LED Lighting for Horticulture

Solid-state lighting is increasingly being used in horticultural applications, including greenhouses and indoor "vertical farms". To meet the needs of the horticultural industry, SSL manufacturers and lighting designers will need to understand the spectral power distribution requirements of photosynthesis for optimal plant health and growth. Ian Ashdown, Chief Scientist of Lighting Analysts, provides an overview of plant action spectra and how to convert lumens and lux into units of PAR and PPFD.

There is a bright future for solid-state lighting in horticulture, including greenhouses and indoor "vertical farms". For SSL product manufacturers and lighting designers, however, the problem is that horticulturalists speak an unfamiliar language. Success in this market will depend on a basic understanding of plant photosynthesis and the spectral power distribution (SPD) requirements for optimal plant health and growth. SSL manufacturers and lighting designers will also need to understand how to convert photometric units of lumens and lux into Photosynthetically Active Radiation and Photosynthetic Photo Flux Density for different light sources, including both white light and quasimonochromatic LEDs. For horticulturalists, the availability of multichannel SSL luminaires with color-tunable SPDs will provide new opportunities to explore the unique spectral requirements of different crops and the integration of SSL products with greenhouse climate control systems.

Plant Photosynthesis

Photosynthesis is the process used by plants to convert electromagnetic radiation - light - into chemical energy that is used for growth and development. All that is needed for this process is carbon dioxide (CO_2), nutrients, and water. The process itself is not particularly efficient; only 4 to 6 percent of the absorbed radiation is converted into chemical energy [9]. Still, it is the engine that drives most life on this planet.

Photosynthetically active radiation (PAR) is defined as electromagnetic radiation over the spectral range of 400 nm to 700 nm that photosynthetic organisms are able to use in the process of photosynthesis to "fix" the carbon in CO_2 into carbohydrates. Horticulturalists measure PAR for both plant research and greenhouse lighting design using specialized photometers [1].

A common unit of measurement for PAR is photosynthetic photon flux density (PPFD), measured in units of moles per square meter per second [i]. In this case, every absorbed photon, regardless of its wavelength (and hence energy), is assumed to contribute equally to the photosynthetic process. This is in accordance with the Stark-Einstein law, which states that every photon (or quantum) that is absorbed will excite one electron, regardless of the photon's energy, between 400 nm and 700 nm. For this reason, photosynthetic photon flux is also referred to as quantum flux.

Whether a photon with a given wavelength is absorbed by a plant leaf is dependent on the spectral absorptance of the leaf, which in turn, is determined largely by the leaf optical properties, including the concentration of plant photopigments such as chlorophyll A and B, various carotenoids (carotenes and xanthophylls), and anthocyanins. (The chlorophylls are responsible for the characteristic green color of leaves; the carotenoids and anthocyanins contribute to the yellow, orange, and red colors respectively of autumn leaves after the chlorophylls decompose.)

Typical absorptance spectra for chlorophyll A, chlorophyll B, beta-carotene, and two isoforms of phytochrome are shown in figure 1. It must be noted, however, that these spectra are approximate. They are measured in vitro by dissolving the pigments as extracts in a solvent, which affects their absorptance spectra. By themselves, they suggest that blue and red LEDs alone are sufficient for horticultural applications. In reality, however, the situation is much more complicated.

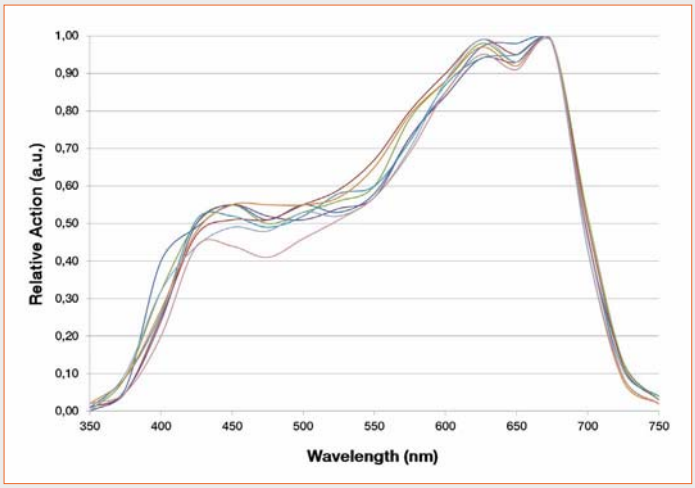
Photosynthetic Action Spectra

McCree [4] measured the quantum yield of CO_2 assimilation for the leaves of 22 species of crop plants [ii]. Taking the average measurements at 25 nm intervals for all plant species, he produced an action spectrum plot (Figure 2) that is representative of most crop plants. -

PHOTOSYNTHESIS AND VISIBLE LIGHT

For illumination engineers, it might seem suspicious that the photosynthetically active radiation is defined over the spectral range 400 nm to 700 nm - exactly the range we commonly assume for human vision. What about longer and shorter wavelengths?

When McCree [4] measured his 22 crop species both in the field and in laboratory growth chambers (with very similar results), he obtained the following action spectra.

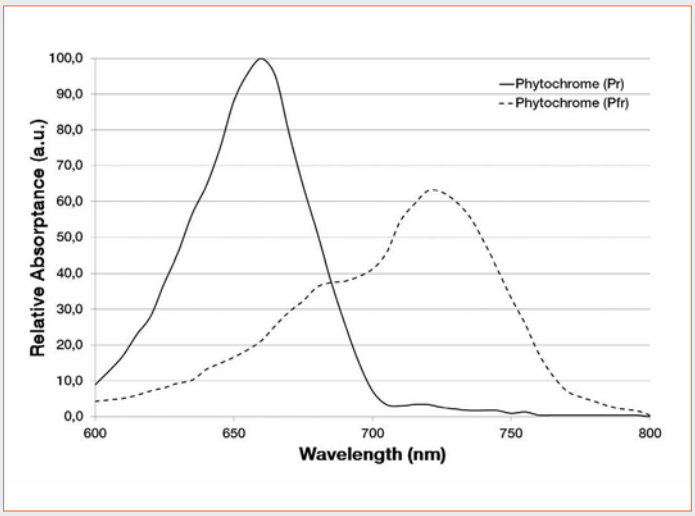


The action spectra clearly explain the logic of the 400 - 700 nm spectral range

Below 400 nm, there is the risk of photooxidation that generates toxic radicals, which can destroy the cell's chlorophyll and other cellular components. Under intense UV radiation , violaxanthin (which is involved in photosynthesis) is converted via the xanthophyll cycle into zeaxanthin. In doing so, it receives excess energy from chlolorphyll and releases it as heat. This process thereby offers the plant photoprotection.

At the same time, other plant photopigments, including cryptochromes and phototropins, do have sensitivities (as measured in vitro) that extend into the ultraviolet, and likely respond under dim light conditions. However, these are likely suppressed under high light conditions by the xanthophyll process.

Above 700 nm, the photon energy is too low to activate the photosynthetic process via the chlorophylls and various cartenoids. However, the phytochrome photopigment, which is responsible for stem elongation, leaf expansion, shade avoidance, neighbor perception, seed germination, and flower induction, has two isoforms called Pr and Pfr. In its ground state Pr, phytochrome has a spectral absorbance peak of 660 nm. When it absorbs a red photon, it converts to its Pfr state, which has a spectral absorbance peak of 730 nm. When the phytochrome molercule absorbs a far-infrared photon, it converts back to its Pr state, and in doing so triggers a physiological change in the plant.



Phytochrome action spectra

Chlorophyllous leaves are transparent to infrared radiation. So the phytochrome signaling mechanism is ideal for sensing the lighting environment on forest floors and in the presence of neighboring plants competing for available direct sunlight.

Ian Ashdown, P. Eng., FIES. Chief Scientist, Lighting Analysts Inc.

An action spectrum is simply a plot of biological effectiveness as a function of wavelength of incident light.

As noted by McCree [4], PPFD is not a perfect measure of photosynthetically active radiation in that it systematically overestimates the effectiveness of blue light relative to red. It is useful, however, in that it is independent of any particular plant species, and it can be measured both in the laboratory and in the field using a radiometer with a spectrally-calibrated quantum sensor such as the LI-190SA from LI-COR [5].

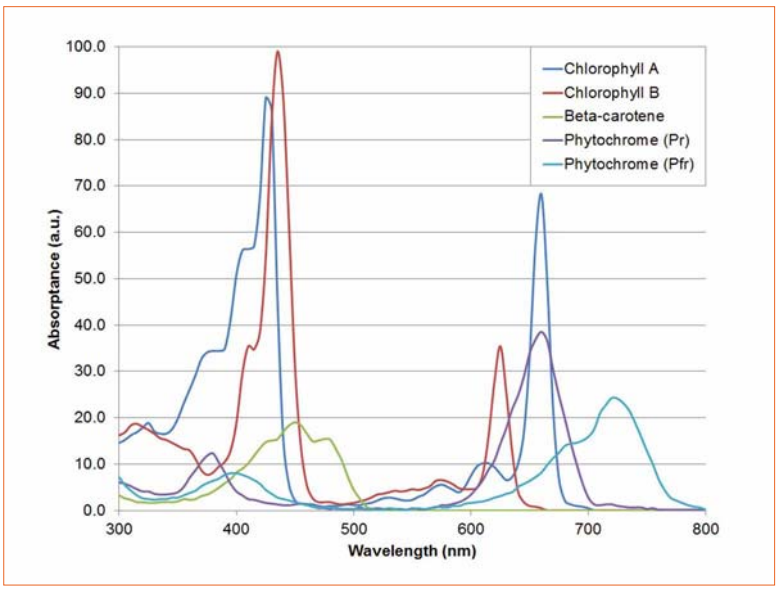


Figure 1:
Photopigment spectral absorptances

Figure 2:
Action spectrum for crop plant photosynthesis

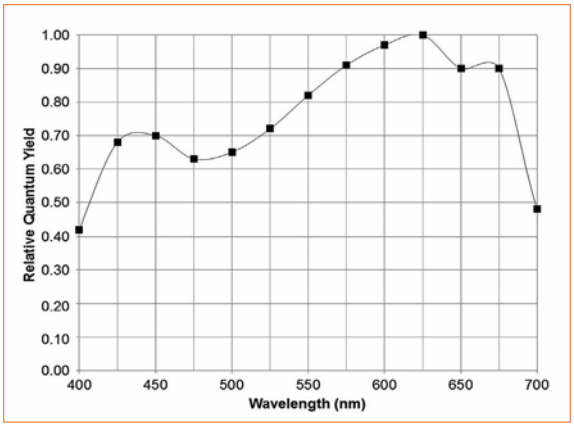


Figure 3:
5000 K LED relative spectral power distribution

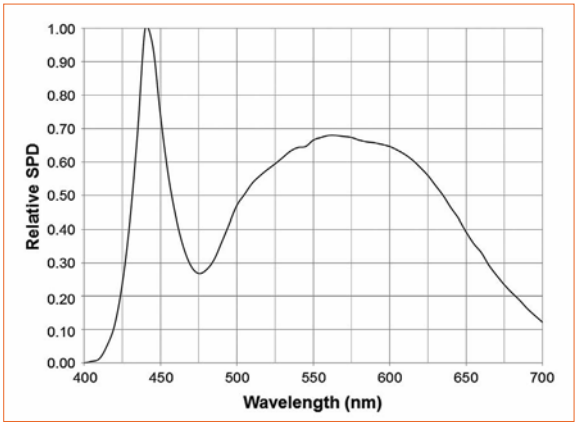
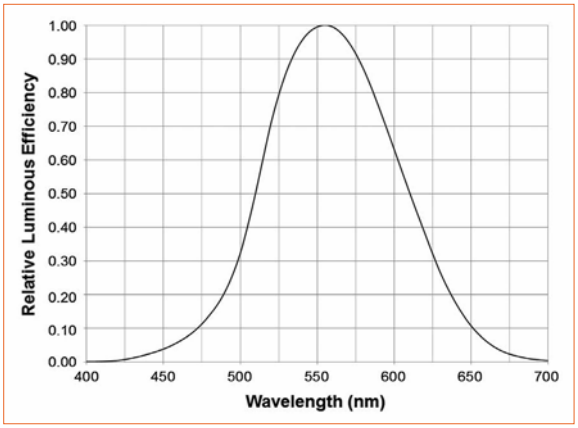


Figure 4:
CIE 1931 luminous efficiency function V(λ)



From Lux to PPFD

As lighting designers, we need some method of converting lumens to quantum flux (PAR) and illuminance to quantum flux density (PPFD). But we can do so only if we know or can estimate the spectral power distribution (SPD) of the light source.

Suppose then that we have a light source with a known relative spectral power distribution (SPD), such as, for example, a typical 5000 K "cool white" LED (Figure 3).

One watt of radiant power at 555 nm is, by definition, equal to 683 lumens. Given the CIE 1931 luminous efficiency function (Figure 4), we can calculate the spectral radiant flux $\Phi(\lambda)$ in watts per nanometer for each lumen as:

$$\Phi(\lambda) / lm = \frac{W_{rel}(\lambda)}{683 \sum_{400}^{700} V(\lambda) W_{rel}(\lambda) \Delta\lambda}$$

where $W_{rel}(\lambda)$ is the relative spectral power distribution, $V(\lambda)$ is the luminous efficiency function at wavelength λ, and $\Delta\lambda$ is the wavelength interval (typically 5 nm). For the above example, the spectral radiant flux per nanometer for each lumen at 440 nm is 22.5 microwatts, while the total radiant flux per lumen is 3.18 milliwatts.

With this, we can calculate the photosynthetic photon flux (PPF) per nanometer in micromoles per second per nanometer:

$$PPF / nm = 10^{-9} \cdot \frac{\lambda \Phi(\lambda)}{(N_a \cdot 10^{-6}) hc}$$

(where N_a is Avogardo's constant), while summing over the range of 400 nm to 700 nm yields the photosynthetic photon flux (PPF) per lumen for the given light source:

$$PPF = \frac{10^{-3}}{N_a hc} \cdot \sum_{400}^{700} \lambda \Phi(\lambda) \Delta\lambda \approx$$

$$8.359\ 10^{-3} \cdot \sum_{400}^{700} \lambda \Phi(\lambda) \Delta\lambda$$

Given an illuminance value (lumens per square meter) and knowing the light source SPD, we can similarly calculate the photosynthetic photon flux density (PPFD) in micromoles per second per square meter (µmol/sec-m²) for the given light source. Again for the above example, one kilolux is equal to 14.62 µmol/sec-m².

Conversion Factors

It is easy enough to find graphical representations of light source spectral power distributions, but it is considerably more difficult to find this information in tabular form suitable for the above calculations. Fortunately, this information is published in CIE 15:4, Colorimetry [2]. It does not include white light LEDs, but this information can be obtained by digitizing manufacturers' product catalog data (e.g., [6]).

Given such information, it is possible to calculate kilolux-to-PPFD conversion factors for common light sources:

Table 1 does not include commercial products such as the Sylvania SHP-TS Grolux (with a CCT of 2050 K) because Sylvania and most other lamp manufacturers do not publish their lamp SPDs in tabular form. It is possible to digitize the graphical representations of white light LEDs because the bandwidth of the blue "pump" LEDs is at least 15 nm. With high-pressure

Light Source	Conversion Factor
CIE A (incandescent, 2856 K)	17.0
CIE 5000K daylight (D50)	28.5
CIE 5500K daylight (D55)	28.0
CIE 6500K daylight (D65)	25.2
CIE 7500K daylight (D75)	22.8
CIE HP1 (standard HPS, 1959 K)	3.9
CIE HP2 (color-enhanced HPS, 2506 K)	13.0
CIE HP3 (metal halide, 3144 K)	9.2
CIE HP4 (metal halide, 4002 K)	9.0
CIE HP5 (metal halide, 4039 K)	13.9
2700 K white light LED	16.9
3000 K white light LED	18.2
3500 K white light LED	17.4
4000 K white light LED	17.7
5000 K white light LED	14.6

Table 1:
Illuminance (kilolux) to PPFD (µmol/sec m^2) conversion factors

sodium and metal halide lamps, however, it is impossible to digitize their published SPDs because the wavelength resolution is unknown. A subnanometer-wide line emission, for example, could vary in height by five times, depending on whether the wavelength binning is 1 nm or 5 nm.

LED Lighting for Horticulture

At this time, high-pressure sodium (HPS) lamps are the most common light source for greenhouse lighting, where it is commonly used to supplement daylight during the winter months. However, with the growing interest in urban horticulture that relies exclusively on electric lighting, light-emitting diodes offer many advantages. This is particularly true for multilayer cultivation, where the close spacing of plants in vertical rack-mounted trays make HPS lighting impractical.

McCree [4] noted that the relative quantum yield for crop plant photosynthesis has two peaks at 440 nm and 620 nm. He also noted however, the Emerson effect, which states that photosynthesis in the presence of two or more wavelengths can be more efficient than the sum of that due to the individual wavelengths. In particular, adding white or blue light to deep red light can beneficially increase the rate of photosynthesis.

Green light is also used in photosynthesis, as can be seen from the crop action spectrum (Figure 2). It has been established that green light drives photosynthesis more effectively than red or blue light deep within the leaf [8]. Further, the insects used in greenhouses as pollinators and biological control agents see best in the green and ultraviolet regions of the spectrum.

It is likely, for this reason, that many horticultural LED modules feature efficient 450 nm indium-gallium-nitride (InGaN) deep blue LEDs and 660 nm aluminum-indium-gallium phosphide (AlInGaP) deep red LEDs. Typical examples of these LEDs are the Philips Luxeon Royal Blue and Deep Red products [7]. Both of these products are quite efficacious, converting some 45% of their electrical input power into visible light. Green LEDs, while beneficial, are rarely used because of their much lower radiant efficacies. (This may soon change however, as Osram Opto recently announced the development of 530 nm InGaN green LEDs with 25% external quantum efficiency.)

Herein, however, lies a problem: 450 nm and 660 nm are close to the limits of our color vision (Figure 4). Consequently, Philips and other manufacturers typically express the optical performance of these products in radiometric rather than photometric terms - milliwatts instead of lumens.

So, the lighting design process becomes a bit more complicated. We first need to digitize the published LED spectral power distributions to determine the conversion factors between milliwatts and lumens - these will be needed for the lighting design simulations. These are given by:

$$\Phi_L = 0.683 \cdot \frac{\sum_{400}^{700} \Phi_R(\lambda)\, V(\lambda)}{\sum_{400}^{700} V(\lambda)}$$

where Φ_L is the luminous flux, $\Phi_R(\lambda)$ is the relative spectral radiant flux and $V(\lambda)$ is the luminous efficiency function at wavelength λ.

Using the Philips Luxeon Royal Blue and Deep Red products as an example, the conversion factors are approximately 0.07 and 0.03 lumens per milliwatt (lm/mW) respectively. However, these figures must be approached with some caution, as they apply to 450 nm and 660 LEDs only. If, for example, the peak wavelength of deep blue LED was 440 nm rather than 450 nm, the conversion factor would be 0.05 lm/mW. Similarly, if the peak wavelength of the deep red LED was 650 nm rather than 660 nm, the conversion factor would be 0.06 lm/mW. The Philips LED binning ranges are 440 to 460 nm and 650 to 670 nm respectively, which equates to (from Figure 4) conversion factor uncertainties of +75%, -50% for blue and +60%, -30% for red. The above conversion factors are therefore decidedly approximate.

(Some horticultural LED module manufacturers bin their LEDs more tightly, as peak maxima shifts as small as 10 nm have been shown to have dramatic effects on plant

Figure 5:
Test installation for horticulture lighting (Credits: Aeon Lighting Technology Inc. - www.aeonlighting.com)

growth. However, unless the binning policy is stated in the manufacturer's product literature, this cannot be assumed.)

A further word of caution: even the best illuminance meters can be wildly inaccurate when measuring deep blue and deep red light levels. Commercially available photometers are usually classified according to their f1' number (with f1' < 3% being preferred), which is basically a measure of how closely the spectral response of the meter matches that of the photopic visual efficiency function (Figure 4). As noted in CIE 127:2007, Measurement of LEDs [3], this is useful for white light measurements only. To quote, "In the case of single-color LEDs, the spectral mismatch errors can be very large even if f1' is reasonably small, due to the fact that some LED spectra are peaking in the wings of the *V(λ)* function where the deviation makes little effects on f1' but can cause large errors."

With these conversion factors in hand, we can now calculate the approximate illuminance-to-PPFD conversion factors for horticultural LEDs:

Table 2:
Illuminance (kilolux) to PPFD (µmol/sec-m2) conversion factors

Light Source	Conversion Factor
450 nm deep blue LED	14.3
525 nm green LED	1.0
660 nm deep red LED	15.6

How horticulturalists choose to balance the ratio of red to blue light will likely depend on the specific plant species being cultivated and their stage of growth. Some plants like shade, while others prefer direct sunlight, with different SPD requirements. Regardless, the above conversion factors will still be useful.

In addition to using chlorophylls and carotenoids for photosynthesis, plants use these and other photopigments for a wide variety of functions. The phytochromes Pr and Pfr, for example, respond to 660 nm red and 735 nm infrared radiation respectively, and in doing so induce seed germination and flowering, regulate leaf expansion and stem elongation, and trigger photoperiod and shade avoidance responses.

Other photopigments regulate phototropism (leaf and stem orientation) and circadian rhythms (for which blue light is the most effective), photomorphogenesis (plant shape), root growth, stomatal opening, chloroplast movement, etc. The list goes on, as horticultural researchers continue to explore the role between lamp SPDs and optimal plant health and growth [iii].

Summary

As a reminder, photosynthetically active radiation (PAR) does not consider the spectral response of plants (Figure 2); it simply represents the number of photons (quanta) per unit area per second within the range of 400 to 700 nm. With the availability of color-tunable LED modules for greenhouse lighting, horticulturalists will likely want to experiment with different SPDs for specific crops and flowering plants, as well as both the directionality and daily timing of the luminaires. Regardless, being able to convert predicted and measured illuminance values to PPFD values for common light sources will certainly ease the communication problems between lighting designers and horticulturalists. ■

Notes:

[i] A mole is a unit of measurement used in chemistry to express the number of elementary entities in a substance that is equal to the number of atoms in 12 grams of the isotope carbon-12. It corresponds to the Avogadro constant, whose value Na is 6.022 10^{23} particles (in this case photons) per mole. A micromole is one millionth of a mole

[ii] The quantum yield in photosynthesis is defined as the micromoles of carbon dioxide fixed per micromole of photons absorbed

[iii] See www.photobiology.info for an informative summary of plant photobiology

References:

[1] Barnes, C., T. Tibbitts, J. Sager, G. Deitzer, D. Bubenheim, G. Koerner, and B. Bugbee. 1993. "Accuracy of Quantum Sensors Measuring Yield Photon Flux and Photosynthetic Photon Flux," Horticultural Science 28(122):1197-1200.

[2] CIE. 2004. Colorimetry, Third Edition. CIE Technical Report 15:2004. Vienna, Austria: Commission Internationale de l'Eclairage.

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[4] McCree, K. J. 1972. "The Action Spectrum, Absorptance and Quantum Yield of Photosynthesis in Crop Plants," Agricultural and Forest Meteorology 9:191-216.

[5] www.licor.com

[6] Philips Lumileds. 2014a. Luxeon Rebel ES Portfolio Datasheet DS61. Philips Lumileds Lighting Company.

[7] Philips Lumileds. 2014b. Luxeon Rebel Color Portfolio Datasheet DS68. Philips Lumileds Lighting Company.

[8] Terashima, I., T. Fujita, T. Inoue, W. S. Chow, and R. Oguchi. 2009. "Green Light Drives Leaf Photosynthesis More Efficiently than Red Light in Strong White Light: Revisiting the Enigmatic Question of Why Leaves are Green," Plant & Cell Physiology 50(4):684-697.

[9] Zhu, X.-G., S. P. Long, and D. R. Ort. 2010. "Improving Photosynthetic Efficiency for Greater Yield," Annual Review of Plant Biology 61:235-261.