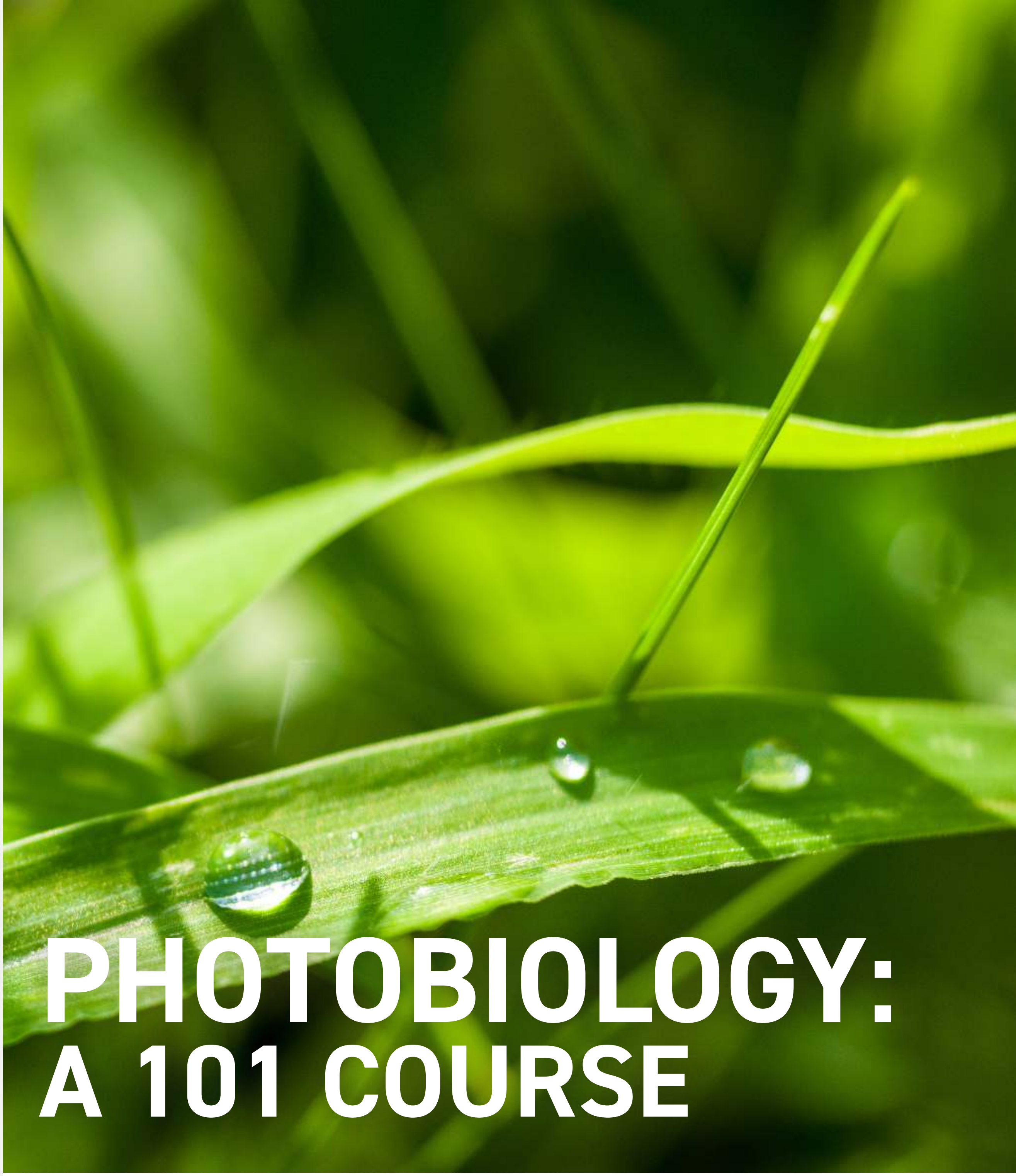
A Reference for the Professional Grower



PHOTOBIOLOGY: A 101 COURSE

A discussion on photobiology and how it affects the indoor farming industry.

SpecGradeLED
Committed to Increasing Yields

Horticultural lighting 101

What is light?
Defining light is quite important for accurately understating plant lighting. The simplest answer may be that light is 'visible radiation' sensed by human eyes. Human eyes see light as having various colors depending on the wavelength, a characteristic of light. Our eyes can sense light that has wavelengths between 380 nm (dark purple) to 780 nm (dark red) with the peak sensitivity around 550 nm (yellow green) (Figure 1). At both edges of this range, our eyes do not have very good sensitivity and therefore, these colors are very dark to our eyes. Plants see (sense) light over the range similar to human eyes but plant responses to different wavelengths of light are different from human eyes.

Visible light is part of electromagnetic radiation and so light is particles (photons) traveling in space like waves (Figure 2 and 3). Light is typically a mix of photons having different wavelengths. Human eyes sense light with different wavelengths as different colors and based on how human eyes sense, visible light is further classified into different colors. In this article, we use the following classifications relative to wavebands: 1) ultraviolet (300-400 nm), 2) blue (400-500 nm), 3) green (500-600 nm), 4) red (600-700 nm), 5) far-red (700-800 nm).

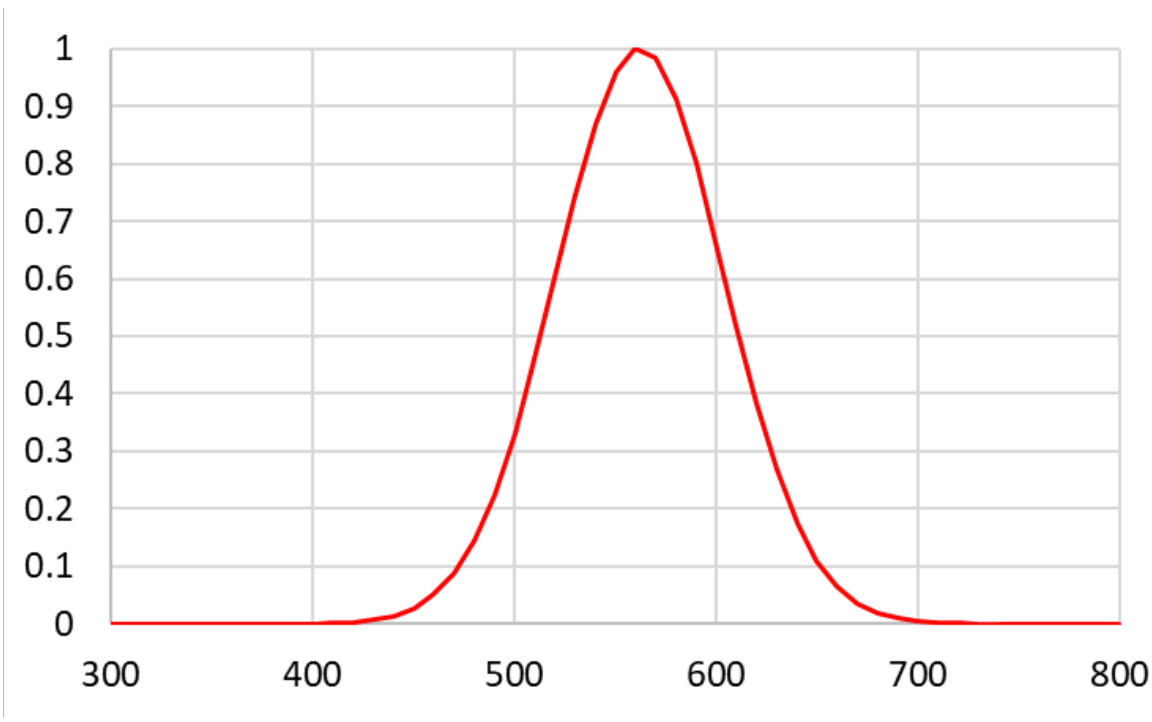


Figure 1. Luminous efficiency curve showing the human eye sensitivity peaking between 500-600 nm (green light).

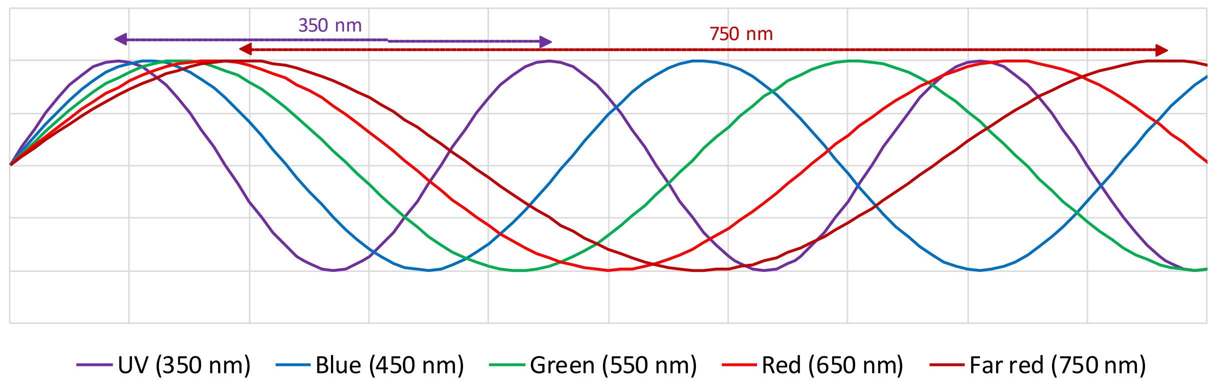


Figure 2. A diagram showing waves of photons traveling in space. Different wavelengths are perceived as different colors. Ultraviolet, blue, green, red, and far-red photons with 350, 450, 550, 650, and 750 nm are shown as example.

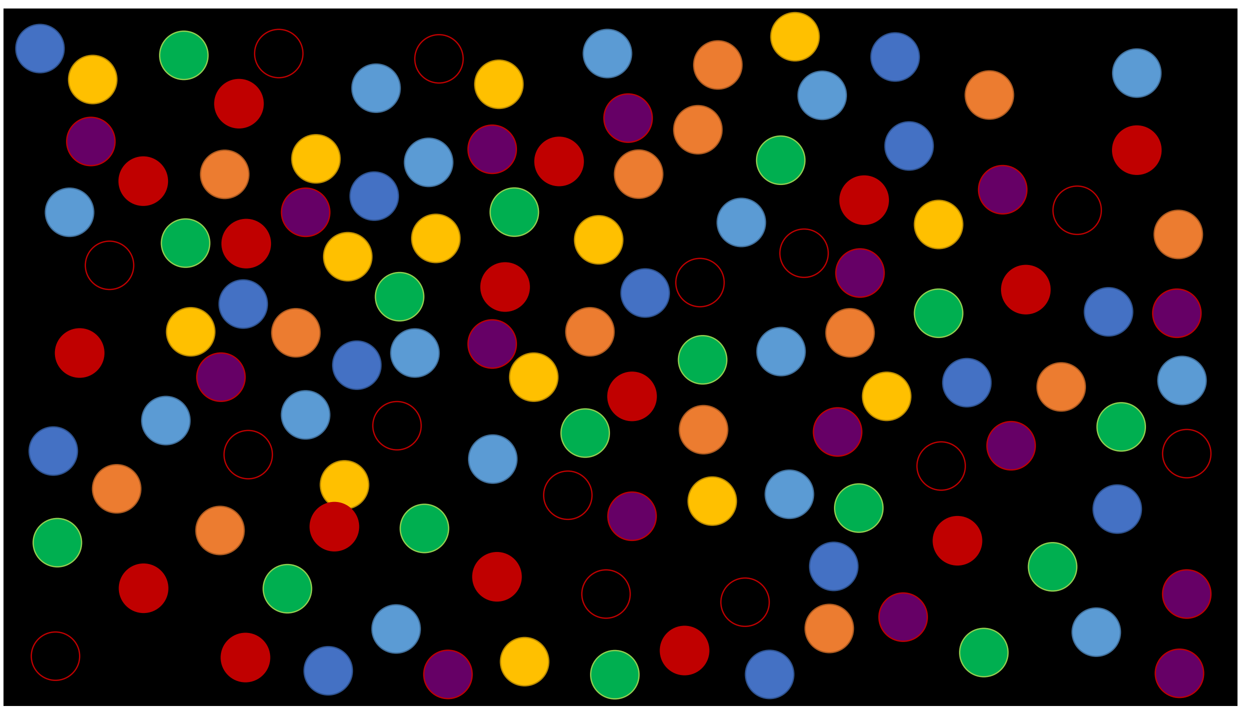


Figure 3. Light consists of photons of many colors traveling in space. Some photons are non-visible (no color).

Light drives plant photosynthesis

Plants have light harvesting pigments to capture light and transfer the energy to drive photosynthesis to grow (increase biomass). Chlorophylls are the major photosynthetic pigments and absorb photons of wavelengths between 400 nm and 700 nm with distinct peaks in red and blue range. Many people misunderstand that plants do not use green light (500-600 nm). However, because of leaf structure and contents of other pigments, leaves can absorb green light and use it for photosynthesis in addition to red and blue light. However, green light does have a slightly lower efficiency to drive photosynthesis, as leaves tend to reflect a bit more green than red or blue light.

Figure 4 shows photosynthetic efficiency of typical leaves grown under controlled environment. As the figure shows, plant photosynthesis is driven in the range of 400-700 nm and therefore this range of light is defined as photosynthetically active radiation (PAR). This curve is often called the McCree curve after the scientist who conducted the research using plants of many different species.

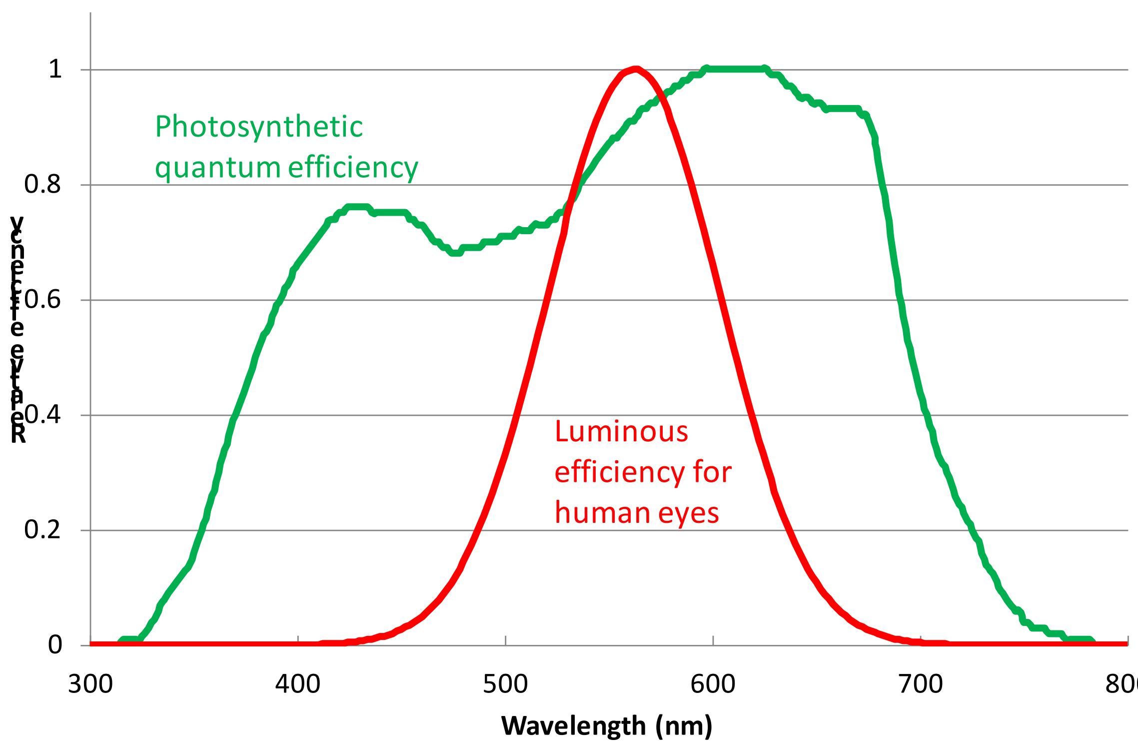


Figure 4. Photosynthetic quantum efficiency (after Sager et al. (1998) and McCree (1972)). A luminous efficiency curve based on human eye response was included for comparison.

The PAR absorbed by plant leaves drives photosynthesis. This means that plants use that light energy and produce carbohydrate used for their growth. In addition to light, plants need water, carbon dioxide (CO_2) as well as good temperature conditions for photosynthesis to occur and any one of them can be a limiting factor to slow down the photosynthetic rate. Under conditions without such limitations, light is the most influential driver for plant growth. Instantaneous light intensity is called photosynthetic photon flux density (PPFD) and its measurement unit is µmol m^{-2} s^{-1} (micro-mole per square meter per second). Sunlight in midday in summer can reach 2000 µmol m^{-2} s^{-1} and cloudy winter day may not even exceed 100 µmol m^{-2} s^{-1} PPFD.

Growth of plants cultivated at high density is typically limited by availability of light, and lower leaves are typically under shadow created by upper leaves. Therefore, total amount of PAR available for plants dictates the potential plant growth. This is why PAR is measured not just as instantaneous intensity, but also as a total amount available for a day. This daily cumulative measurement is called daily light integral (DLI) and the unit is mol m^{-1} d^{-1} (mole per square meter per day). Natural light (sunlight) can provide as high as 60 mol m^{-2} d^{-1} DLI outdoor in summer and as low as 1 mol m^{-2} d^{-1} DLI in dark winter in northern states. A web-based DLI map developed by Logan and Faust (2018) is a very useful resource to find the outdoor DLI in your selected locations.

Greenhouse tomato is a good example where the plant growth and therefore tomato fruit yield are highly correlated with DLI. Most greenhouse and indoor crops have such good correlation, meaning that their growth and productivity increase almost linearly with increasing DLI, with some exceptions. One such exception is lettuce which may exhibit a disorder caused by calcium imbalance caused by the fast growth under high DLI. For such crops, it is very important to find the upper threshold DLI that does not cause such disorders (typically between 12-17 mol m^{-2} d^{-1} DLI). Table 1 shows typical signs of plants when DLI is too low to be productive and Table 2 shows anecdotal minimum and optimum DLI recommended for different crops by researchers.

Table 1. Typical appearances of plants under low daily light integral (DLI).

	Not enough DLI	**Optimum DLI**
Overall vigor	Weak	Strong
Plant height	Elongated	Compact
Leaf color	Pale green	Dark green
Leaf shape	Elongated	Round
Leaf thickness	Thin	Thick
Flowers	Fewer	More
Fruit size	Small	Large
Productivity	Low	High

Table 2. Minimum and optimum daily light integral (DLI, mol m^{-2} d^{-1}) recommended for different crops. Recommendations modified from Dorais et al. (2016).

	Seedlings	Lettuce	Cucumber	Tomato	Strawberry
Minimum DLI	12	12	12	12	12
Optimum DLI	15-20	15-20	> 30*	> 30*	15-25**

*Higher DLI than 30 mol m^{-2} d^{-1} as long as temperature is in optimal range.
**Suggested by Chieri Kubota (the Ohio State University).

Light quality changes plant architecture and shape
Light quality (colors of light) affects plant growth in two ways. One is through photosynthesis and the other is through photomorphogenesis (shape and flowering). As described above, photosynthetic efficiency is slightly different for different colors (wavelengths) of light. McCree curve (Figure 4) tells you that red light is the most efficient light, followed by blue and then green. While green light has the lowest efficiency, green light can penetrate deeper in the plant canopy due to its high transmittance and reflectance. Therefore, theoretically, photosynthetic efficiency of a dense plant canopy should be more equalized over 400-700 nm range. In fact, a research group in the Netherlands showed that plants growing at a high density exhibited photosynthetic efficiency of green light similar to red light. This is quite useful information for indoor farms as it means that plant morphological response to light qualities and the lighting electric energy use efficiency are more critical than photosynthetic response to light qualities.

This light quality effect on plant growth and morphology (architecture) is a very intensively studied area of modern horticultural science, partly because of the advanced lighting technologies such as LEDs (light emitting diodes) that would virtually create desirable spectra. As a result of such studies, we have now fairly good understanding of effects of blue (400-500 nm), red (500-600 nm) and far-red (700-800 nm) light on plant morphology. For example:

- Blue light makes the plants more compact. More blue light proportion in the spectrum makes smaller plants at the same PPFD.
- UV and blue light promote pigmentation. More intensive color development can be expected under light containing higher UV and blue light. Anthocyanins, pigments that make plants look red or purple, are particularly responsive to UV and blue light.
- Far-red light makes the plants taller. However, this function is relative to red light. When far-red light is relatively greater to red light, plants tend to stretch and become taller.

Sunlight spectrum typically has ~30% blue and ~35% red out of PAR (400-700 nm) and it has far-red light at about the same proportion as red light. Sunlight contains not just PAR, and its waveband range is in fact much wider (300-2500 nm). PAR proportion is less than half of sunlight (energy basis). The rest of sunlight is mainly near infrared light (thermal radiation) and a small amount of UV light (300-400 nm) (Figure 4). When you grow plants under the same PPFD and DLI, but different light quality of electric lighting, you may see plant architecture, color and overall growth being very different from what you see under sunlight. Many scientists and engineers work to find the optimum light intensity, quality, and application timing to achieve more productivity and improve product quality. International conferences focusing on horticultural lighting have been held once in 4 years hosted by various research groups (e.g., Michigan State University in 2016).

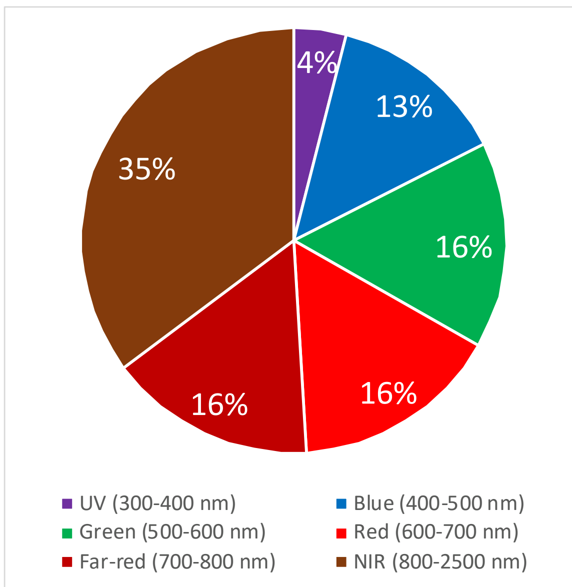


Figure 5. Percentages of radiation of different wavebands in sunlight (300-2500 nm).

Day/night duration triggers flowering response

Plants sense environmental cues that result in reproductive growth. Photoperiod (length of day) and temperature are two major factors affecting initiation of flower development. While some plants are insensitive to photoperiod (called day-neutral plants), many plants are known as 'photoperiodic'. Photoperiodic plants require time periods of light either longer or shorter than a specific threshold length to initiate flower development (otherwise no flowers are developed or are largely delayed). Based on the response, plants are classified as 'short day' and 'long day' plants. For example, a cultivar of chrysanthemum is a short-day plant that has a critical daylength of 14.5 hours. This means that plants develop flowers under any hours of daylength shorter than 14.5 hours (e.g., 11, 12, 13, and 14 hours) but not under hours longer than 14.5 hours (e.g., 15, 16, 17, and 18 hours). This knowledge is applied in flowering initiation for finishing pot mums (by assuring short days) as well as preventing flowering for cutting propagation (by assuring long days) in chrysanthemum.

We also know that for most cases the length of night is more critical than the day length. This means that critical photoperiod requirement is in fact a critical night period requirement. Short-day plants are in fact long-night plants. It is important to remember that the night period must be uninterrupted when you want to assure the necessary length of night period. Breaking the long night in the middle to make two periods of shorter nights has the same influence of a "long day" (Figure 6). This understanding is applied as a technology called night interruption lighting, which is in fact widely used to prevent flowering in the propagation of short-day plants.

It is also important to know that plants can sense light at very low intensity. Therefore, PPFD as low as 1-2 μmol m^{-2} s^{-1} received by plants is effective to trigger the cue for preventing or initiating flower development. This actually means that a small amount of contaminating light from surrounding greenhouses where a much stronger light is used needs to be avoided when photoperiodic plants are grown under short day condition. It also means that growers do not need to place too many lights if initiating flowers is the main purpose of lighting (instead of driving photosynthesis). Some plants are sensitive to light quality of photoperiodic lighting and so it is recommendable to consider a balanced red and far-red light (approximately 1:1 ratio, similar to sunlight).

Plants also need repeated exposure to an effective photoperiod (night period) inducing flowers. The exposure needed to see the visible response (under microscope) is typically 3-4 weeks under optimum temperature conditions and the time to actually see open flowers needs additional several weeks depending on the crop species and cultivar. Therefore inducing flowers requires precise scheduling as well as management relative to the target timing of flowering.

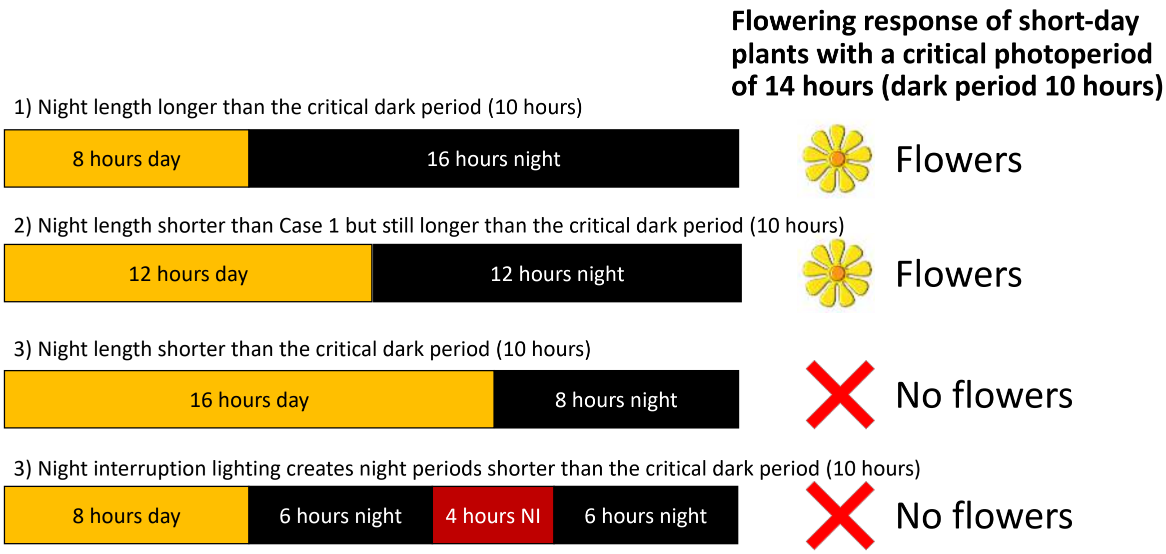


Figure 6. Examples of short-day plant flowering response under different photoperiods (dark periods).

How do you measure light?

As mentioned earlier, human eyes have the highest sensitivity in green and yellow (the waveband between blue and red). This response is very different from what plants respond to and this is why light measurements for human environment (lumen, lux, and foot-candle) are absolutely useless for evaluating light environment for plant growth. Human eyes also have a mechanism to adjust their eyes to adapt to various levels of light. This allows us to see things under fairly low light conditions; however, the same ability makes it difficult for the human eye to accurately tell the actual light level in the environment. Furthermore, human eyes have the ability to adjust specific color sensitivities to normalize (to some extent) object colors seen. For example, when you are in a light environment deficient in green light, your visual system would try to increase the sensitivity to green color, so that green objects (such as plants) in such a biased light environment can appear greener to your eyes. This is the very reason why things look greenish the moment you return to a normal light environment from a red and blue light environment. Therefore, your eyes are an unreliable sensor to measure how much light and what colors of light are in the environment. So *don't judge plant light environment, based on how it looks to your eyes!*

As seen in this article, the most appropriate measurements for plant lighting for photosynthesis is photon-base, and so they are measured in units of µmol m^{-2} s^{-1} (instantaneous) or mol m^{-2} d^{-1} (cumulative). These units express the amount of photons having the specific wavelength received by a horizontal unit area of one square meter per unit of time (second or day). If a sensor measures photons of 400-700 nm, these values are photosynthetic photon flux density

(PPFD). If the sensor measures another range, for example 400-500 nm (blue), the values can be called blue photon flux density. Ratios of these photon flux densities measured for different ranges are often used to evaluate light quality. A red-to-far-red ratio is a good example widely used among scientists. To find these waveband-specific photon flux densities, you will need to use a spectroradiometer that can provide light measurements at different wavelengths.

For measuring solar DLI in greenhouse, you will need to record the PPFD inside the greenhouse over the entire light period using a climate controller or an independent recording device. Measurement frequency should be more than hourly to achieve better accuracy. Greenhouse computers should be programmed to average PPFD over 15-30 min intervals to find the cumulative value (DLI) over the day. In contrast, finding DLI is very simple in indoor farms where the electric lighting is the sole source of light, from the PPFD (value per second) and photoperiod (Table 3).

In addition to these units, energy-based units (W m^{-2} for instantaneous measurement and MJ m^{-2} d^{-1} or J cm^{-2} d^{-1} for cumulative measurement) are used for sunlight as it contains more thermal radiation and is valuable for greenhouse environment control. Weather station data sometimes use another unit for cumulative solar radiation, ly (Langley), which is defined as calories per square centimeter (1 cal = 4.18 J). Energy-based measurements and photon-based measurements are inter-convertible as long as the correct conversion factor is known. These factors are light source specific as energy level per photon is wave-length specific. For sunlight, 1 W m^{-2} sunlight contains approximately 2 µmol m^{-2} s^{-1} PPFD. Therefore, when your greenhouse or weather station reports that there was 400 W m^{-2} solar radiation, PPFD is roughly estimated as 800 µmol m^{-2} s^{-1}.

How to improve your light environment in greenhouse and indoor farms

To increase DLI in greenhouse, installing supplemental lighting is a typical approach. From the target PPFD and duration of lighting, you can compute the additional DLI you can add to your solar DLI (Table 3). PPFD can be increased by increasing number of light fixtures to place in the space or replacing the fixtures with ones with higher output. Reduction of DLI of supplemental lighting can be done either by reducing number of hours of illumination or reducing PPFD (number of light fixtures or fixture light output if dimmable). Typically during summer in greenhouse, there is a need to reduce the solar DLI. Use of an external or internal shade screen of selected shade percentage is common as is applying removable whitewash over glazing.

Improving light quality of greenhouse can be done to some extent by selecting glazing materials and/or supplemental light quality. However, selections of glazing materials need to be done carefully as it is a permanent change, which is difficult to reverse especially for glazings that have a long operation life (glass, rigid plastic panel, or long-life film). As sunlight acts as the main light source in greenhouse, impact of supplemental light quality may be less pronounced than that in indoor farms where the electric light is the sole source.

Table 3. Daily light integral (mol m^{-2} d^{-1}) achieved by different instantaneous light intensity (photosynthetic photon flux density, PPFD) and daily operation hours.

PPFD (µmol m^{-2} s^{-1})	8 hrs	10 hrs	12 hrs	14 hrs	16 hrs	18 hrs	20 hrs
50	1.44	1.80	2.16	2.52	2.88	3.24	3.60
100	2.88	3.60	4.32	5.04	5.76	6.48	7.20
150	4.32	5.40	6.48	7.56	8.64	9.72	10.80
200	5.76	7.20	8.64	10.08	11.52	12.96	14.40
250	7.20	9.00	10.80	12.60	14.40	16.20	18.00
300	8.64	10.80	12.96	15.12	17.28	19.44	21.60

Tips for horticultural lighting design

When electric lighting is the concern, the most important characteristics to consider depend on the application purpose of the lighting – what you expect by installing lighting. Selection criteria for greenhouse lighting and indoor lighting may be different. Growers who manage multiple species with diverse lighting requirement may want flexibility or versatility of light intensity and quality. Facility design and usage need to consider when short-day plants and long-day plants are grown in the same operation. Regardless, energy conversion efficiency is a common criterion for energy savings of lighting. The efficiency must be expressed in µmol J^{-1} rather than the more generic or human sensitivity-driven measurement, lm W^{-1} (lumen per watt). This is because, lumens are measurements representing human eye response. For example, blue and red LEDs have very high efficiency in µmol J^{-1} but very low efficiency in lm W^{-1}. Other criteria include 1) beam angle, 2) uniformity of light distribution over target area, 3) light quality, and 4) resilience to moist or dusty environment.

References and useful information

Dorais, M., C. Mitchell, and C. Kubota. 2017. Lighting greenhouse fruit vegetables. In: R. Lopez and E.S. Runkle (eds.) Light management in controlled environments. Meister Media

Logan, J. and J. Faust 2018. U.S. Daily light integral map. https://myutk.maps.arcgis.com/apps/MapSeries/index.html?appid=d91ba9eb487d43f3a82161a1247853b6

McCree, K.J. 1972. The action spectrum, absorbance and quantum yield of photosynthesis in crop plants. Agricultural Meteorology 9:191-216.

Sager, J., W.O. Smith, J.L. Edwards, and K.L. Cyr. 1998. Photosynthetic efficiency and phytochrome photoequilibria determination using spectral data. Transactions of the ASAE 31:1882-1889.