Chapter 4
Some Aspects of the Light Environment

Toyoki Kozai and Geng Zhang

Abstract Roles of light as energy and signal sources for growing plants are discussed mainly with respect to photosynthesis and photomorphogenesis. Components of the light environment above and within a plant canopy, such as spectral distribution, photosynthetic photon flux density (PPFD), lighting cycle, and lighting direction, are shown. Characteristics of LED arrays as light source and characteristics of light environment in plant factory with artificial lighting (PFAL) are discussed. Concepts and significances of supplemental upward lighting in the PFAL and supplemental lighting in greenhouse are described. Advantages of supplemental upward lighting in the PFAL to prevent senescence of lower leaves and increase marketable fresh weight of leaf lettuce plants are shown. Strategy of environmental control under artificial lighting is discussed.

Keywords Energy source • Light environment • Photomorphogenesis • Photosynthesis • Signal source

4.1 Light as an Energy and Signal Source

Light is a source of energy for photosynthesis as well as a source of signals or information activating photomorphogenesis and other physiological processes such as secondary metabolite production in plants (Fig. 4.1). Light is also a source of information for human eyes. The wavelengths of photosynthetically active light (400–700 nm) and physiologically active light (300–800 nm) overlap, so that photosynthesis and photomorphogenesis are often concurrent. Both are photochemical reactions, and the amount of light received by plants is measured in units of moles (1 mol = 6.03×10^{23} photons), not in joules (energy). In addition, light affects human color and shape perception, along with health (Chap. 31). (More detailed explanations

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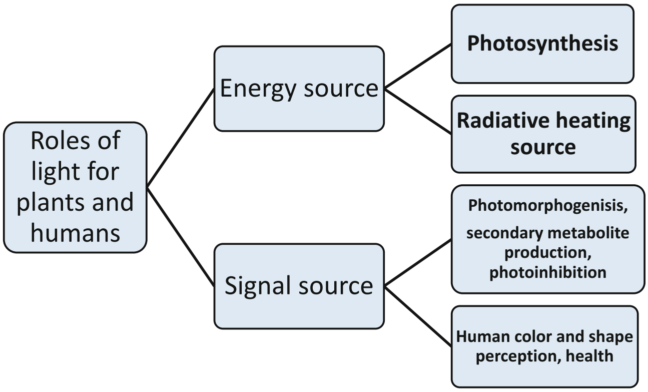

Fig. 4.1 Roles of light for plants and humans

of light and its units are given in Chaps. 26 and 28). Active light for human eyes ranges between 380 and 780 nm with a peak wave length of 555 nm.

Light is absorbed, reflected, or transmitted when it reaches plants. Some photosynthetic photons are captured and converted into chemical energy as carbohydrates in plants, while the remaining light absorbed is ultimately converted into heat (Kozai 2013; Chap. 9). In this sense, photosynthesis is a process of energy conversion from light or photosynthetically active radiation (PAR) to chemical and heat energy as measured in joules. The conversion from joules to moles is determined once the wavelength is specified (Chap. 26). This chapter describes the light environment in plant factories with artificial lighting (PFALs) and greenhouses with supplemental lighting, with details not discussed in other chapters.

4.2 Components of the Light Environment

Components of the light environment above and within a plant canopy (or community) are shown in Fig. 4.2. The photosynthetic photon flux density (PPFD) or PAR flux density on the horizontal plane is the most important variable in the light environment. The average PPFD or PAR flux density decreases exponentially with increasing plant canopy depth (referred to as the cumulative leaf area index [LAI] (Chaps. 10 and 11).

4.2.1 Spectral Distribution of Light Within the Plant Canopy

The light quality or spectral distribution of light over the plant canopy differs significantly from that within it. Green light generally penetrates the plant canopy more easily than blue and red light, because its transmissivity, reflectivity, and

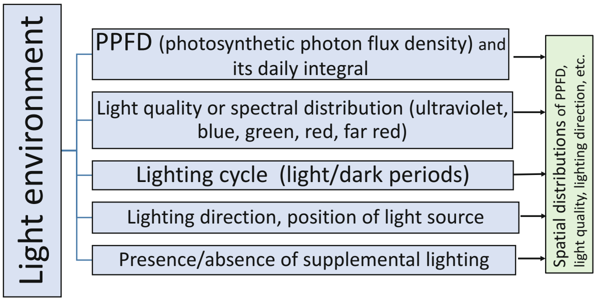

Fig. 4.2 Components of the light environment

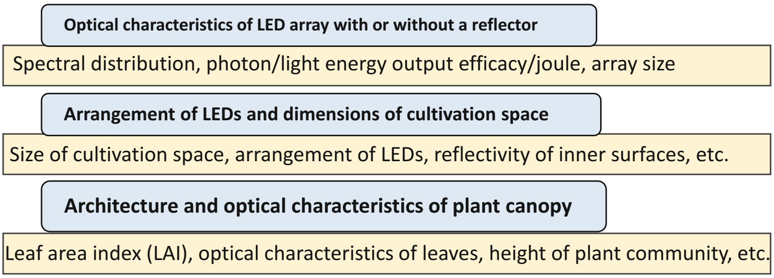

Fig. 4.3 Factors affecting the light environment in the cultivation space of a PFAL

absorptivity by green leaves are about 30 %, 20 %, and 50 %, respectively (Kozai et al. 2015), while those of blue and red light are about 0 %, 100 % and 100 %, respectively. Blue and red light is mostly absorbed by the uppermost layer of the plant canopy. A detailed description of the optical and physiological properties of leaves and canopies is given in Part III (Chaps. 8, 9, 10, 11, 12, and 13).

4.3 Light Environment in PFALs

In PFALs, the light environment over plant canopies in cultivation spaces is significantly affected not only by the optical characteristics of light-emitting diode (LED) arrays and their layout but also by the optical characteristics of each cultivation space and plant canopy (Fig. 4.3).

4.3.1 Characteristics of LED Arrays as Light Source

LEDs as a light source are characterized by the: (1) dimension and structure of the LED array; (2) spectral distribution (ultraviolet, blue, green, red, and far red) of photons emitted from the LED array; (3) directional (spatial) distribution of photons emitted from the LED array; (4) ratio of light energy emitted to electric energy consumed (joule/joule) or ratio of photosynthetic photons emitted to electric energy consumed (μmol /joule); and (5) control of the lighting cycle (light/dark periods), spectral distribution, and photosynthetic photon flux (see Part VII).

4.3.2 *Spatial Distribution of PPFD in Empty Cultivation Spaces in PFALs*

The spatial distribution of PPFD in an empty cultivation space is affected by the optical characteristics of the LED array mentioned above, layout of LED arrays installed on the ceiling of cultivation spaces, and dimension (width, height, and length) of empty cultivation spaces and optical characteristics (diffused/mirrored reflection, reflectivity, etc.) of their inner surfaces.

4.3.3 *Light Environment as Affected by Plant Canopies in Cultivation Spaces*

The light environment in a cultivation space with a plant canopy differs significantly from that in an empty cultivation space. In a PFAL, the PPFD and light quality above and within a plant canopy change markedly with time as the canopy grows for two main reasons. First, the top layer of a canopy approaches the light source with upward growth; second, immediately after transplanting seedlings onto a white culture panel, most (about 80 %) of downward-directed light is reflected back to the ceiling. As the plant canopy grows, the downward blue and red light is mostly absorbed by plant leaves, while about 50 % only of green light, if any, is absorbed by plant leaves; about 20 % is reflected back to the ceiling and about 30 % is transmitted through leaves (Fig. 4.4). Therefore, in a PFAL lit with red and blue

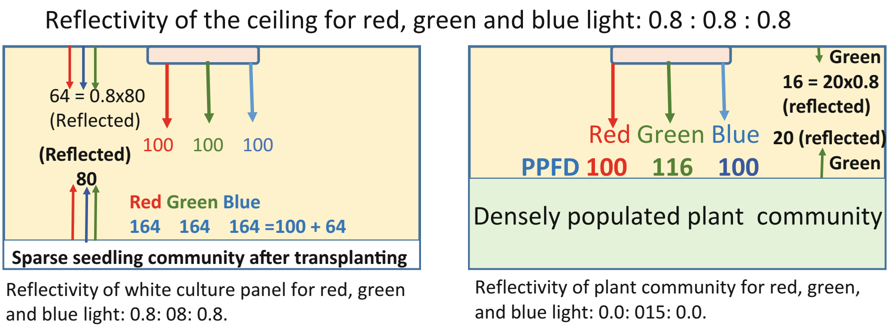

Fig. 4.4 Scheme showing the effect of reflectivity of the plant canopy/culture panels on the PPFD above the plant canopy in a PFAL. The PPFD immediately before harvesting is 67 % of that immediately after transplanting

LEDs alone, the PPFD above a densely populated plant canopy is decreased by about 40 % (=100–100/(100 + 100 × 0.8 × 0.8), compared with that immediately after seedling transplant onto white culture panels.

4.4 Supplemental Upward Lighting

High planting density in a PFAL tends to accelerate leaf senescence in the lower (or outer) leaves as a result of shading by the upper (or inner) leaves and neighboring plants, which decreases yields and increases labor costs for trimming senescent leaves. Thus, the development of cultivation systems to retard outer leaf senescence is an important research goal to improve the yield and profitability of PFALs.

Zhang et al. (2015) developed an upward-directed LED lighting system to improve the light environment for PFAL cultivation of leafy vegetables (Fig. 4.5). Romaine lettuce (*Lactuca sativa* L.) was grown hydroponically under downward-directed white LEDs at a PPFD of 200 μmol $m^{-2}s^{-1}$, with or without supplemental upward white LED lighting (PPFD facing the culture panel of 40 μmol m^{-2} s^{-1} 4 cm above the culture panel). They showed that the supplemental lighting retarded the senescence of outer leaves and decreased the percent waste (i.e., dead or low-quality senescent leaves), leading to an improvement in the marketable leaf fresh weight (Zhang et al. 2015). After 16 days, romaine lettuce grown with downward lighting plus supplemental upward white LED lighting had a leaf fresh weight and marketable leaf fresh weight 11 % and 18 % greater, respectively, and the percent waste was 6 % less than in lettuce grown without supplemental lighting (Table 4.1). In addition, the average chlorophyll (a+b) content of the first to sixth leaves from the lowest leaf and net photosynthetic rate of the third leaf from the lowest leaf were significantly higher with supplemental white LED upward lighting (Table 4.1).

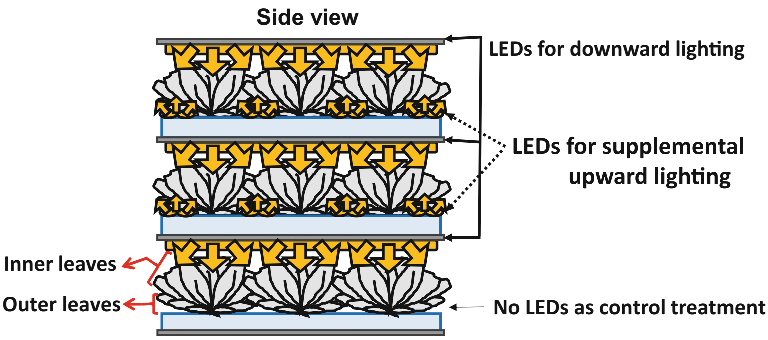

Fig. 4.5 Schematic diagram of supplemental upward LED lighting in the cultivation space of a PFAL (Zhang et al.,2015)

Table 4.1 Growth parameters of romaine lettuce grown under downward-directed white LED lighting with or without supplemental upward-directed white LED lighting

	Supplemental upward lighting (A)	No supplemental lighting (B)	A/B
Fresh leaf weight (g/plant)	170	154	1.11
Marketable fresh leaf weight (g/plant)	158	134	1.18
Percent waste	7.2	12.8	0.56
Average chlorophyll (a+b) content (g m^{-2}) of 1st to 6th leaves from the lowest	231	185	1.28
Net photosynthetic rate (μmol m^{-2} s^{-1}) of 3rd leaf from the lowest	1.08	−0.19	–

4.5 Supplemental Lighting in Greenhouses

4.5.1 Purpose of Supplemental Lighting in Greenhouses

Supplemental lighting in greenhouses is used to promote photosynthesis by adding artificial light as an energy and/or to control photomorphogenesis or other physiological processes such as secondary metabolite production, since the artificial light acts as a signal to the photoreceptors in leaves. When used to promote photosynthesis, the spectral distribution of light emitted by LEDs is not critical physiologically as long as it ranges between 400 and 700 nm. In reality, however, red-rich LEDs are currently used in most cases to save on the initial and operating (electricity) costs for lighting. On the other hand, the initial cost of white LEDs has been decreasing since 2015.

LEDs are often placed within plant communities at an LAI of 2 or 3 and higher in greenhouses for cultivating tomatoes, cucumbers, and roses. The supplemental light is directed to the sides of plants and/or upward (Chap. 19), mainly because lower leaves receive less natural light than upper ones. When photomorphogenesis is controlled by changing the light/dark periods, LEDs emitting specific wavelengths (e.g., red and/or far red) are used (Chap. 6).

4.5.2 Environmental Control for Efficient Supplemental Lighting

Supplemental lighting for the promotion of greenhouse crop photosynthesis is significantly affected by other environmental factors. Figure 4.6 shows the effects of PPFD on greenhouse crop net photosynthetic rate under optimal temperature, vapor pressure deficit, CO_2 concentration, air current speed, water irrigation, and nutrient composition/strength conditions. Since the cost of electricity for supplemental lighting to promote photosynthesis is generally the highest among all costs

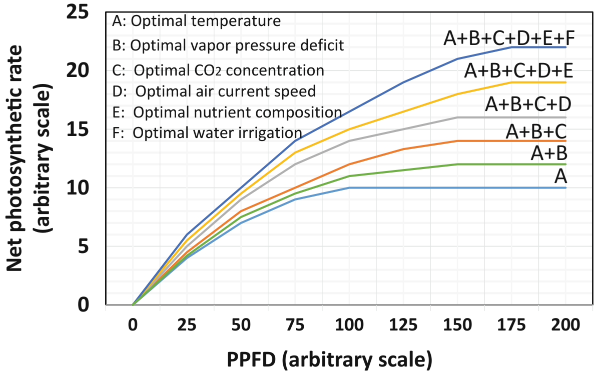

Fig. 4.6 A scheme showing the effects of PPFD on the net photosynthetic rate of plants under optimal temperature, vapor pressure deficit, CO_2 concentration, air current speed, nutrient composition/strength, and water irrigation conditions

for controlling environmental factors, those other factors need to be optimized. Costs for optimizing air current speed and water irrigation systems are generally relatively low, for example.

Supplemental lighting for photosynthesis in greenhouses can affect spatial distributions of temperature, relative humidity or water vapor pressure deficit, air movement, and CO_2 concentration. This is because light absorbed by plants is converted into sensible heat energy, latent heat energy, and/or thermal radiation energy, causing changes in air temperature, water vapor pressure deficit, etc.

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