPC) was then proposed as a criterion for evaluating the efficiency of supplementary lighting (Ibaraki and Shigemoto 2013). IPPC was calculated by the following equation:

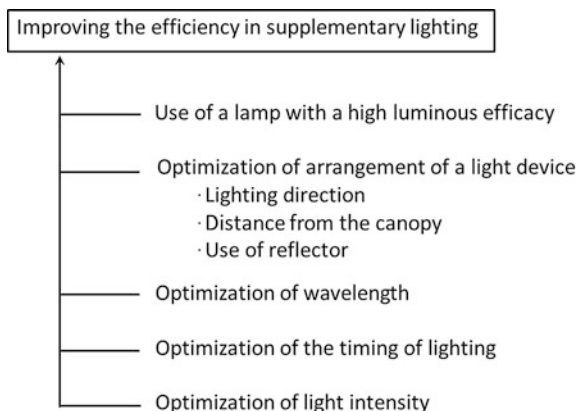
$$\text{IPPC } (\mu\text{mol s}^{-1} \text{ W}^{-1} \text{ or } \mu\text{mol J}^{-1}) = \frac{\text{Averaged PPFD } (\mu\text{mol m}^{-2} \text{ s}^{-1}) \times \text{Projected leaf area } (\text{m}^2)}{\text{Power consumption for lighting } (\text{W})}.$$

Ibaraki and Shigemoto (2013) reported that the histogram pattern of PPFD on a tomato plant canopy surface under supplementary lighting depended on the canopy structures, types of light sources, and distance between lamps and the canopy surfaces, along with the difference in the efficiency, IPPC. Figure 2.2 shows an example of variation of the efficiency, IPPC, when each plant was irradiated by the same type of supplementary devices set at the same distance from plants in tomato cultivation in a greenhouse (Fig. 2.2). It should be noted that lighting efficiency depended on the canopy structure (leaf distribution pattern); therefore, lighting efficiency changed with time corresponding to plant growth.

2.6.2 Practices to Increase the Efficiency of Supplementary Lighting

Figure 2.3 shows a strategy for improving the efficiency of supplementary lighting. An effective method is to use lamps with high luminous efficacy. However, lighting

Fig. 2.3 Practices for improving the efficiency of supplementary lighting



efficiency also depends on the arrangement of the lamps and/or the plant canopy structure being irradiated (Ibaraki 2016). Minimizing unnecessary irradiation, such as irradiation that excludes plants, should be considered. This might depend on several factors, including lighting direction, light distribution of lamps, and the distance from plants. The timing of lighting is also important for supplementary lighting (Ibaraki 2016): Lighting at night is effective for promoting the growth of lettuce (Fukuda et al. 2004), and end-of-day lighting, which is irradiation just before the onset of darkness, is effective in controlling plant morphological events (e.g., Yang et al. 2012). The efficiency of supplementary lighting can be improved in regard to irradiation position (Ibaraki 2016). Moreover, the parts of plants to be irradiated should be considered based on the physiological properties of the plants.

2.7 Conclusion

LED supplementary lighting is a promising technology for improving crop productivity and quality by controlling plant growth and development. The most significant merit of LED technology as a light source for supplementary lighting is its flexibility for controlling the light environment. By using LEDs, the effects of light quality, i.e., light spectrum, on plant growth and development can be revealed in detail, thereby allowing effective supplementary lighting guidelines to be developed. To take full advantage of LED supplementary lighting, it is essential to adequately evaluate the efficiency of LED lighting. Therefore, for evaluating the efficiency of supplementary lighting, it is important to determine how much of the light distributed on the plant canopy surface is changed by the supplementary lighting. Moreover, this contributes to improve stability and reproducibility in both research and application of supplementary lighting.

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Smart Lighting

Dutta Gupta, S. (Ed.)

2017, XIX, 334 p. 71 illus., Hardcover

ISBN: 978-981-10-5806-6