Chapter 7
Light Environment in the Cultivation Space of Plant Factory with LEDs

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Abstract Spatial distributions of photosynthetic photon flux density (PPFD) in the cultivation space of a plant factory with light-emitting diodes (LEDs) are simulated using the free software package DIALux under different design conditions including (1) reflectance of cultivation panel surfaces, (2) width of side reflectors, (3) layout of LED tubes on the ceiling, (4) angular light distribution of LED lamp, and (5) height of the plant canopy. The simulation shows that the average and uniformity of PPFD above the cultivation panels and percent loss of photosynthetic photons to the outside of the cultivation space are affected not only by the characteristics of LED tubes but also by those of the cultivation space.

Keywords PPFD (photosynthetic photon flux density) distribution • Optimal light environment • Reflectance of culture panels

7.1 Introduction

Light is one of the most important environmental factors affecting plant growth and development. In plant factories with artificial lighting (PFALs), electricity consumption for lighting is a major component of production cost. As described in Chap. 4, the light environment in the cultivation space of a PFAL is affected by the optical and geometric characteristics of the light source, cultivation space, and plant canopy.

Computer software for simulating the light environment is a powerful tool to analyze and design the light source, cultivation space, and plant canopy architecture. This chapter presents the effects of these factors on the light environment in the cultivation space of PFALs.

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7.2 Materials and Methods

7.2.1 Software

DIALux (version 4.12) (DIAL GmbH), a free software package, was used in the present simulation of photosynthetic photon flux density (PPFD) distribution in the cultivation space, which can be downloaded from https://www.dial.de/en/dialux/. A similar simulation can be conducted using Relux, another free software package downloaded from http://www.relux.biz/. In this chapter, the simulated results for tube-type LEDs alone are presented, although similar simulations can be conducted for surface-type and point-source-type LEDs.

7.2.2 Variables and Their Values Assumed as Unique Input Data

Table 7.1 gives variable names and their assumed values as unique input data for the simulations. The assumed spectral light distribution of white LEDs (tube-type lamps) containing fluorescent substances as additives is shown in Fig. 7.1. Since white LEDs are basically blue LEDs, fluorescent substances are added to convert substantial portion of the blue light to red/green/yellow light.

The cross section of the cultivation space (0.3 m high, 1.2 m wide) is assumed to be as shown in Fig. 7.2a. The reflectance (r) of the ceiling is assumed to be 0.9. Averaged reflectance (r) and transmittance of the plant canopy cover are assumed to be 0.08 and 0.04, respectively, for the light source with spectral light distribution of LEDs shown in Fig. 7.1.

7.2.3 Factors Examined to Show Their Effects on PPFD Distribution

Table 7.2 gives factors (variables) examined in the simulation to determine their effects on PPFD distribution in the cultivation space: (1) r (reflectance, ratio of photosynthetic photons reflected to those received) of cultivation panel surfaces, (2) width of light reflectors at the upper sides of the cultivation space, (3) even and uneven spacing between LED tubes for the parallel layout (Fig. 7.3C), (4) layout of LED tubes parallel and perpendicular to the longitudinal cultivation space (Fig. 7.3A, B), (5) wide- and narrow-angle light distributions of LED tubes (Fig. 7.4), and (6) plant canopy height (h), in the cultivation space.

Table 7.1 Parameters and their values assumed as unique input data in the simulation

No.	Category	Variable name	Symbol	Unit	Values
1	LED (tube-type LED lamp)	Electric energy consumption per LED tube	E	W (= J s^{-1})	20
2		Photosynthetic photon number efficacy	h	mmol J^{-1}	2
3		Number of LEDs /(1.2 m wide × 1.2 m long)	n	–	6
4		Photosynthetic photon flux of LEDs	$F = E \times h \times n$	mmol s^{-1}	240
5		Length, width, and thickness of tube-type LED lamp		m	1.2, 0.03, and 0.03 m
6		Spectral distribution of LED light		–	Fig. 7.1
7	Cultivation space	Height, width, and length of cultivation space (0.3 high, 1.2 wide, and 10 m long)		m	Fig. 7.2
8		Reflectance of inner surfaces of ceiling and vertical reflectors at both upper sides	r	–	0.9
9		Spectral distribution of reflectance (r) and transmittance (t) of leaves		–	$r = 0.08$ $t = 0.04$

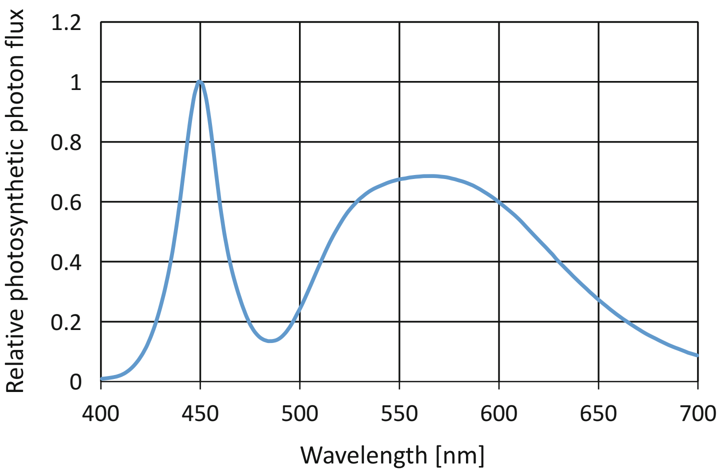


Fig. 7.1 Spectral light distribution of white LEDs (tube-type lamps) with fluorescent substances as additives to modify the spectrum, assumed in the simulation

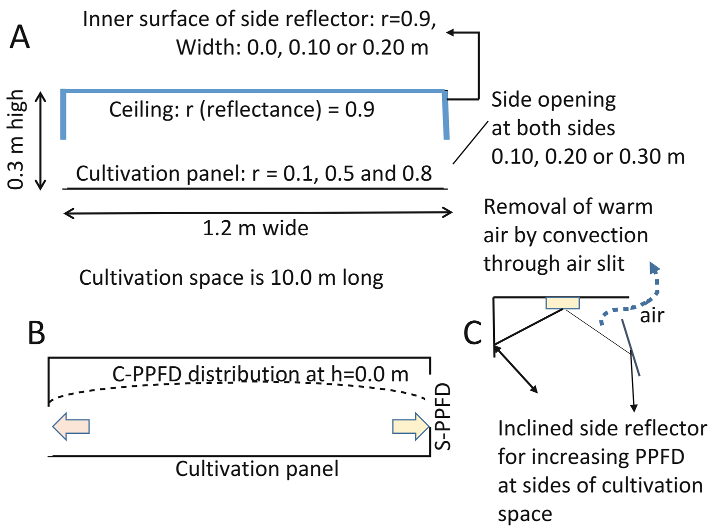


Fig. 7.2 (**a**) Cross section of the cultivation space (0.3 m high and 1.2 m wide) assumed in the simulation. Reflectance of inner surfaces of ceiling and upper side reflectors: 0.9, Reflectance of cultivation panel surface: 0.1, 0.5 and 0.8. (**b**) Definitions of C-PPFD and S-PPFD (see also, Table 7.2). (**c**) Inclined side reflectors for increasing C-PPFD at sides, and air gap for enhancing the air exchange between inside and outside the cultivation space

Table 7.2 Factors examined in the simulation to show their effects on C-PPFD and S-PPFD distributions in the cultivation space

No.	Category	Factors (variables) examined in the simulation	Variable name	Values
1	LED (tube-type LED lamp)	Layout of LED tubes on ceiling (perpendicular or parallel to longitudinal cultivation space)	Parallel or perpendicular	Fig. 7.4a, b
2		Angular light distribution curves of wide- and narrow-angle LED tubes	Wide or narrow	Fig. 7.5
3		Layout of LED tubes on ceiling (even or uneven spacing between LED tubes placed parallel to longitudinal cultivation space)	Even or uneven	Fig. 7.4a, c
4	Cultivation space	Reflectance (r) of culture panel surface	r	0.1, 0.5, and 0.8
5		Width of side vertical reflectors at both upper sides	W	0.0, 0.1, and 0.20 m
6		Height of plant canopy. "$h = 0.0$ m" means that the cultivation space is empty (no plant canopy)	h	0.0, 0.15, and 0.20 m

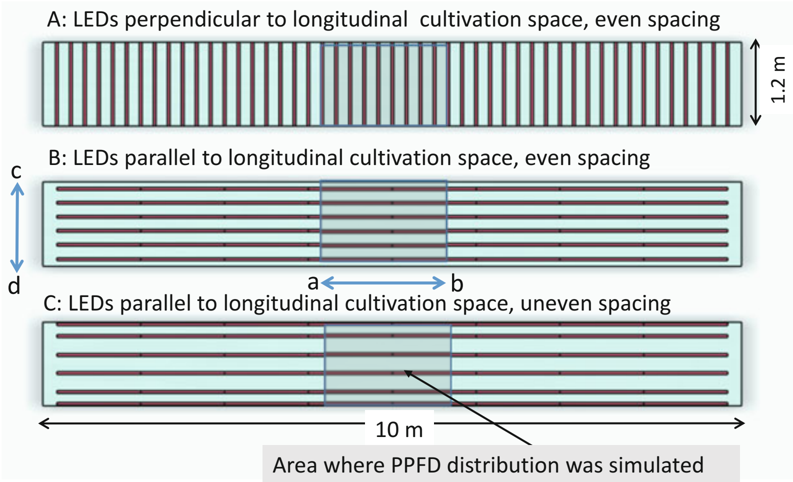


Fig. 7.3 Three types of LED tube layout on the ceiling in the cultivation space. A: Perpendicular to the longitudinal cultivation space and even distance between LED tubes. B: Parallel to the longitudinal cultivation space and even distance between LED tubes. C: Parallel to the longitudinal cultivation space and uneven distance between LED tubes

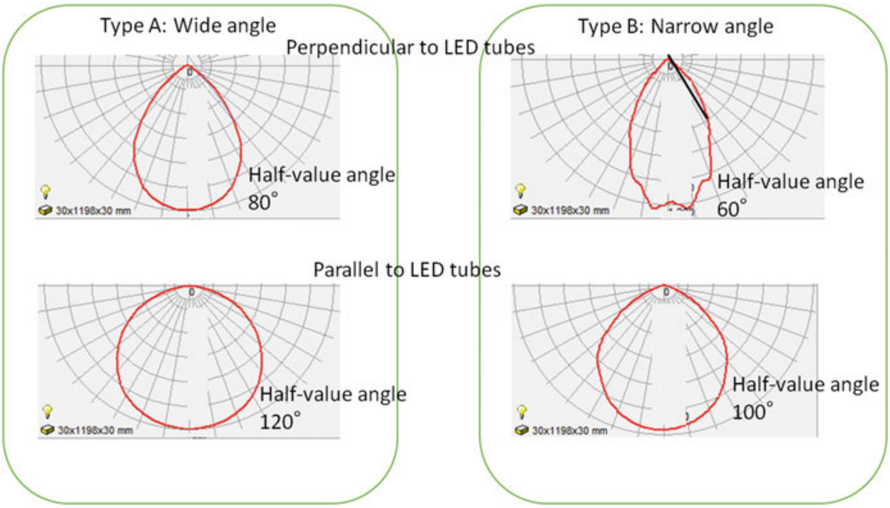


Fig. 7.4 Angular light distribution curves of type A (*wide angle*) LED and type B (*narrow angle*) LED. Half value angle means the angle at which the photosynthetic photon flux is 50 % of its maximum value. Upper: cross-sectional angular distribution (perpendicular to LED tubes), *Lower*: longitudinal angular distribution (parallel to LED tubes)

Table 7.3 Parameters characterizing C-PPFD (μmol m^{-2} s^{-1}) distribution in the cultivation space

A		
No.	Variables characterizing PPFD distribution in the cultivation space	Symbol
1	Average	AVE
2	Maximum	Max
3	Minimum	Min
4	Standard deviation	SD
5	Percentage of photosynthetic photons lost to outside the cultivation space	%L

B	
Variable name	Types of PPFD simulated
C-PPFD	Horizontal PPFD across the cultivation space. Average PPFD over the longitudinal direction shown as line a–b in Fig. 7.4b
S-PPFD	PPFD facing perpendicular to inside of the cultivation space at side openings (Fig. 7.2b)

7.2.3.1 Variables Characterizing Horizontal and Vertical PPFD Distributions

Table 7.3A gives parameters (average [AVE], minimum [Min], maximum [Max], and standard deviation [SD]) characterizing C-PPFD (μmol m^{-2} s^{-1}) distribution at $h = 0.00$ m (on the cultivation panel) across the cultivation space and the PPFD at side openings facing inside the cultivation space (S-PPFD). Table 7.3B and Fig. 7.2B give definitions of C-PPFD and S-PPFD.

Percent loss (%L) of photosynthetic photons emitted by LEDs (Table 7.4) is defined as the percentage of photosynthetic photons emitted by LED tubes but lost through the side openings to the outside of the cultivation space (F in Table 7.1).

7.3 Results and Discussion

7.3.1 Summary of C-PPFD and %L

In Table 7.4, simulated results of C-PPFD, its average (AVE), minimum (Min), maximum (Max), standard deviation (SD), and percent loss (%L) as affected by the variables shown in Table 7.2 are summarized.

7.3.2 Summary of S-PPFD

Table 7.5 summarizes the simulated results of S-PPFD and its AVE, Min, Max, and SD values as affected by the variables shown in Table 7.2.

Table 7.4 Summary of simulated results of C-PPFD (μmol m^{-2} s^{-1}) distribution in the cultivation space. "%L" denotes as the percentage of photosynthetic photons lost through the openings at sides to the outside of cultivation stage to the total photosynthetic photons emitted by LEDs

Category	Variables affecting C-PPFD (Table 7.2b) distribution	Case	Value of variables	C-PPFD AVE	Min	Max	SD	%L
Cultivation space	Effect of reflectance of culture panel surface (r) (Fig. 7.6) Variable values fixed: wide angle, parallel orientation, even spacing $W = 0.1$ m, $h = 0.0$ m (see Table 7.2 for variable names)	1-1	$r = 0.1$	158	101	176	22	13
		1-2	$r = 0.5$	219	137	247	33	26
		1-3	$r = 0.8$	309	192	353	49	47
	Effect of width (W) of vertical reflectors at both upper sides of cultivation space (Fig. 7.8) Variable values fixed: wide angle, parallel orientation, even spacing, $r = 0.8$, $h = 0.0$ m (see case 1-3 for $W = 0.1$ m)	2-1	$W = 0.00$ m	273	166	319	48	55
		2-2	$W = 0.15$ m	341	214	383	50	39
LED tubes and their layout	Effect of uneven spacing between LED tubes (Fig. 7.9) Parameter values fixed: wide, parallel orientation, $r = 0.8$, $W = 0.1$ m, $h = 0.0$ m (see case 1-3 for even spacing)	3-1	Uneven	290	240	305	16	46
	Effects of LED tube orientation (perpendicular) and r (Fig. 7.10) Variable values fixed: wide angle, perpendicular orientation, even spacing, $W = 0.1$ m, $h = 0.0$ m (see cases 1-1 and 1-3 for parallel orientation)	4-1	$r = 0.1$	153	99	172	22	15
		4-2	$r = 0.8$	299	187	345	49	48
	Effects of narrow-angle distribution of LED tubes and r (Fig. 7.11) Variable values fixed: narrow angle, parallel orientation, even spacing, $W = 0.1$ m, $h = 0.0$ m (see cases 1-1 and 1-3 for wide angle)	5-1	$r = 0.1$	160	100	178	21	11
		5-2	$r = 0.8$	313	192	357	48	46
Plant canopy height	Effect of plant canopy height (h) (Fig. 7.12) Variable values fixed: wide angle, parallel orientation, even spacing, $W = 0.1$ m; reflectance (r) and transmittance of plant canopy cover are 0.08 and 0.4, respectively	6-1	$h = 0.00$ m	156	99	173	22	12
		6-2	h = 0.15 m	162	97	204	41	10
		6-3	$h = 0.20$ m	164	44	290	118	10

It is noted that significant amounts of photosynthetic photons are lost through the side openings to the outside. Percent loss (%L) is higher at higher *r* and lower W. Wide side reflectors are beneficial to reduce %L for perpendicular layout of LED tubes (case 3) and uneven distance layout (case 4).

7.3.3 Case 1: Reflectance (r) of Culture Panel Surface

Figure 7.5a shows the C-PPFD curve at $h = 0.0$ m across the cultivation space for *r* values of 0.1, 0.5, and 0.8. The AVE of C-PPFD at $h = 0.0$ m and of S-PPFD is about twofold greater when $r = 0.8$ (case 1-3) and 1.4-fold greater when $r = 0.5$ (case 1-2) than when $r = 0.1$ (case 1-1) due to multiple light reflections of photosynthetic photons, mostly between the ceiling and cultivation panel and/or plant canopy (Table 7.4 and Fig. 7.5b).

%L is three fold and twofold greater, respectively, when $r = 0.8$ and $r = 0.5$ than that when $r = 0.1$ due to the increased loss of reflected photosynthetic photons to the outside (Table 7.4), while the number of photosynthetic photons emitted by LED tubes and lost directly to the outside (without reflection) remains the same regardless of the *r* value.

Figure 7.6a shows a schematic diagram of multiple reflections between the cultivation panel surface ($r = 0.8$) and ceiling ($r = 0.9$) for a photosynthetic photon flux at LED tubes (*F*) of 240 mol s^{-1}. As shown in Fig. 7.6b, C-PPFD increases exponentially with increasing *r* or with decreasing leaf area index (LAI; total leaf area divided by cultivation area) of the plant canopy. Therefore, in order to maintain the C-PPFD at the plant canopy at a fixed level throughout the culture period, the F of LED tubes must be increased as plants grow (as total leaf area increases). For example, when C-PPFD is 325 (relative value) at $r = 0.8$, it will decrease to 200 at $r = 0.6$, 145 at $r = 0.4$, 106 at $r = 0.2$, and 100 at $r = 0.1$. Thus, to maintain C-PPFD at 325 at $r = 0.6$, 0.4, 0.2, and 0.1, F needs to be increased by 1.6-, 2.2-, 3.1-, and 3.3-fold, respectively, compared with F at $r = 0.8$.

7.3.4 Case 2: Width (W) of Vertical Side Reflectors

As shown in Table 7.4 and Fig. 7.7a, the AVE C-PPFD for the side reflector width (*W*) of 0.15 m is 341 μmol m^{-2} s^{-1}, which is 10 % greater than that for side reflector W of 0.1 m and 25 % greater than that for W of 0.0 m (with no side reflectors). Thus, side reflectors are beneficial in increasing the AVE C-PPFD.

The nonuniformity or SD of C-PPFD can be improved by inclining the side reflectors inward at angle of approximately 30° (Fig. 7.2c). On the other hand, wide side reflectors restrict the air exchange between the inside and outside of the cultivation space, resulting in less air movement and higher air temperatures in the cultivation space during photoperiod. Heat removal from LED tubes and/or the

Table 7.5 Summary of simulated results of S-PPFD (μmol m^{-2} s^{-1}) at the side openings facing to the inside of cultivation space

Category	Variables affecting C- PPFD (Table 7.2b) distribution	Case	Value of variables	S-PPFD			
				AVE	Min	Max	SD
Cultivation space	Effect of reflectance of culture panel surface (r) (Fig. 7.6)	1-1	$r = 0.1$	63	57	68	4
	Variable values fixed: wide, parallel orientation, even spacing, $W = 0.1$ m, $h = 0.0$ m (see Table 7.2 for variable names)	1-2	$r = 0.5$	132	121	140	6
		1-3	r = 0.8	233	215	245	11
	Effect of width (W) of vertical reflectors at both upper sides of cultivation space (Fig. 7.11)	2-1	$W = 0.00$ m	184	139	211	25
	Variable values fixed: Wide, parallel orientation, even spacing, $r = 0.8$, h 0.0 m (see case 1-3 for $W = 0.10$ m)	2-2	$W = 0.15$ m	260	242	275	13
LED tubes and their layout	Effect of uneven spacing between LED tubes (Fig. 7.10) Parameter values fixed: wide, parallel orientation, $r = 0.8$, $W = 0.1$ m, $h = 0.0$ m (see case 1-3 for even spacing)	3-1	Uneven	232	220	245	9
	Effects of LED tube orientation (perpendicular) and r (Fig. 7.8)	4-1	$r = 0.1$	74	64	95	9
	Variable values fixed: wide, perpendicular orientation, even spacing, $W = 0.1$ m, $h = 0.0$ m (see cases 1-1 and 1-3 for parallel orientation)	4-2	$r = 0.8$	239	223	266	13
	Effects of angular distribution (narrow) of LED tubes and r (Fig. 7.9)	5-1	$r = 0.1$	57	48	65	4
	Variable values fixed: narrow, parallel orientation, even spacing, $W = 0.1$ m, $h = 0.0$ m (see cases 1-1 and 1-, for wide-angle LED tubes)	5-2	$r = 0.8$	230	212	244	10
Plant canopy height	Effect of plant canopy height (h) (Fig. 7.12)	6-1	$h = 0.00$ m	60	55	66	4
	Variable values fixed: wide, parallel orientation, even spacing, $W = 0.1$ m; reflectance (r) and transmittance of plant canopy cover are 0.08 and 0.4, respectively	6-2	$h = 0.15$ m	52	49	57	3
		6-3	$h = 0.20$ m	52	49	57	3

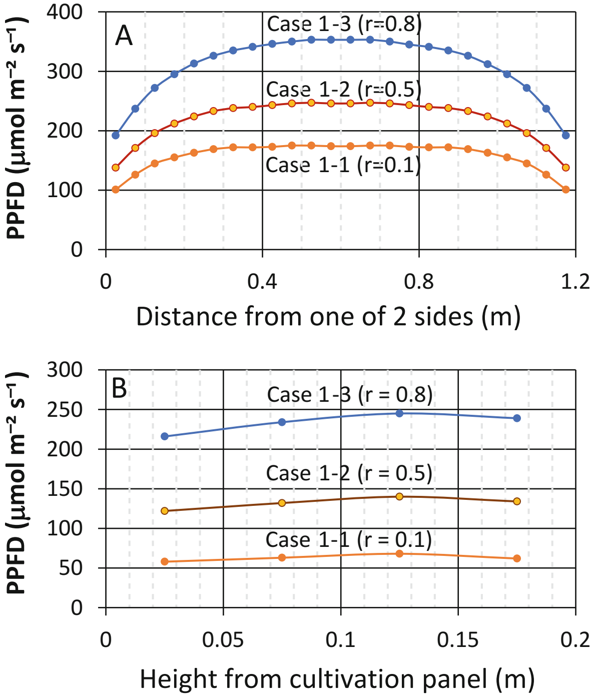


Fig. 7.5 (Case 1) (**a**) Effect of reflectance ($r = 0.1$, 0.5, and 0.8) of cultivation panel surface on C-PPFD distribution across the cultivation space. (**b**) S-PPFD for $r = 0.1$, 0.5, and 0.8. $W = 0.1$ m, $h = 0.0$ m, wide angle, even distance, and parallel orientation

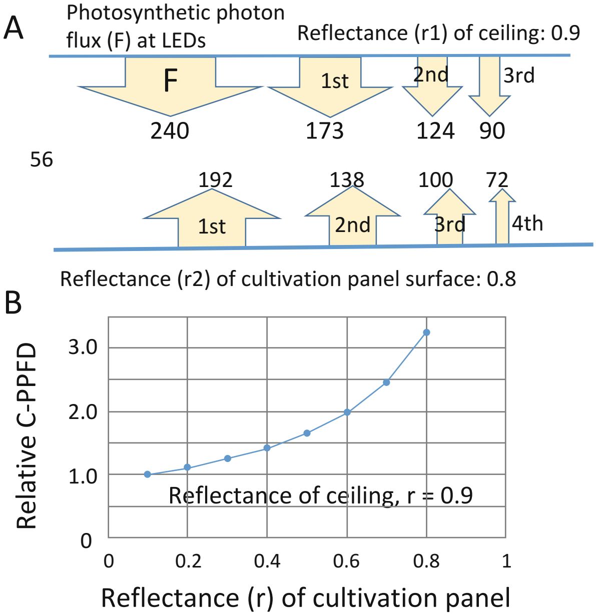


Fig. 7.6 (**a**) Schematic diagram of PPFD under multiple reflection between two infinite flat surfaces (r; =0.8 and 0.9, respectively) placed in parallel under photosynthetic photon flux at LEDs (F) of 240 μmol s^{-1}. (**a**) The PPFD is roughly expressed by $F \times \sum_{(k=0)}^{n} (r1 \times r2)$ n floor area. (**b**) Relative C-PPFD as affected by reflectance of cultivation panel surface (r) when reflectance of ceiling is 0.9

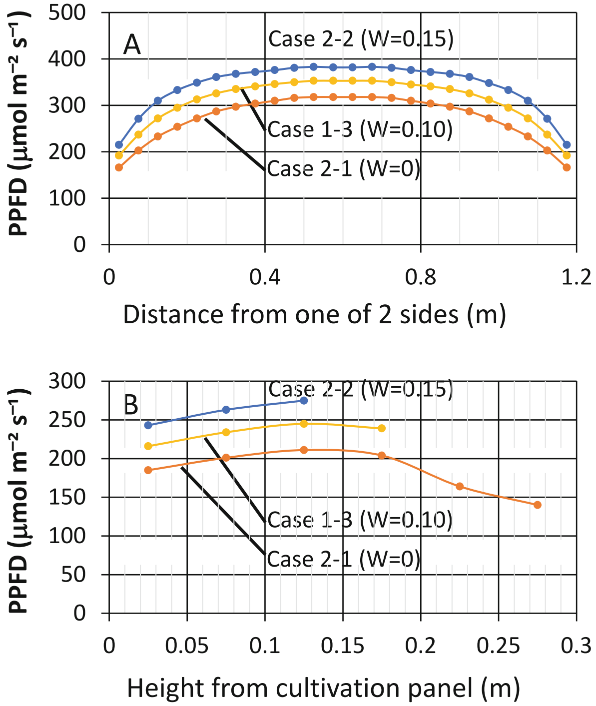


Fig. 7.7 (Case 2) (**a**) Effect of side reflectors width ($W = 0.0$, 0.10 and 0.15 m) at upper sides on C-PPFD distribution. (**b**) Vertical profile of S-PPFD at the side openings. $r = 0.8$, $W = 0.1$ m, $h = 0.0$ m, wide angle, even distance, and parallel orientation

cultivation space with minimum loss of photosynthetic photons can be enhanced, for example, by promoting air exchange through air slits near the ceiling (Fig. 7.2c).

7.3.5 *Case 3: Uneven Distance Between LED Tubes*

In Fig. 7.8a, C-PPFD distribution with uneven spacing between LED tubes is significantly flatter across the cultivation space compared with that with even spacing between LED tubes, although the AVE distribution for the uneven layout is 7 % less than that for the even layout. This reduction in C-PPFD at both sides can also be improved by the use of inclined reflectors instead of vertical reflectors (Fig. 7.2c).

7.3.6 *Case 4: Perpendicular Layout (Fig. 7.4a)*

There are no significant differences in AVE, SD, and %L between the perpendicular layout and parallel layout of LED tubes to the longitudinal cultivation space (Table 7.4, Figs. 7.5a and 7.9a).

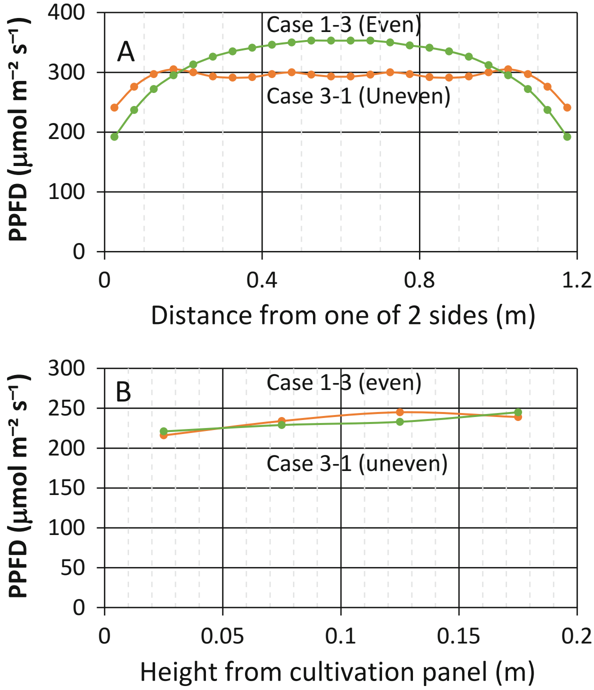


Fig. 7.8 (Case 3) (**a**) C-PPFD distribution for layout of uneven distance between LED tubes. (**b**) Vertical profile of S-PPFD at the side openings. $r = 0.8$, $W = 0.1$ m, $h = 0.0$ m, wide angle, and parallel orientation

In actuality, however, a reduction in C-PPFD should occur just below the joint of LED tubes in the parallel layout, because there is a metal socket (about 2 cm long) at each end of the tubes, which is not considered in the present simulation. If the presence of sockets were considered, the reduction in C-PPFD would be about 4 % for the AVE and about 10 % immediately below the joints. To compensate for the reduction in C-PPFD in the parallel layout, another LED tube can be placed perpendicular to the longitudinal LED tubes at the joints in the parallel layout.

Installation, maintenance and exchange of LED tubes may be easier in the perpendicular layout than in the parallel layout. In addition, the distance between LED tubes and number of LED tubes per unit of cultivation area can be changed after initial installation more easily in the perpendicular layout.

7.3.7 Case 5: Narrow Angular Light Distribution

There are no significant differences in C-PPFD between wide- and narrow-angle light distribution LED tubes examined in the present simulation (Fig. 7.10). It

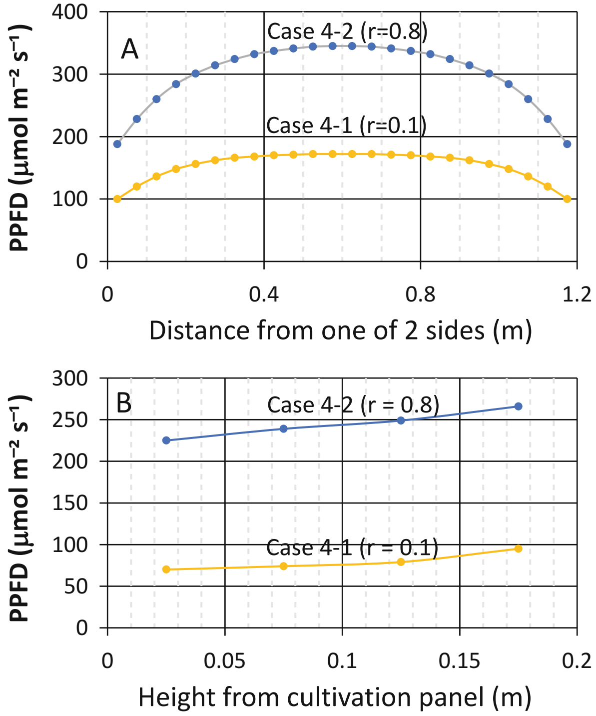


Fig. 7.9 (Case 4) (**a**) C-PPFD distribution for perpendicular LED tube orientation for $r = 0.1$ and 0.8. (**b**) Vertical profile of S-PPFD at the side openings. $W = 0.1$ m, $h = 0.0$ m, wide angle, and even distance

should be noted, however, that LED tubes with a narrower angle of light distribution than shown by type B in Table 7.5 are commercially available, which might be useful to improve the reduction in C-PPFD at the sides of the cultivation space. A mix of wide- and narrow-angle LED tubes may give a better C-PPFD distribution than that shown in Fig. 7.10.

7.3.8 *Case 6: Height of Plant Canopy* (h)

As the plant canopy grows and covers the cultivation panel, the average r for both the canopy and cultivation panel decreases. At the same time, the plant canopy cover approaches the ceiling with growth.

As shown in Table 7.4, the AVE and %L are not significantly affected by h. However, the SD is 22, 41, and 118 at an h of 0.00, 0.15, and 0.10 m, respectively. This is because the C-PPFD at the plant canopy cover becomes greater immediately below the LED tubes as well as lower between the LED tubes (Figs. 7.11a and 7.12). This large difference in C-PPFD may cause significant variation in plant growth rates.

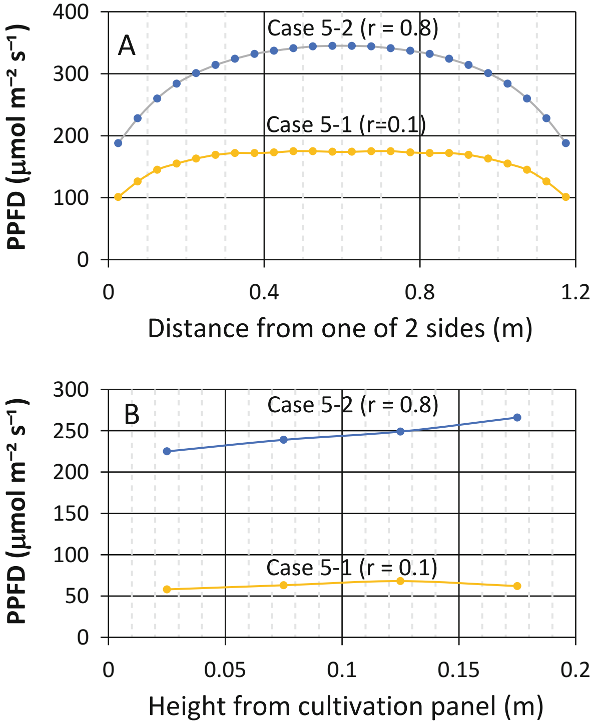


Fig. 7.10 (Case 5) (**a**) C-PPFD distribution for narrow and wide angular light distributions of LED tubes and $r = 0.1$ and 0.8. (**b**) Vertical profile of S-PPFD at the side openings. $W = 0.1$ m. $h = 0.0$ m., even distance, and parallel orientation

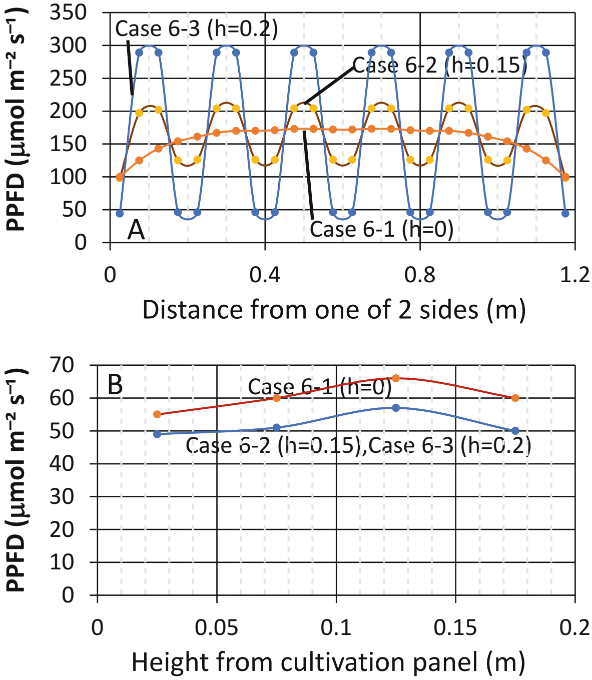
7.4 Some Consideration on Optimal Light Environment

This section discusses general questions on the optimal light environment in PFALs in terms of PPFD, light quality, photoperiod, and daily light integral (DLI; = PPFD × photoperiod). Similar questions are often asked about the optimal temperature, CO_2 concentration, and other environmental factors. Answers to these questions about PFALs differ from those about greenhouses, because PPFD, light quality, and photoperiod as well as temperature and CO_2 concentration can be controlled in PFALs more precisely than in greenhouses, regardless of the weather. On the other hand, the costs for lighting and air-conditioning in PFALs are significant.

7.4.1 Optimal PPFD?

The PPFD in a PFAL can be controlled at its optimal value, if known, to maximize plant growth or profitability. On the other hand, the optimal PPFD can change significantly with the cultivar, plant species, planting density (plants/m^2), LAI, light

Fig. 7.11 (Case 6) (**a**) Effects of plant canopy height ($h = 0.0$, 0.15 and 0.20 m) on C-PPFD distribution. (**b**) Vertical profile of S-PPFD at the side openings. $W = 0.1$ m, wide angle, even distance, and parallel orientation. r of plant canopy = 0.08 and transmittance of plant canopy = 0.04



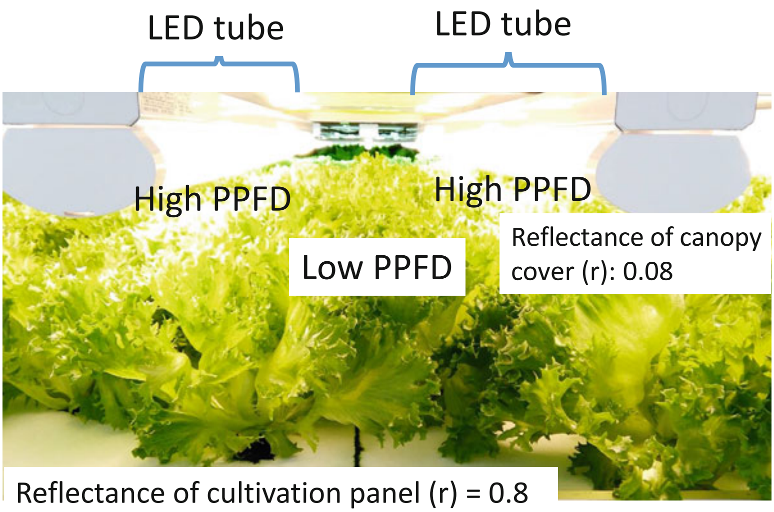


Fig. 7.12 Photograph showing high C-PPFD just under LED tube and low C-PPFD between two LED tubes in the cross section of cultivation space

quality, photoperiod or lighting schedule, and lighting direction (downward, horizontal, and upward lighting).

C-PPFD decreases exponentially with the depth of the plant canopy from the top, since the lower leaves receive much fewer photosynthetic photons than the upper ones. Thus, the optimal PPFD of a plant canopy is generally higher than that of a single leaf. Similarly, the optimal PPFD increases with increasing LAI and CO_2 concentration, for example. In short, the optimal PPFD is affected by many factors.

7.4.1.1 Optimal Lighting Direction

Theoretically, to maximize the photosynthesis of a plant canopy, photosynthetic photons emitted from LEDs should be distributed equally over all leaves, providing the same PPFD perpendicular to each point of the leaf surface. In this case, the light environment in the plant canopy would be better expressed by spherical PPFD rather than horizontal PPFD. A novel LED lighting system can be developed to provide photosynthetic photons more evenly over all leaves by a combination of downward, horizontal, and upward lighting (Chap. 4).

7.4.2 Optimal Photo- and Dark Periods?

Questions are often asked regarding the light/dark periods or lighting cycle in PFALs. Is plant growth at PPFD of 200 μmol m^{-2} s^{-1} with a 16-h light/8-h dark period (24-h cycle) the same as growth with 2 cycles/day of 8-h light and 4-h dark periods or with 4 cycles/day of 4-h light and 2-h dark? The DLI under these 3 conditions is the same ($3.2 = 16 \times 200/10^6$) mol m^{-2} d^{-1} at a PPFD of 200 μmol m^{-2} s^{-1}), so that the daily net photosynthetic rate of the plant canopy would be similar. However, plant height or stem internode and other growth parameters may differ, affecting the net photosynthesis of the canopy.

Another example is that the DLI for a 16-h/day photoperiod at 200 μmol m^{-2} s^{-1} is the same as for a 12-h/day photoperiod at 267 μmol m^{-2} s^{-1} and for a 20-h/day photoperiod at 160 μmol m^{-2} s^{-1} if the PPFD of 267 μmol m^{-2} s^{-1} is not too high. Therefore, the net photosynthetic rate and thus the plant canopy growth rate should be similar under these conditions. In actuality, plant growth differs in some cases due to the interactions among photosynthesis, leaf area expansion, and stem elongation. In case that the electricity charge (price) depends on maximum power consumption rate (kW) and time of day (night time reduction), the cost for electricity varies under the same DLI. The initial cost for LED installation also varies.

The lighting schedule and DLI must be decided by taking into account the yield and quality of produce, electricity costs for lighting, etc. (Kubota et al. 2016). Since the lighting schedule can be set relatively arbitrarily in PFALs, this is important to maximize profitability. On the other hand, the PPFD over the plant canopy can be changed relatively arbitrarily if the DLI can be maintained at a specific level. This is important when variable natural energy sources such as solar energy, wind power, and biomass are used for generation of electricity in PFALs.

7.4.3 Optimal Light Quality?

The spectral light distribution of LEDs used in PFALs (see Chap. 1 for definition) is roughly divided into 5 wavelength bands: ultraviolet (UV), blue, green, red, and far-red (some LEDs do not emit ultraviolet and/or far-red). For growing high-quality plants, photon flux ratios of the red/far-red and blue/red bands are often critical.

To determine the quasi-optimal light quality, experiments with 243 (= 3^5) conditions must be performed for three levels of photon flux density for each wavelength band. Since the optimal light quality is often affected by PPFD (400–700 nm), 729 (= 243 × 3) conditions must be examined to determine the optimal light quality under three PPFD levels. In addition, the optimal combinations of light quality and PPFD depend on other environmental factors and plant growth stage. Then, we need simulation models and muti-variable data analyses, in addtion to experiments (See Chap. 32).

7.4.3.1 Light Source for Far-Red and Ultraviolet (UV)

In addition to photosynthetically active radiation (PAR; 400–700 nm), far-red and/or UV radiation is often necessary at specific growth stages to improve the morphology and functional components of plants. Required flux densities for far-red and UV are much lower than those for PAR. Thus, it may be beneficial to install far-red/UV lamps separately from PAR lamps or to turn far-red/UV lamps on and off independent of PAR lamps.

7.4.4 Interactions Among Environmental Factors

When light quality changes, leaf thickness (Shibuya et al. 2015), leaf inclination angle, internode (stem) length, leaf area, light reflectance/transmittance, etc. also change. Those ecophysiological characteristics of plants affect the subsequent growth of the plant canopy.

Changes in plant growth in turn affect the microenvironment within the plant canopy, again affecting plant growth. Plant growth is thus a result of multiple interactions among light quality, changes in ecophysiological characteristics, and microenvironments. All of these must be kept in mind when interpreting the results of experiments on light quality effects.

7.5 Future Work

In the present simulations, *r* of the LAI of the plant canopy is considered as a variable, but its three-dimensional (3D) structure of the canopy is not. In the near future, a 3D plant canopy model needs to be introduced, which is not too difficult technically and theoretically, as described in Parts 3 and 4 of this volume. That will allow light environment simulation models to be integrated with models for plant growth and development, heat and mass balance, spatial distributions of environmental factors, cost and benefit analysis, etc. (Fig. 7.13).

7.5.1 Challenges

To determine the optimal light environment for PFALs, a combination of the following methodologies may be useful, which will be challenges in the development of next-generation PFALs (See also Chap. 32):

1. Using self-learning systems with artificial intelligence (AI) including big data mining and image-processing technologies
2. Using models for simulating the growth, development, and functional components of the plant canopy under different environmental conditions

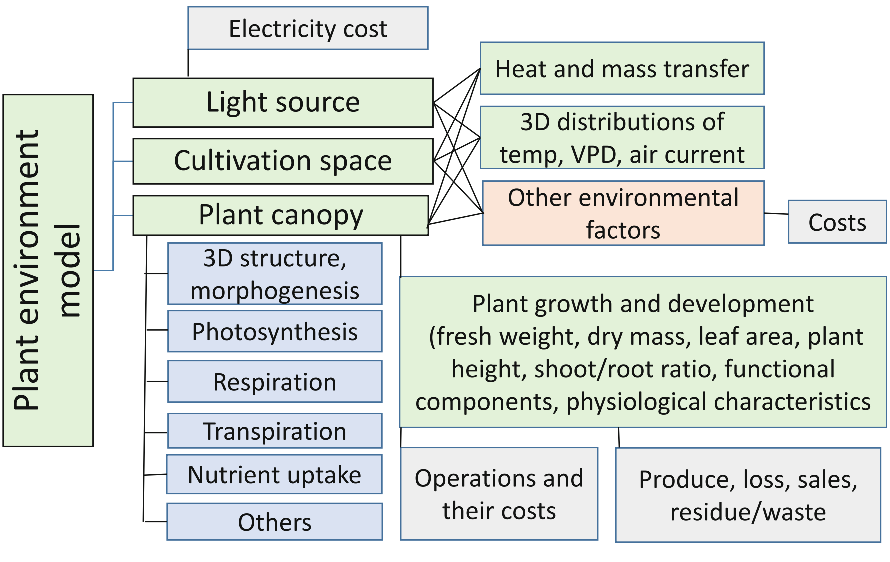


Fig. 7.13 Scheme showing the plant environment model and its components for plant production process in PFAL

3. Developing a flexible, adaptive LED lighting system using the outputs from self-learning and simulation systems
4. Noninvasive capture and processing of 3D camera images of plant canopy architecture for estimating its 3D structure (leaf inclination angle distribution, LAI, etc.) and biochemical characteristics of plants (chlorophyll fluorescence, functional components, etc.)
5. Developing an intelligent, distributed autonomous PFAL system that can generate electricity using natural energy sources such as solar energy, wind power, biomass, and geothermal energy

References

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