JARQ 33, 177–183 (1999)

Effects of Various Radiant Sources on Plant Growth (Part 2)

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Abstract

In Part 2 of this report, we analyzed the spectrum distribution of several high intensity discharge lamps, in which the spectrum values were multiplied by the average values for 4 different photosynthesis curves developed by McCree(1972) and Inada(1976), and we calculated the photoelectric conversion efficiency expressed as the plant growth radiant efficiency. As a result, we confirmed the high effectiveness of high pressure sodium lamps for plant growth within the PAR range of wavelengths, and concluded that a metal halide lamp 3,500 K (150 W high color rendering index type) was a suitable light source for indoor maintenance of ornamental plants. We also analyzed the light quality within the PAR range of different artificial light sources, by using the R/B and R/FR ratios as a reference to photomorphogenesis.

Discipline: Agricultural facilities/Crop production/Horticulture
Additional key words: artificial light source, supplemental lighting, plant factory

Introduction

Part 2 of this report deals with an evaluation of various radiant sources for plant growth and the quality of the light balance.

Evaluation of various radiant sources for plant growth

Broadly speaking, 2 aspects must be considered in the evaluation of radiant sources for plant growth. The first is the efficiency of light energy transformation which is expressed by the ratio of the radiant energy of a lamp to the effective light energy for photosynthesis. This efficiency is a measure of how close the spectral distribution of a light source is to the photosynthesis action spectrum of the plants. To obtain this efficiency, the value for spectral distribution of a light source is multiplied by the sensitivity of the photosynthesis action spectrum of the plants, and then divided by the input power of the light source used. However, it is virtually impossible to analyze the photosynthesis action spectra of hundreds of thousands of plants on the earth. Therefore only the main typical species are used to calculate the efficiency. The quantum sensor, in which the sensitivity is close to the photosynthesis action spectrum, is considered to be a suitable device for measuring the efficiency. Fig. 1 shows the curve of luminous efficiency and quantum sensitivity. The second aspect to be considered is the quality of the light balance. In general, it is recognized that light with a large red light component promotes intercalary growth, and that light with a large blue light component controls plant growth. The ratio of blue, green and red light components controls plant growth. The ratio of blue, green and red light components in PAR radiation is the key factor determining plant growth. In addition, the ratio of red light and far-red light is an important factor in the elongation of plants.

1) Evaluation of light energy transformation efficiency

To obtain the light energy transformation efficiency, the radiant energy of the light source is multiplied by either the quantum sensitivity or the operational sensitivity of photosynthesis, then divided by the input power of the lamp. Equations used to calculate the light energy transformation efficiency of the light sources are shown below (Eqns. 1 to 3).

Radiant energy of artificial light source;

$$\int_{380}^{780} P(\lambda)d\lambda / P\ in \quad \ldots\ldots (1)$$

Radiant energy × quantum sensitivity;

$$\int_{400}^{700} P(\lambda)\, Q(\lambda) d\lambda \,/\, P\ \text{in} \quad\text{.....................}\quad (2)$$

Radiant energy × average sensitivity of photosynthesis spectra;

$$\int_{400}^{700} P(\lambda)\, S(\lambda) d\lambda \,/\, P\ \text{in} \quad\text{......................}\quad (3)$$

P (λ): spectrum distribution,
Q (λ): quantum sensitivity,
S (λ): average sensitivity of photosynthesis action spectra,
P in : input power of lamp.

Table 1 shows the radiant energy and light energy transformation efficiency of various 660 to 1,000 W high intensity discharge lamps (HID lamps) used in closed system plant factories. Line ① in Table 1 shows the transformation efficiency to visible light

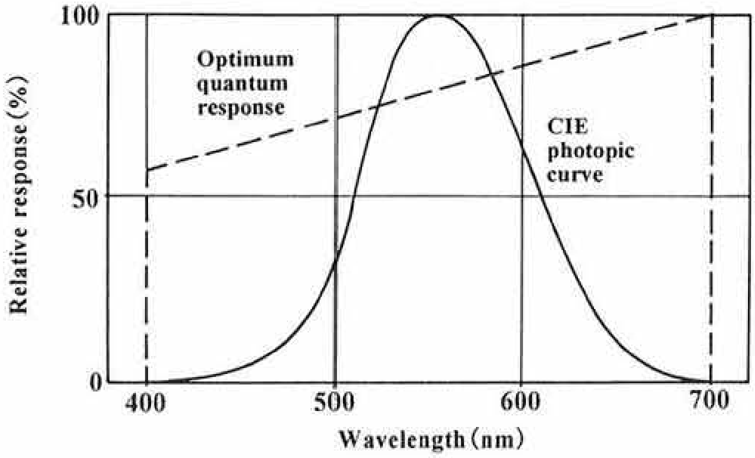

Fig. 1. Curve of luminous efficiency and quantum sensitivity

Table 1. Radiation energy of various HID lamps (660 to 1,000 W)

Lamp name	HPMVL		MHL		HPSL		
Lamp type	HF1000-X	HF1000-XW	M1000	MF1000	NH660L	NH660-DL	NH940L
Luminous efficiency (lm/W)	59.5	63.0	90.0	87.0	152.0	111.0	157.4
Radiation energy of visible light (W) (380–780 nm)	171.5	188.7	293.4	291.9	280.6	245.7	415.3
①Efficiency of light energy transformation (%)	17.2	18.9	29.3	29.2	42.5	37.2	44.2
Radiation energy × quantum sensitivity (W) (400–700 nm)	125.2	136.8	203.2	202.8	215.0	182.3	318.2
②Efficiency × quantum sensitivity (%)	12.5	13.7	20.3	20.3	32.6	27.6	33.9
Radiation energy × photosynthesis sensitivity (W)(400–700 nm)	109.3	119.7	177.5	178.4	207.0	175.6	306.4
③Plant growth radiant efficiency (PGRE)(%)	10.9	12.0	17.8	17.8	31.4	26.6	32.6

from electric energy supplied by actual light sources as radiant energy. Line ② shows the light transformation efficiency multiplied by the quantum sensitivity for evaluating measurements. Line ③ shows the efficiency of light energy transformation actually used, which is calculated from the efficiency of light energy transformation multiplied by the average sensitivity of the photosynthesis action spectra of 33 plant species examined by Inada (1976)[2] and 28 by McCree (1972)[4]. As shown in Table 1, from the standpoint of photosynthesis sensitivity and quantum sensitivity, the most effective lamp for plant growth is the HPSL, in which the red light component is large and the efficiency of light energy transformation is high. However, normal growth cannot be expected with a light with a large red light component only. That is, an adequate balance with blue and green light is also necessary.

Table 2 shows the efficiency of light energy transformation of 400 W HIDLs used in hybrid type plant factories and in greenhouses for supplemental lighting. Compared with HPMVL, MHL and HPSL show a higher efficiency. In addition, comparison of Tables 1 and 2, shows that high-wattage type HPSLs have a higher efficiency than 400 W HPLSs, and 400 W MHLs have a higher efficiency than high-wattage type MHLs.

Table 3 shows the efficiency of light energy transformation of compact type HID lamps installed for indoor ornamental plants. All MHLs have a high efficiency of light energy transformation, as shown in Table 3. In particular, the 150 W 4,500 K lamp shows the highest efficiency, based on the multiplication with the average photosynthesis sensitivity.

2) Evaluation of quality of light balance

Evaluation of the quality of the light balance involves the determination of the relative balance of blue light, green light, and red light in the effective radiation range of photosynthesis. Among these, the balance of red light and blue light (R/B ratio) is a typical factor for consideration. High R/B ratio, depending on the light quantity, is associated with intercalary growth of the internodes, and a low R/B ratio is associated with growth control, i.e. suppression of elongation, and production of thick, strong

Table 2. Radiation energy of various HID lamps (400 W)

Lamp name	HPMVL				MHL			HPSL		
Lamp type	Clear bulb type	Fluorescent type X	Fluorescent type XW	Self-ballasted	Clear bulb type	Fluorescent type	High color type	Clear bulb type	Color-improved	High color type
Wattage (W)	400	400	400	500	400	400	400	360	360	400
Luminous efficiency (lm/W)	51	55	60	28	100	95	80	139	106	60
Radiation energy of visible light (380–780 nm)(W)	55.5	63.5	71.9	59.0	130.4	127.5	136.5	140.3	127.9	119.6
①Efficiency of light energy transformation (%)	13.9	15.9	18.0	11.8	32.6	31.9	34.1	39.0	35.5	29.9
Radiation energy × quantum sensitivity (400–700 nm)(W)	39.5	46.3	52.1	35.1	90.4	88.6	89.3	107.5	94.9	77.6
②Efficiency × quantum sensitivity (%)	9.9	11.6	13.0	7.0	22.6	22.2	22.3	29.9	26.4	19.4
Radiation energy × photosynthesis sensitivity (400–700 nm)(W)	33.3	40.6	45.6	31.4	78.9	77.8	76.5	103.4	91.4	76.6
③Plant growth radiant efficiency (PGRE)(%)	8.3	10.2	11.4	6.3	19.7	19.5	19.1	28.7	25.4	19.2

leaves. Table 4 shows the quality of the light balance of various kinds of photosynthesis action spectra and quantum sensitivities. Considering quantum sensitivity as an indicator, an effective light balance is represented by an R/B ratio of 1.44, obtained with 27.3% blue light, 33.3% green light and 39.4% red light. The average quality of the light balance of 4 photosynthesis action spectra includes 23.5% blue light, 32.0% green light and 44.5% red light. From these values, the R/B ratio is calculated to be 2.71, indicating that light with a large red light component is effective. However, studies carried out by Inada & Yabumoto[3] using lettuce and radish, showed that an R/B ratio of 10 or higher was effective for cultivation. Takatsuji et al.[5] irradiated lettuce with red LED (660 nm, half wavelength about 30 nm)

Table 3. Light transformation efficiency of compact HID lamps

Lamp type	HPSL2500K	MH3500K	MH4500K	MH6500K
Wattage (W)	150	150	150	150
Luminous efficiency (lm/W)	52.0	66.7	73.3	73.3
Radiation energy of visible light (380–780 nm) (W)	38.6	44.2	48.5	51.2
①Efficiency of light energy transformation (%)	25.7	29.5	32.3	34.1
Radiation energy × quantum sensitivity (400–700 nm) (W)	25.2	30.5	33.2	33.5
②Efficiency × quantum sensitivity (%)	16.8	20.3	22.1	22.3
Radiation energy × photosynthesis sensitivity (400–700 nm) (W)	24.0	27.7	29.6	28.8
③Plant growth radiant efficiency (PGRE) (%)	16.0	18.5	19.7	19.2

Table 4. Quality of light balance of photosynthesis action spectra

		Blue light (%) (400–500 nm)	Green light (%) (500–600 nm)	Red light (%) (600–700 nm)	R/B ratio	Remarks
Quantum sensitivity		27.3	33.3	39.4	1.44	
Photosynthesis action spectra	Inada ①	26.1	31.5	42.4	2.22	Average of 26 species of herbaceous plants
	Inada ②	19.3	33.5	47.2	3.49	Average of 7 species of arboreous plants
	McCree ①	25.0	31.2	43.8	2.52	Average of 20 species (chamber)
	McCree ②	23.5	31.5	45.0	2.74	Average of 8 species (field)
Photosynthesis action spectra (Average)		23.5	32.0	44.5	2.71	

and blue LED (450 nm, half wavelength about 70 nm) and showed that an R/B ratio of 10 was effective.

Another factor for the evaluation is the photomorphogenesis reaction discussed in Section 5 (Part 1). Based on the red light to far-red light ratio (R/FR ratio) it can be determined whether plants will have elongated or controlled growth. High R/FR values indicate controlled growth, and low values indicate elongated growth. The R/FR ratio is calculated by multiplying the light spectrum distribution by the quantum sensitivity. Inada & Yabumoto[3] using lettuce and radish, showed that an R/FR ratio between 1.00 to 2.00 was effective for cultivation. Horaguchi et al.[1], who cultivated lettuce and sunflower using irradiation from several 4-band fluorescent lamps where an FR light was added to 3-band fluorescent lamps, showed that an R/FR ratio of 0.78 was effective. In general, the wavelength ranges are broadly defined as 600 to 700 nm for red light and 700 to 800 nm for far-red light. Equation (4) is used for the calculation of the R/FR ratio as follows;

R/FR ratio:

$$\int_{600}^{700} P(\lambda)\,Q(\lambda)d\,\lambda \,/ \int_{700}^{800} P(\lambda)Q(\lambda)d\,\lambda \quad \text{.....} (4)$$

Table 5 shows the quality of the light balance, R/B ratio and R/FR ratio of various HID lamps (660 to 1,000 W). The light balance is adjusted on the basis of the visibility curve for human eyes, and therefore tends to contain a large green light component (500 to 600 nm). There is no lamp with an R/B ratio in the range of the quantum sensitivity and the average photosynthesis sensitivity (1.44 to 2.71), except for SBML that shows a low efficiency of light energy transformation. HPSLs, which have a large red light component, induce elongated growth, and are therefore used for cultivating herbage crops in plant factories of the closed system type because of their high efficiency. HPMVLs, and MHLs have a large blue light component, and therefore induce growth suppression. However, MHLs are currently the only high wattage lamps that can be used on their own to induce relatively good quality growth.

Table 6 shows the quality of the light balance of radiant energy, R/B ratio and R/FR ratio of various HID lamps (400 W). SBMLs show the optimum R/B ratio, but their R/FR ratio is associated with elongated growth because of the large FR component. The R/B ratios of HPMVL and MHL are associated with growth control, and that of HPSL with growth elongation. The R/FR ratio of the XW type of HPMVL, the MHL and the high color type of HPSL are all associated with growth elongation.

Table 7 shows the quality of the light balance, R/B ratio and R/FR ratio of compact type HID lamps for indoor ornamental plants. To achieve adequate growth in indoor shops, MHL 3,500 K may be recommended because of the high R/B ratio, R/FR ratio and light quality balance. For maintenance growth and esthetic displays, MHL 6,500 K can be recommended because it enhances the green color of leaves of ornamental plants. MHL 4,500 K or 6,500 K can be recommended because their R/B ratios are associated with growth control. If HPSL 2,500 K is used, ornamental plants may become overgrown indoors because both the R/B ratio

Table 5. Quality of light balance, R/B ratio and R/FR ratio of HID lamps

Lamp name		HPMVL		MHL		HPSL		
Lamp type		HF1000-X	HF1000-XW	M1000	MF1000	NH660L	NH660-DL	NH940L
Quality of light balance (%)	Blue light (400-500 nm)	31 (51.1)	31 (54.4)	29 (76.1)	29 (75.0)	9 (22.9)	6 (12.8)	9 (33.8)
	Green light (500-600 nm)	51 (84.1)	49 (87.9)	54 (144.9)	51 (136.5)	51 (131.8)	38 (80.7)	51 (195.1)
	Red light (600-700 nm)	18 (29.1)	20 (36.0)	17 (44.3)	20 (51.6)	40 (101.8)	56 (119.0)	40 (150.7)
Red light/Blue light ratio[a)]		0.83	0.98	0.80	0.95	6.06	13.21	6.06
Red light/Far-red light ratio		4.61	3.96	5.88	4.34	3.85	3.23	3.85

Figures in parentheses indicate light power in watts.
a): Figures indicate the ratio when the blue light value is 1.

and R/FR ratio lead to the optimum conditions for growth.

Conclusion

To compare different artificial light sources, we determined the spectrum distribution of different light sources and multiplied the values by the average values for the photosynthesis curves derived from 4 sets of data to give an efficiency which we designated as the PGRE (plant growth radiant efficiency). As a result, the PGRE of high pressure mercury

Table 6. Quality of light balance, R/B ratio and R/FR ratio of HID lamps

		Wattage (W)	Blue light (%) (400–500 nm)	Green light (%) (500–600 nm)	Red light (%) (600–700 nm)	R/B ratio[a)]	R/FR ratio
HPMVL	Clear bulb type	400	38 (20.5)	59 (31.7)	2 (1.6)	0.12	2.11
	Fluorescent type X	400	31 (18.9)	51 (31.1)	18 (10.7)	0.83	4.61
	Fluorescent type XW	400	31 (20.7)	49 (33.5)	20 (13.7)	0.98	3.96
	Self-ballasted type	500	22 (9.7)	43 (18.9)	35 (15.0)	2.32	0.93
MHL	Clear bulb type	400	29 (34.7)	54 (63.7)	17 (19.5)	0.80	5.88
	Fluorescent type	400	29 (33.6)	51 (59.0)	20 (22.3)	0.95	4.34
	High color type	400	38 (44.0)	39 (45.7)	23 (27.1)	0.88	2.13
HPSL	Clear bulb type	360	9 (11.4)	51 (65.9)	40 (50.9)	6.06	3.85
	Color-improved type	360	6 (6.4)	38 (42.3)	56 (61.9)	13.21	3.23
	High color type	400	9 (8.2)	28 (25.3)	63 (56.5)	9.73	1.74

Figures in parentheses indicate light power in watts.
a): Figures indicate the ratio when the blue light value is 1.

Table 7. Quality of light balance, R/B ratio and R/FR ratio of compact HID lamps with good color rendition

Lamp type		HPSL2500K	MH3500K	MH4500K	MH6500K
General color rendering index (Ra)		85	96	96	96
Wattage (W)		150	150	150	150
Luminous efficiency (lm/W)		52.0	66.7	73.3	73.3
Quality of light balance (%) (W)	Blue light (400–500 nm)	9 2.7	20 7.4	28 11.6	40 17.3
	Green light (500–600 nm)	28 8.2	36 13.2	36 14.9	35 15.4
	Red light (600–700 nm)	63 18.4	44 16.5	36 15.2	25 11.1
R/B light ratio		9.73	3.22	1.89	0.92
R/FR light ratio		1.74	2.18	2.29	2.09

fluorescent lamps amounted to 8 to 12%, metal halide lamps (MHL) to 17 to 19% and high pressure sodium lamps to about 18 to 32%, respectively. Metal halide lamps were found to be the most efficient. High color rendition type HPSL and SBML gave excellent light quality balance and high R/B and R/FR ratios, but both exhibited a low basic photoelectric conversion efficiency. For the maintenance of ornamental plants, high color rendition type 4,500 K and 6,500 K lamps show a high PGRE and are effective, but we recommend the 3,500 K lamps due to the high light quality balance and R/B and R/FR ratios. However, if the esthetic effects of a certain store atmosphere are required, we may recommend MHL 4,500 K or 6,500 K in terms of color warmth as well as other factors. The HPSL 2,500 K lamps provide the highest combination of light quality balance, R/B and R/FR ratios, and lead to superior plant growth characteristics. Since many factors relating to plant growth and light irradiation remain unclear, we hope that this report will be a useful point of reference for the research and development of artificial light sources for horticultural applications.

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(Received for publication, December 18, 1998)