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What Light Do Plants Need?

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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, Cannabis or other 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, horticultural/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" or vertical farm, 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.

Lettuce Growing under EconoLux lights at a vertical farm in Hong Kong

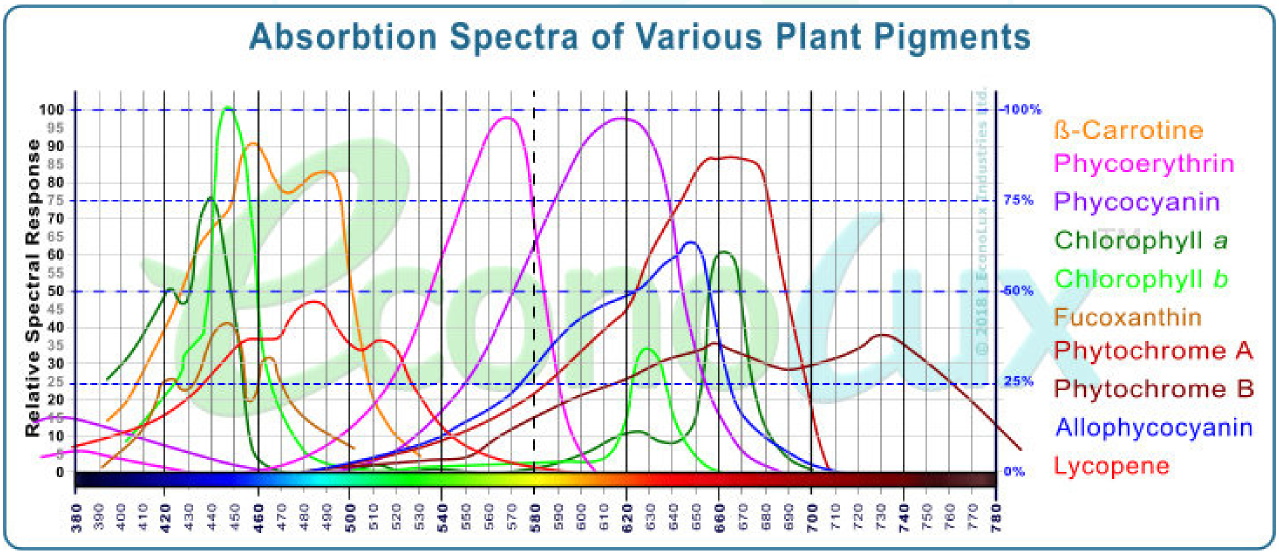
What Light Do Plants Need?

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.

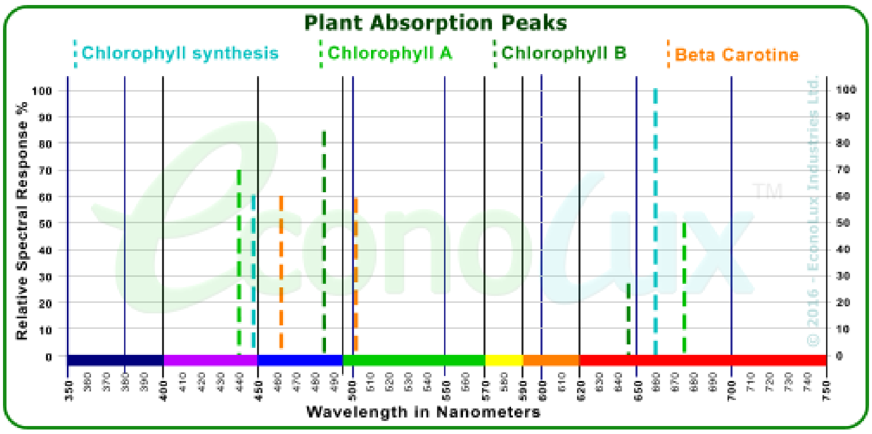
The spectrum typically used by plants lies between 380nm (UVA/deep blue) and 750nm (Infra Red). The portion of the spectrum that lies between the 400nm and 700nm wavelength region is known as Photosynthetically Active Radiation or PAR.[1] Generally speaking, plants also make some use of light in the 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 UVA, blue, blue/green, yellow, orange and red regions of the spectrum. Much 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 some of the various absorption peaks of the many photosensitive substances in plants which require light:

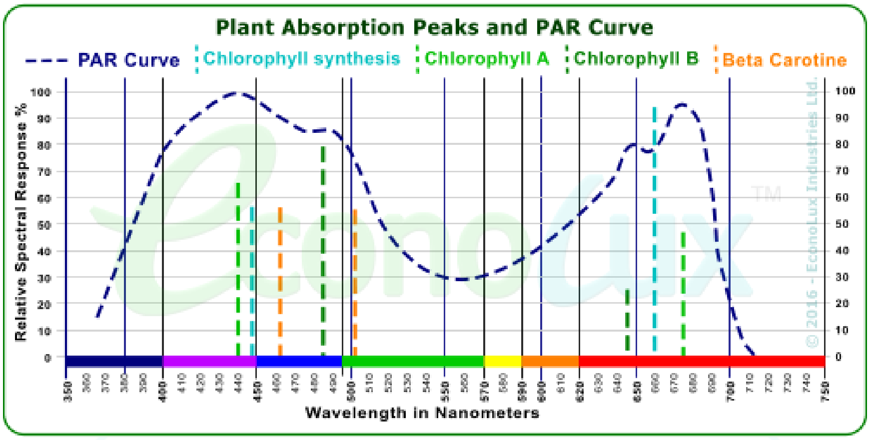


Generally speaking, the major photosensitive substances in plants, Chlorophyll A, Chlorophyll B, Beta Carotene, and Chlorophyll synthesis are taken into account. This is not to diminish the importance of other substances, or the so called "antenna pigments" in plants, but it does simplify the diagrams. 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 called the PAR curve and is the oldest 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 and was mostly determined "in vitro" (in a test tube). 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 mutch 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 (according to the PAR curve).

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]

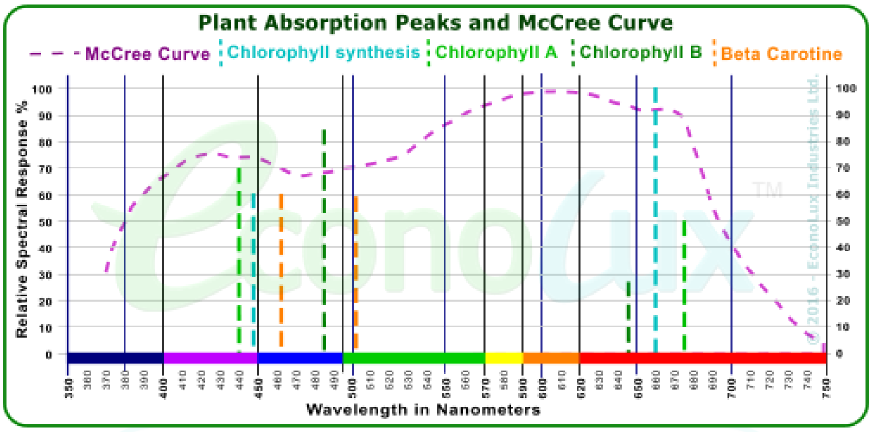
The McCree Curve[3]

In the 1970s, 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. It has been replicated and the science was found to be correct.

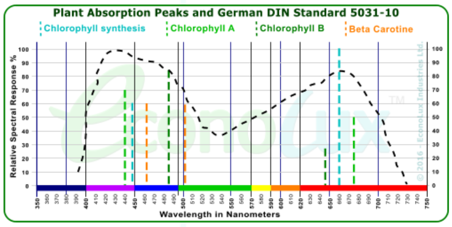
From his study data, Dr McCree was able to create a generalized plant light absorption curve (the same principal as the generalized PAR curve) which is known as the McCree curve, and looks like this graph on the right (dashed purple line). As you can see, the McCree curve based on "in vivo" science, is considerably different to the "in vitro" PAR curve.



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

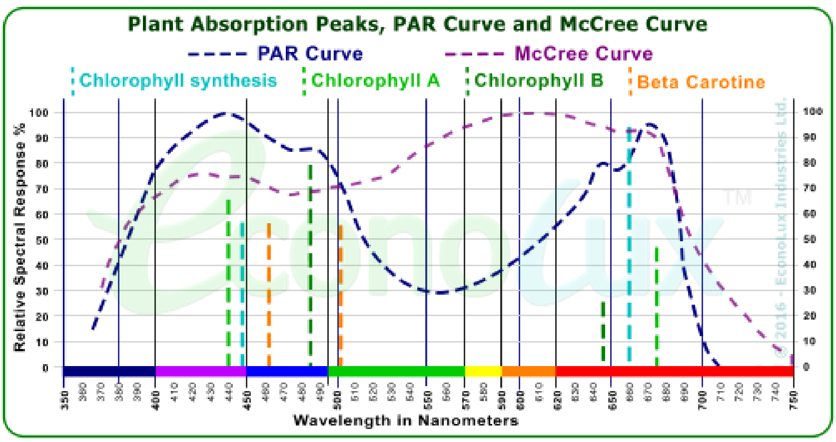
There are some other curves in use, but the PAR curve is for the most popular, followed by the McCree curve. For example there is the German DIN Standard 5031-10 curve, which is shown on the right (dashed black line). This curve is somewhat similar to the PAR curve, but is not widely used in the horticultural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

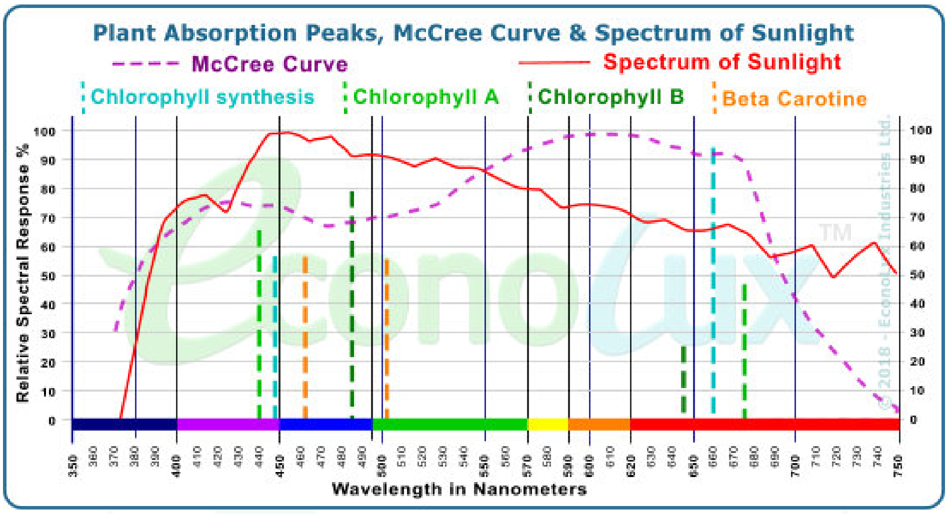


This is not surprising as the PAR curve was mostly determined "in vitro" - dissolving leaves in a glass test tube of solvent. On the other hand, the McCree curve was determined "in vivo" - measuring the response of live leaves. In addition, Dr. McCree measured the response on both the front and back (adaxial and abaxial surfaces) of the leaves, and measured the response of 22 different types of crop plants. which he then averaged to produce the McCree curve. Thus the McCree curve is the best publically available data on the light needs of plants.

Sunlight

A 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 McCree curve (dashed purple line) and the visible (370nm to 750nm) portion of the spectrum of sunlight at noon[4] (solid red line). Sunlight does not closely follow the McCree curve, as can be seen from the graph.



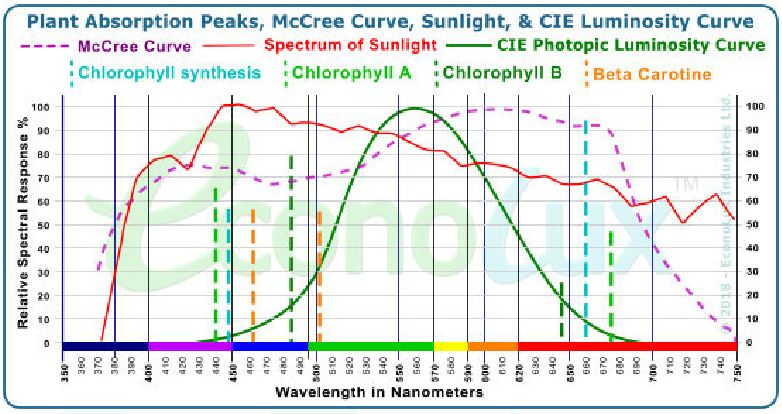
Note that the above graph shows sunlight provides an abundance of green to yellow light in the 470nm to 590nm range, even though the plants don't absorb much of these wavelengths (according to the McCree curve). This "overabundance" of certain wavelengths (colours) is not a problem for the plants, as 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 an artificial plant/grow-light, it is important to produce a spectrum that fits the McCree curve, (as closely as possible), or ideally the spectral curve of sunlight, as any excess light produced, or light produced outside of the 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 horticultural/plant/grow-light.

Despite the science represented by the McCree curve, 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. 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/grow-light which can accommodate the needs of all types of plants, even if it produces a 90% or more match to the McCree curve. 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 luminosity curve (green line) overlaid onto 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. This is the point at which the human eye is most sensitive to light. As we know from the McCree curve, plants have the peak of their sensitivity at 2 broad maxima, centered at 620 and 440 nm, with a shoulder at 670 nm, with the average height of the blue peak at 70% of the red peak.

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, without having to buy PPFD maters or plant-light spectrometers.

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

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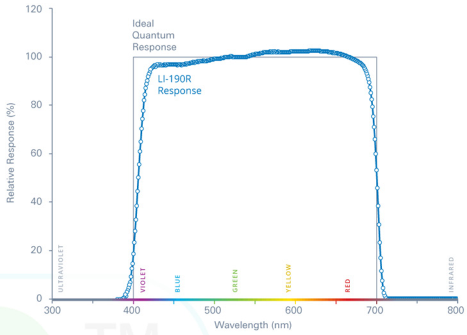
Plant/Grow Light Measurements

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

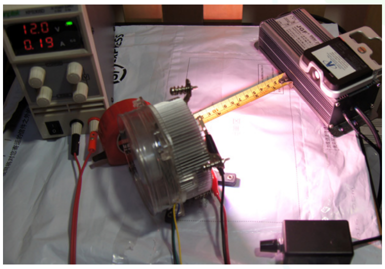
As we can see from the quotation on the previous page, the unit of measurement for plant/grow light output is **PAR** (Photosynthetically Active Radiation). PAR is measured using a quantum flux meter[7], which has a response curve between 400nm and 700nm and is a measure of the Micromoles per square 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 right 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, especially the UV light.

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/M²/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/m²/s-1) and duration (day). It is expressed as moles of light (mol) per square meter (m-2) per day (d-1), or: mol/m²/d-1 (moles per day).

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 McCree curve. This will allow the reader to determine which type of grow light produces the best spectrum for their use.

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

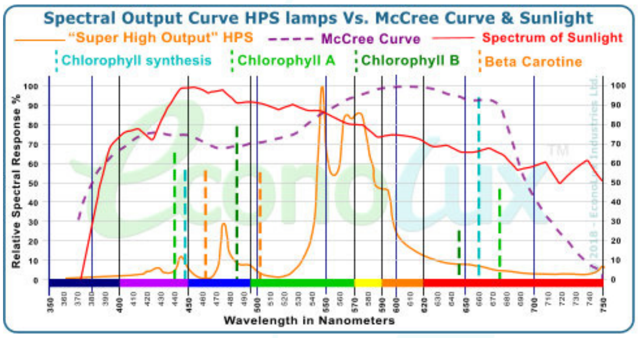
The following is a set of graphs of typical popular grow lights where the McCree curve has been overlaid on a representative sample of the grow light spectrum (from manufacturers data sheets). The PAR and McCree curves have been scaled to match the peak of the plant light output in the blue region for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

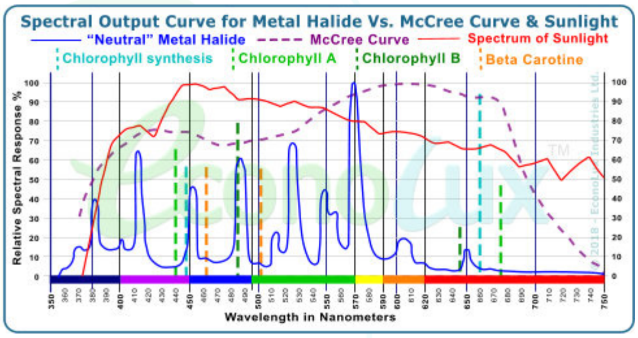
High Intensity Discharge Plant-lights

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 less use of the light (wavelengths), thus this light energy is largely wasted. Neither of the example lamps are generating significant amounts of red light, and neither type has a good match to the McCree curve or sunlight.





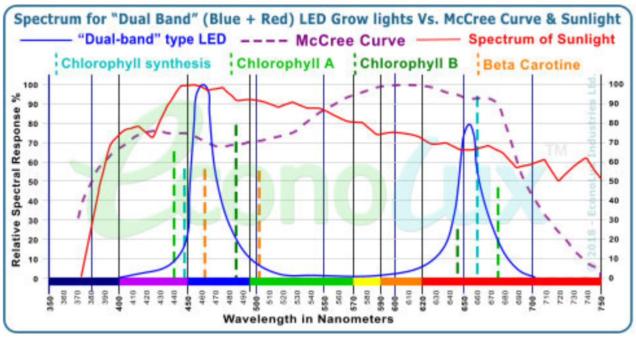
Looking at the vertical dashed lines, which show the peaks of the plant’s pigment absorption, one notes that most of the lamps produce spikes in the spectrum at, or near, these absorption peaks in the blue region. In the red region of the spectrum, light output spikes are produced at, or near, the Chlorophyll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

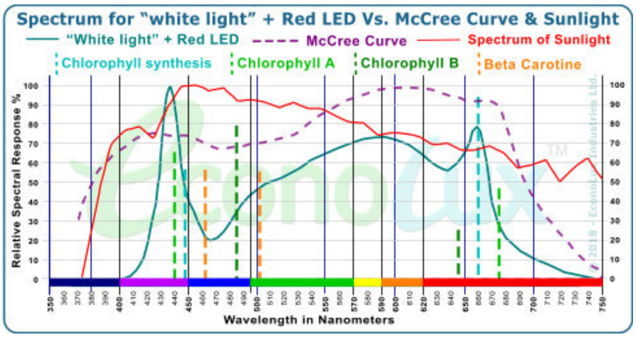
Despite the lack of energy efficiency of the HID lamps (due to ballast overhead), and also due to producing an overabundance of light not very useful to the plants in various areas of the spectrum, plants still grow well under these types of lights as they provide sufficient energy from the light, at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

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 on next page):



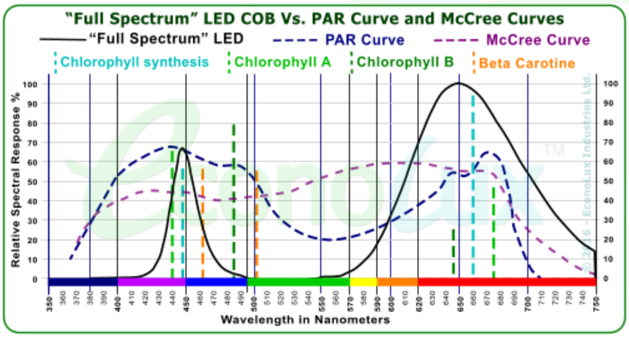


You can see from the graph that the output of the Blue + Red LED grow lights is actually a pair of spikes in the blue and red regions of the spectrum. There is almost no light at all in the 500nm to 580nm green to yellow portion of the spectrum, which is necessary (especially if one is considering the 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.

Recently, grow-light based on "white" LEDs have become popular. The graph on the right above shows an example of the spectrum of a popular US manufacture that makes grow-light that are mostly 'white' LEDs, with a few 660nm red LEDs added.

While the spectrum of the light is a significant improvement on the dual-band (Blue + Red) grow-light, it is not a good match to the McCree curve. The 'White' + Red grow-light has a poor blue portion of the spectrum with a narrow peak and little deep blue or UV light, 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.

SUMMARY

To summarize the major points we have learned in this paper, plants need light energy as the major driving force of photosynthesis, the process whereby they convert CO_2 into oxygen and food. The lighting needs of plants are complex and go well beyond the spectrum that simple Blue + Red or 'White' LED grow-lights can provide (although plants will grow under those types of lights).

While the PAR curve provides some basic insight into the lighting spectrum that plants need, the extensive research by Keith. J. McCree, which resulted in the McCree curve, shows that plants need a full spectrum of light from 380nm to 750nm in order to thrive under artificial lighting. McCree also showed that PPFD is the best way to measure light levels for plants, as PPFD is the best predictor of the rate of photosynthesis.

EconoLux McCree Curve Grow-lights

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:

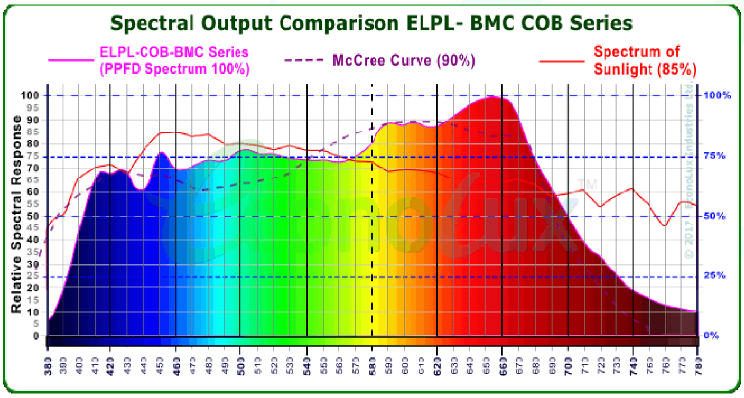
1] We use high quality imported LED chips from selected international sources. These are more costly but we have chosen them because they consistently demonstrate better quality than cheaper mass produced chips.

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 COB chips need to make multiple passes to handle the plethora of discreet bandwidths we cover. This is another time and labour intensive operation.

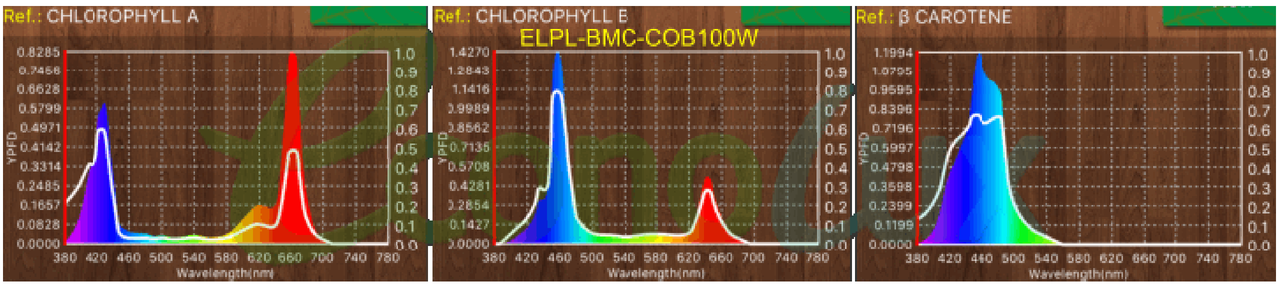
4] EconoLux uses 99.99% pure gold wire for all of our wire-bonding. Other manufacturers use cheaper 99.9% gold wire, and some even use aluminum wire to cut costs.

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 90+% match to the McCree curve (see spectrum on left).

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



Left: Photo of the ELPL-BMC-100W COB, with a 90+ % match to the McCree curve. This is achieved by using Multiple wavelengths/bands of LEDs along with 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
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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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