CONTROL OF ARTIFICIAL LIGHT FOR PLANTS

I. MEASUREMENT AND CONTROL OF LIGHT

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Some instruments of control and measurement of artificial light for plants were made in an attempt to analyze precisely the plant responses to the light.

Measurement of total and spectral irradiances. Two different instruments were used for measurement of light. One kind was a radiometer by which total irradiance in the wavelength range between about 300 nm and 800 nm was measured. The other was a spectroradiometer which was a newly assembled instrument, consisting of an integrating sphere (light receiver), a grating monochrometer, a photomultiplier, an amplifier, and a recorder. This spectroradiometer was able to measure spectral irradiance in the wavelength range between 300 nm and 800 nm, and in the irradiation range between $0.5 \mu\text{W}/\text{cm}^2 \cdot \text{nm}$ and $500 \mu\text{W}/\text{cm}^2 \cdot \text{nm}$ with high resolution and reliable cosine response.

Light control. Six different lamps were used as light sources. They gave specific spectral emissions in the wavelength range between 350 nm and 800 nm. The lamp compartment of the growth cabinet was provided with these lamps. To control the radiant flux (light output) of each lamp, independent controllers corresponding to each lamp were used; the radiant flux control was achieved by SCR element for changing the effective current through the lamp. Both combined spectral and total irradiances were due to the radiant flux of each lamp. This instrument was able to control the total and spectral irradiances by changing the radiant flux of each lamp in the wavelength range between 350 nm and 800 nm and in the range between 0% and 100% of rated capacity.

Light is an important factor for plants. It is well known that the plant growth is affected by both intensity and spectral composition of light. It is necessary to control both total and spectral irradiances as well as photoperiod for exact analyses of the plant responses to the light. Several methods have been used for the control of total and spectral irradiances so far. The total irradiance was controlled by changing the number of lamps⁸⁾ and the distance between the light source and plants,⁵⁾ using some spectrally neutral filter,¹⁹⁾ or varying electrical input to light source.^{6, 11)} The spectral irradiance was controlled by some filters^{22, 24)} or different lamps.¹⁸⁾ However, the precise control of spectral irradiance remained as a difficult problem.

The purpose of our studies was to improve the instruments in order to control and measure the total and spectral irradiances in the physiologically effective wavelength of artificial light for plants.

LIGHT MEASUREMENT

Measurement of total irradiance. A radiometer (RMD-8, Japan Spectroscopic Co., Ltd.) was used for measuring total irradiance. The receiver consisted of both optical chopper (8 Hz) and Schwartz type vacuum thermocouple with a fused-quartz window. The sensitivity of the thermocouple which was coated with gold-black was almost uniform in the wavelength range between 200 nm and 2.5μ .²⁾ In front of the chopper, a glass plate (Heat Glass, Ohara Optical Glass Mfg. Co., Ltd.) was fixed to absorb the light of long wavelength. Figure 1 shows the transmittance curve of the glass plate. A lock-in type amplifier was used for amplifying the signal from thermocouple with eliminating effect of temperature. The output signal was calibrated by a 1,000 W tungsten-iodine lamp¹⁷⁾ (the standard of spectral irradiance, National Bureau of Standards); the irradiance sensitivity was $8\mu\text{V}/\text{mW}/\text{cm}^2$. In the measurement of artificial light, it was necessary to consider the cosine law of incident light. In this instrument, the light from the canopy was caught into the receiver within 40° of incident angle as shown in Fig. 2.

Fig. 1 Transmittance curve of long wavelength cutoff glass.

Fig. 2 Cosine response.

— Theoretical response. $\triangle \cdots \triangle$ Radiometer response. $\circ - \circ$ Spectroradiometer response.

Measurement of spectral irradiance. Although the spectroradiometers were constructed for measurement of spectral irradiance,^{1, 3, 12, 15, 21)} the instrument became to be demanded for evaluation of spectral irradiance in controlled environments for plant, to make accurate measurement, to correct cosine response of entrance optics, and to extend the ranges of wavelength and irradiance. Thus, a new instrument was assembled to satisfy the following requirement. (1) to be able to measure spectral irradiance in the range between 300 nm and 800 nm which mainly contains the physiologically effective light for plants, (2) to have a high resolution, (3) to minimize the cosine error, (4) to possess a high signal-to-noise ratio under low light levels, and (5) to accommodate rapid and continuous wavelength-scanning system.

Fig. 3 Schematic diagram of the spectroradiometer.

C, optical chopper; F, filter; G, grating; IS, integrating sphere; L, lens; LS, light source; M1 and M4, plane mirrors; M2 and M3, off-axis parabolic mirrors; S1, entrance slit; S2, exit slit; PMT, photomultiplier tube.

The schematic diagram of the spectroradiometer is shown in Fig. 3. The entrance optics consisted of an integrating sphere of 15 cm in diameter with an entrance aperture of 3 cm and exit aperture of 2 cm. Barium sulfate⁹⁾ was coated inside the sphere. The sphere was adopted for minimizing the cosine error.^{1, 3, 13, 20)} In the growth cabinet, it is necessary for evaluation of irradiance to measure direct light from the extended surface in the canopy and light reflected from walls. Thus, characteristics of the cosine response in light receiver is, in general, very important for the measurement of light in the growth cabinet. Figure 2 shows a comparison of the experimental response with the theoretical cosine curve. It was clear from this response that the integrating sphere contributed to decrease the error in the cosine response. Between the sphere and entrance slit of monochromator, a optical chopper (30 Hz) was installed for AC amplification. A filter pocket was made in order to set a red filter in a optical path. The dispersing element was a monochromator (Nikon Monochromator, P250, Nippon Kogaku K.K.) consisting of a grating brazed at 750 nm with 600 g/mm and two off-axis parabolic mirrors (focal length 25 cm), with a linear dispersion of 6 nm/mm in the range between 170 nm and 1,600 nm. The wavelength was scanned by a synchronous motor with a maximum speed of 270 nm/min. A pulse signal per 10 nm was recorded for marking wavelength. Both width and height of the slit were change-

able from 0.01 mm to 2 mm and from 2 mm to 20 mm respectively. It was founded from our trials that a half bandwidth from 2 nm to 5 nm was satisfactory for exact evaluation of spectral irradiance in artificial light. Therefore, the slit was fixed at $0.4 \text{ W} \times 10 \text{ Hmm}$. In this condition, the half bandwidth was 2.6 nm. The detector was a head-on type photomultiplier (R593, Hamamatsu TV Co., Ltd.) with a fused-quartz window. This detector displayed high spectral sensitivity enough to measure the spectral irradiance in the range between 160 nm and 850 nm with a maximum sensitivity at 420 nm. The first-order spectrum between 170 nm and 630 nm and the second-order spectrum between 85 nm and 315 nm overlapped each other. The second-order spectrum, however, was negligibly low in measuring the artificial light. For measurements in the range between 630 nm and 800 nm, a red filter (V-R62, Toshiba Kasei Co., Ltd.) was set in the optical path in order to eliminate second-order spectrum between 315 nm and 400 nm.

Fig. 4 Spectroradiometer.

A, amplifier and anode voltage supply; C, optical chopper; DV, digital voltmeter for monitoring anode voltage; IS, integrating sphere; M, grating monochromator; R, recorder; PMT, photomultiplier tube.

The photomultiplier was operated at $750 \pm 0.5 \text{ V}$ by a anode-voltage supply. The anode current was amplified by a lock-in type amplifier (Nikon Electrophotometer, SP-104). The output was recorded with a electronic self-balancing recorder (type 3046, Yokogawa Electric Works, Ltd.). Figure 4 shows a photograph of the spectroradiometer which consisted of a receiver, an optical chopper, a monochromator, a photomultiplier, an amplifier/anode-voltage supply, a digital voltmeter for monitoring anode-voltage, and a recorder.

The calibration for spectral irradiance was based on the NBS standard of spectral irradiance.¹⁷⁾ A tungsten-iodine lamp of 1,000 W was used as the standard lamp which operated at 7.9 A AC from a variable-transformer power supply. The over-all response of the instrument depended on spectral transmissions of integrating sphere and monochromator, and spectral sensitivity of photomultiplier cathode. Figure 5 shows the spectral response measured at 750 V of anode-voltage, 0.4 mm of slit width, and 10 mm of slit height. The spectral irradiance at wavelength λ was given as following equation:

Fig. 5 Spectral response of the spectroradiometer at 750 V of anode voltage, 0.4 mm of slit width, and 10 mm of slit height.

Fig. 6 Spectral irradiance from a 20 W white-fluorescent lamp at a distance of 25 cm. A, recorded curve; B, corrected curve.

$$E_i = K_i \cdot A_i$$

Where E_i is spectral irradiance ($\mu\text{W}/\text{cm}^2 \cdot \text{nm}$) from light source, K_i is correction factor ($\mu\text{W}/\text{cm}^2 \cdot \text{nm}/\text{nA}$) which is the reciprocal of the response of the spectroradiometer (see Fig. 5), and A_i is output signal (nA) from the spectroradiometer. This instrument brought about satisfactory stability for measuring spectral irradiance: the change of response was within 4% over the range between 300 nm and 800 nm in 3 times observations during 2 months.

As described before, the anode voltage, slit width and slit height were fixed at 750 V, 0.4 mm and 10 mm respectively. In this condition, the instrument was able to measure the spectral irradiance in the range between $0.5 \mu\text{W}/\text{cm}^2 \cdot \text{nm}$ and $500 \mu\text{W}/\text{cm}^2 \cdot \text{nm}$ and in the wavelength range between 300 nm and 800 nm with half bandwidth of 2.6 nm. With the maximum slit width of 2 mm and anode voltage of 1,000 V, the instrument was able to measure the irradiance as low as $2 \times 10^{-3} \mu\text{W}/\text{cm}^2 \cdot \text{nm}$. Figure 6 shows an example of the recorded curve of spectral irradiance from a 20 W white fluorescent lamp at a distance of 25 cm, and its corrected curve. For measurement of the energy in spectral lines of the mercury arc in fluorescent lamps, three principal methods have been used so far.^{10, 14-16)} In the present experiment, the method of integrated net area was adopted.¹⁵⁾ The energy in mercury lines was graphically represented by rectangular blocks per 10 nm in width.

LIGHT CONTROL

The basic requirements in the light control system were as follows: (1) to control the total irradiance which was continuously ranging from the darkness to the full light; (2) to regulate the spectral irradiance in physiologically effective range for plants.

Light source. Six kinds of lamps which were 55 bulbs in total (Tokyo Shibaura Electric Co., Ltd.) were applied to light sources. They were fluorescent lamps of 10 blue (FLR-110EH-B/A), 10 blue-white (FLR-110EH-BW/A), 10 yellow (FLR-110EH-Y-S/A), 10 pink (FLR-110EH-Pk/A) and 5 red (FLR-110EH-Re-S/A), and beam lamps of 10 red (BRC-100 V-100 WR). The fluorescent lamps were 110 W extra-high-output ones. The radiant flux per unit bulb length was about 2.5 times as high as that of a 40 W fluorescent lamp.⁷⁾ The bulbs of yellow as well as red fluorescent lamps and red beam lamps were coated with filter materials to eliminate the light of short wavelength region. The growth cabinet⁸⁾ was provided with these lamps into a lamp compartment. The arrangement of lamps and the lamp compartment are shown in Fig. 7-a and -b respectively. The fluorescent bulbs were arranged in two tiers. The total irradiance in these two tiers was 1.35 times as high as that in conventional single tier.⁴⁾ The beam lamps were equipped at upper side of the tiers of fluorescent lamps. Figure 8 shows the spectral irradiances from single or combined lamps at 25 cm above the floor of growth compartment. Each lamp showed specific spectral emission characteristics. The combination of these lamps gave the light in the range between about 350 nm and over 800 nm. The seven mercury lines at 313, 334, 365, 404.6-407.7, 435.8, 546, and 577-579 nm were observed in general. The intensities of mercury lines at 313 and 334 nm were extremely weak in the growth compartment, because of their low spectral transmission through the glass pane by which the

Fig. 7-a Arrangement of the lamps.
A, blue; B, blue-white; C, yellow; D, pink; E, red fluorescent lamps; F, red beam lamps.

Fig. 7-b General view of the lamp compartment.

Fig. 8 Spectral irradiances from single or combined lamps at their rated capacities.

A, blue; B, blue-white; C, yellow; D, pink; E, red fluorescent lamps; F, red beam lamp; G, combined lamps.

growth compartment was partitioned off from the lamp compartment as described below. Thus, the intensities of these two lines were too low to show in this figure. The mercury lines at 365, 404.6–407.7, and 435.8 nm of yellow and red fluorescent lamps became weak by the filter material which was coated on bulbs of these lamps. The irradiances at 25 cm above the floor of growth compartment at their rated capacities were: blue, 0.88; blue-white, 1.12; yellow, 0.66; pink, 1.20; and red fluorescent lamps, 0.17; red beam lamps, 0.51; and sum of them, 4.54 mW/cm². These values were estimated lower than that of integrated net area of spectral irradiance measured by the spectroradiometer in the range between 350 nm and 800 nm. This fact could be due to the difference in cosine response between the radiometer and the spectroradiometer as shown in Fig. 2.

Lamp compartment. It is well known that the fluorescent lamp is the most efficient light source in common usage. About 20% of input wattage is used as light, while 80% of input energy is converted into the heat.⁷⁾ The radiant flux and spectral emission of fluorescent lamps are greatly affected by the bulb wall temperature.^{7, 23)} Therefore, it is necessary to keep the bulb wall at optimal temperature for maximizing and stabilizing the efficiency of radiant flux of lamps. For this purpose, an air temperature control system was applied to the lamp compartment. The sectional structure of the lamp compartment is shown in Fig. 9. The cooling system with constant capacity of 5,000 kcal/h was continuously operated to keep lower air temperature than the desired value. The temperature of the air which passed through the cooling coil was controlled by on-off action of an electric heater (3,000 kcal/h). The controlled air was supplied into the lamp compartment through air ducts located in each side of the fluorescent bulb ends and was circulated into the return air duct at a central part of the

Fig. 9 Sectional structures of the lamp compartment.
C, cooling coil; D1, supply air ducts; D2, return air duct; F, fans; GC, growth compartment; GP, glass pane; H, electric heater; L1, fluorescent lamps; L2, beam lamps.

Fig. 10 Effect of air temperature in lamp compartment on radiant flux indicated as the total irradiance.

ceiling. The lamp compartment was partitioned off from the growth compartment (inside dimension; 100 H×150 W×100 Dcm) by the glass pane. Figure 10 shows the effect of air temperature in the lamp compartment on radiant flux indicated

Fig. 11 Schematic diagram of light control system.

Fig. 12 Light control instrument.

Right: light control panel.

SW, switches; V, voltmeters for monitoring voltages supplied to SCR elements; VS, voltage suppliers.

Left : inside view of the instrument.

S, SCR elements; T, timer for setting irradiation time.

as the total irradiance at 25 cm above the floor of the growth compartment. The maximum irradiance was obtained at about 29°C; at lower and higher temperatures, the total irradiance was decreased.

Control of total irradiance. The radiant flux of lamp was controlled by a system regulating electrical input to the light source. The schematic diagram and photographs of the control system are shown in Figs. 11 and 12. The radiant flux of each lamp was controlled by a SCR element (SCR dimming elements; UF-102030 and UL-102030 for fluorescent lamps and beam lamps respectively, Tokyo Shibaura Electric Co., Ltd.). The set value of radiant flux was set in a voltage supplier which supplied the voltage between 0 V DC and 20 V DC to a pulse signal transmitter. SCR regulated the current through the lamp corresponding to the signal from the transmitter. The controlled variable of radiant flux was indicated as the total irradiance in the plant area. An irradiation period was regulated by the timer. Some flicker in radiant flux remained at low radiant flux. Therefore, the radiant flux was controlled between 10% and 100% of set value, and the darkness was kept in the range less than 10%. The response curves in control of total irradiance are shown in Fig. 13. It was found, thus,

Fig. 13 Response curves in irradiance control.

- Blue, blue-white, yellow, and pink fluorescent lamps.
- △—△ Red fluorescent lamp.
- Red beam lamp.

that the response characteristic in control of the total irradiance was similar to each other in the range between 10% and 100% at about 10 V DC to 20 V DC of the set voltage. The spectral irradiances from the lamps in different set values are shown in Figs. 14 and 15. In these conditions, any shift of spectral emission was unable to be observed.

Fig. 14 Spectral irradiances from one kind of lamps in different set values of radiant flux.

A, 100; B, 80; C, 60; D, 40; E, 20; F, 10% of rated capacity.

a : Blue fluorescent lamp.

b : Blue-white fluorescent lamp.

c : Yellow fluorescent lamp.

d : Pink fluorescent lamp.

e : Red fluorescent lamp.

f : Red beam lamp.

Control of spectral irradiance. As mentioned before, each lamp indicated specific spectral emission and the radiant flux of the lamp was independently controlled by the control system. In the combination of these lamps, spectral irradiance was in the range between 350 nm and 800 nm. Thus, the new system was able to change combined spectral irradiance by controlling radiant flux of each lamp. Figures 16 and 17 show combined spectral irradiances: the radiant flux of one kind of lamps was controlled at different values, and that of the other lamps

Fig. 15 Spectral irradiances from combined lamps in different set values of radiant flux.
A, 100; B, 80; C, 60; D, 40; E, 20; F, 10% of rated capacity.

Fig. 16 Combined spectral irradiances: the radiant flux of pink fluorescent lamp was controlled at 0(G), 10(F), 20(E), 40(D), 60(C), 80(B), and 100% (A) of its rated capacities, and that of other lamps were fixed at constant capacities of 100%.

were fixed at constant capacities. The flexibility in control range of spectral irradiance was responsible for the rated capacity and the spectral emission-characteristics of each kind of the lamps.

Fig. 17 Combined spectral irradiances: the radiant flux of blue-white fluorescent lamp was controlled at 0(G), 10(F), 20(E), 40(D), 60(C), 80(B), and 100% (A) of its rated capacities, and that of other lamps were fixed at constant capacities of 100%.

CONCLUSION

Various methods have been applied to light measurement.¹²⁾ However, further developments are now being demanded to establish standard methods for measuring physiologically effective radiation for plants. Spectral irradiance as well as total one should be taken into consideration for the analyses of plant responses to the light. In the present study, both radiometer and spectroradiometer were employed for measuring total and spectral irradiances. In this spectroradiometer, the spectral irradiance between 300 nm and 800 nm was able to be measured in the range between $0.5 \mu\text{W}/\text{cm}^2 \cdot \text{nm}$ and $500 \mu\text{W}/\text{cm}^2 \cdot \text{nm}$ within the accuracy of $\pm 4\%$ and with half bandwidth of 2.6 nm. Those instruments could greatly contribute to evaluate radiation for plants. The newly assembled spectroradiometer resulted in becoming a powerful and reliable tool for the analyses of spectral irradiance in controlled environments.

The controls of total and spectral irradiances in artificial light were made possible in the present system. The new system could offer a new criterion of artificial light radiation for plants. The control ranges of total and spectral irradiances are able to be changed by exchanging the lamps into the other ones. The model of spectral composition of solar radiation might be made in the present system, and the other optional composition of spectral irradiance could be brought to control the plant growth and differentiation. The present system offers many possibilities to improve methods of the light control for plants.

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<和文抄録>

植物に対する人工光照射の制御

1. 人工光の計測と制御

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光に対する植物の反応を詳細に解析するためには光の質と量について、より高精度で計測し制御することが望まれる。本研究では、グロースキャビネットにおける分光放射照度と放射照度の計測と制御方法を改善することを目標として、装置の開発とその性能解析を行った。

光の計測 放射照度の計測にはラジオメーターを用いた。光検出器としては真空熱電対を用い、その前面に赤外カットフィルターを設置して、およそ 300~800 nm の波長域における放射照度を計測することにした。分光放射照度計測には、新たに試作したスペクトロラジオメーターを用いた。この装置は、積分球（受光部）、回析格子モノクロメーター、光電子倍增管から構成されていて、波長範囲 300~800 nm、分光放射照度 $0.5\sim500\ \mu\text{W}/\text{cm}^2\cdot\text{nm}$ の光を高精度、高分解能（半値幅 2.6 nm）で計測可能にした。また、コサイン則も、十分に満足した。装置の校正には NBS 規格の分光放射照度標準ランプ（1,000 W よう素電球）を用いた。

光制御装置 植物に対する有効波長域を考慮して 350 nm~800 nm における放射照度と分光放射照度の制御を目的にした。光源として、分光放射分布の異なる 6 種のランプを選んだ。すなわちカラード蛍光ランプ 5 種（ブルー、ブルーホワイト、イエロー、ピンクを各 10 個、レッド 5 個）およびレッドビームランプ 10 個である。これらのランプの光束の効率と安定性を高めるためにランプコンパートメントには温度制御装置を装備した。各ランプの光束を SCR 調光装置によって設定する方法を採った。蛍光ランプを調光した場合、その分光放射分布のシフトは、ほとんど認められなかった。

この装置において、各ランプの光束を設定することにより、グロースコンパートメント内の放射照度と分光放射照度を制御することが可能となった。制御範囲は 350 nm~800 nm、ランプ定格の 0~100% である。