JARQ 33, 163–176 (1999)

Effects of Various Radiant Sources on Plant Growth (Part 1)

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Abstract

In Part 1 of this report, we introduced fundamental aspects of the use of artificial light in horticulture, giving an outline of a number of different artificial light sources and discussing recent research trends (such as the use of microwave-powered lamps, light-emitting diode and laser diode devices) in Japan.

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

Introduction

Most terrestrial plants grow by selective absorption of natural light from the sun. In plant factories and indoor living spaces, artificial light is necessary as a source of light energy. Therefore, it is necessary to develop technologies to control the light environment and provide effective and economical irradiation for plants. Part 1 of this report covers basic issues related to plant growth and light.

Wavelengths for effective plant growth

Solar radiation is subject to extensive scattering and absorption by the atmosphere before it reaches the surface of the earth. Direct solar radiation has wavelengths ranging from 300 to 3,000 nm, and is divided into 3 bands: ultraviolet radiation, visible radiation and infrared radiation. The wavelengths of visible radiation for humans are in the range from 380 to 780 nm, and the peak of the visibility curve (photopic vision) is at 555 nm. Similarly, plants have a range of wavelengths that are physiologically effective. There are 2 types of effective radiation for plants: physiologically active radiation and photosynthetically active radiation (PAR). These 2 types of radiation, ranging from 300 to 800 nm, are physiologically effective in photosynthesis, pigment biosynthesis, photoperiodism, phototropism and photomorphogenesis[8].

Physiologically active radiation is divided into 5 wavebands: near ultraviolet light (UV) 300–400 nm, blue light (B) 400–500 nm, green light (G) 500–600 nm, red light (R) 600–700 nm, and far-red light (FR) 700–800 nm (Fig. 1). Photosynthesis, which uses PAR (waveband 400 to 700 nm), requires an energy source with high intensity. The units of PAR radiation are expressed as total photon fluxes in this waveband, since this radiation induces chemical reactions. The total energy emitted from the light source is designated as photosynthetic photon flux (PPF). On the other hand, the energy actually received by plants is designated as photosynthetic photon flux density (PPFD), and its S. I. units are expressed as $\mu mol \cdot m^{-2} \cdot sec^{-1}$. Although quantum sensors are

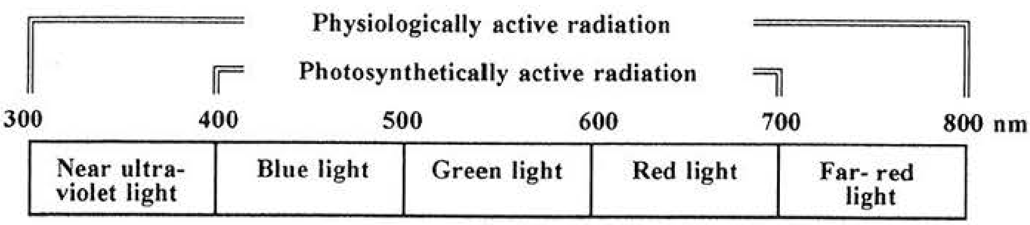

Fig. 1. Classification of effective wavebands for plant growth

preferable for measuring the photon flux, because of their high cost, radiation is often measured by PPFD with conversion factors for illuminance.

Light intensity suitable for photosynthesis

Light intensity suitable for photosynthesis depends on the light adaptation and acclimation properties of the plants, which in turn depend on the environment of their place of origin. The effect of the light intensity can be estimated to some extent by changes in morphology. Generally, plants which grow in the shade or at low light intensities (shade plants) have large, and thin leaves. Inside their leaves, parenchymatous cells do not adequately develop, resulting in an increase of the development of the grana structure and of the chlorophyll content in chloroplasts. The same morphological changes also occur with exposure to red light. On the other hand, plants which grow at high light intensities (sun plants) have thick leaves. Inside their leaves, parenchymatous cells are remarkably developed, resulting in a lower development of the grana structure. However, many enzymes important for photosynthesis can be observed. The same morphological changes occur with exposure to blue light. These differences in the morphology can also be observed in a single plant. Leaves that grow at low light intensities are referred to as shade leaves, and leaves that grow at high light intensities are referred to as sun leaves. Accordingly, leaves in the upper and lower parts of trees have different photosynthetic capabilities[9]. Morphological adaptation through changes of the light environment is related to the speed of photosynthesis. Plants growing at high light intensities (for example, watermelons, tomatoes, cucumbers, melons and C_4 plants) have high saturation points, and they show a maximum photosynthetic rate at the light saturation point. Therefore, a large amount of light energy is required to cultivate plants that grow better at high light intensities. Fig. 2 was obtained by measuring the absorption and release of carbon dioxide during photosynthesis, and indicates the light adaption capability for photosynthesis. When the light intensity is low, the amount of carbon dioxide released by plant respiration is higher than the amount of that absorbed for photosynthesis, resulting in a net release of carbon dioxide. As the light intensity increases, absorbed and released amounts of carbon dioxide change and reach an equilibrium at point A where a net release of carbon dioxide is no longer observed. This point is referred to as the compensation point. If the light intensity increases further, the amount absorbed reaches point B. This point is the saturation point. A suitable light intensity can be determined somewhere between these points A and B according to the particular requirements. On the other hand, since plants that grow under a low light energy (for example, lettuce, *Cryptotaenia japonica*, herbage crops, and most of the indoor ornamental plants) have low saturation and compensation points, it is relatively easy to cultivate them, to provide them with supplemental lighting and to maintain growth with artificial lighting. Table 1 shows the saturation and compensation points of major crops, and Table 2 shows the saturation and compensation points of ornamental plants. Indoor ornamental plants, most of which are derived from jungle undergrowth, can maintain growth at a relatively low light intensity.

In cultivation facilities for plants utilized for salad, and lettuce in closed-system type plant factories in

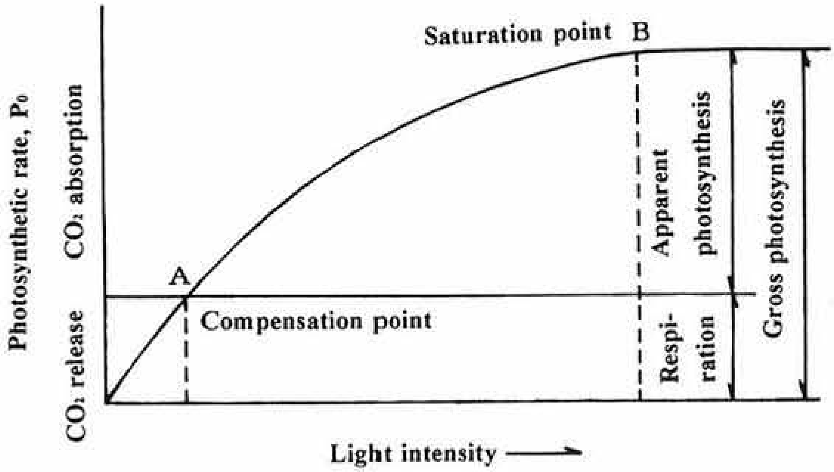

Fig. 2. Relationship between light intensity and photosynthetic rate

Table 1. Light saturation and compensation points of major crops

Species	Saturation point (klx)	Compensation point (klx)	Remarks
Rice	40-50 (672-840)	0.5-1.0 (8-17)	Murata (1961)[21]
Barley	50 (840)	-	Takeda (1978)[29]
Maize	80-100 (1344-1680)	1.8 (30)	Hesketh & Moss (1963)[4]
Sugar beet	80 (1344)	-	Hesketh (1963)[5]
Soybean	20-25 (336-420)	1.0-1.5 (17-25)	Böhning & Burnside (1956)[2]
Kidney bean	20-25 (336-420)	1.0-1.5 (17-25)	Böhning & Burnside (1956)[2]
Sweet potato	30 (504)	-	Tsuno & Fuzise (1965)[33]
Potato	30 (504)	-	Chapman & Loomis (1953)[3]
Sugar beet	30 (504)	0.8-1.0 (13-17)	Ito (1965)[13]
Castor bean	20-25 (336-420)	2.4 (40)	Böhning & Burnside (1956)[2], Hesketh (1963)[5]
Tobacco	20-25 (336-420)	1.0-1.5 (17-25)	Böhning & Burnside (1956)[2]
Cotton	20-25 (336-420)	1.0-1.5 (17-25)	Böhning & Burnside (1956)[2]
Tomato	70 (1176)	-	Tatsumi & Hori (1969)[30]
Eggplant	40 (672)	2.0 (34)	Tatsumi & Hori (1969)[30]
Red pepper	30 (504)	1.5 (25)	Tatsumi & Hori (1969)[30]
Cucumber	55 (924)	-	Tatsumi & Hori (1969)[30]
Squash	45 (756)	1.5 (25)	Tatsumi & Hori (1969)[30]
Melon	55 (924)	0.4 (7)	Tatsumi & Hori (1969)[30]
Watermelon	80 (1344)	4.0 (67)	Tatsumi & Hori (1969)[30]
Cabbage	40 (672)	2.0 (34)	Tatsumi & Hori (1969)[30]
Chinese cabbage	40 (672)	1.5-2.0 (25-34)	Tatsumi & Hori (1969)[30]
Turnip	55 (924)	4.0 (67)	Tatsumi & Hori (1969)[30]
Taro	80 (1344)	4.0 (67)	Tatsumi & Hori (1969)[30]
Pea	40 (672)	2.0 (34)	Tatsumi & Hori (1969)[30]
Celery	45 (756)	2.0 (34)	Tatsumi & Hori (1969)[30]
Lettuce	25 (420)	1.5-2.0 (25-34)	Tatsumi & Hori (1969)[30]
Cryptotaenia	20 (336)	1.0 (17)	Tatsumi & Hori (1969)[30]
Zingiber mioga	20 (336)	1.5 (25)	Tatsumi & Hori (1969)[30]

Figures in parentheses indicate the quantum flux.
The quantum flux densities in parentheses indicate the values for each illuminance multiplied by the conversion factor for natural daylight (16.8 $\mu mol \cdot m^{-2} \cdot s^{-1}/klx$).

Japan, a light intensity of about 300 to 400 $\mu mol \cdot m^{-2} \cdot sec^{-1}$ is used. Factories where a higher light intensity is needed are hybrid type plant factories where supplemental lighting of 100 to 150 $\mu mol \cdot m^{-2} \cdot sec^{-1}$ is provided. For indoor ornamental plants, supplemental lighting of 10 to 50 $\mu mol \cdot m^{-2} \cdot sec^{-1}$, depending on the variety, has been gradually employed.

Photosynthesis action spectrum

The efficiency of plant photosynthesis is not the same throughout the 400 to 700 nm waveband. Just as human eyes have visual curves, plants have sensitivity curves over a wide range. Plants select effective wavelengths from white light and utilize them. Fig. 3 shows the photosynthesis action spectra described by Inada (1976)[7]. Curve 1 shows the average values for 26 species of herbaceous plants, and curve 2 shows the average values for arboreous plants. Fig. 4 shows the photosynthesis action spectra described by McCree (1972)[14]. Curve 1 shows the average values for 20 species of plants in chambers, and curve 2 shows the average values for 8 species of plants in fields. The sample plants used are listed in Table 3. Each of these 4 photosynthesis action spectra has a large peak composed of 2 peaks at about 675 and 625 nm in the red light region, and a small peak between 440 and 450 nm. All 4 photosynthesis action spectra show that red light has a strong action and blue light a weak action. Fig. 5 shows the average values for the 4 photosynthesis action spectra, and is used to evaluate light sources for plant growth.

Photomorphogenesis

Light acts on plant morphogenesis, including

Table 2. Light saturation and compensation points for some indoor ornamental plants[1,2)]

Plant species	Saturation point (klx)	Compensation point (klx)
Hedera helix 'English ivy'	18.5 – 19.0 (311 – 319)	0.2 – 0.3 (3.4 – 5)
Cypripedium insigne	18.0 – 18.5 (302 – 311)	max. 0.1 (1.7)
Dracaena concine	18.0 – 18.5 (302 – 311)	0.2 – 0.3 (3.4 – 5)
Streptocarpus rexii	18.0 – 18.5 (302 – 311)	0.2 – 0.3 (3.4 – 5)
Fuchsia hybrida	17.5 – 18.0 (294 – 302)	0.4 – 0.5 (6.7 – 8.4)
Pelargonium zonale	17.0 – 18.0 (286 – 302)	0.2 – 0.3 (3.4 – 5)
Nephrolepis exaltata	17.0 – 17.5 (286 – 294)	0.5 – 0.6 (8.4 – 10.1)
Philidendron laciniatum	16.0 – 16.5 (269 – 277)	0.2 – 0.3 (3.4 – 5)
Cyclamen persicum	14.5 – 15.0 (244 – 252)	0.2 – 0.3 (3.4 – 5)
Begonia coccina	14.0 – 15.0 (235 – 252)	0.2 – 0.3 (3.4 – 5)
Cordyline terminalis	14.0 – 14.5 (235 – 244)	0.3 – 0.4 (5 – 6.7)
Oncidium flexuosum	13.0 – 13.5 (218 – 227)	0.2 – 0.3 (3.4 – 5)
Primula obconica	12.0 – 13.0 (202 – 218)	0.2 – 0.3 (3.4 – 5)
Chamaedorea elegans	12.0 – 12.5 (202 – 210)	0.1 – 0.2 (1.7 – 3.4)
Primula malacoides	11.0 – 12.0 (185 – 202)	0.2 – 0.3 (3.4 – 5)
Cymbidium ensifolium	11.0 – 11.5 (185 – 193)	0.2 – 0.3 (3.4 – 5)
Begonia rex	9.5 – 12.5 (160 – 210)	0.2 – 0.3 (3.4 – 5)
Rhoeo discolor	9.0 – 9.5 (151 – 160)	0.5 – 0.6 (8.4 – 10.1)
Nepenthes maxima	8.0 – 8.5 (134 – 143)	0.2 – 0.3 (3.4 – 5)
Adiantum pedatum	8.0 – 8.5 (134 – 143)	0.2 – 0.3 (3.4 – 5)
Begonia margaritae	6.0 – 6.5 (101 – 109)	max. 0.1 (1.7)
Begonia iron cross	5.0 – 6.5 (84 – 109)	0.2 – 0.3 (3.4 – 5)
Dendrobium merlin	4.5 – 5.0 (76 – 84)	0.2 – 0.3 (3.4 – 5)
Chlorophytum elatum	4.5 – 5.0 (76 – 84)	max. 0.1 (1.7)
Pilea cadierei	3.5 – 4.0 (59 – 67)	0.2 – 0.3 (3.4 – 5)
Anthurium andraeanum	3.0 – 3.5 (50 – 59)	0.2 – 0.3 (3.4 – 5)
Coleus	20 – 25 (336 – 420)	1 – 1.5 (16.8 – 25.2)
Philodendron	5 – 10 (84 – 168)	0.5 (8.4)
Saintpaulia	5 – 10 (84 – 168)	0.5 (8.4)

The quantum flux densities in parentheses indicate the values for each illuminance multiplied by the conversion factor for natural daylight (16.8 $\mu mol \cdot m^{-2} \cdot sec^{-1}/klx$).

Table 3. Plant materials used for the determination of photosynthesis action spectra

	Plant species
Inada ① (26 species of herbaceous plants, 1976)	rice, maize, wheat, barley, oat, soybean, peanut, kidney bean, pea, cabbage, turnip, radish, tomato, eggplant, cucumber, squash, lettuce, garland, chrysanthemum, spinach, onion, sugar beet, sweet potato, perilla, buckwheat, strawberry
Inada ② (7 species of arboreous plants, 1976)	peach, Japanese pear, grape, satsuma mandarin, tea, Japanese black pine, ginkgo
McCree ① (20 species tested in chamber, 1972)	maize, sorghum, wheat, oat, barley, secalotricum, sunflower, soybean, tampala, peanut, lettuce, tomato, radish, cabbage, cucumber, oriental melon, squash, clover, sugar beet, castor-oil plant
McCree ② (8 species tested in field, 1972)	maize, wheat, oat, secalotricum, rice, sunflower, squash, cotton

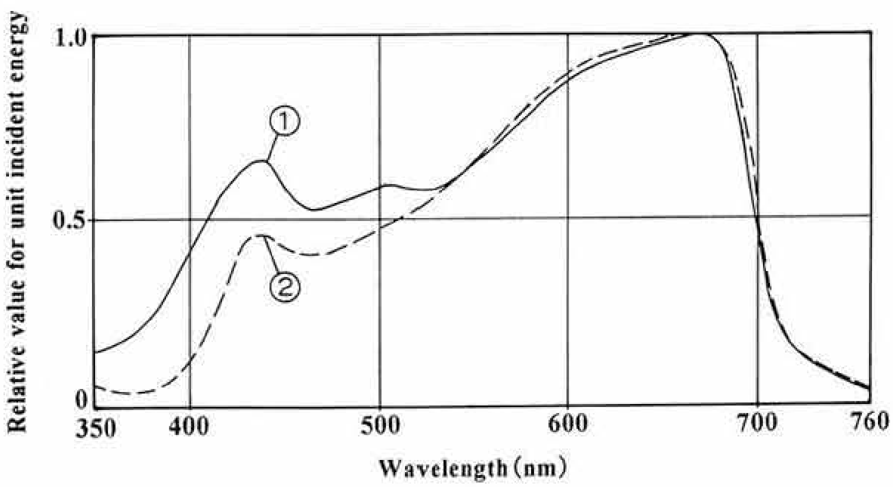

Fig. 3. Average values for photosynthesis action spectra (Inada, 1976)
① Average of 26 species of herbaceous plants.
② Average of 7 species of arboreous plants.

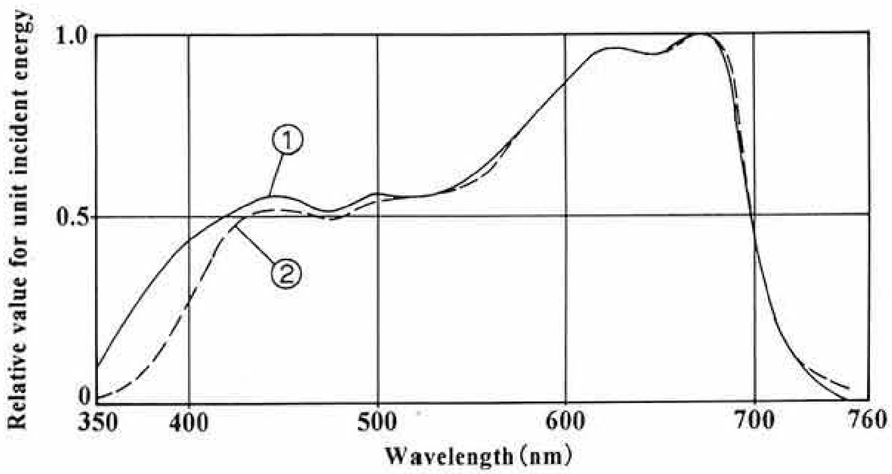

Fig. 4. Average values for photosynthesis action spectra (McCree, 1972)
① Average of 20 species grown in plant growth chambers.
② Average of 8 species grown in the field.

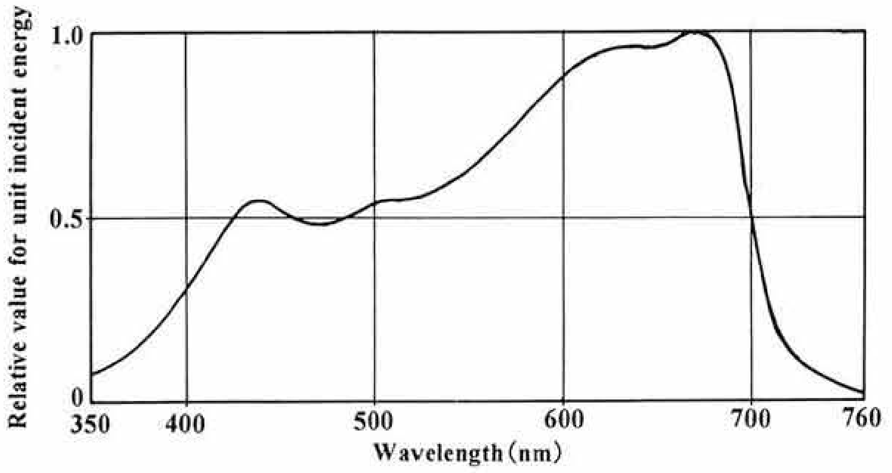

Fig. 5. Average values for photosynthesis action spectra for 61 species
Inada; 33 species, McCree; 28 species.

germination, flowering, stem growth, and leaf opening. Light is also a source of stimuli or information in different ways depending on the plant species and the stage of growth. In general, light with blue, red, and far-red components acts on plants. Table 4 shows the action of each range of wavelengths[31].

Among these actions, the red and far-red reversible reaction of phytochrome (a photoreceptor involved in seed germination) is particularly well known. In the reaction, the promotive effect of germination by red light (660 nm) irradiation is cancelled out by far-red light (730 nm) irradiation. That is, the effect of the previously irradiated light appears when red and far-red light is irradiated alternately. High intensity blue light and low intensity red light induce strong control of internodal growth. It is well known that with combined irradiation, far-red light is necessary, and that the ratio of red to far-red light controls internodal growth[12,15,17]. In addition, blue or high energy light promotes the growth of sun leaves, and red or low energy light promotes the growth of shade leaves. Daylength controls flowerbud formation (photoperiod). Plants are generally divided by daylength into 3 groups in which flowerbud formation is differentiated by specific daytime length: short-day plants, long-day plants, and intermediate-day plants. In flowerbud formation, light acts as a stimulus, with red light, far-red light or blue light being particularly effective, depending on the plant species. Besides photomorphogenesis, blue light with a wavelength of 500 nm or less acts phototropically, and blue light also acts on stomatal movement.

Artificial light sources for plant growth

The artificial light sources shown in Fig. 6 can be divided into 2 systems: thermal radiation and luminescence. Among these light sources, 6 light sources which are actually used for plant growth are incandescent lamps, high pressure mercury fluorescent lamps, self-ballasted mercury lamps, metal halide lamps, high pressure sodium lamps and fluorescent lamps. Also, xenon lamps and low pressure sodium lamps are used for research. Fig. 7 shows the energy spectrum of each lamp, and Table 5 shows the radiant energy balance and reduced values of PPFD per 1,000 lx in the 400 to 700 nm waveband.

1) Incandescent lamps (IL)

Incandescent lamps radiate visible light by thermal radiation generated from tungsten filaments heated to a high temperature by an electric current. The energy distribution is continuous, but the intensity of red light is higher than that of blue light, which possibly leads to intercalary plant growth. Therefore, these lamps are not suitable for photosynthesis. Furthermore, since they have a low light

Table 4. Effect of various wavelengths on plants

Wavelength (nm)				Action
Infrared radiation	IR-A	1400 780	800	No specific action, but thermal effects on plants.
Visible radiation	Red	760	700	Specific elongation effect on plants. Germination control (730 nm).
	Red Orange	640	610	Maximum absorption by chlorophyll. Maximum photosynthesis (675 nm). Promotion of germination (660 nm), opening of leaves and flowerbud formation.
	Yellow	590 570	510	Significant contribution to photosynthesis.
	Green Blue Violet	500 450	400	Absorbed by yellow pigments, resulting in a peak of chlorophyll absorption. Phototropism (blue light).
Ultraviolet radiation	UV-A	380	315	Generally controls plant height, makes leaves thick. Promotes coloring pigments.
	UV-B		280	Excessive intensity exerts adverse effects; pronounced effects on many synthetic processes.
	UV-C		100	Plants wither rapidly.

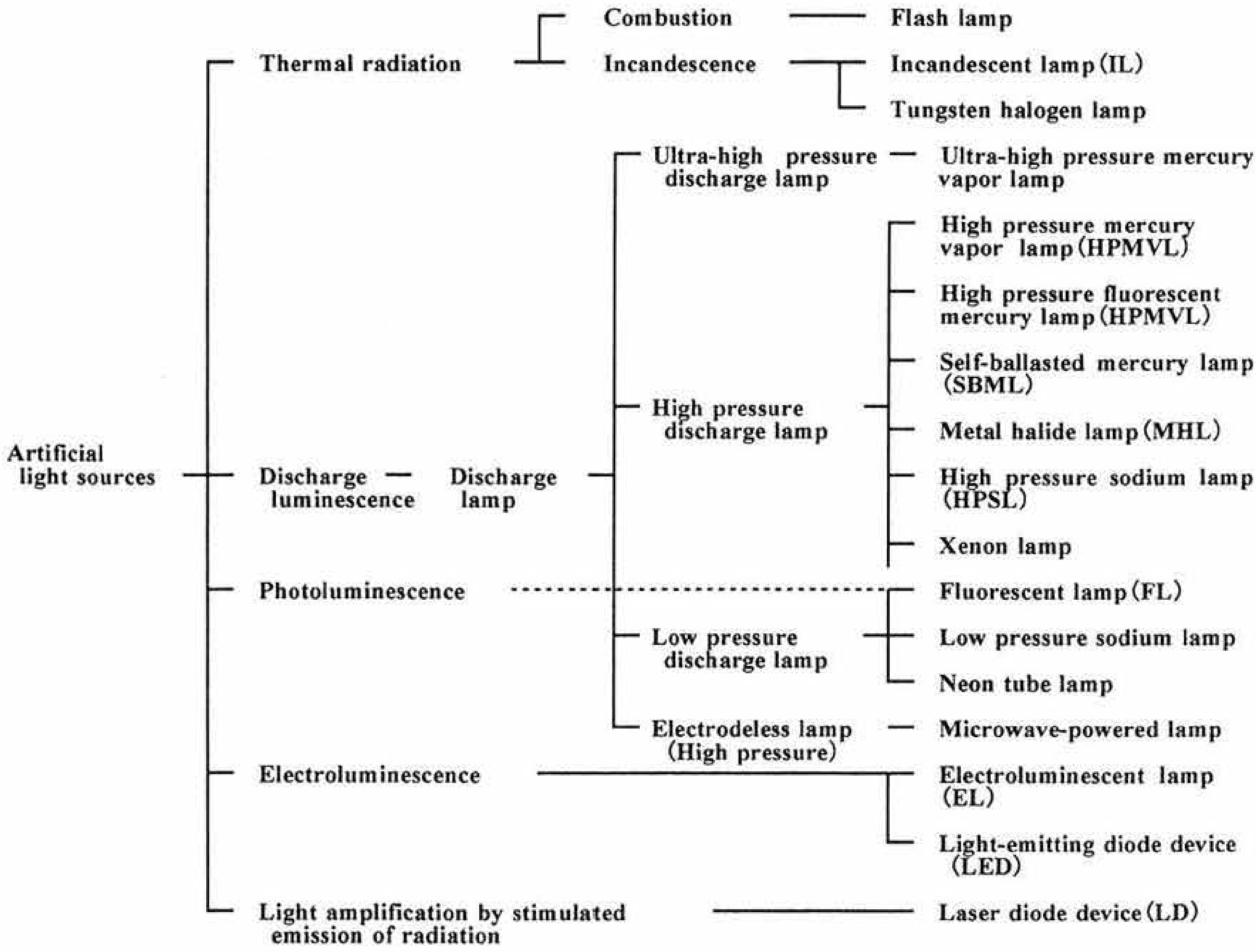

Fig. 6. Classification of artificial light sources

conversion efficiency of around 10 lm/W, as well as high thermal radiation, they are not used for the cultivation of plants. These lamps are used mainly to control photomorphogenesis, and for example, in some factories they are used to control the flowering of chrysanthemums under low light intensities, to prevent dormancy of strawberries and to promote germination.

2) Fluorescent lamps (FL)

Fluorescent lamps are low pressure mercury vapor discharge lamps with a hot cathode. Ultraviolet light generated by the discharge is transduced to visible light by phosphor coating on the inside of a glass tube. These lamps easily provide the required radiant energy by use of an appropriately selected phosphor, but cannot provide sufficiently high energy light on their own for cultivation. These lamps are often used to grow seedlings in plant factories. Fluorescent lamps for plants are used not only as supplemental lighting for ornamental plants in flower shops but also for tissue culture, especially for plant growth. In addition, a plant factory system has recently been developed, in which an average value of 650 $\mu mol \cdot m^{-2} \cdot sec^{-1}$ can be achieved by employing a total lamp system where a 110 W 3-band fluorescent lamp irradiates cultivated plants at a distance of 30 cm[6]. Furthermore, the compact fluorescent lamp has become popular, and is able to provide local supplemental lighting to indoor ornamental plants by recessed lights.

3) High pressure mercury fluorescent lamps (HPMVL, phosphor-coated type)

HPMVLs are based on the principle that the luminous efficiency of sources is enhanced when the vapor pressure of mercury is increased. These lamps are the most stable lamps, and have been used for many years to grow plants. They provide light composed mainly of the radiation line spectrum of

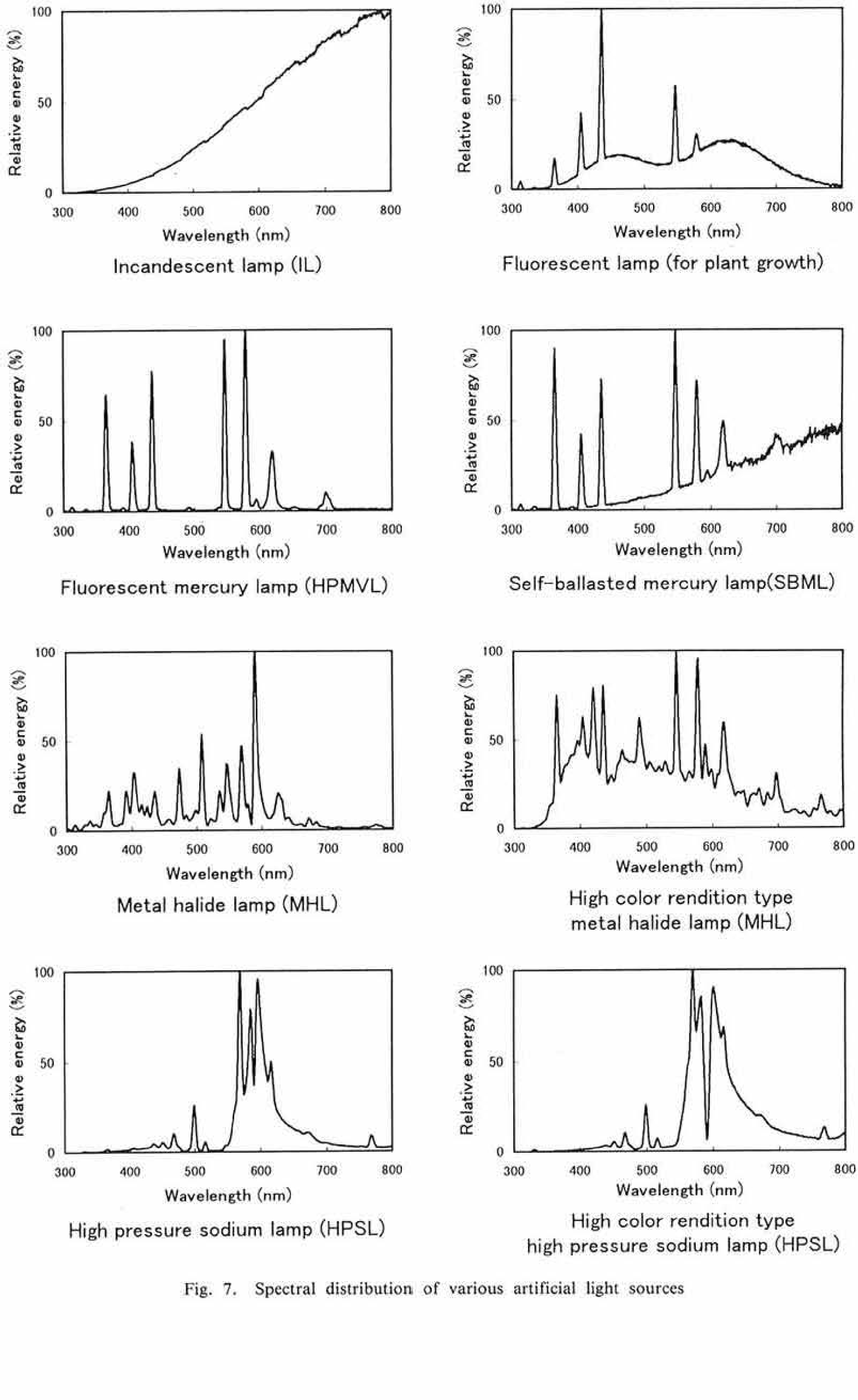

Fig. 7. Spectral distribution of various artificial light sources

Table 5. Radiant energy balance and PPFD transformed value of various light sources

	Blue light (400 - 500 nm) (%)	Green light (500 - 600 nm) (%)	Red light (600 - 700 nm) (%)	PPFD transformation factor[a)]
Quantum sensitivity spectrum	27.3	33.3	39.4	-
Photosynthesis action spectrum	23.5	32.0	44.5	-
Incandescent lamp (IL)	12.3	33.3	54.4	21.0
Self-ballasted mercury lamp (SBML)	22.3	43.3	34.4	16.8
Fluorescent mercury lamp (HPMVL)	31.1	51.2	17.7	12.3
Metal halide lamp (MHL)	29.2	51.4	19.4	13.6
High color rendering index type MHL	37.7	39.1	23.2	16.7
High pressure sodium lamp (HPSL)	8.9	51.4	39.7	13.3
Color-improved type HPSL	5.8	38.2	56.0	15.4
High color rendering index type HPSL	9.1	28.1	62.8	22.1
Fluorescent lamp for plant growth	29.9	26.8	43.3	22.4
Fluorescent lamp for color evaluation	29.0	39.8	31.2	17.6
White color type fluorescent lamp	26.4	50.3	23.3	12.4
Daylight type fluorescent lamp	37.8	45.9	16.3	14.0
Three-band type fluorescent lamp	32.7	44.9	22.4	13.7
Day white type fluorescent lamp	31.6	42.9	25.5	13.3

Figures indicate the ratio (wattage) of various light sources within PAR radiation energy (400 to 700 nm).
a): Unit of PPFD transformation factor; $\mu mol \cdot m^{-2} \cdot sec^{-1}/klx$.

mercury, that is, the light lacks the red light component. These lamps therefore enable to control plant growth. To compensate for the lack of red light, a phosphor lamp which provides red light was developed. The efficiency of this lamp is around 60 lm/W. It has been used for many years in foreign countries to provide supplemental lighting and lengthening of daytime. Two types of lamps are available: a clear bulb type and a phosphor-coated type. The phosphor-coated type is a type of fluorescent lamp. The phosphor-coated type is further classified into 2 types: the X type for general use, and the XW type, which compensates for the missing red light component. The range of this lamp is from 50 to 2,000 W. Regarding the outer bulb shape of this lamp, a BT type and an R type are available.

4) Self-ballasted mercury lamps (SBML)

In SBMLs, the arc tube is connected in series to the tungsten filament as a ballast. These lamps compensate for the red light component, which high pressure mercury vapor lamps lack. They provide a good spectral distribution, but since the efficiency is as low as 20 to 27 lm/W, they are used as supplemental lighting for ornamental plants. For plants, lamps where the input ratio of the arc tube of mercury lamps to that of the tungsten filament is adjusted are also available. Two types of outer bulbs are available: a clear bulb type and a fluorescent type. A BT type and an R type for the outer bulb form of this lamp are available. The lamps can be selected in the range from 100 to 750 W.

5) Metal halide lamps (MHL)

The structure of metal halide lamps is based on that of mercury lamps, but they contain various halide additives. There is a wide selection available, including lamps mainly with line spectra and lamps mainly with continuous spectra. The efficiency of MHLs is around 100 lm/W, and they provide light with a reduced red light component above 600 nm. Therefore they are used in plant factories in combination with high pressure sodium lamps. MHLs on their own are used for supplemental lighting in greenhouses, and high color rendition type MHLs which provide light with a spectrum distribution similar to that of natural daylight are used in hybrid type plants factories and growth chambers. Recently, high color rendering index types(70 to 150 W) have gradually been used for supplemental lighting and display lighting for indoor ornamental plants[20]. Murakami et al.[18] carried out research on high color rendering MHLs containing Dy, Nd, Cs, In, Tl, and Na for use in horticulture. Two types of these lamps are available: a high efficiency lamp with a built-in starter and a high color rendition type. BT, T and R types (only for high color rendition lamps) for outer bulb shapes are available. The lamps can be selected in the range from 70 W and 2,000 W. Typical additives are as follows: indium (blue light), thallium (green light), sodium(yellow light), and lithium (red light).

6) High pressure sodium lamps (HPSL)

HPSLs use alumina ceramic for the arc tube, and in the arc tube, sodium and mercury from an amalgam acting as a buffer gas are enclosed. Neon-argon penning gas is also sealed in the arc tube to help starting. The efficiency of some of these lamps exceeds 150 lm/W. Since they have a large red light component which can cause intercalary growth, they are used with metal halide lamps which provide compensating blue light. These lamps are used on their own to cultivate herbage crops with green leaves. These lamps are used solely in hybrid type plants factories. Three types are available: a high efficiency type with a built-in starter, an improved color type with a built-in starter, and a high color rendition type. BT type, T type and R type for outer bulb shapes are available. The lamps can be selected in the range from 50 to 940 W. A lamp in which the lack of blue light component is compensated by the addition of sealed mercury has recently been developed for plants. Inagaki et al.[10] developed a high pressure sodium lamp with an output of 1.2 kW and an efficiency of 180 lm/W. Xenon, an inert gas for starter assistance, was sealed in the double-end type lamp at nearly three times the normal pressure.

7) Research trends

(a) Electrodeless discharge lamps (Microwave-powered lamps)

There are several designs of electrodeless discharge lamps depending on the method of illumination, with the microwave-powered lamp being the most promising future development for use in horticulture. Until now, microwave-powered lamps have solely been used for ultraviolet curing in photoengraving processes. Research is currently being conducted on the application of high intensities (130 lm/W, 1,000 $\mu mol \cdot m^{-2} \cdot sec^{-1}$) which could be achieved by the variation of the sealed gas[13]. The next challenge facing microwave-powered lamps would concern the production cost and the life-span of magnetrons. Fig. 8 shows the structure of a microwave-powered lamp and emission spectrum.

(b) Light-emitting diode devices (LED)

LEDs are light-emitting semiconductors with uses ranging from simple indicator lamps to more complicated bar and numeric displays, where the development of the blue LED leads to the practical use of full color displays. The LED is a remarkable technical invention. When current flows through the p-n junction of compound semiconductors consisting of Gap (gallium phosphide) or GaAsP (gallium arsenide phosphide), light is emitted as a result of electrons recombining with holes near the p-n junction. The characteristics of LEDs are as follows: low voltage operation, low heat emission, a compact and lightweight design, lack of noise (electron discharge tubes produce noise) and easy control. Horticultural applications are being considered for plant cultivation in space[32]. In this application, an irradiation source (surface) consisting of a bundle of LED devices irradiates the plant at a close proximity, moving with the plant as it grows. At a distance of 1 cm, a 5,000 mcd, 660 nm LED is able

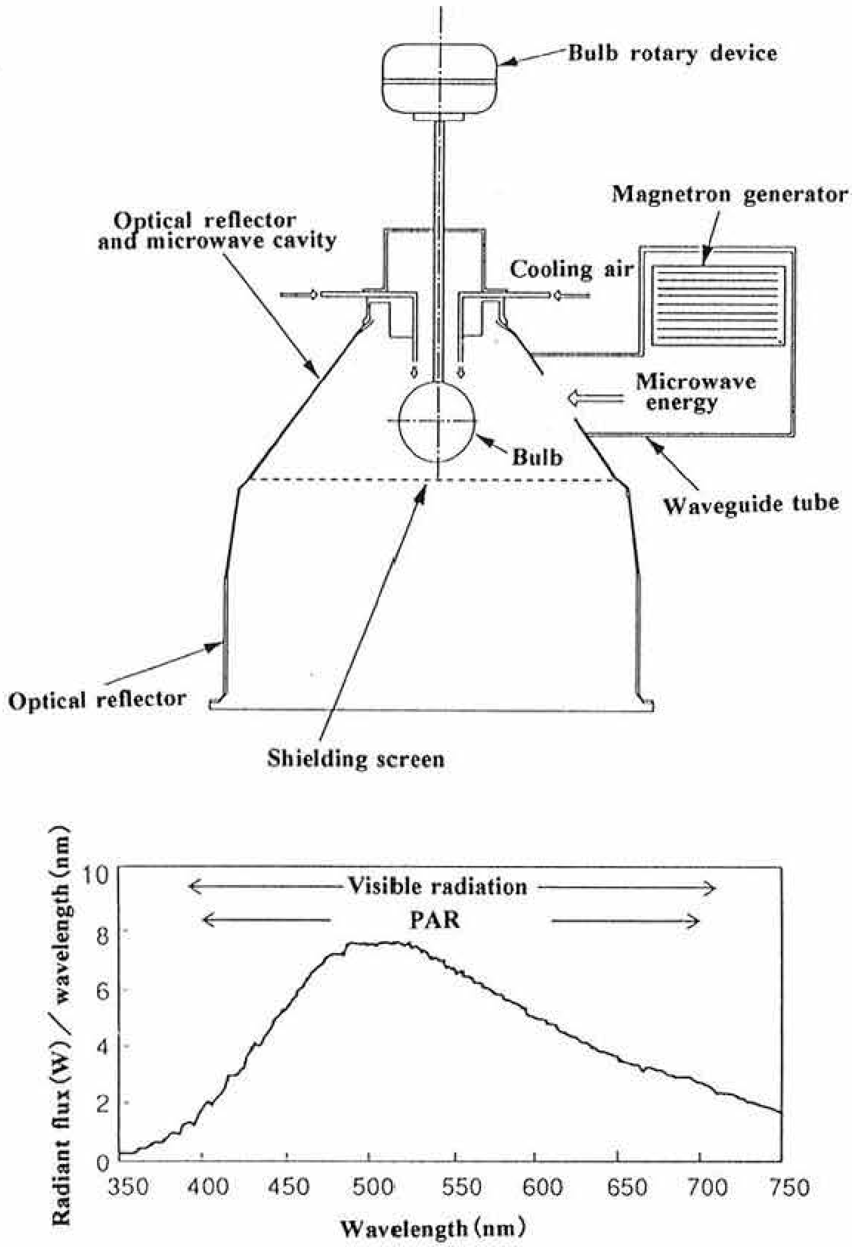

Fig. 8. Structure of microwave-powered lamp and its emission spectrum (Kozai and Kitaya, 1993)

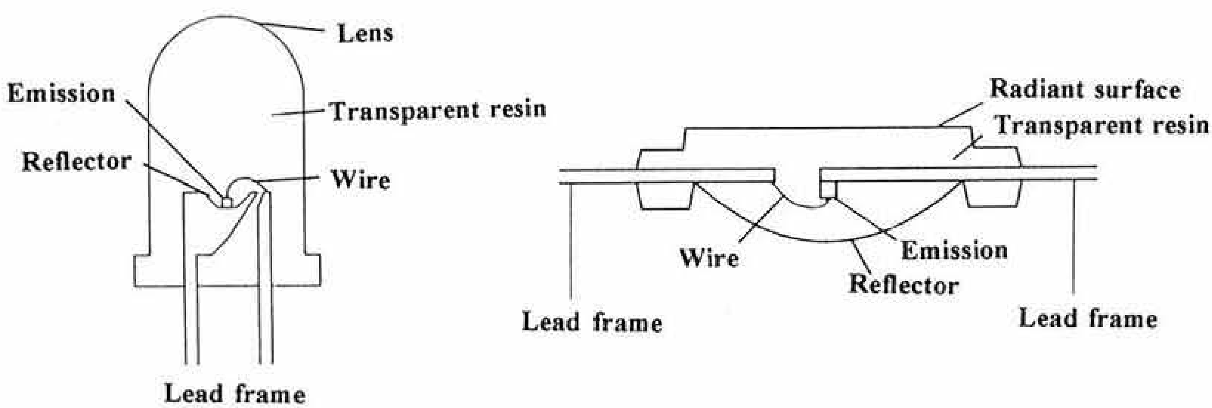

Fig. 9. Structure of LED device (Suehiro et al., 1995)

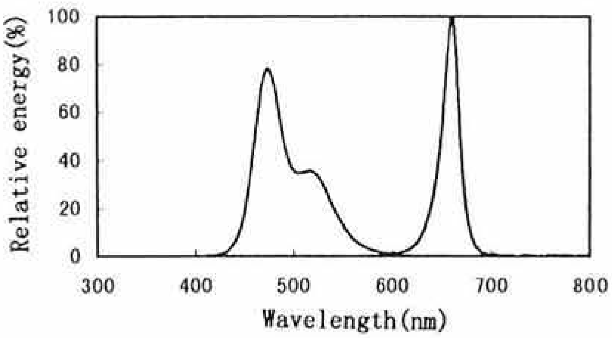

Fig. 10. Spectral distribution in composite lighting

to produce an intensity of almost 50,000 lx. In addition, a combination of red, green and blue devices together with lighting control can produce a balance that is compatible with photosynthesis. The next challenge facing LEDs concerns the production cost and the heating effects resulting from the concentrated use of LED devices. Fig. 9 shows the structure of a LED device[23] and Fig. 10 shows the spectral distribution in composite lighting. Table 6 shows the characteristics of red, green and blue LED devices[21].

(c) Laser diode devices (LD)

LDs are light-emitting semiconductors like LEDs. LDs are mainly used in bar-code readers, writeable compact disks(CD), mini disks(MD), compact disk read only memory(CDROM), optical communication transmission, and photocopiers or optical printers. The operation principle of an LD is equivalent to that of laser oscillation. Light emitted from an LED is reflected by a mirror and amplified by stimulated emission. The light is finally emitted through the mirror surface. Fig. 11 shows a simple LD structure[22]. Table 7 shows the wavelengths produced by several kinds of LDs[22]. Takatsuji & Yamanaka[24] investigated the possibility of using LDs as light sources in greenhouses since the photo-electronic transducer efficiency of LDs is very high. Results showed that irradiation combined with red and blue LD light pulses was a promising future development in view of the production cost. In addition, Takatsuji & Mori[25] confirmed the growth of lettuce using mixed light irradiation (PPFD: 50 $\mu mol \cdot m^{-2} \cdot sec^{-1}$) of red LD (660 nm) and blue LED (450 nm). Tsuchiya et al.[28] developed an LD with a wavelength of 680 nm and output of 200 mW. A 35% photo-electronic transducer efficiency was achieved (theoretical maximum 60%). Results of tests carried out on lettuce at 200 $\mu mol \cdot m^{-2} \cdot sec^{-1}$ PPFD showed that growth was slow. The leaves were thin, presumably due to the use of monochromatic and coherent light. In the mixed irradiation test using red LDs and blue fluorescent lamps (about 6%), plants showed an increased weight and a normal leaf shape, confirming the effect of blue light[29]. Mori & Takatsuji[16] cultivated lettuce by irradiating light from different kinds of LEDs and red LDs (650 nm) alone

Table 7. Wavelengths of various LDs (Shimoda, 1997)

Material	Wavelength (nm)
GaN	440
$Zn_XCd_{1-X}Se$	490–530
$Ga_{1-X}Al_XAs$	650–840
$In_XGa_{1-X}Al_YP_{1-Y}$	660–690
GaAs	840
InP	910
$In_XGa_{1-X}As_YP_{1-Y}$	1,350–1,560
$In_XGa_{1-X}As$	840–3,100
InAs	3,100
InSb	5,200
$Pb_XSn_{1-X}Te$	6,500–32,000

Table 6. Characteristics of red, green and blue LED devices (modification of Nakamura, 1995)

Color	Material	Peak wavelength (nm)	Luminous intensity (mcd)	Output power (μW)	External quantum efficiency (%)
Red	GaAlAs	660	5,000	4,500	12.0
Green	AlInGaP	570	1,000	400	1.0
	GaP	555	100	40	0.1
	ZnTeSe*	512	4,000	1,300	5.3
	InGaN	520	12,000	3,000	6.3
Blue	SiC	470	20	20	0.04
	ZnCdSe*	489	700	327	1.3
	InGaN	450	2,500	5,000	9.1

Under a forward current of 20 mA. *Under a forward current of 10 mA.

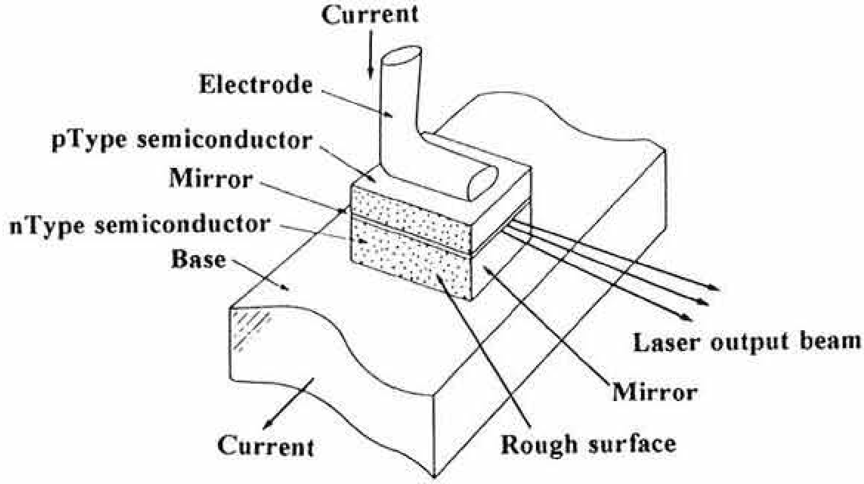

Fig. 11. Simple LD structure (Shimoda, 1997)

or in combination (PPFD: 50 $\mu mol \cdot m^{-2} \cdot sec^{-1}$) and found that the growth was poor in cases where only red LD irradiation was used. This effect was considered to be due to the monochromatic characteristic of red LD light. The following problems in the application of LDs are as follows: sensitivity to electrostatic and current surges, wavelength increase of about 10 nm as the temperature rises, and need for development of a blue light LD.

Conclusion

Two main requirements dominate the utilization of artificial light sources in horticulture in both gardens and commercial greenhouses, the first being efficiency. High pressure sodium lamps are generally adopted to offer the highest efficiency in terms of plant growth rate and economy. However, to remain within current standards of farm products (such as leaf greenness and coloration, internode length, stem diameter, and leaf thickness), combination with metal halide lamps is recommended. The second requirement is related to the esthetic improvement of store or house environments, where the primary concern is not growth but maintenance of a plant natural appearance. High efficiency is not a prerequisite, but the light quality balance becomes important in order to bring out the essential color characteristics of plants and flowers as well as maintaining plant health. To meet these requirements, high color rendering index type MHLs are recommended. Current horticultural research trends lead to the development of 1.2 kW HPSL, 180 lm/W, LED and LD devices for use in commercial greenhouses and the application of microwave and 400 W MHL lamps in growth chambers.

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(Received for publication, December 18, 1998)