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WHAT LIGHT DO PLANTS NEED?

What Light Do Plants Need?

By Michael Roberts

Abstract

Agricultural (or Horticultural) lighting (plant/grow lights), are widely used in greenhouses, with and without glass walls/ceilings, and in other locations for example, grow tents or indoor controlled environments with no natural daylight; to either replace, or augment, natural sunlight (daylight) in the growing of many different types of crops. These crops may include, peppers, tomatoes, leafy greens, herbs, flowers or medicinal plants.

In many cases, the most popular type of lights used are HID (Metal Halide or High Pressure Sodium) lamps. These lamps are generally deficient in spectrum of the light delivered to the plants, and the electrical energy needed to operate the plant/grow-lights accounts for a significant amount of the input costs involved in the production of the crops.

This paper discusses the various curves used to quantify the light spectrum that is most desirable for plant cultivation. The information provided herein relies on publically available scientific research, and references are provided where they are available.

This paper also compares the various plant-light solutions already on the market, comparing the spectrum of each type, with the standard curves for plant light absorption.

Introduction

In many locations, artificial lighting, plant/grow lights, are used for the production of agricultural crops. The plant/grow-lighting is used for a number of reasons:

- In a greenhouse setting where natural light is available, seasonal variations in the hours of daylight available may require artificial lighting to augment the natural light (daylight "bookends", or "daylight-extension") – this is usually in more northern and southern latitudes where seasonal daylight hour variations are greatest.
- Even when abundant natural light is available, it may be desirable to use artificial lighting to extend the number of hours of light exposure the plants receive, in order to "force" growth, to increase crop yields, or to shorten growing cycles.
- The use of artificial lighting allows for plants to be grown in locations where no existing light is available such as in underground or enclosed locations, or in places such as the arctic, where the ambient environment is hostile to the growth of many types of plants.
- The use of artificial lighting also allows some kinds of plants to be grown in regions where existing sunshine is too plentiful and the heat of the sun would dry out, or burn, the plants.
- Artificial lighting, in an enclosed location where no natural light is allowed to enter such as a "Food Factory", also allows for control of many other variables such as humidity, CO_2 concentrations, etc., so as to provide optimum and controlled conditions for the cultivation of specific plant types.
- In a controlled environment, artificial lighting can also allow for changes in light levels (intensity), or light output spectrum, so as to more closely tailor the lighting conditions to the plant's requirements.

T5HO Installation in a California Greenhouse (Photo courtesy of Marigold Lighting)

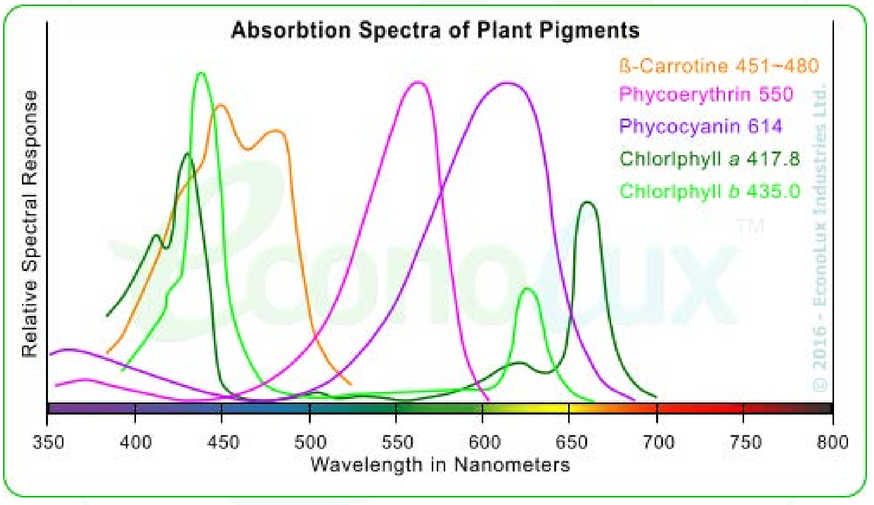
What Light Do Plants Need?

Light, which is a form of energy, is used by plants for producing food through the process of photosynthesis. The spectral composition of the light in the plant's environment is used to activate pigment cells (colored cells in the plant). The light affects the developmental aspects of the plants such as size, proportion of shoots to roots, flowering/fruiting, etc.

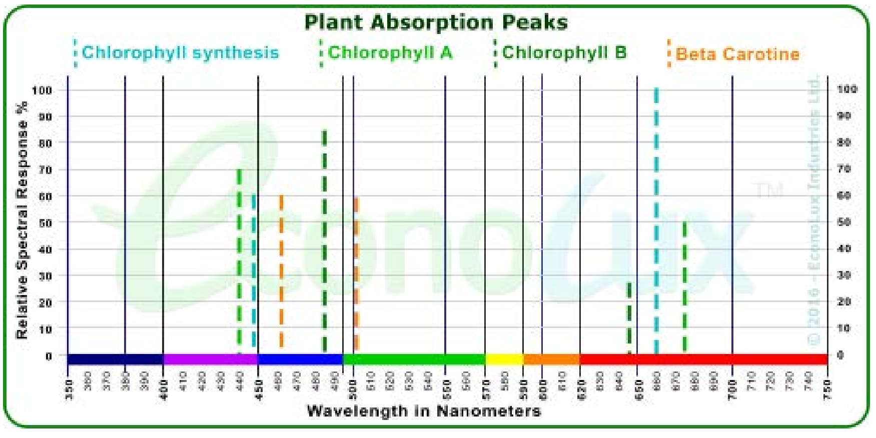
The spectrum typically used by plants lies between 380nm (UVA/deep blue) and 750nm (Infra Red). The portion of the spectrum that lies between the 400nm and 700nm wavelength region is known as Photosynthetically Active Radiation or PAR.[1] Generally speaking, plants also make some use of light in the region between 380nm and 400nm, and between 700nm and 750nm, which includes UVA, and Infra Red light. Some plants also make use of light in the UVB region for coloration development.

Within the Photosynthetically Active Radiation range of the spectrum, various pigments and photosensitive compounds in the plants have peak absorption of differing amounts and at different wavelengths (colours), mostly in the blue and red regions of the spectrum. The majority of the green light is reflected back towards the eye, which is why plants look green.[2] For example, Beta Carotene (the substance that gives carrots their yellow/orange colour) has absorption peaks at around 462nm and around 501nm.

The graph below shows the various absorption peaks of the major photosensitive substances in plants which require light:

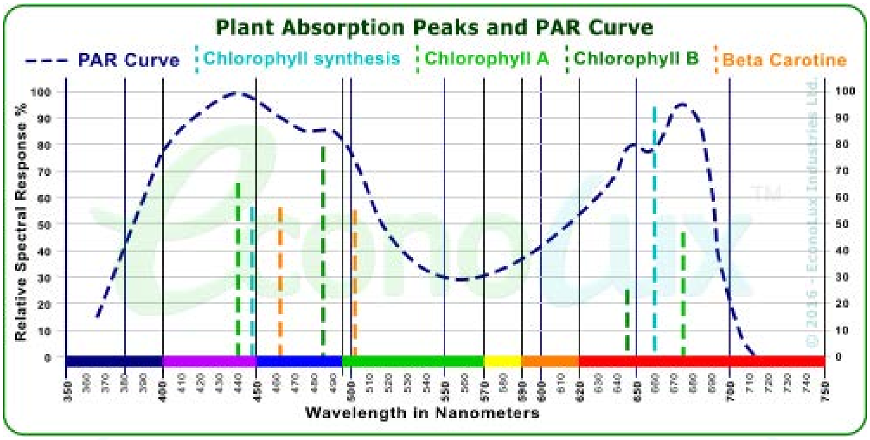


Generally speaking, the major photosensitive substances in plants, Chlorophyll A, Chlorophyll B, Beta Carotene, and Chlorophyll synthesis are taken into account. This is not to diminish the importance of other substances, or the so called "antenna pigments" in plants, but it does simplify the diagrams. Here is a simplified chart of the plant absorption peaks:



The PAR Curve [1]

We can average out this information, and plot it into a generalized curve, which indicates the spectrum of light that plants need. This curve is call the PAR curve and is the oldest and still the most popular way of determining the light that plants need. Here is a graph of the PAR curve (dashed dark blue line), plotted with the plant absorption peaks from the previous page:



Note that in reality, the PAR curve is an average of the light absorption needs of plants. In actual fact, different plants have slightly different PAR curves as the different species absorb light in different ways. In order to come up with the PAR curve we are using in our graphs, we averaged the PAR curves from a number of different plant types.

You will note that the PAR curve has its peak (100%) in the Blue region, around 440nm, and another, lower, peak in the red region around 675nm. You can also see that the plants don't use much of the light in the green region from 540nm to 570nm (the “trough” of the PAR curve). This is why most plants appear green to the human eye, because most of the green light hitting the plant is reflected, while the blue and red light is absorbed by the plants to make nutrients.[4]

Plants make use of the blue portion of the spectrum (even though it is not as abundant in sunlight as the orange/red wavelengths), for the higher energy levels provided by the shorter blue wavelengths. Plants make use of the red portion of the spectrum, even though that has lower energy levels, due to the abundance of orange/red wavelengths available in sunlight. The plants make more use of the blue light as the PAR curve peaks at 440nm (100%), while the red peak at 675nm only reaches 95%, thus plants prefer to have slightly more blue than red light generally speaking.

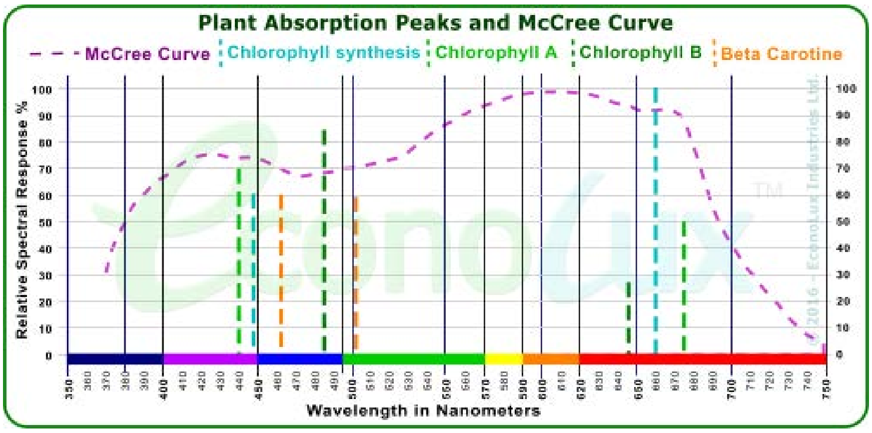
The blue portion of the spectrum is used by plants for root, stem and leaf formation, while the red portion of the spectrum is used mainly for chlorophyll synthesis and during the flowering and fruiting phase of plant growth.[4]

The McCree Curve[3]

In the 1970s, a Dr. Keith. J. McCree, who was a professor at Texas A&M in the Soils and Crop Sciences department and a physicist by education, published a seminal paper entitled “The action spectrum, absorptance and quantum yield of photosynthesis in crop plants”.

To quote from the abstract of the paper: *“The action spectrum, absorptance and spectral quantum yield of CO^2 uptake were measured, for leaves of 22 species of crop plant, over the wavelength range 350 to 750 nm. The following factors were varied: species, variety, age of leaf, growth conditions (field or growth chamber), test conditions such as temperature, CO^2 concentration, flux of monochromatic radiation, flux of supplementary white radiation, orientation of leaf (adaxial or abaxial surface exposed). For all species and conditions the quantum yield curve had 2 broad maxima, centered at 620 and 440 nm, with a shoulder at 670 nm. The average height of the blue peak was 70% of that of the red peak.”*[3]

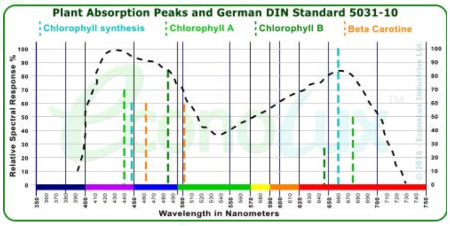
This study was one of the most detailed on plant light absorption and is still referenced and cited today. From his study data, Dr McCree was able to create a generalized plant light absorption curve (the same principal as the generalized PAR curve) which is known as the McCree curve, and looks like this (dashed purple line):



Like the PAR curve, the McCree curve is a generalized (average) of the light absorption curves from various plants. Individual plant species will have slightly different light absorption curves. For example, leafy green plants such as lettuce and chard prefer more blue light, while flowering and fruiting plants such as tomatoes, cucumbers and chilies prefer more red light.

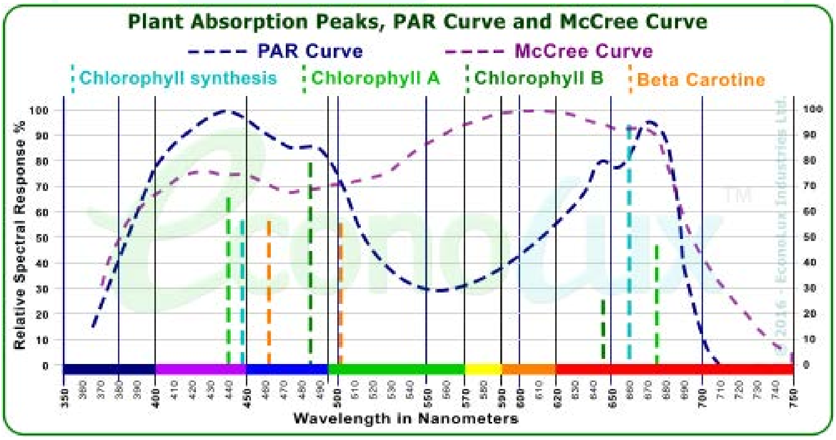
Other Plant Light Absorption Curves

There are some other curves in use, but the PAR curve is for the most popular, followed by the McCree curve. For example there is the German DIN Standard 5031-10 curve, which is shown on the right (dashed black line). This curve is somewhat similar to the PAR curve, but is not widely used in the horticultural industry.



Comparison of the PAR and McCree Curves

The graph below provides a comparison of the PAR curve (dashed dark blue line), and the McCree curve (dashed purple line):



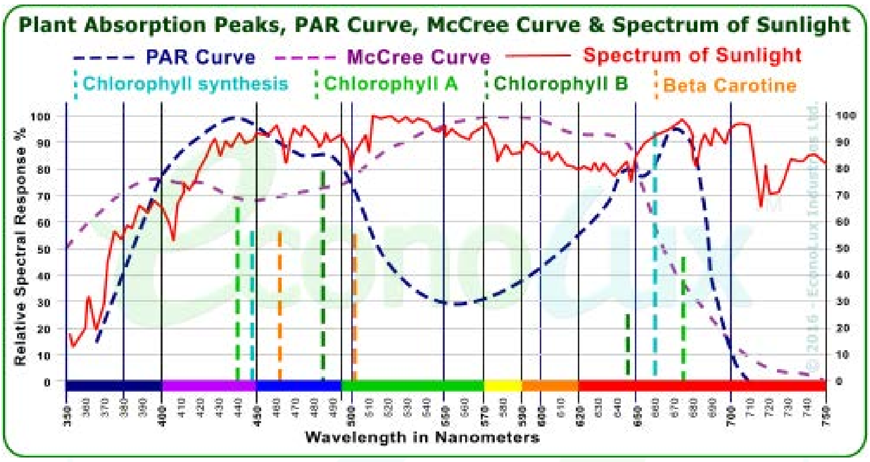
While the DIN curve and the PAR curve are somewhat similar, the McCree curve is quite different from the PAR curve. Compared to the PAR curve, the McCree curve shows that plants need more UV light, less blue light, make more use of the light in the 520nm (green) to 620nm (orange) region, and also need less deep red light overall compared to the PAR curve.

We will use this graph for the comparisons of lighting spectra so that the reader can see both curves at the same time.

Sunlight

A base-line comparison to the Sun is useful as sunlight is the most prevalent, and natural, source of light for growing plants. All other horticultural light sources are essentially, to a greater or lesser degree, trying to mimic sunlight.

The graph below shows the PAR curve (dashed dark blue line), the McCree curve (dashed purple line) and the visible portion (350nm to 750nm) portion of the spectrum of sunlight at noon[4] (solid red line). Sunlight does not closely follow either the PAR curve, or the McCree curve, as can be seen from the graph below.



Note that sunlight provides an abundance of green to yellow light in the 520~590nm range, even though the plants need very little of these wavelengths. This "overabundance" of certain wavelengths (colours) is not a problem for the plants, as they absorb only as much light in the blue, green, yellow, orange and red wavelengths as they need, and simply ignore the rest. However, for a plant-light, it is important to produce a spectrum that fits within the PAR curve, or the McCree curve, (as closely as possible) as any excess light produced, or light produced outside of the PAR or McCree curve spectrum, is simply wasted light. The 'wasted' light represents energy being used producing that light, which the plants don't need, thereby reducing the overall efficiency of the plant/grow-light.

Thus we can determine, from this data, that for proper plant growth, an artificial light source should produce primarily blue and red light with a spectral intensity curve which matches the PAR curve, or the McCree curve as closely as possible.

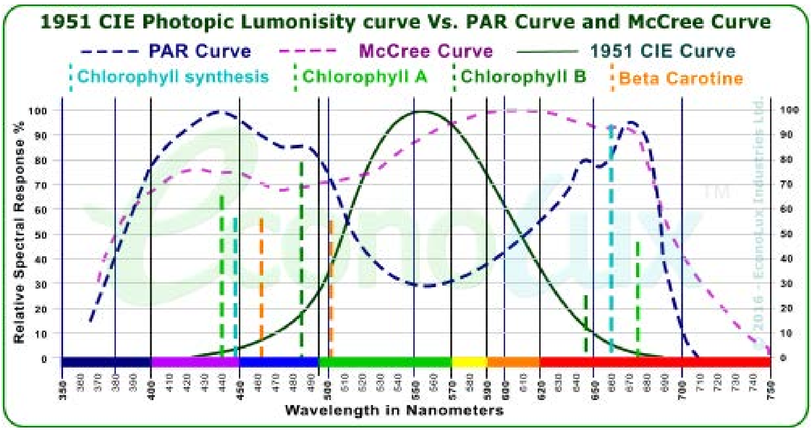
However, it is well known that plants, in the germination and vegetative phase of their growth, need more blue (high energy) light, while plants in the budding/flowering/fruiting phase need more red (lower energy) light. Ignoring the green portion of the spectrum, the PAR curve is approximately 57% blue and 43% red.

To complicate matters further, certain types of plants, for example Red Leaf Lettuce (*Lactuca sativa L.*) do not require a lot of red light, but do require some UV light during certain phases of the growth cycle. Thus, there is not one type of plant-light which can accommodate the needs of all types of plants grown under artificial lighting. This has lead to a proliferation of plant/grow-lights, many designed to work with specific plant-types.

Measuring Light for Plant Cultivation

Many manufacturers of plant-lights (MH, HPS, LED and others), quote the output of their lamps in Lumens (and sometimes Lumens/Watt [L/W]). This is a measure of the amount of Lumens (measured according to the 1951 CEI Photopic Luminosity curve[6]), that a light source is producing. This is a very standard way of evaluating the output efficiency/performance of light sources, used in illuminating spaces for humans.

However, the CIE Luminosity curve used in the Lumens measurement applies to light sources designed to produce light for human vision, not to agricultural/plant lights! Thus the Lumens figure, when applied to plant-lights, can be very misleading and/or deceptive.



The graph (right) shows the 1951 CIE Photopic curve (green line) overlaid on the PAR curve (dashed dark blue line), the McCree curve (dashed purple line) and the plant absorption peaks (dashed vertical lines). You will note that CIE curve has its peak around 550nm. The PAR curve is almost the opposite with its lowest point at 555nm and it's peak around 440nm.

The point where the plants are least sensitive to light according to the PAR curve (540nm), is almost the same point at which the human eye is most sensitive to light (550nm) according to the CIE photopic curve.

If a manufacturer wanted to improve their Lumen output figures to make their plant-lights seem like they have more output, then they could adjust the lamp spectrum so that they have more green and yellow output. Even though the plants can't use a lot of this light, it would inflate the Lumen number.

Lumens are for Humans!

Lumens are not a suitable way to measure the performance of plant/grow-lights, since a plant light producing primarily blue and red light is going to show a low lumen output. The reason why most manufacturers provide Lumen (and L/W measurements) is because integrating spheres have these functions built into them, or a simple light meter can be used, so it's easy to get test results.

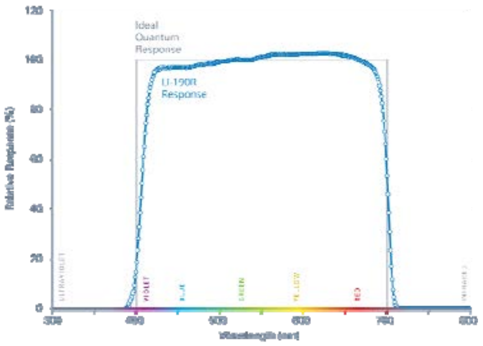
Plant/Grow Light Measurements

How then do we measure light used for horticultural (plant growing) applications?

> Lighting for plants is different from lighting for humans. Light energy for humans is measured in lumens, with light falling onto a surface measured as illuminance with units of lux (lumens per square meter) or footcandles (lumens per square foot).
>
> Light energy for plants, on the other hand, is measured as **Photosynthetic Active Radiation (PAR),** with light per second falling onto a surface measured as **Photosynthetic Photon Flux Density (PPFD).** - http://docs.agi32.com/AGi32/Content/adding_calculation_points/PPFD_Concepts.htm

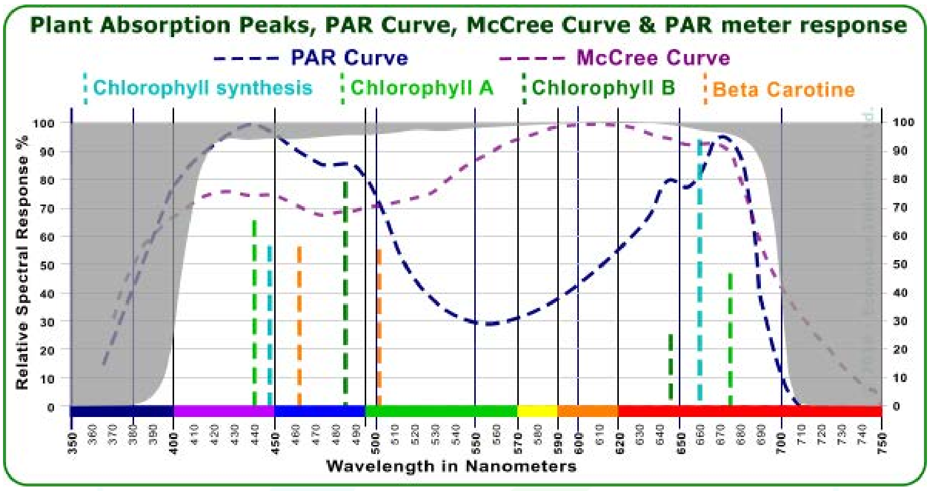
As we can see from the above quotation, the unit of measurement for plant/grow light output is **PAR** (Photosynthetically Active Radiation). PAR is measured using a quantum flux meter[7], which has a response curve between 400nm and 700nm and is a measure of the Micromoles per square meter, per second fallen on the plants (µmol/M²/S). The photo on the left shows some example PAR meters.

PAR meters measure the light falling onto their sensors in the range of from 400nm to 700nm

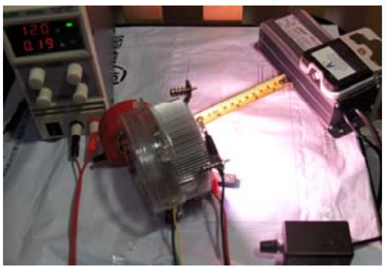


to cover the Photosynthetically Active region. PAR meter makers try to manufacturer their sensors with a rather square response to cover the range of from 400nm to 700nm (see image on the left from a popular brand of professional PAR meter manufacturer).

As a result, light below 400nm, and above 700nm is ignored, by the typical PAR meter, even though some of that light is useful to plants. When the typical PAR meter response is overlaid onto the PAR and McCree curves, we get a measurement area like this, where light in the greyed out areas is ignored by the PAR meters:



When it comes to measuring overall intensity of the light falling onto the plants, the unit of measurement is **PPFD** (Photosynthetic Photon Flux Density), also measured in Micromoles per square meter per second (μmol/M^2/S). This is an important measurement as it allows us to show the overall efficiency of a plant/grow lights in **PPFD/Watt**.



Testing the output of an LED COB Grow-light with a PPFD meter

Another important, but less used, measurement is the Daily Light Integral (**DLI**)[5]. The DLI is defined as the amount of PPFD received by plants each day as a function of light intensity (instantaneous light: μmol/m^2/s-1) and duration (day). It is expressed as moles of light (mol) per square meter (m-2) per day (d-1), or: mol/m^2/d-1 (moles per day).

Examples of popular Grow Lights (L to R): Metal Halide, High Pressure Sodium, LED and T5HO

Survey of Popular Plant/Grow-light Spectra

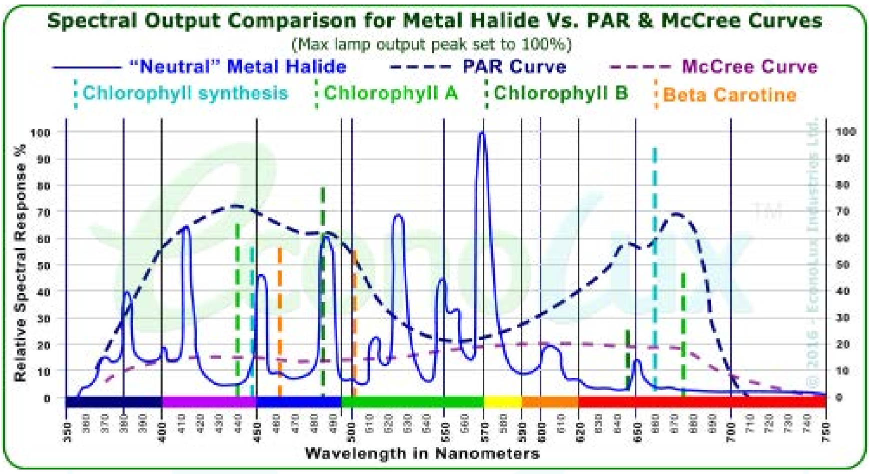
It would be useful to compare the spectrum of some of the more popular types of grow lights, to the PAR and McCree curves. This will allow the reader to determine which type of grow light produces the best spectrum for their use.

The following is a set of graphs of typical grow lights where the PAR and McCree curves have been overlaid on a representative sample of the grow light spectrum (from manufacturers data sheets). The PAR and McCree curves have been scaled to match the peak of the plant light output in the blue region for the PAR curve, and in the orange region for the McCree curve.

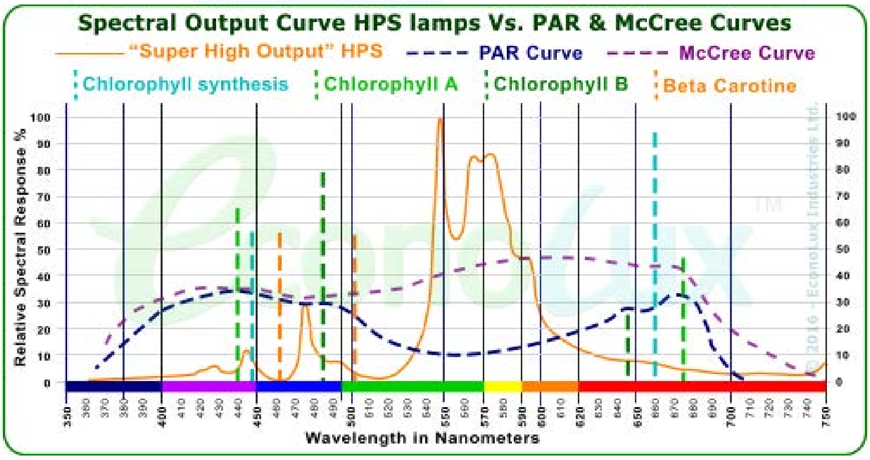
High Intensity Discharge Plant-lights

The graphs below shows the spectra of various HID plant lights (coloured lines), as taken from the manufacturers data sheets, compared to the PAR curve (dashed navy blue line), the McCree curve (dashed purple line), and plant absorption peaks (dashed vertical lines). The spectra for the HID lamps have been reproduced, as provided by the manufacturers, with the highest peak output wavelength shown at 100%.

Metal Halide



High Pressure Sodium (HPS)



It is interesting to note that the spectral output of these example HID lamps is not a smooth curve, but rather a series of "spikes". The spectral distribution shows that a significant portion of the light spectrum is in the green to yellow range (520~590nm), where the plants can make little use of the light (wavelengths), thus this light energy is largely wasted. Neither of the example lamps are generating significant amounts of red light.

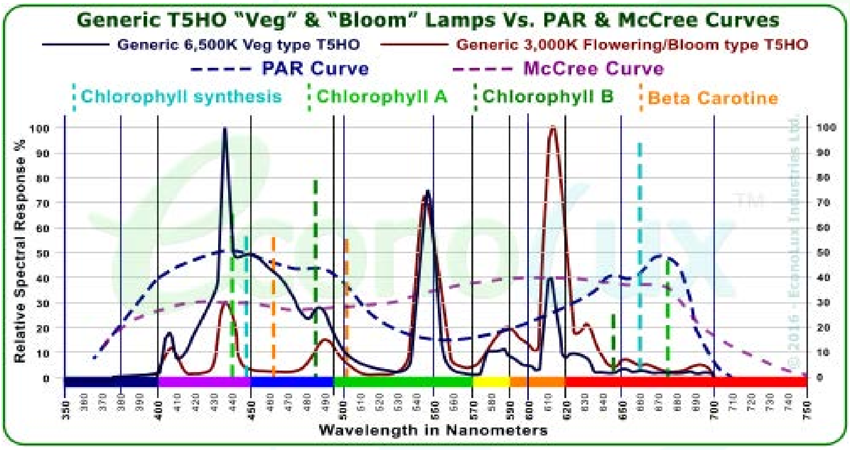
Looking at the vertical dashed lines, which show the peaks of the plant's pigment absorption, one notes that most of the lamps produce spikes in the spectrum at, or near, these absorption peaks in the blue region. In the red region of the spectrum, light output spikes are produced at, or near, the Chlorophyll B absorption peak, but there is no significant blue or red output at, or near, the Chlorophyll synthesis and Chlorophyll A absorption line peaks.

Despite the lack of energy efficiency of the HID lamps (due to ballast overhead), and also due to producing an overabundance of light not very useful to the plants in various areas of the spectrum, plants still grow well under these types of lights as they provide sufficient energy from the light, at a high enough intensity, for the vegetation.

T5HO (fluorescent) Grow Light Lamps/Tubes

There are a plethora of T5HO "grow lights" on the market today. Many of them are just ordinary 3,000K and 6,500K tubes, sold as "Bloom/Flowering" or "Vegetative" lamps under fanciful brand names. While these types of T5HO grow lamps can successfully grow plants, especially when they are used as supplemental light to daylight, they lack the spectrum necessary for proper plant growth, especially in controlled environments where they are the sole source of light for the plants.

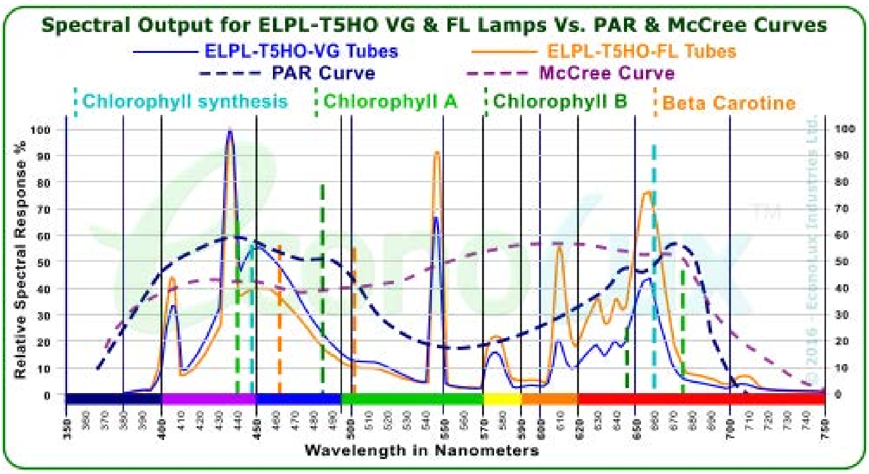
The graph below shows some generic examples of 6,500K (veg) and 3,000K (bloom) types:



The output spectrum has a number of 'spikes', and is generally lacking in 500nm to 630nm green light, and also 660nm to 575nm yellow light. The "red" light is a very narrow band from 605nm orange to 635nm red. These lamps are not a close match to either the PAR or McCree curves.

However, since these are generally re-purposed "white light" T5HO lamps/tubes, they do have the advantage of being lower cost, and they can be used with readily available T5HO fixtures, thus they are quite popular with home gardeners.

There are more specialised, and purpose deigned, T5HO grow lamps on the market, such as the EconoLux ELPL-T5HO series. The graph below shows the spectra of the VG (Vegetative) and FL (Flowering) models, compared to the PAR and McCree curves:

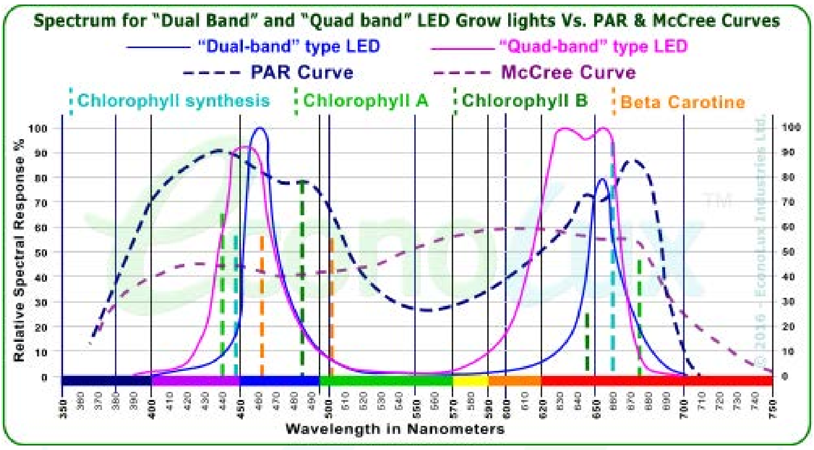


These lamps also have a number of spikes, but one can see that the blue part of the output curve is wider and also produces more light (especially the VG model), and is a better match to the PAR curve. The red portion of the spectrum is much improved, with light output from 605nm all the way through to 670nm, covering the important Chlorophyll synthesis line at 660nm.

Light Emitting Diode (LED) Plant-Lights

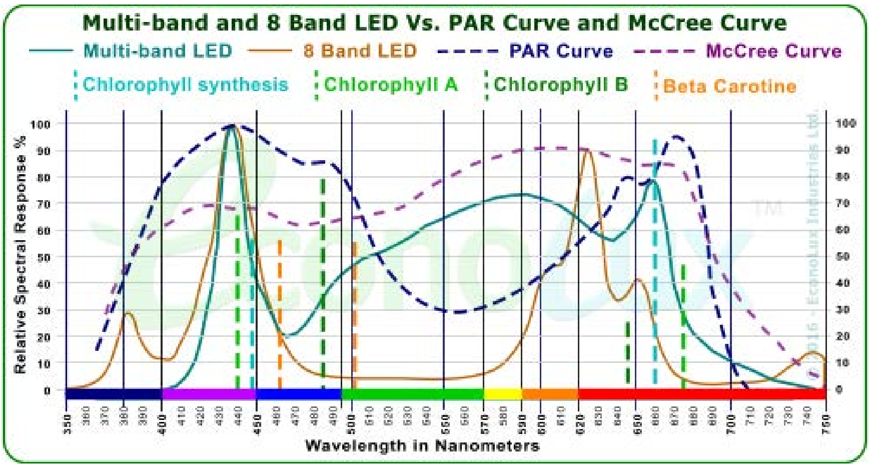
LED grow lights have become increasingly popular as the cost of LEDs have dropped. In addition, they use far less energy for the same PAR/PPFD output than conventional HID grow lights, and they also have a longer lifespan saving on maintenance and re-lamping costs.

They are usually classified by "bands", that is the number of different wavelengths of LEDs that are used in the light. The simplest and cheapest types may have only 2 bands (2 different wavelengths, one red and one blue), or 4 bands (2 different wavelengths of blue, and 2 different wavelengths of red LEDs). Adding different wavelengths of blue and red LEDs, allows for a broader peak of light in each of the blue and red areas (see graph below):



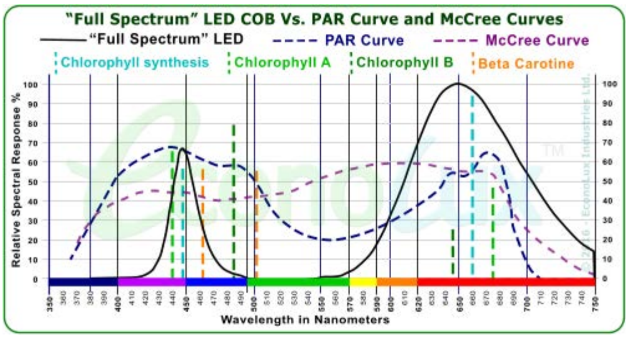
You can see from the graph that the output of these LED grow lights is actually a pair of spikes in the blue and red regions of the spectrum, with the quad (4 band) type having broader output spikes. There is almost no light at all in the 500nm to 580nm green to yellow portion of the spectrum, which is necessary (especially if one is considering the McCree curve). The dual band type's light output in the red barely covers the chlorophyll synthesis line at 660nm. These LED grow lights do not have a close match to the PAR, or the McCree, curves.

In all fairness to vendors, more advanced LED grow lights with 6, 8 or even 10 bands are now on the market, The more different bands (wavelengths) of LEDs that are used, the higher the cost to produce the light, thus many of these multi-band LED grow lights are found in the high end consumer or professional market. Here is a comparison graph of a Multi-band (the exact number was not specified by the manufacturer) and an 8 band LED grow light:



The 8 band LED grow light has two narrow peaks in the blue, and not much far red light above 650nm. It is not a good match to either the PAR curve or the McCree curve. The multi-band LED on the other hand, also has a poor blue portion of the spectrum with a narrow peak, but has a much closer match to the McCree curve in the Green/Yellow/Orange part of the spectrum, up to 640nm where it dips, then increases again to peak at 660nm.

“Full-Spectrum” LEDs



Recently so called “Full Spectrum” LEDs (both as single LEDs and as COBs) have appeared on the market. They are quite low cost to make as they are essentially a single band of Blue LEDs, which are both cheap, and plentiful, as they are used to make ‘white-light’ LEDs. The blue LEDs are coated with a low-Kelvin phosphor, to produce a lot of red light. The leakage of blue light through the phosphor coating produces a spike of blue light, while the phosphor coating produces the orange and red light.

Calling these ‘full spectrum’ LEDs is a serious misnomer, as they have a very narrow spike of blue between 420nm and 445nm, minuscule amounts of green light, very little yellow light, and an overabundance of red light, peaking at 650nm. They don’t match the PAR or McCree curves at all.

As mentioned before, the more bands (wavelengths) of LEDs one can include, the truer the final spectrum. Adding wavelengths however, increases costs, not only from the larger numbers of bands but the fact that some of the components are proprietary and thus expensive. Additionally:

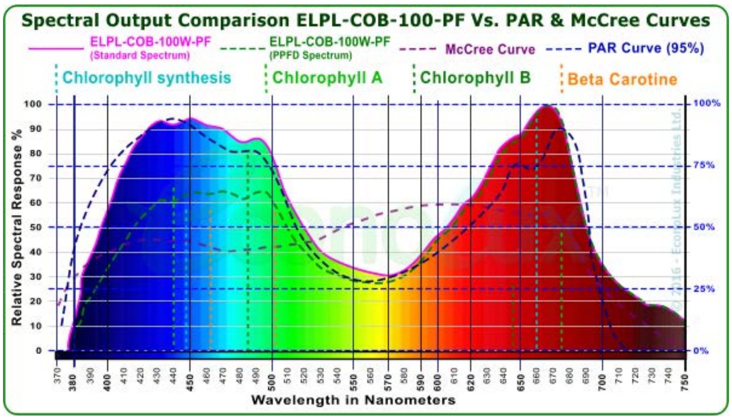
1] We use high quality imported LED chips from selected international sources. These are more costly but we have chosen them because they consistently demonstrate better quality than cheaper mass produced chips.

2] To get the exact wavelengths desired, the LED chips have to be individually tested and certified before encapsulation and assembly. This is a time and labour intensive process especially since numerous chips do not make the grade.

3] The robotic assembly machines (photo on right) that are used to assemble our chips need to make multiple passes to handle the plethora of discreet bandwidths we cover. This is another time and labour intensive operation.

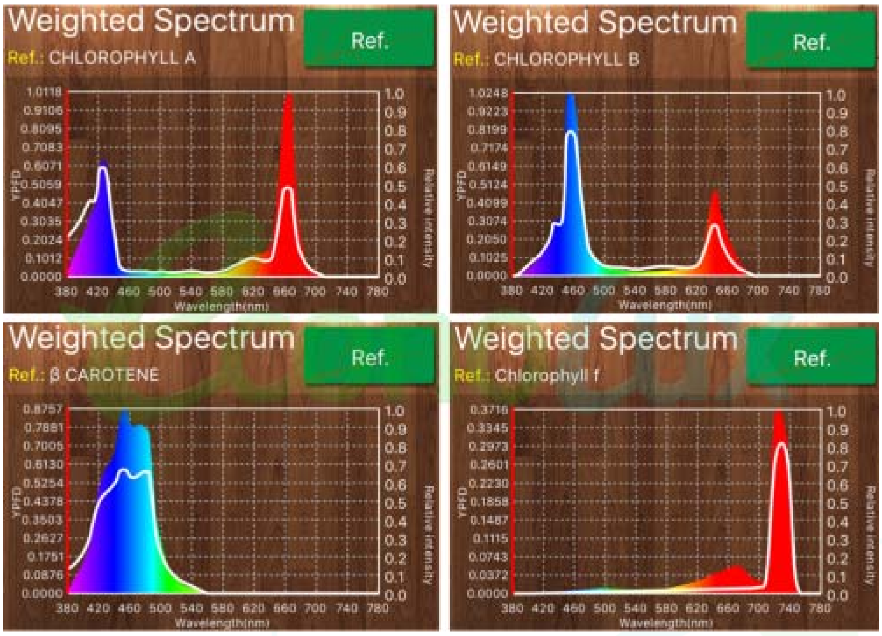
4] EconoLux uses 99.99% pure gold wire for all of our wire-bonding. Other manufacturers use cheaper 99.9% gold wire, and some even use aluminum wire to cut costs.

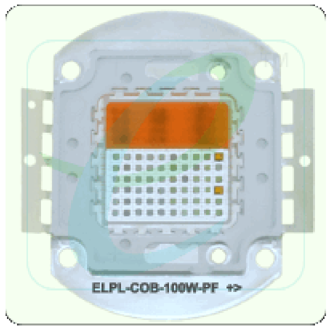
5] Each unit we produce is "aged" for 12 hours (operated at full power for 12 hours) and then analyzed comparatively with our optimized spectrum to ensure that the emitted curve stays within our stringent quality assurance parameters.



It is this devotion to excellence that has enabled EconoLux Industries to create the world's first HG (High Granularity) multi-band, 100W, LED COB that has a 95% match to the PAR curve.

In addition, when compared to standard absorption curves for Chlorophyll A, B and F, and Beta Carotene (shown below), the matches are almost perfect:





Above: Photo of the ELPL-COB-100W-PF COB, with 40% of our emissions biased toward the red range of the PAR spectrum, and 60% towards the blue. This is achieved by using our proprietary, custom broadband phosphor formulations.

References:

NOTE: Links to website provided in the references were current at time of publication. Due to the nature of the Internet, there links may have changed.

1. "Photosynthetically Active Radiation (PAR) is defined as the photons of radiation in the 400 to 700 nm waveband. PAR is a general term that can describe either the photosynthetic photon flux density (PPF), or the photosynthetic irradiance (PI)." - Plant Physiology: Manipulating Plant Growth with Solar Radiation - Dennis Decoteau, Ph.D., Department of Horticulture, The Pennsylvania State University.
2. "The energy contained in light is absorbed in the chlorophyll of plants. Not all wavelengths of light are utilized with equal efficiency. Looking at a chlorophyll/light absorption curve, one can deduce that red and blue light are more effective than green. This is logical. Plants do not use all of the green light. They reflect it. This is why plants appear green." - Wayne Vandre – Fluorescent Lights For Plant Growth- University Of Alaska, Fairbanks.
3. "The action spectrum, absorptance and quantum yield of photosynthesis in crop plants" - McCree, Keith J . Agricultural and Forest Meteorology 9: 191–216. doi:10.1016/0002-1571(71)90022-7
4. "Life Under The Sun" by Peter A. Ensminger, Yale University Press (March 1, 2001)
5. DLI Definition from Measuring Daily Light Integral in a Greenhouse Ariana P. Torres and Roberto G. Lopez; Department of Horticulture and Landscape Architecture, Purdue University - http://www.extension.purdue.edu/extmedia/ho/ho-238-w.pdf
6. Judd, D. B. (1951). Report of U.S. Secretariat Committee on Colorimetry and Artificial Daylight. In Proceedings of the Twelfth Session of the CIE, Stockholm (vol. 1, pp. 11). Paris: Bureau Central de la CIE.
7. Examples of PAR meters are those made by Apogee Instruments Inc. - http://www.apogeeinstruments.com/quantum/ or those made by Li-Cor - http://www.licor.com/env/products/light/terrestrial.html

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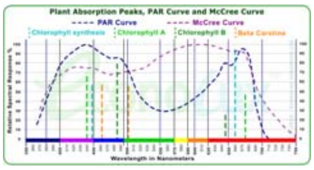
SUMMARY

We have seen in this publication that light for growing plants can be quantified both by the spectrum of the light and by and by measuring PAR and PPFD.

Spectrum

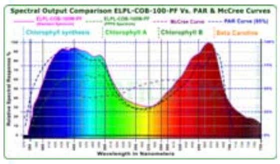


Scientific research has show that plants use mostly Blue and Red light for growth. This is summarized in the PAR curve. More recent research shows that plants actually make use of more green, yellow and orange light than was previous known, and that has led to the development of the McCree Curve.

Measurements

Horticultural lighting (Plant/Grow lights) are measured using PAR and PPFD units, which are defined as Micromoles per square meter, per second, (µmol/M²/S), of Photosynthetically Active Radiation between 400nm and 700nm. Remember, Lumens are for Humans; PAR/PPFD are for plants.

Survey of Popular Grow Light Spectra



A quick survey of popular grow light spectrums (such as MH, HPS, LED and T5HO) show that very few of them produce light that matches the PAR or McCree curves - with the exception of the EconoLux ELPL-COB-100W series of LED COB (Chip On Board) light engines which has a 95% match to the PAR curve.

This copy of the "What Light Do Plants need?" paper Courtesy of:

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