Chapter 26
Radiometric, Photometric and Photonmetric Quantities and Their Units

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Abstract The article provides a simple explanation to facilitate systematic understanding of quantities, especially relating to "light intensity", and the SI units necessary to describe the specifications of light output of artificial light sources and of light environments for plant cultivation. Important quantities similarly situated in radiometry, photometry and photonmetry, respectively, are explained, contradistinguished from one another.

Keywords Artificial lighting • Illuminance • Irradiance • Light environment • Radiometry • Photometry • Photonmetry • Photon flux density • Plant cultivation • SI unit • Terminology

26.1 Introduction

For plant cultivation, several fundamental quantities, especially those related to "light intensity", and their units for artificial light sources, including LEDs, must be understood appropriately and effectively. This article simply explains fundamental and important quantities relating to "light intensity" and their SI units necessary to specify light output of artificial light sources and light environments for plant cultivation. For that purpose, those quantities similarly situated in radiometry, photometry and photonmetry are explained, respectively, and are mutually contradistinguished.

Terminology definitions are mostly quoted from International Electrotechnical Commission (IEC) 60050-845-01 (1987). Some terms associated with the fundamental quantities are also explained using illustrations and graphs. Part of this chapter includes partially reconstituted and modified contents of the author's previous works (Fujiwara 2013, 2015).

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26.2 Importance of Photonmetric Quantities for Plant Cultivation

Quantities related to “light intensity” are classified into three measurement categories: radiometry, photometry and photonmetry. Radiometry, photometry and photonmetry can be restated, respectively, as energy-based, luminosity-based and photon-based measurements. Radiometry and photometry are well known. Their explanations are found with relative ease in books and articles (e.g. Meyer-Arendt 1968). In contrast, “photonmetry” is rarely found in books and articles, but quantities in “photonmetry” are those which must be used to describe “light intensity” for plant responses to light because many plant responses to light are observed as a result of photochemical reactions.

26.3 Fundamental Quantities in Radiometry, Photometry and Photonmetry and Their SI Units

Fundamental quantities in radiometry, photometry and photonmetry and their SI units are shown in Table 26.1. Four fundamental quantities, with their SI units, in radiometry and photonmetry are placed, respectively, in both side columns of the following four fundamental quantities in photonmetry: luminous intensity, luminous flux, quantity of light and illuminance so that the relations among the quantities and SI units can be readily understood. Relational expressions among the quantities in the same column are provided in the rightmost column to indicate quantitative relations. Quantities in the same row are mutually equivalent in a metric sense.

Definitions of these terms are presented clearly in IEC 60050-845-01 (1987). The following definition in the first sentence for each term is fundamentally a direct quote from IEC 60050-845-01 (1987). Quantity symbols are deleted from the original definitions, and SI units are added. Supplementary explanations are subsequently added for most terms to elucidate their definitions.

26.3.1 *Radiant Intensity [W sr^{-1}]*

Quotient of the radiant flux [W] leaving the source and propagated in the element of solid angle (see Fig. 26.2 for an explanation of “solid angle”) containing the given direction, by the element of solid angle [sr]. In other words, it is the radiant flux [W] leaving the source per unit solid angle [sr] in the direction considered.

Table 26.1 Fundamental quantities in radiometry, photometry and photonmetry and their SI units

Radiometry (Energy basis)	Radiant intensity $[W\ sr^{-1}]$	Radiant flux $[(W\ sr^{-1})\ sr]$ $= [W]$	Radiant energy $[W\ s]$ $= [J]$	Irradiance $[W\ m^{-2}]$
Photometry (Luminosity basis)	Luminous intensity [cd]	Luminous flux [cd sr] = [lm]	Quantity of light [lm s]	Illuminance $[lm\ m^{-2}]$ = [lx]
Photonmetry (Photon basis)	Photon intensity $[mol\ s^{-1}\ sr^{-1}]$	Photon flux $[(mol\ s^{-1}\ sr^{-1})\ sr]$ $= [mol\ s^{-1}]$	Photon number $[(mol\ s^{-1})\ s]$ $= [mol]$	Photon flux density (Photon irradiance) $[(mol\ s^{-1})\ m^{-2}]$ $= [mol\ m^{-2}\ s^{-1}]$
Relations	A	A·sr = B	A·sr·s = B·s	$A \cdot sr \cdot m^{-2}$ $= B \cdot m^{-2}$

Modified from Fujiwara (2013)

26.3.2 Radiant Flux (Radiant Power) [W] (= $[J\ s^{-1}]$)

Power [W] emitted, transmitted or received in the form of radiation. The amount of radiant energy [J] emitted, transmitted or received per unit time [s].

26.3.3 Radiant Energy [J]

Time integral of the radiant flux [W] over a given duration [s].

26.3.4 Irradiance $[W\ m^{-2}]$

Quotient of the radiant flux [W] incident on an element of the surface containing the point, by the area $[m^2]$ of that element.

26.3.5 Luminous Intensity [cd]

Quotient of the luminous flux [lm] leaving the source and propagated in the element of solid angle containing the given direction, by the element of solid angle [sr]. In other words, it is the luminous flux [lm] leaving the source per unit solid angle [sr] in the direction considered.

26.3.6 Luminous Flux [lm]

Quantity derived from radiant flux [W] by evaluating the radiation according to its action upon the CIE standard photometric observer. The luminous flux is calculated by integrating from 0 nm to infinity (actually 360–830 nm for photopic vision) the product of spectral radiant flux [W nm^{-1}], the CIE standard spectral luminous efficiency function for photopic vision (usually denoted as $V(\lambda)$, with value ranges of 0–1 according to wavelength λ), and the maximum spectral luminous efficacy (of radiation) for photopic vision [lm W^{-1}] (usually denoted as K_m; approximately 683 lm W^{-1} at 555 nm (540 THz)). Explicit and detailed descriptions of the relation between radiometric and photometric quantities are presented by Ohno (1997).

26.3.7 Quantity of Light [lm s]

Time integral of the luminous flux [lm] over a given duration [s].

26.3.8 Illuminance [lx]

Quotient of the luminous flux [lm] incident on an element of the surface containing the point, by the area [m^2] of that element.

26.3.9 Photon Intensity [mol s^{-1} sr^{-1}]

Quotient of the photon flux [mol s^{-1}] leaving the source and propagated in the element of solid angle containing the given direction, by the element of solid angle [sr]. In other words, it is the photon flux [mol s^{-1}] leaving the source per unit solid angle [sr] in the direction considered.

26.3.10 Photon Flux [mol s^{-1}]

Quotient of the number of photons [mol] emitted, transmitted or received in an element of time [s], by that element.

26.3.11 Photon Number (Number of Photons) [mol]

Time integral of the photon flux [mol s^{-1}] over a given duration [s].

26.3.12 Photon Flux Density (Photon Irradiance) [mol m^{-2} s^{-1}]

Quotient of the photon flux [mol s^{-1}] incident on an element of the surface containing the point, by the area [m^2] of that element. In IEC 60050-845-01 (1987), the term “photon flux density” is not listed, but the term “photon irradiance” is listed. In fields related to plant cultivation and related sciences such as horticultural science and environmental plant physiology, “photon flux density” has been widely used instead of “photon irradiance” (Fig. 26.1).

26.4 Spectral Distribution of Radiometric, Photometric and Photonmetric Quantities

Spectral distribution is a generic term used to describe a quantity as a function of wavelength or quantity per unit wavelength, e.g. 1 nm, arranged in wavelength sequence. In this chapter, the spectral distribution is used exclusively in the latter meaning. The adjective “spectral” is useful for the 12 terms described above and the other terms describing quantities pertaining to radiation when the property or wavelength dependency of the quantity is described, such as spectral irradiance.

The relations of spectral irradiance, illuminance and photon flux density for wavelengths of 300–800 nm are presented in Fig. 26.2 in the case of spectral irradiance, taking a constant value of 0.1 W m^{-2} nm^{-1}. Values outside and inside of parentheses presented in the upper right of each graph are the irradiance, illuminance and photon flux density, respectively, for wavelengths of 300–800 nm and 400–700 nm. Actually they are the integrals of spectral irradiance, illuminance and photon flux density in the respective wavelength ranges. As a useful example, we also prepared Fig. 26.3 showing the reference solar spectral irradiance (IEC 60904-3-2 2008) and its corresponding spectral illuminance and photon flux density for wavelengths of 300–800 nm. The reference solar spectral irradiance was prepared by IEC as a reference for terrestrial photovoltaic solar devices.

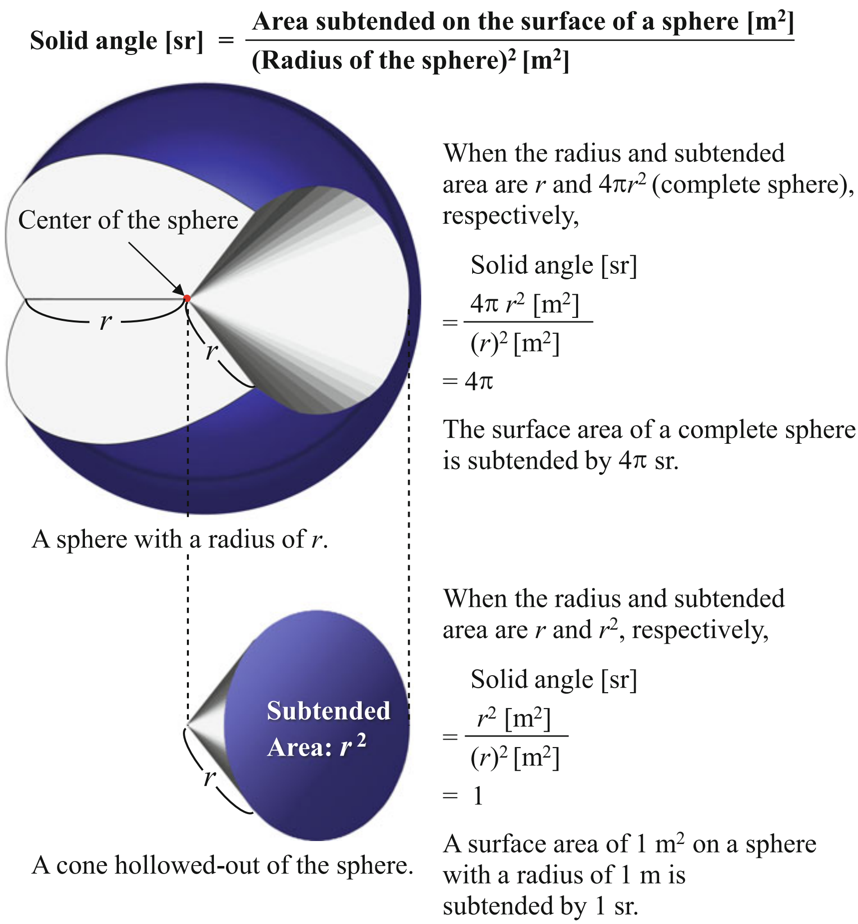

Fig. 26.1 Solid angle and its mathematical explanation

26.5 Quantitative Relations of Radiometric, Photometric and Photonmetric Quantities

The spectral illuminance curves in Figs. 26.2 and 26.3 were drawn using the CIE standard spectral luminous efficiency function for photopic vision ($V(\lambda)$) by CIE Standard (2005), in which the values of the function at 1-nm increments are tabulated. The value of spectral illuminance (for photopic vision) at a wavelength of λ [nm], $L_{is,\lambda}$ is calculable as

$$L_{is,\lambda} = K_m \cdot R_{is,\lambda} \cdot V(\lambda) \tag{26.1}$$

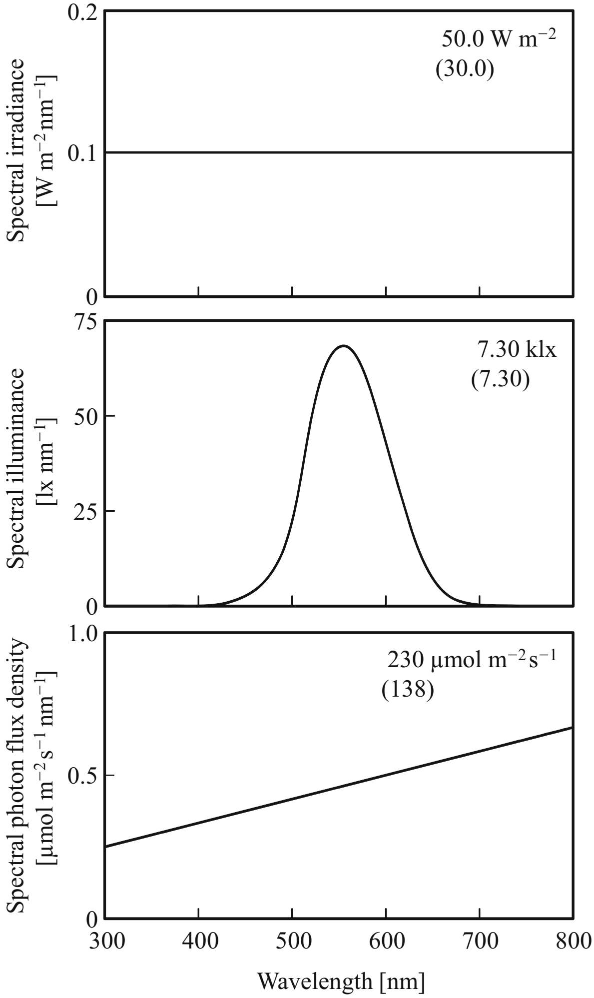

Fig. 26.2 Spectral irradiance taking a constant value of 0.1 W m^{-2} nm^{-1} and its corresponding spectral illuminance and photon flux density for wavelengths of 300–800 nm. Values outside and inside of parentheses shown in the upper right of each graph, respectively, represent the irradiance, illuminance and photon flux density for respective wavelengths of 300–800 nm and 400–700 nm

where $R_{is,\lambda}$ stands for the spectral irradiance at wavelength λ [W m^{-2} nm^{-1}] and where K_m is a constant relating the radiometric quantities and photometric quantities, called the "maximum spectral luminous efficacy of radiation for photopic vision". The value of K_m is given by the 1979 definition of candela, which defines the spectral luminous efficacy of light at 540×10^{12} Hz (at 555-nm wavelength) to be 683 lm W^{-1} (Ohno 1997).

The curves of spectral photon flux density in Figs. 26.2 and 26.3 were drawn using a theoretically simple equation described below. Energy, E [J], that n moles of photons with a wavelength of λ [nm] possess is given as the following equation:

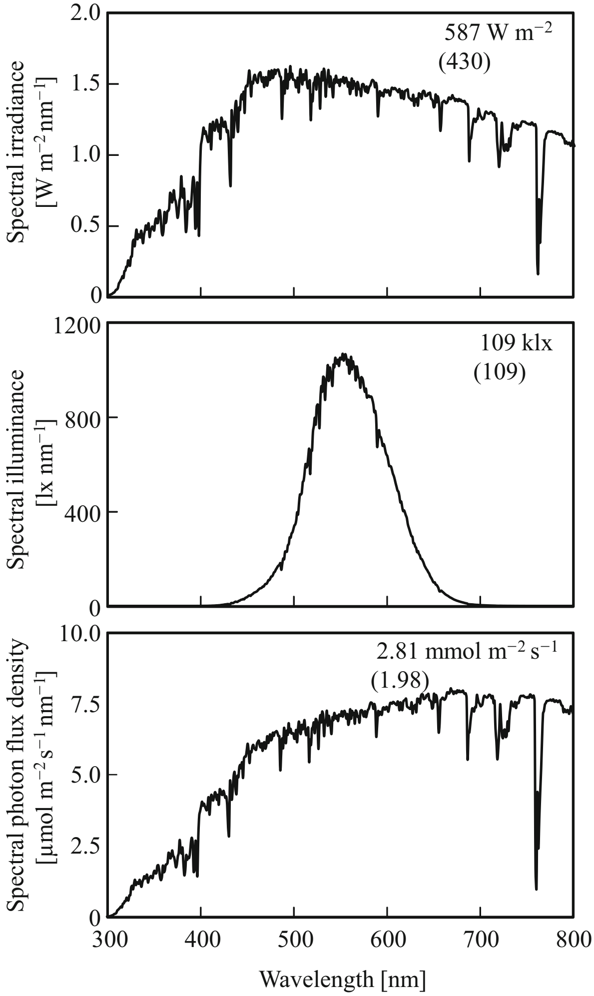

Fig. 26.3 Reference solar spectral irradiance (IEC 60904-3-2 2008) and its corresponding spectral illuminance and photon flux density for wavelengths of 300–800 nm. Values outside and inside of parentheses shown in the upper right of each graph, respectively, represent the irradiance, illuminance and photon flux density for respective wavelengths of 300–800 nm and 400–700 nm

$$E = n \cdot N_{\mathrm{A}} \cdot h \cdot v = \frac{n \cdot N_{\mathrm{A}} \cdot h \cdot c}{\lambda \times 10^{-9}} \tag{26.2}$$

Therein, h stands for Planck's constant (6.626×10^{-34} J s), c is the speed of light (2.998×10^{8} m s^{-1}) and N_{A} is Avogadro's number (6.022×10^{23} mol^{-1}).

Provided that spectral irradiance $R_{\mathrm{is},\lambda\mathrm{c}}$ [W m^{-2} nm^{-1}], which is the irradiance [W m^{-2}] per wavelength range [nm] with its central wavelength at λ_{c} [nm], is given, then the spectral photon flux density at λ_{c} is calculable by substituting $R_{\mathrm{is},\lambda\mathrm{c}}$ into E and $P_{\mathrm{is},\lambda\mathrm{c}}$ into n in Eq. 26.2.

$$R_{\mathrm{is},\lambda\mathrm{c}} = \frac{P_{\mathrm{is},\lambda\mathrm{c}} \cdot N_{\mathrm{A}} \cdot h \cdot c}{\lambda_{\mathrm{c}} \times 10^{-9}} \tag{26.3}$$

$$\therefore P_{\mathrm{is},\lambda\mathrm{c}} = R_{\mathrm{is},\lambda\mathrm{c}} \frac{\lambda_{\mathrm{c}} \times 10^{-9}}{N_{\mathrm{A}} \cdot h \cdot c} \tag{26.4}$$

For example, the spectral photon flux density for λ_{c} of 600 nm, $P_{\mathrm{is},600}$ in Fig. 26.2, is calculable by substituting $R_{\mathrm{is},600}$ (=0.1 in Fig. 26.2) into $R_{\mathrm{is},\lambda\mathrm{c}}$ in Eq. 26.4.

$$\begin{aligned} &P_{\mathrm{is},600} = R_{\mathrm{is},600} \frac{\lambda_{\mathrm{c}} \times 10^{-9}}{N_{\mathrm{A}} \cdot h \cdot c} \\ &= 0.1 \times \frac{600 \times 10^{-9}}{(6.022 \times 10^{23}) \times (6.626 \times 10^{-34}) \times (2.998 \times 10^{8})} \\ &= 0.5016 \times 10^{-6} \mathrm{mol m^{-2} s^{-1} nm^{-1}} \end{aligned}$$

It is to be noted that the spectral photon flux density at λ_{c} of 600 nm, taking an approximate value of 0.5 μmol m^{-2} s^{-1} nm^{-1}, means that the photon flux density within a 1-nm wavelength range of 599.5–600.5 nm is 0.5 μmol m^{-2} s^{-1}.

Quantitative relations among the three metrics are held for the other categories (i.e. for the other columns in Table 26.1), e.g. spectral radiant flux, luminous flux and photon flux.

26.6 Photosynthetically Active Radiation

Radiation in the wavelength range of 400–700 nm is regarded as "photosynthetically active radiation". The photon flux density in the wavelength range is therefore designated as "photosynthetic photon flux density" (see Chap. 28 for a detailed explanation). The photosynthetic photon flux density is a frequently measured quantity when plants are cultivated under artificial lighting. Figure 26.4 presents a typical spectral response of a quantum sensor and ideal quantum response for measurement of the photosynthetic photon flux density.

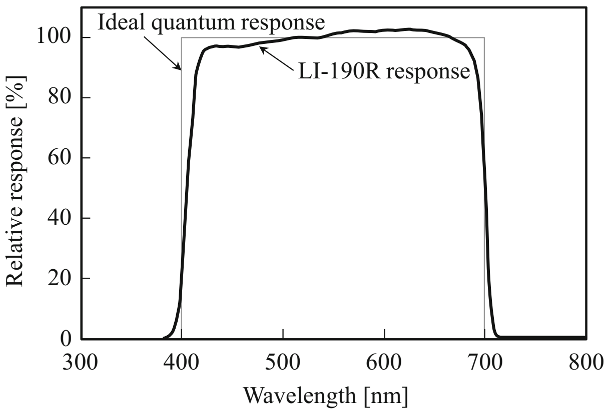

Fig. 26.4 Typical spectral response of LI-190R quantum sensors and ideal quantum response for the measurement of photosynthetic photon flux density (photosynthetic photon irradiance). The figure was redrawn from an LI-190R catalogue

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