Chapter 11
Lighting Efficiency in Plant Production Under Artificial Lighting and Plant Growth Modeling for Evaluating the Lighting Efficiency

Yasuomi Ibaraki

Abstract As it is critical that plant growers improve the efficiency of their lighting when it uses artificial lighting, the lighting efficiency should be evaluated properly. One possible way to evaluate the lighting efficiency is to compare the amount of biomass produced per unit of energy used to irradiate the plants. A simpler index uses the fraction of the light energy or photons received by plants. Lighting efficiency can also be evaluated from the viewpoint of how much the irradiance/photon flux density on leaf surfaces can be improved. It is useful to obtain information of canopy structure or leaf spatial distribution in addition to determining plant mass (dry weight, fresh weight, or LAI) increments for evaluating the lighting efficiency. Modeling leaf growth and development can be used for this purpose.

Keywords Electrical energy use efficiency • Energy consumption • Functional–structural plant model • Light use efficiency • L-system • PPFD distribution • Radiation use efficiency • Reflection image

11.1 Introduction

Although the use of artificial lighting in plant production has been increasing, little attention has been paid to the efficiency of the lighting (Ibaraki and Shigemoto 2013). As artificial lighting consumes energy, thereby increasing the cost of production, it is critical that plant growers improve the efficiency of their lighting. One possible solution is to use lamps with high luminous efficacy. However, lighting efficiency also depends on the arrangement of the lamps and/or the plant canopy structure being irradiated. The total luminous flux emitted by a lamp may not always irradiate the plant body, and unnecessary irradiation is often produced by

Y. Ibaraki (✉)
Faculty of Agriculture, Yamaguchi University, 1677-1 Yoshida, Yamaguchi 753-8515, Japan
e-mail: ibaraki@yamaguchi-u.ac.jp

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artificial lighting, particularly when the plant canopy has a low leaf area index (LAI). The plant canopy structure changes as the plants grow during cultivation. Accordingly, the light environment also changes in line with the change in the canopy structure, even if the light source, lighting direction, and distance from plants remain constant. The lighting efficiency may therefore change with plant growth, and the dynamics of this process should be evaluated properly.

Lighting efficiency can be evaluated from several viewpoints. First, the efficiency can be evaluated in terms of energy conversion efficiency, comparing biomass production per unit of energy used for the irradiating light. A simpler index uses the fraction of the light energy or photons received by plants. It is also important to understand the extent to which the irradiance (W m^{-2}) or photon flux density (mol m^{-2} s^{-1}) is improved by the artificial lighting because the objective of artificial lighting is to irradiate the leaves and increase the irradiance/photon flux density on them for photosynthesis or other light-induced biological processes.

In this chapter, the evaluation methods for lighting efficiency are introduced, focusing on the energy use efficiency and the photosynthetic photon flux density (PPFD) distribution on the canopy surface provided by artificial lighting. The use of plant growth modeling for estimating the lighting efficiency will also be discussed.

11.2 Light Energy Received by Leaves

11.2.1 Light Use Efficiency

Plants absorb light energy and convert it into chemical energy stored as organic matter (biomass). The lighting efficiency can therefore be assessed by the energy conversion efficiency. One possible way to evaluate the efficiency is to compare the amount of biomass produced per unit of energy used to irradiate the plants or those absorbed by the plants.

A ratio between accumulated biomass and the photosynthetically active radiation (PAR) absorbed by plants is sometimes referred to as light use efficiency (LUE) or radiation use efficiency (RUE), having units of μg J^{-1}, and has been used as an index for assessing canopy productivity (Gitelson and Gamon 2015) for natural ecosystems or field crops. This approach is based on Monteith's observation (1972) that the net primary productivity of the plant canopy is proportional to the intercepted solar radiation (Rosati and Dejong 2003). However, the lack of a universally agreed definition of LUE may cause difficulties in comparison of the results from different studies (McCallum et al. 2009). The denominators of LUE range from simple incident PAR (or PPFD), through total PAR absorbed (intercepted), to total PAR absorbed by green vegetation (photosynthetically active leaves) (Gitelson and Gamon 2015). The numerator is also variable and may be net primary production (NPP) (g C), gross primary production (GPP) (g C), weight of biomass (g), or weight of aboveground biomass (g). In botanical studies, LUE is

Table 11.1 LUE values for several crops reported in the literature

Species	LUE value (μg J^{-1})	Description of the term in the literature	Reference
Tomato	2.8–4.0	Light use efficiency	Dorais (2003)
Sweet pepper	2.1	Light use efficiency	Dorais (2003)
Lettuce	1.44–2.43	Conversion efficiency of absorbed PAR	Tei et al. (1996)
	1.26	Radiation conversion efficiency	Javanovic et al. (1999)
Onion	0.99–5.08	Conversion efficiency of absorbed PAR	Tei et al. (1996)
	1.08	Radiation conversion efficiency	Javanovic et al. (1999)
Rice	4.15	Efficiency of light utilization for DM production	Sands (1999)
Maize	3.4	Efficiency of light utilization for DM production	Sands (1999)
Soybean	1.29	Efficiency of light utilization for DM production	Sands (1999)

often evaluated as the slope of a light photosynthetic curve or a quantum yield of oxygen evolution, having units of mol mol^{-1}. When referring to LUEs or RUEs reported in the literature, the definition and method of measurement must be specified.

LUE varies between crops, depending on the plant physiological status, including the nitrogen status (Rosati and Dejong 2003), as well as environmental conditions such as temperature or CO_2 concentration. Table 11.1 shows the LUEs for several crops are expressed in terms of dry mass formed (μg) per unit of PAR absorbed (J).

11.2.2 Ratio of Light Energy Received by the Plants

An alternative index uses the fraction of light energy or photons received by the plants to evaluate the lighting efficiency. The ratio of the PAR (PAR_P) received at the plant canopy surface to that (PAR_L) emitted from the lamps, often referred to as the "utilization factor" in illumination engineering (Kozai 2013), can be used for this purpose. The ratio of PAR_P to PAR_L depends not only on the lamp properties (i.e., spatial distribution of the light intensity emitted from the lamp) but also on the canopy structure. The ratio thus changes over time. Improving the ratio of PAR_P to PAR_L is a way to minimize the unnecessary irradiation, reduce energy consumption, and consequently lower the cost of production.

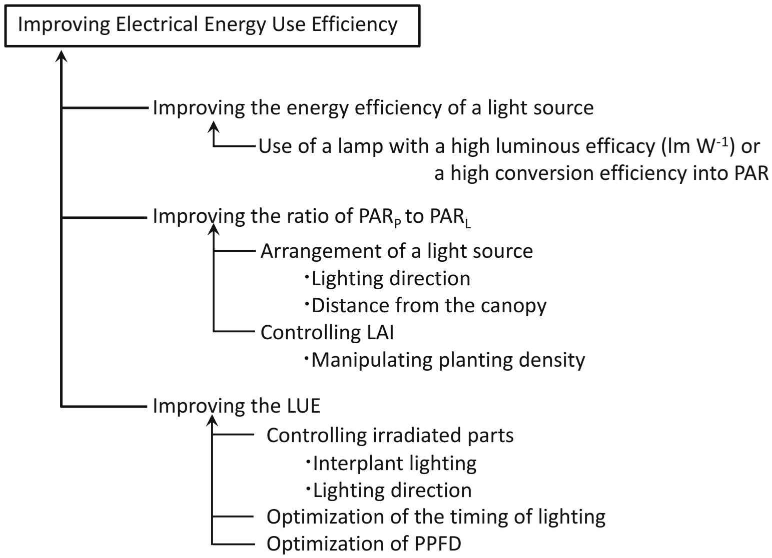

Fig. 11.1 Factors affecting electrical energy use efficiency

11.2.3 Improving Electrical Energy Use Efficiency

For crop production under artificial lighting, electrical energy use efficiency estimated based on the power consumption is also an important index to evaluate the lighting efficiency. The methods of estimation of the electrical energy use efficiency are described in detail in Chap. 29.

Various methods can be considered to improve the electrical energy use efficiency (Kozai 2013). These methods can be divided into the following approaches: improving the energy efficiency of a light source, improving the ratio of PAR_P to PAR_L, and improving the LUE based on the plant physiological (photosynthetic) properties (Fig. 11.1).

A direct method for improving the energy efficiency is to use a light source with a high luminous efficacy (lm W^{-1}) as described before. The energy efficiency of LEDs and LED lighting systems was described in detail in Chap. 29.

To improve the ratio of PAR_P to PAR_L, it is important to minimize unnecessary irradiation. The ratio can be improved by well-designed light reflectors or by a reduction in the vertical distance between lamps and plants (Massa et al. 2008). Reflectors may be placed behind (above) the lamps to direct the backward light to the forward (downward) or on the side of the cultivation tray to minimize the amount of light irradiated outside the tray. The reduction of distance between lamps and plants also leads to minimizing the amount of light irradiated outside the plant canopy. Moreover, controlling the lighting direction may also be effective, depending on the canopy structure and spatial distribution of the lamps. Plant density also affects the ratio of PAR_P to PAR_L (Kozai 2013; Yokoi et al. 2003; Massa et al. 2008).

The electrical energy use efficiency can be improved from the aspects of both irradiation time and position, based on the physiological properties of the plants, i.e., when plants are irradiated and which parts of plants are irradiated affect the efficiency. For example, the net photosynthetic rate of the upper leaves that have already received light at a high level (near the light saturation level) may not be increased by further increasing PPFD by supplemental lighting. On the other hand, the net photosynthetic rate of the lower leaves, which is often negative or nearly zero, will become positive by increasing PPFD. From this point of view, the interplant lighting provides more light energy to the lower leaves than downward lighting only, potentially improving the light energy use efficiency (Kozai 2013; Massa et al. 2008).

The timing of lighting is also important for supplemental lighting. It has been reported that lighting during the night period is effective for promoting the growth of lettuce (Fukuda et al. 2004), and end-of-day lighting is effective in controlling plant morphological events (e.g., Yang et al. 2012). Furthermore, diurnal variation of LUE has been reported (e.g., Mukherjee et al. 2014).

11.3 Lighting Efficiency Based on PPFD Distribution on a Canopy Surface

PPFD on a leaf surface is critical for plant production. Lighting efficiency can also be evaluated from the viewpoint of how much the PPFD on leaf surfaces can be improved.

A method of evaluating the efficiency of supplemental lighting based on PPFD distribution on a canopy surface under artificial lighting conditions was developed (Ibaraki and Shigemoto 2013), and several indices for lighting efficiency derived from the PPFD distribution histogram estimated by using a reflection image of the canopy surface were proposed. In this method, the reflection images of plant canopy surfaces were acquired from three directions with a digital camera, and PPFD on leaf surfaces was estimated from the pixel values of the image by a regression model determined from PPFD measured at one point on the canopy simultaneously with imaging (see Chap. 10 for details). Then, the histogram of the pixel values after gamma correction was converted to a PPFD histogram (Fig. 11.2). To characterize the PPFD distribution, an average PPFD, a median PPFD, and the coefficient of variances (CV) of PPFD over the illuminated canopy surface were calculated from the PPFD histogram. Integrated PPFD over all illuminated leaves per unit power consumption (IPPC) was then proposed as a criterion for evaluating the efficiency of supplemental lighting. IPPC was calculated by the following equation:

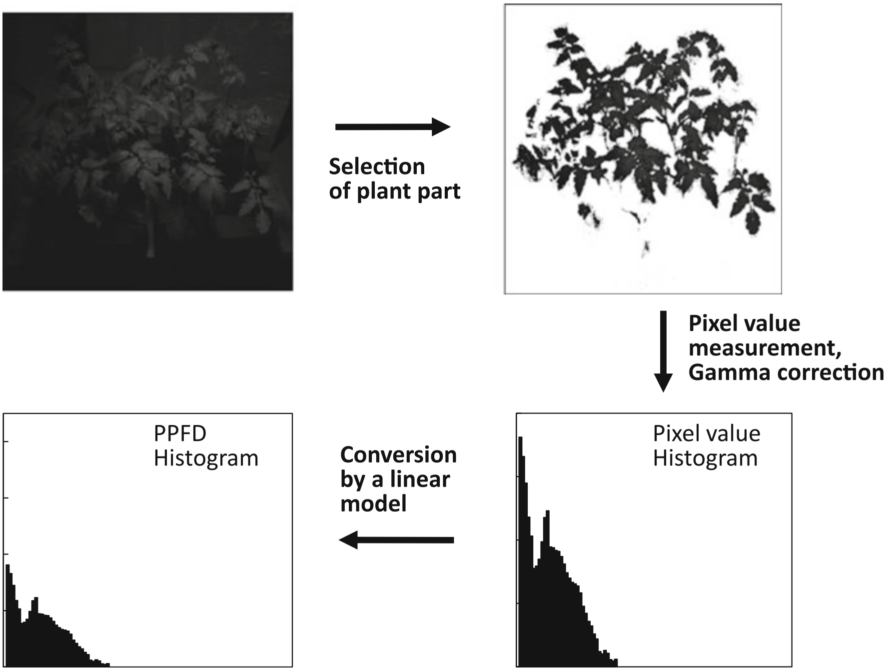

Fig. 11.2 Flow diagram of PPFD histogram construction from reflection images (Reproduced from Ibaraki and Shigemoto (2013))

$$\mathrm{IPPC}\left(\mu\mathrm{mol\ s^{-1}\ W^{-1}\ or\ \mu mol\ J^{-1}}\right) = \frac{\text{Averaged PPFD } (\mu\mathrm{mol\ m^{-2}\ s^{-1}}) \times \text{Projected leaf area } (\mathrm{m^{-2}})}{\text{Power consumption of light source (W)}} \tag{11.1}$$

The projected leaf area was estimated from the image of the canopy surface by selecting pixels corresponding to leaves. Ibaraki and Shigemoto (2013) reported that the histogram pattern of PPFD on a tomato plant canopy surface under supplemental lighting depended on the light source and canopy structure. Histograms estimated from images could depict the differences, showing average values and CVs close to the measured values. The IPPC also depended on the types of light sources, canopy structures, and the distance between lamps and the canopy surfaces.

Bornwaβer and Tantau (2012) calculated a similar index, the energy efficiency with PPFD (μmol s^{-1} W^{-1}), to evaluate the lighting efficiency of the LED lighting system in in vitro culture. They calculated the index for both average PPFD and PPFD at the center of the irradiated surface to represent the PPFD distribution.

When artificial lights are used, it is easy to convert PPFD into total photon flux density or irradiance because, for the same light source, the light spectrum is constant. Therefore, these PPFD-based methods can be applied for supplemental lighting, which should be evaluated by total photon flux density or irradiance rather than by PPFD. If irradiance is used instead of PPFD, the integrated irradiance per unit power consumption is dimensionless (W $m^{-2} \times m^2$/W).

It is important to know the actual irradiance/photon flux density on the plant canopy surface not only to evaluate the lighting efficiency but also to improve stability and repeatability in controlling the environmental conditions when supplemental lighting is used. The image-based PPFD histogram estimation method is also expected to be used for this purpose (Ibaraki and Shigemoto 2013).

11.4 Plant Growth Modeling for Evaluating Lighting Efficiency

11.4.1 Simple Growth Model

Plant growth modeling is an effective tool for understanding light distribution and estimating the lighting efficiency. For vegetative growth, an exponential model is often used. Assuming that the relative growth rate (RGR) or the relative leaf area growth rate (RLGR) is constant during a given period, growth (in terms of dry weight, W, or leaf area, L) can be expressed as exponential growth (an exponential function of time t, see Fig. 11.3a) by the following equations:

$$W = W_0 e^{\mathrm{RGR}t} \tag{11.2}$$

$$L = L_0 e^{\mathrm{RLGR}t} \tag{11.3}$$

where W_0 and L_0 are initial values of W and L, respectively.

For leafy vegetables and seedlings that are dominant crops in a plant factory with artificial lights, such exponential models are often used to estimate the vegetative growth. For example, Yokoi et al. (2003) used an exponential model to fit the

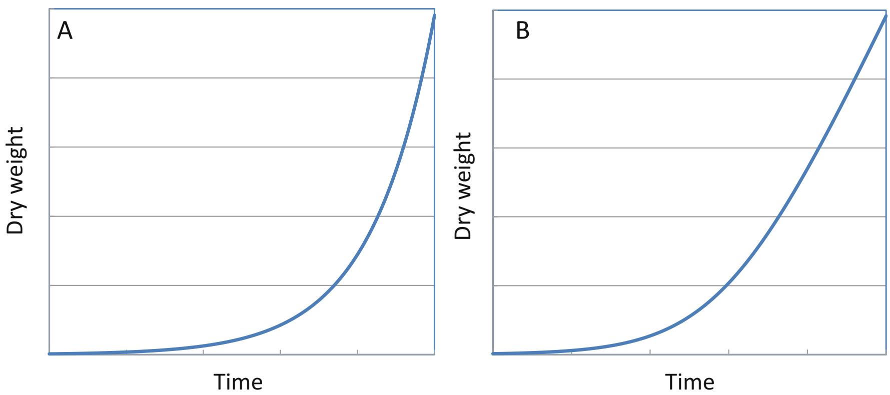

Fig. 11.3 Examples of an exponential growth curve (**a**) and an expolinear growth curve (**b**)

increments in LAI and dry weight and to calculate the electrical energy use efficiency in the production of tomato seedlings under artificial lighting.

For individual plants, such as seedlings growing without competition between neighbors, RGR is assumed to be constant (Monteith 2000) under constant environmental conditions. However, RGR may decline if there is competition for resources (Monteith 2000). In addition, RGR depends on both environmental conditions and plant physiological state, such as leaf nitrogen content. Models for changing RGR include an expolinear model (Goudriaan and Monteith 1990; Dennett and Ishag 1998; Monteith 2000) available for longer period of growth (Fig. 11.3b), a model expressing RGR as a function of temperature and PAR (Aikman and Scaife 1993), and a model using a Gompertz function (Shimizu et al. 2008).

11.4.2 2D and 3D Modeling for Vegetative Growth

It is useful to obtain (simulate) information of canopy structure or leaf spatial distribution in addition to determining plant mass (dry weight, fresh weight, or LAI) increments for evaluating lighting efficiency. Therefore, modeling leaf growth and development is effective. Leaves of vascular plants are arranged in an orderly, often spectacular pattern (Lubkin 1995). Normally, the leaf arrangement pattern, i.e., phyllotaxis, depends on plant species or cultivar and includes alternate, opposite, whorled, and rosulate patterns (Fig. 11.4). It is useful to know the leaf arrangement pattern of the target plant for modeling leaf growth and development. Considering both this pattern and the spectral distribution of light, we may estimate the PAR_P/PAR_L ratio.

Recently, 3D measurements, including lidar (Hosoi and Omasa 2009) and stereo imaging (Biskup et al. 2007; Müller-Linow et al. 2015), have been used to analyze plant canopy structure. From 3D data of plant architecture, leaf angle distribution

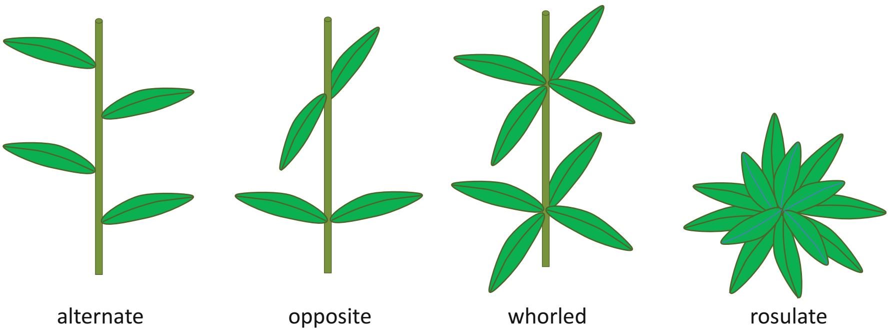

Fig. 11.4 Leaf arrangement patterns

and leaf area density distribution, which are important parameters, can be estimated.

Models for simulating the 3D architecture of plants have been developed based mainly on L-systems or similar approaches (Fournier and Andrieu 1998). An L-system, developed by Lindenmayer (1968), is a string rewriting system and is a powerful tool to model the growth of plants (Fournier and Andrieu 1998). In general, rewriting is a technique for defining complex objects by successively replacing parts of a simple initial object using a set of rewriting rules or productions (Prusinkiewicz and Lindenmayer 1990). In an L-system, plant architecture is represented by a string symbol, each symbol representing a plant component such as a leaf or internode (Kaitaniemi et al. 2000). A simple example of L-systems is shown in Fig. 11.5. Plant growth and development can be simulated by the symbols changing according to the production rules. A comprehensive overview of the simulation of plant development using L-systems is reviewed by Prusinkiewicz and Lindenmayer (1990).

Recently, new computer models of plant functioning and growth, called functional–structural plant models (FSPMs), have been developed (Godin and Sinoquet 2005). FSPMs combine the representation of 3D plant structure with selected physiological functions, consisting of an architectural part (plant structure) and a process part (plant functioning) (Vos et al. 2010). In FSPMs, L-systems are often adopted as a paradigm to model plant development (Godin and Sinoquet 2005). FSPMs were used to compare lamp positioning scenarios to identify the most efficient lighting strategy in greenhouse production of tomatoes, being combined with 3D models of light distribution from the lamps and greenhouse architecture (Visser et al. 2012, 2014).

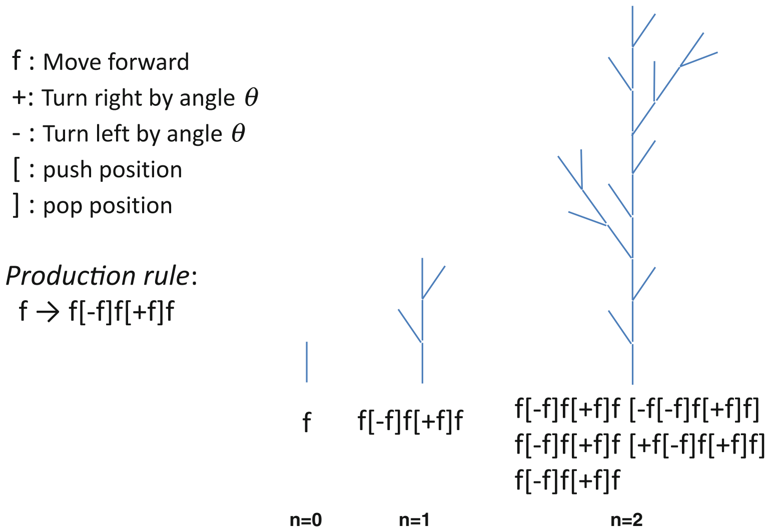

Fig. 11.5 A simple example of L-systems

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