

# HORTICULTURE LIGHTING

## Technical Brief



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# INTRODUCTION

Light Emitting Diodes (LEDs) represent a relatively new and disruptive lighting technology, especially for growers who have vast experience with older technologies such as high pressure sodium (HPS), ceramic metal halide (CMH) and fluorescent lighting. While LEDs offer a host of benefits to growers, the switch to LEDs is more complicated than simply swapping light bulbs. This technical brief was assembled to support our controlled environment agriculture (CEA) customers in that transition.

There are substantive differences between LEDs and other lighting technologies. In this brochure, we begin with lighting basics, and then take a deep dive into how LEDs impact other control aspects within CEA facilities such as: vapor pressure deficit (VPD), CO<sub>2</sub> supplementation, temperature controls, and nutrient strategies.

One of the key themes that runs throughout this document is the interdependence of the various control parameters such as: light, CO<sub>2</sub>, temperature, humidity and nutrients. In the final section we bring it all together and make specific recommendations for the environmental settings that will promote optimal plant development during propagation, vegetative growth and flowering of cannabis.





# OVERVIEW OF HORTICULTURE LIGHTING

## Background

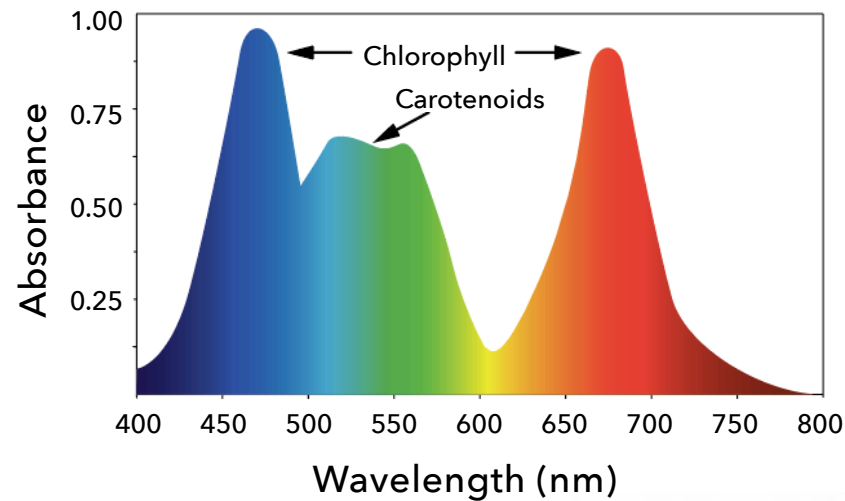
Plants grown outdoors in sunlight have a plentiful supply of free light for photosynthesis. But plants grown in controlled environments require electric light, which opens a Pandora's Box of questions and complications. Maximizing yield requires indoor growers to optimize artificial lighting metrics such as intensity, uniformity, efficiency and spectrum - to name a few.

## Definitions & Terminology

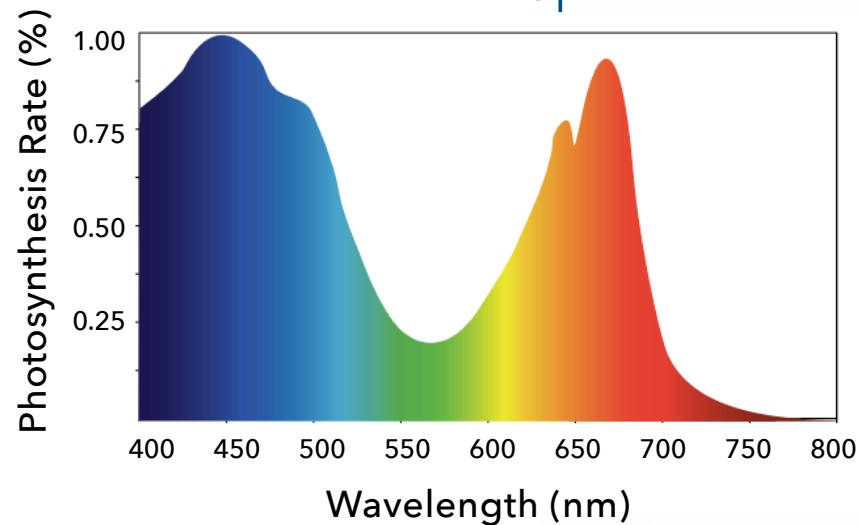
In horticulture, the amount of light emitted from a lighting fixture is measured in units of moles, or micromoles ( $\mu\text{mols}$ ), where a mole of light is equal to  $6.02 \times 10^{23}$  photons. For example, a manufacturer's data sheet may state the light emits 800  $\mu\text{mols/sec}$ . This means the light is emitting  $4.82 \times 10^{20}$  photons each second. The intensity of light is the amount of light landing on a specified area ( $\mu\text{mols/sec/m}^2$ ), which is frequently referred to as photosynthetic photon flux density (PPFD). The efficiency of a grow light is measured in units of  $\mu\text{mols/joule}$ , which defines the amount of electrical energy consumed to produce photons in the Photosynthetically Active Radiation (PAR) spectrum. PAR is the amount of light available for photosynthesis, and is defined as the amount of light emitted in the 400 to 700 nanometer wavelength range.



## Plant Absorption Spectra



## PAR Action Spectra



## Plant Biology

Growers aim to maximize production yield and plant quality with minimum energy usage and expense. Much research has gone into understanding how light spectrum interacts with plants. It is clearly understood that plants absorb light with chlorophyll A & B and carotenoid photoreceptors as shown in the Plant Absorption Spectra - top left. Closely related to this is the PAR Action Spectra graph that displays the efficiency of photosynthesis as a function of wavelength. Matching emission spectrum from a light source to the PAR Action Spectra would appear to be a good first step.

At first blush it appears that green light is relatively ineffective in promoting photosynthesis as compared to blue and red light. While the PAR action spectra in the figure on the bottom left may be valid at low light intensities, recent research has demonstrated that plants irradiated with green light at modest/high intensities (more than 200  $\mu\text{mol}/\text{m}^2/\text{sec}$ ) experienced substantial growth benefits.<sup>1</sup>

<sup>1</sup>Jokan, M. & Hsoji, K., (2012) "Effect of green light wavelength and intensity on photomorphogenesis and photosynthesis in *Lactuca sativa*." Environmental and Experimental Botany. 75. 128-133.

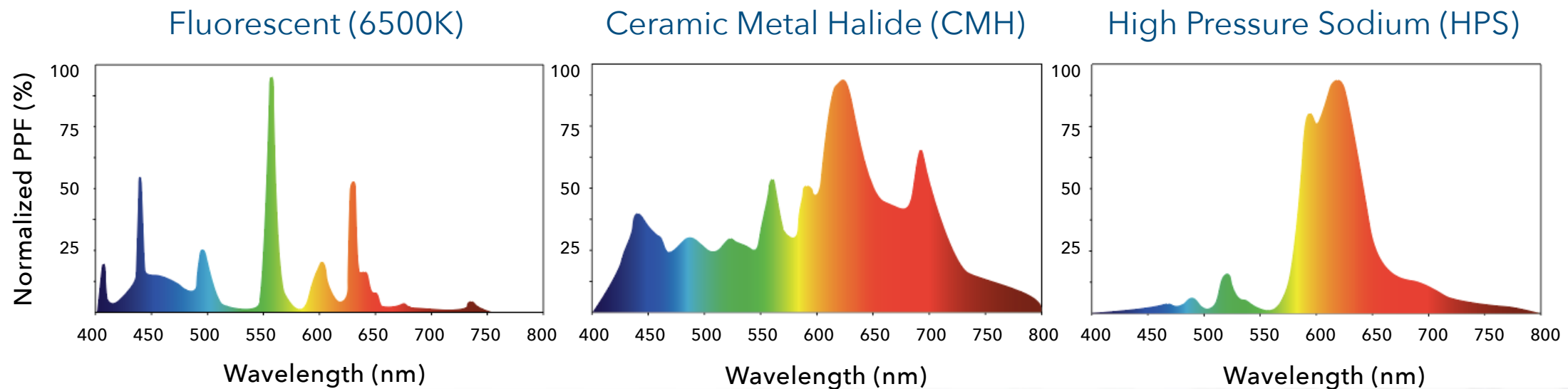


Photomorphogenesis is defined as the influence of light spectrum on plant development. While there can be significant differences amongst plant species, light spectrum tends to impact plants in the following ways:

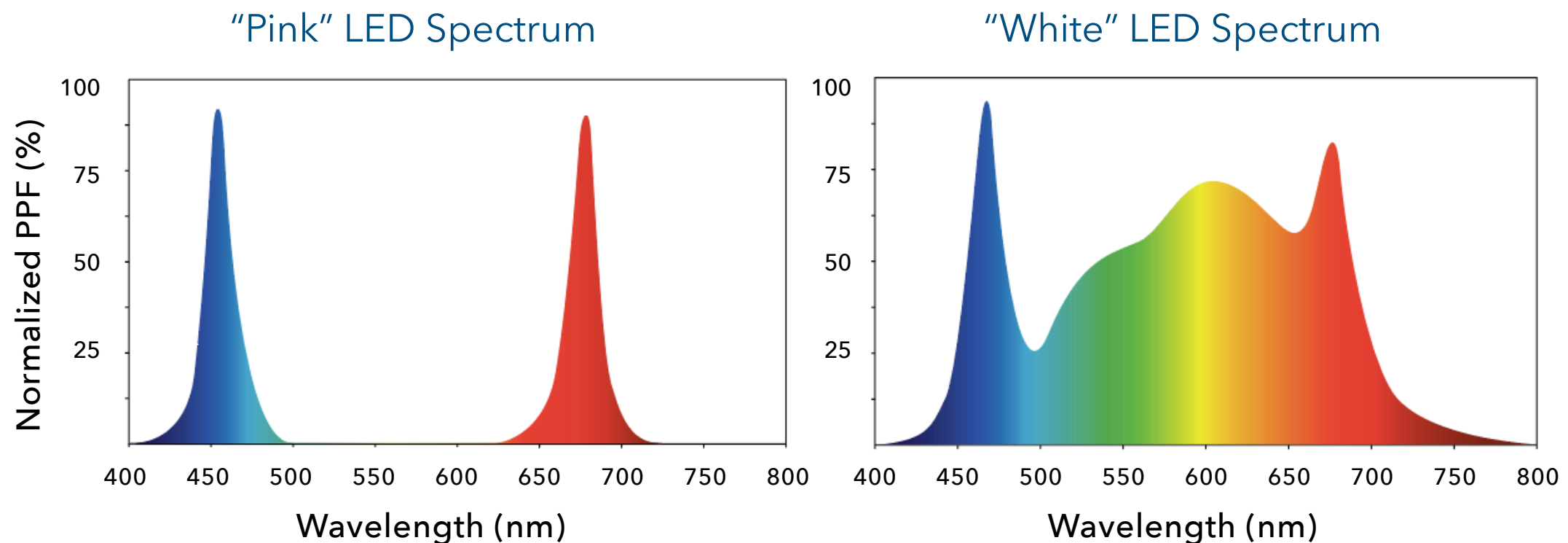
- **Blue** (400-500nm): Promotes leaf/root growth, inhibits stem elongation
- **Green** (500-600nm): Photosynthesis, may inhibit nutrients (such as anthocyanin)
- **Red** (600-700nm): Promotes flowering/fruiting
- **Far Red** (700-800nm): Promotes stem elongation
- **UV** (300-400nm): Activates plant defenses, disease resistance

### Lighting Technologies

Over the past decade LEDs have displaced incumbent lighting technologies for most applications. In the case of grow lights, benefits of LEDs include high energy efficiency, long life and tunable spectrum. Today, LEDs are commonly used where fluorescent and ceramic metal halide (CMH) formerly dominated. High pressure sodium (HPS) lights maintain a substantial share in greenhouses and other very high light intensity applications, but LEDs are currently being designed into many new construction installations for those applications. Emission spectra for fluorescent, CMH & HPS are shown below.



LED grow lights are typically sold as either fixed spectrum or dynamically controllable spectrum. Lighting solutions that allow for on-demand intensity control of individual LED diodes can produce virtually any spectrum imaginable. Today, most large-scale commercial growers use fixed spectrum lights due to their inherently lower cost and higher efficacy. Fixed spectrum lights tend to be sold in one of two colors: pink & white as illustrated in the figures below. Pink lights can achieve the highest efficiency ( $\mu\text{mols}/\text{joule}$ ), while white lights can achieve lowest cost ( $\mu\text{mols}/\$$ ). The effect of pink vs white on biomass production, yield and quality varies by plant species. "Human factors" is an additional consideration when choosing between pink light and white light. Many workers, especially those working in indoor/warehouse facilities, find it difficult to work with pink lighting due to its very low color rendering index (CRI).





## Light Intensity & Uniformity

In addition to spectrum, we know that light intensity ( $\mu\text{mols}/\text{sec}/\text{m}^2$ ) plays a significant role in determining outcomes. The ideal intensity of light on the canopy is a function of plant species and stage of growth. Thrive Agritech offers a portfolio of LED grow lights to support growers' wide-ranging needs.

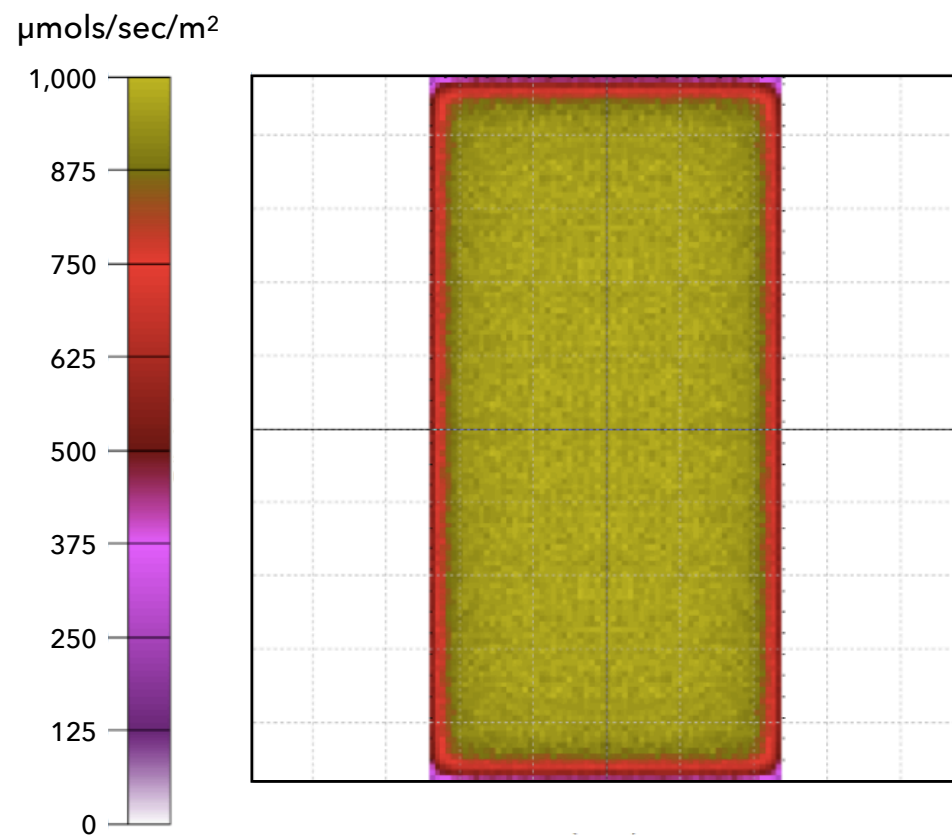
	INFINITY 2.0	BOOST	APEX
			
Input Power	65 Watts	130 Watts	300 Watts
Input Voltage	110-277V	110-277V	110-277V
Photon Flux	156 $\mu\text{mols}/\text{sec}$	312 $\mu\text{mols}/\text{sec}$	780 $\mu\text{mols}/\text{sec}$
Efficiency	2.4 $\mu\text{mols}/\text{sec}$	2.4 $\mu\text{mols}/\text{sec}$	2.6 $\mu\text{mols}/\text{sec}$
Beam Angle	120 degrees	120 degrees	120 degrees
Dimensions	47.25'x2.15"x2.75"	47.25'x2.15"x2.75"	47.25'x3.43"x4.57"
Driver	Internal	Internal	External
Weight	3.8 lbs	5.2 lbs	12.8 lbs
Dimming	Yes	Yes	Yes
IP66	Yes	Yes	Yes
UL / DLC Listed	Yes	Yes	Yes
Warranty	5 Years	5 Years	5 Years



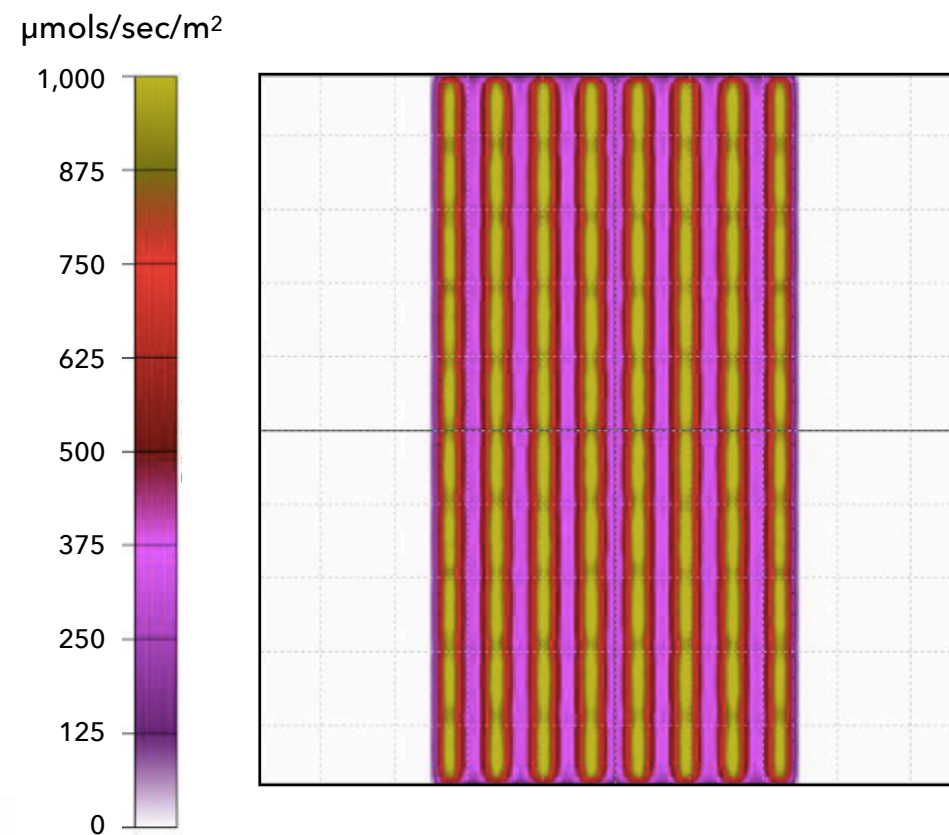


It's important to note that not only does the light intensity need to be correct, but the intensity needs to be uniformly distributed to ensure consistent growth throughout the canopy. Frequently, controlled environment agriculture facilities have lighting solutions that create "hot spots" where the intensity is too high in some areas of the canopy and too low in others. As a rule of thumb, there should be no more than  $\pm 15\%$  uniformity variation in intensity across the canopy. Achieving this requirement is the job of the lighting designer, who balances the intensity of the light coming from the fixture with the mounting height of the fixture above the canopy. Examples of a lighting design with excellent uniformity and a design with poor uniformity are shown below. In the case of the figure on the right with non-uniformity in excess of 50%, the hot spots are caused by the lighting fixtures being mounted too closely to the canopy.

### Excellent Light Uniformity



### Poor Light Uniformity



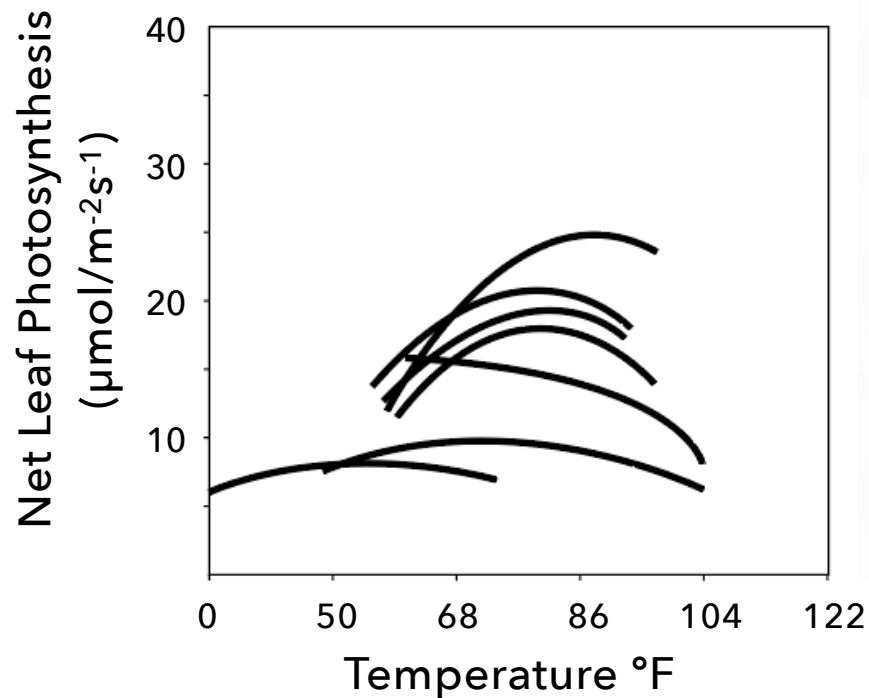
## Applications & Solutions

The right lighting solution depends not only on the plant species and growth stage, but also the proper mounting height of the light fixture above the canopy. A generalized guideline describing the best Thrive Agritech lighting product for each application and mounting height is shown in the chart below. For detailed custom lighting plans, please contact Thrive Agritech technical support.

APPLICATION	PRODUCT	LIGHT INTENSITY ( $\mu\text{mols/sec/m}^2$ )	MOUNTING HEIGHT
PROPAGATION	Infinity 2.0	50 - 150	6" - 24"
	Boost	50 - 150	12" - 36"
LEAFY GREENS	Infinity 2.0	150 - 250	6" - 24"
	Boost	150 - 250	18" - 36"
CANNABIS VEGETATIVE	Infinity 2.0	350 - 450	6" - 12"
	Boost	350 - 450	12" - 24"
	Apex	350 - 450	18" - 48"
CANNABIS FLOWER	Boost	700 - 1,200	12" - 24"
	Apex	700 - 1,200	18" - 60"
GREENHOUSE	Boost	50 - 450	18" - 48"
	Apex	50 - 450	24" - 192"



# VAPOR PRESSURE DEFICIT



It is well-established in plant biology that leaf surface temperature must be kept within a specific window to optimize primary metabolism (photosynthesis), as well as production of secondary metabolites. The relationship between leaf surface temperature and photosynthesis is shown in the figure at the left. Photosynthesis increases with increasing leaf surface temperature, and then decreases as leaf temperature continues to rise. The figure on the left is comprised of data from a variety of plant species.

Tree Physiology, Volume 32, Issue 2, February 2012, Pages 219-231

But leaf surface temperature is only part of the story. The critical factor is the interplay between leaf temperature and the relative humidity in the grow room. Those two factors (temperature and humidity) determine the vapor pressure deficit (VPD), which, in turn, determines transpiration efficacy and ultimately photosynthetic rates. Vapor pressure is the pressure at which liquid becomes a vapor. VPD refers to the difference between vapor pressure within a plant and the vapor pressure of the air surrounding the plant. If VPD is too low, photosynthesis is constrained, peak growth rates are not achieved, and problems like mold or root rot may occur. If VPD is too high, the plant stomata may close to limit transpiration, which can result in tip burn and leaf curl.





Temperature and humidity affect the vapor pressure. An example of the relationship between temperature, humidity and VPD is illustrated in the chart below. To optimize production yield, the VPD must remain in the “sweet spot” identified in the green boxes. The numbers in the chart are the vapor pressure differential, and use millibars (mb) as the unit of measure. VPD is frequently reported in units of kilopascals (kPa). To convert kPa to mb, simply multiply kPa by 10.

°C	°F	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%	45%	40%	35%
15	59	0.0	0.8	1.7	2.5	3.4	4.2	5.1	5.9	6.8	7.6	8.5	9.4	10.2	11.1
16	60.8	0.0	0.9	1.8	2.8	3.7	4.6	5.5	6.4	7.3	8.2	9.1	10.0	10.9	11.8
17	62.6	0.0	1.0	2.0	2.9	3.9	4.9	5.8	6.8	7.8	8.8	9.7	10.6	11.6	12.6
18	64.4	0.0	1.0	2.0	3.1	4.1	5.1	6.2	7.2	8.2	9.3	10.3	11.3	12.4	13.4
19	66.2	0.0	1.1	2.2	3.3	4.4	5.5	6.6	7.7	8.8	9.9	11.0	12.1	13.2	14.3
20	68	0.0	1.2	2.4	3.5	4.7	5.9	7.0	8.2	9.4	10.6	11.7	12.8	14.0	15.2
21	69.8	0.0	1.2	2.4	3.7	4.9	6.2	7.4	8.6	9.9	11.1	12.4	13.7	14.9	16.1
22	71.6	0.0	1.3	2.6	3.9	5.3	6.6	7.9	9.2	10.5	11.9	13.2	14.5	15.8	17.2
23	73.4	0.0	1.4	2.8	4.2	5.6	7.0	8.5	9.9	11.3	12.7	14.1	15.4	16.8	18.2
24	75.2	0.0	1.5	3.0	4.5	5.9	7.4	8.9	10.4	11.9	13.4	14.9	16.4	17.9	19.4
25	77	0.0	1.6	3.2	4.8	6.4	8.0	9.5	11.1	12.7	14.3	15.9	17.4	19.0	20.5
26	78.8	0.0	1.7	3.4	5.1	6.7	8.4	10.1	11.8	13.4	15.1	16.8	18.4	20.1	21.8
27	80.6	0.0	1.8	3.5	5.3	7.1	8.9	10.7	12.4	14.2	16.0	17.8	19.6	21.3	23.1
28	82.4	0.0	1.9	3.8	5.7	7.6	9.5	11.4	13.3	15.1	17.0	18.9	20.7	22.6	24.5
29	84.2	0.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	22.1	24.1	26.1
30	86	0.0	2.1	4.2	6.4	8.5	10.6	12.7	14.8	17.0	19.1	21.2	23.3	25.4	27.5
31	87.8	0.0	2.2	4.5	6.7	9.0	11.2	13.4	15.7	17.9	20.2	22.4	24.6	26.9	29.1
32	89.6	0.0	2.4	4.7	7.1	9.5	11.9	14.2	16.6	19.0	21.3	23.7	26.1	28.4	30.8
33	91.4	0.0	2.5	5.0	7.5	10.0	12.5	15.0	17.6	20.1	22.6	25.1	27.6	30.1	32.6
34	93.2	0.0	2.7	5.3	8.0	10.6	13.3	15.9	18.6	21.2	23.9	26.5	29.2	31.8	34.5
35	95	0.0	2.8	5.6	8.4	11.2	14.0	16.8	19.6	22.4	25.2	28.0	30.8	33.6	36.4



For cannabis growers, although the precise VPDs for propagation, vegetative growth and flowering are strain specific, the following target ranges for each growth stage are instructive. The VPD tends to increase as the plant moves through its growth stages. For instance, for propagation a VPD in the range of 5-8mb is recommended, while in vegetative growth and flowering VPD ranges of 8-12mb and 10-15mb respectively are more appropriate. To achieve the suggested VPDs, ambient temperatures will need to increase while relative humidity decreases. VPD guidance for cannabis growers at each stage of growth can be found online. One such source is: [http://www.just4growers.com/media/23631/vpd\\_2degree.gif](http://www.just4growers.com/media/23631/vpd_2degree.gif)

When using LED lighting instead of high pressure sodium (HPS), there are differences that need to be considered when optimizing VPD. HPS emits in a broad portion of the electromagnetic spectrum that includes infrared (IR) energy - otherwise known as heat. IR energy from HPS heats the canopy and increases the leaf surface temperature. LEDs typically have only a small fraction of their emission in the IR portion of the spectrum, so they do not increase leaf surface temperature like HPS. In fact, it is typical to see a 5-10 degree decrease in leaf surface temperature by changing the lighting from HPS to LED. If no other action is taken, the decrease in leaf temperature may throw the VPD out of its sweet spot - thereby decreasing transpiration and photosynthesis.

### **So how do you ensure you are still in the proper VPD range after installing LED lights?**

1. Understand your baseline. Measure the leaf surface temperature and relative humidity while you're still using HPS. Although humidity is easily measured, measuring leaf surface temperature requires specialized equipment such as a forward-looking infrared camera. Here's one IR camera that will do the job: [tequipment.net/fliri7.html](http://tequipment.net/fliri7.html). Don't assume the leaf surface temperature is the same as the ambient air; this is rarely the case. Once you've taken the measurements, the VPD can be determined.
2. Repeat step #1 after switching to LED.
3. Determine if your VPD is still in the optimal range. If it isn't, you should:
  - A. Increase the ambient air temperature to raise the leaf temperature to the target temperature that satisfies the VPD requirement.
  - B. Modify the relative humidity in the room to bring the VPD into the ideal range.

One reason LED grow lights are so efficient is that they don't produce excess heat in the light beam like older technologies (including HPS). However, to fully achieve all the benefits of LED technology, growers must understand how the lower heat content will affect their plants and take the proper steps to achieve optimal production.

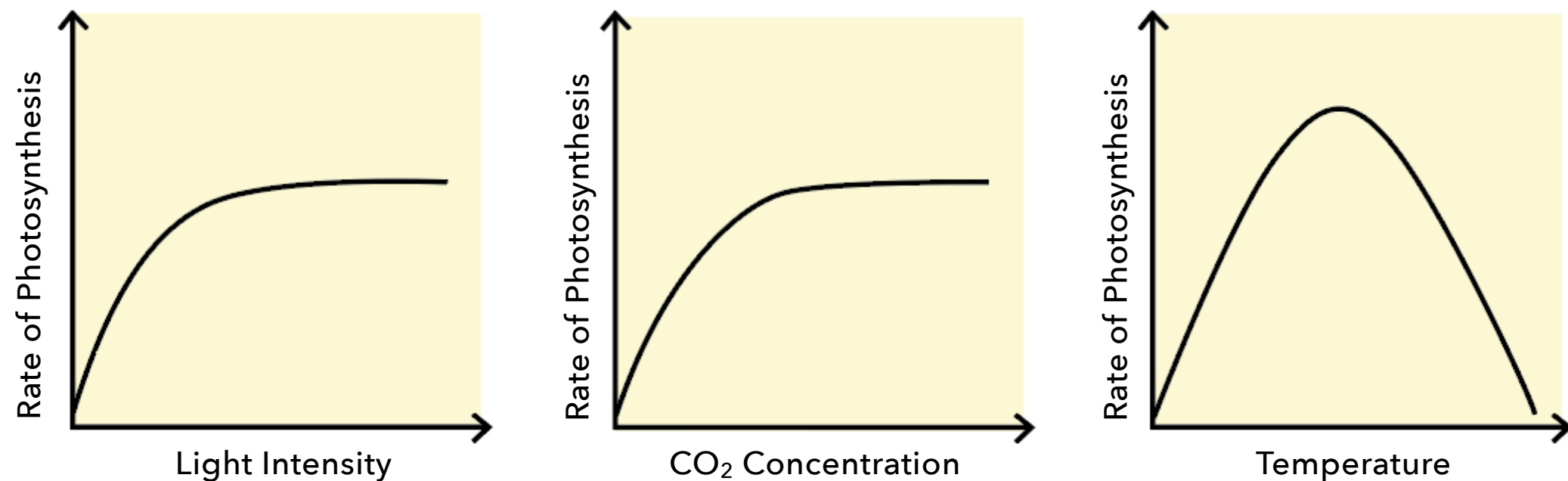


# CO<sub>2</sub> SUPPLEMENTATION

Growers working in controlled environment agriculture strive to optimize the variables at their disposal to produce the highest yield and best quality products. These key variables include temperature, humidity, nutrients, light and CO<sub>2</sub>. This section examines how switching to LED technology from older lighting technologies such as high pressure sodium could impact CO<sub>2</sub> supplementation.

First, some background on the critical role of CO<sub>2</sub> in plant development. During the Calvin cycle of photosynthesis, the plant enzyme rubisco enables carbon fixation, which ultimately results in CO<sub>2</sub> and water being converted into simple sugars (carbohydrates). The chemical reaction involving rubisco is temperature dependent, so to optimize photosynthesis we need to understand the interplay between light, temperature and CO<sub>2</sub> concentration.

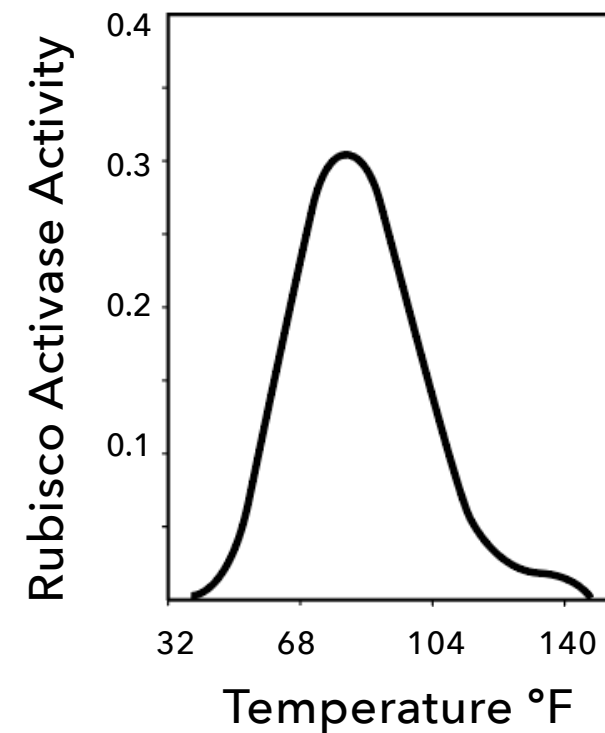
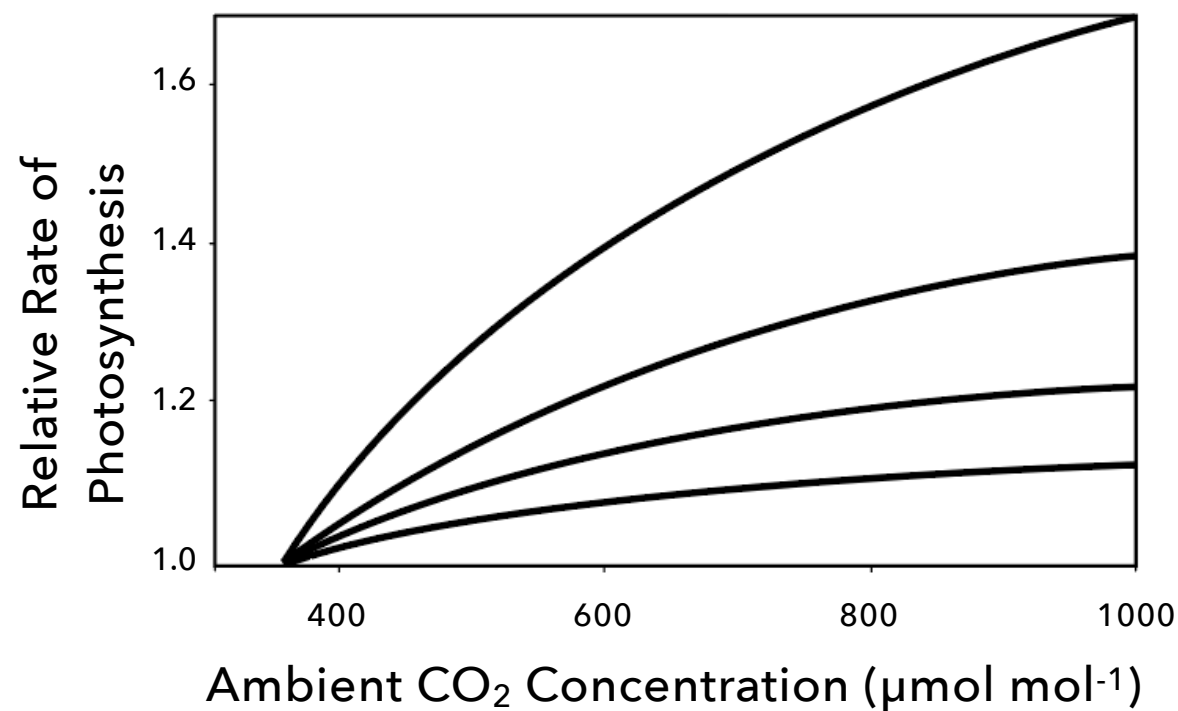
Looking at each variable independently in the figures below, we see that increasing light, CO<sub>2</sub> and temperature (leaf surface temperature) increases photosynthesis. There are clearly diminishing returns in the photosynthetic rate at very high levels of light and CO<sub>2</sub>.





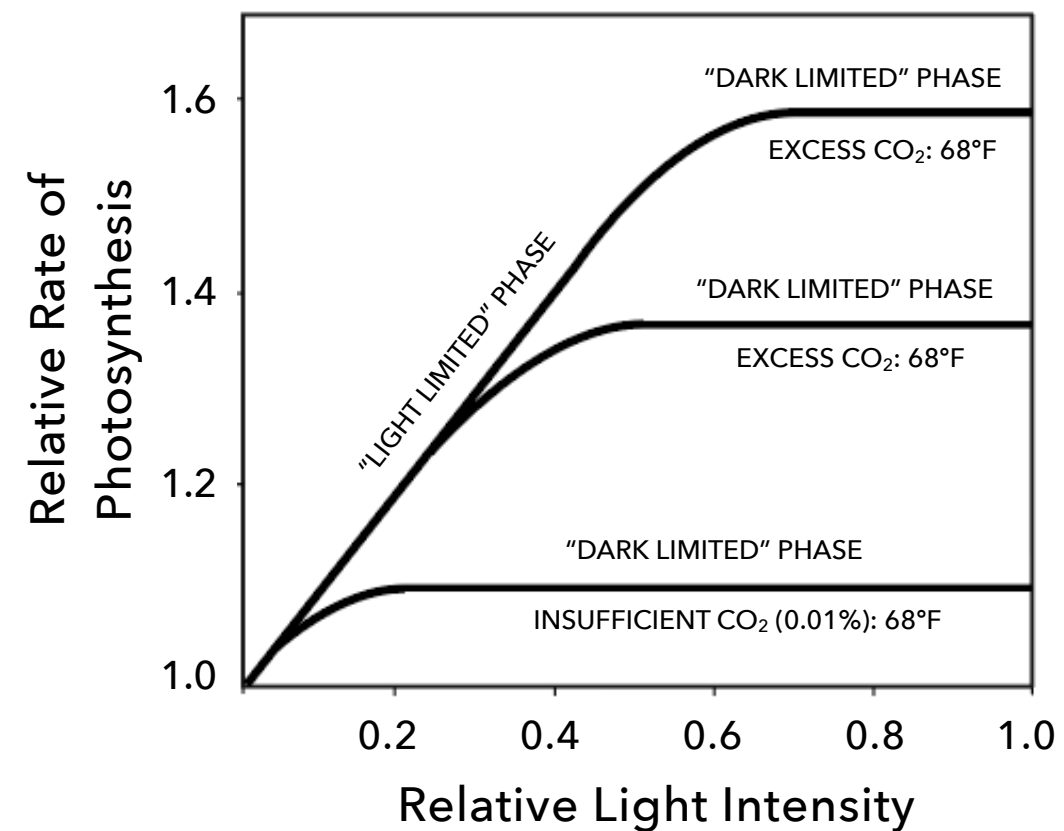
Interestingly, increasing temperature beyond an ideal point actually decreases the photosynthetic rate. This is attributable to the temperature dependence of the rubisco reaction - see figure bottom right. Without supplementing, the concentration of CO<sub>2</sub> in ambient air is roughly 300 parts per million (PPM). Under these ambient conditions the ideal leaf temperature is about 77°F.

If we add CO<sub>2</sub> to the environment, we can generate higher rates of photosynthesis at higher leaf surface temperatures - see figure bottom left.



So, the key to CO<sub>2</sub> supplementation is to achieve the concentration where you begin to experience minimal additional photosynthetic production by adding more CO<sub>2</sub>. That ideal concentration will depend on the light intensity and the leaf surface temperature (figure right).

The grower will ensure the leaf surface temperature is within a narrow window to achieve the required vapor pressure deficit. An optimized VPD enables maximal transpiration and photosynthesis.



The controlled environment agriculture industry is experiencing a shift in lighting technology. LEDs are rapidly displacing HPS, metal halide and fluorescent technologies. LED lighting has some unique characteristics that must be taken into account when upgrading a grow facility from older lighting technologies. LED lights typically have very little infrared energy in the beam, which reduces the leaf surface temperature. With a lower leaf temperature, the grower may choose to either decrease the relative humidity or increase the heat in the room in order to maintain the necessary VPD. And this decision is likely to influence the ideal set point for CO<sub>2</sub> concentration. For example, if the leaf temperature is lower, the CO<sub>2</sub> concentration should be lowered to prevent working in the "dark-limited" phase as shown in the figure above. Conversely, if the grow facility can return the leaf surface temperature to its previous level, then an adjustment in CO<sub>2</sub> would not be required.



Although the ideal CO<sub>2</sub> concentration is a function of the plant species, light intensity and leaf surface temperature, the chart below presents typical CO<sub>2</sub> values for the various phases of cannabis development.

CANNABIS GROWTH STAGE	TYPICAL CO <sub>2</sub> CONCENTRATION (PPM)
Propagation	400
Vegetative	500 - 800
Flowering	1,000 - 1,500

Maximizing biomass production in a commercial grow facility requires a deep understanding of the critical control parameters. While the benefits of LED grow lights are obvious, growers need to consider how the new technology impacts the canopy - especially as it relates to CO<sub>2</sub> supplementation.

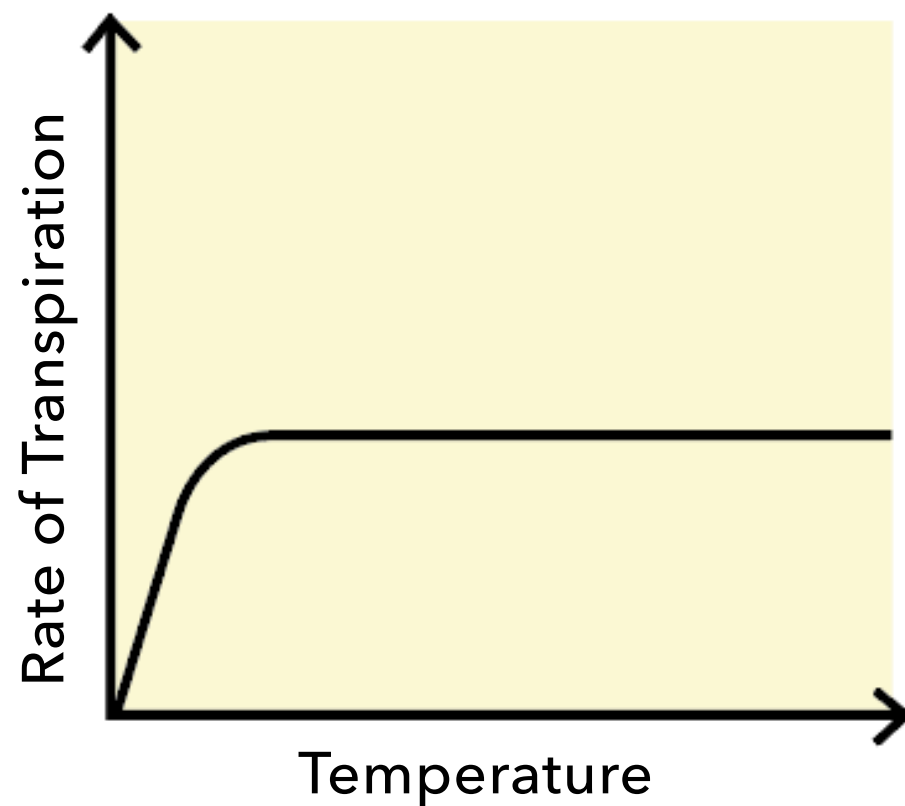




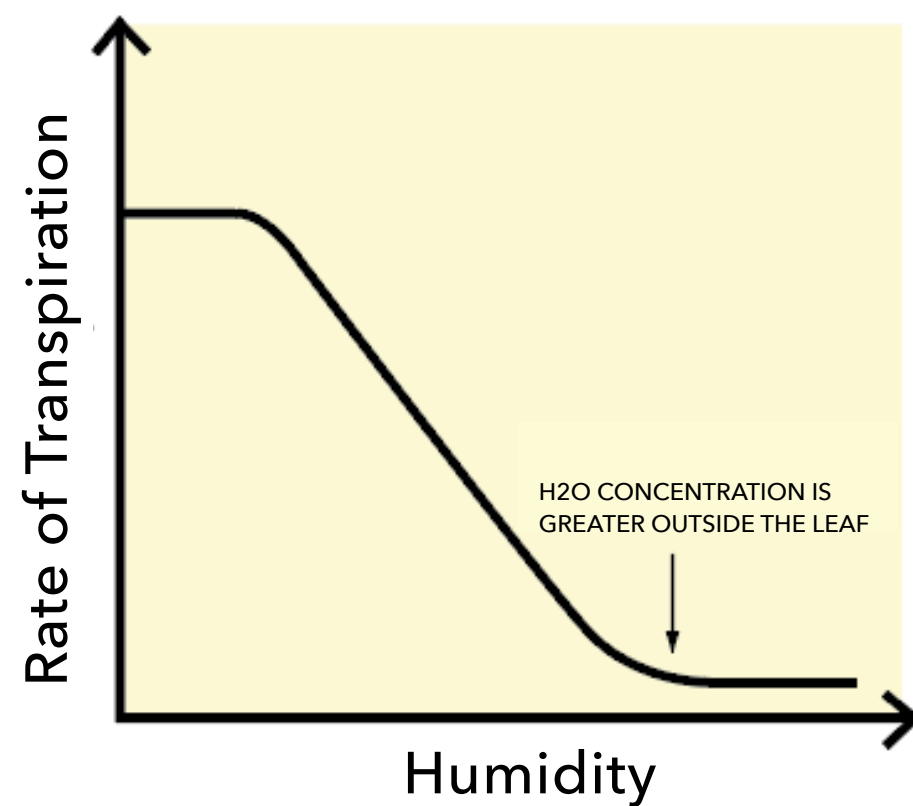
# LATENT vs SENSIBLE HEAT

Proper control of temperature and humidity inside a grow room can be the difference between success and failure. Grow room temperature directly impacts leaf surface temperature, CO<sub>2</sub> supplementation, relative humidity, transpiration rates and nutrient uptake - to name a few. Temperature control may appear as simple as setting a programmable thermostat; but of course, it's more complicated than that.

EFFECT OF TEMPERATURE ON PLANT TRANSPIRATION



EFFECT OF HUMIDITY ON PLANT TRANSPIRATION



Overheating forces plants to take up more water and then quickly transpire it, which can cause humidity overload when the lights go off. During nighttime periods of plant respiration, lights are off, which typically reduces the grow room ambient temperature by 5-10 degrees. The temperature drop and high relative humidity frequently create a wet environment that approaches the dew point. The high relative humidity can lead to devastating problems like powdery mildew, botrytis, and other unintended mold sporulation.

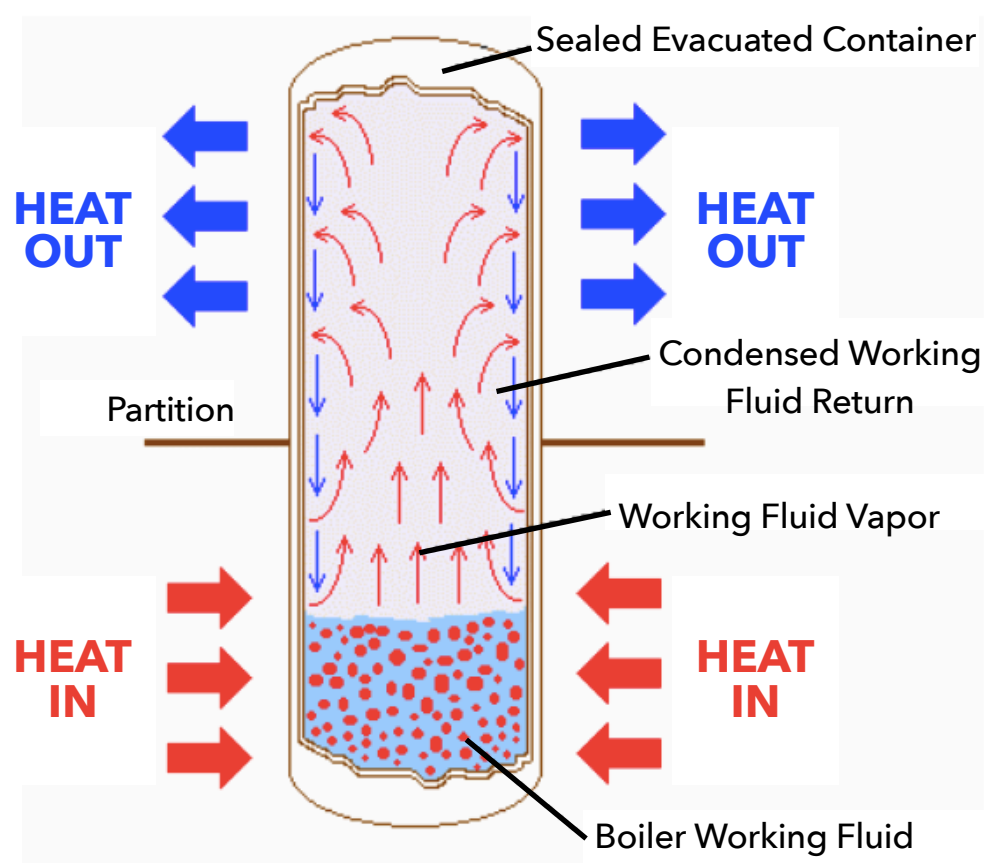
The leading strategies for controlling temperature and humidity in a grow room include ventilation and dehumidification, or some combination of the two. Determining which strategy to implement depends on the prevailing type of heat in the room. When plants transpire, stomata open, releasing water vapor through an evaporative process that cools the leaf. Water molecules in the plant absorb heat and are converted to a gas - water vapor. Since there is a phase change during this process, the heat absorbed by the water molecules is defined as latent heat. The other type of heat is called sensible heat, which is heat that is either added or subtracted without a phase change.

For the case of an overheated grow room dominated by sensible heat, a simple method for lowering the temperature is ventilation. Ventilation can be used to lower both temperature and humidity. Passive ventilation techniques have been utilized for thousands of years, so the technology is proven and so are its limitations. The efficacy of ventilation can be subject to local climate conditions and can be challenging during CO<sub>2</sub> supplementation.



Dehumidification should be considered when cooling a grow room with excessive latent heat and corresponding high humidity. Latent heat converters (LHC) transform excess water vapor into liquid, which dehumidifies the air and converts the heat of condensation (latent heat) into sensible heat that can be used to heat the environment when needed. Ventilation can be reduced, which lowers heating costs and allows atmospheric CO<sub>2</sub> enrichment. In addition to converting “wet” heat to “dry” heat, an LHC can be a good source of clean, readily accessible water. Moisture from inside the grow room can be recycled and used again.

**LHC SCHEMATIC**

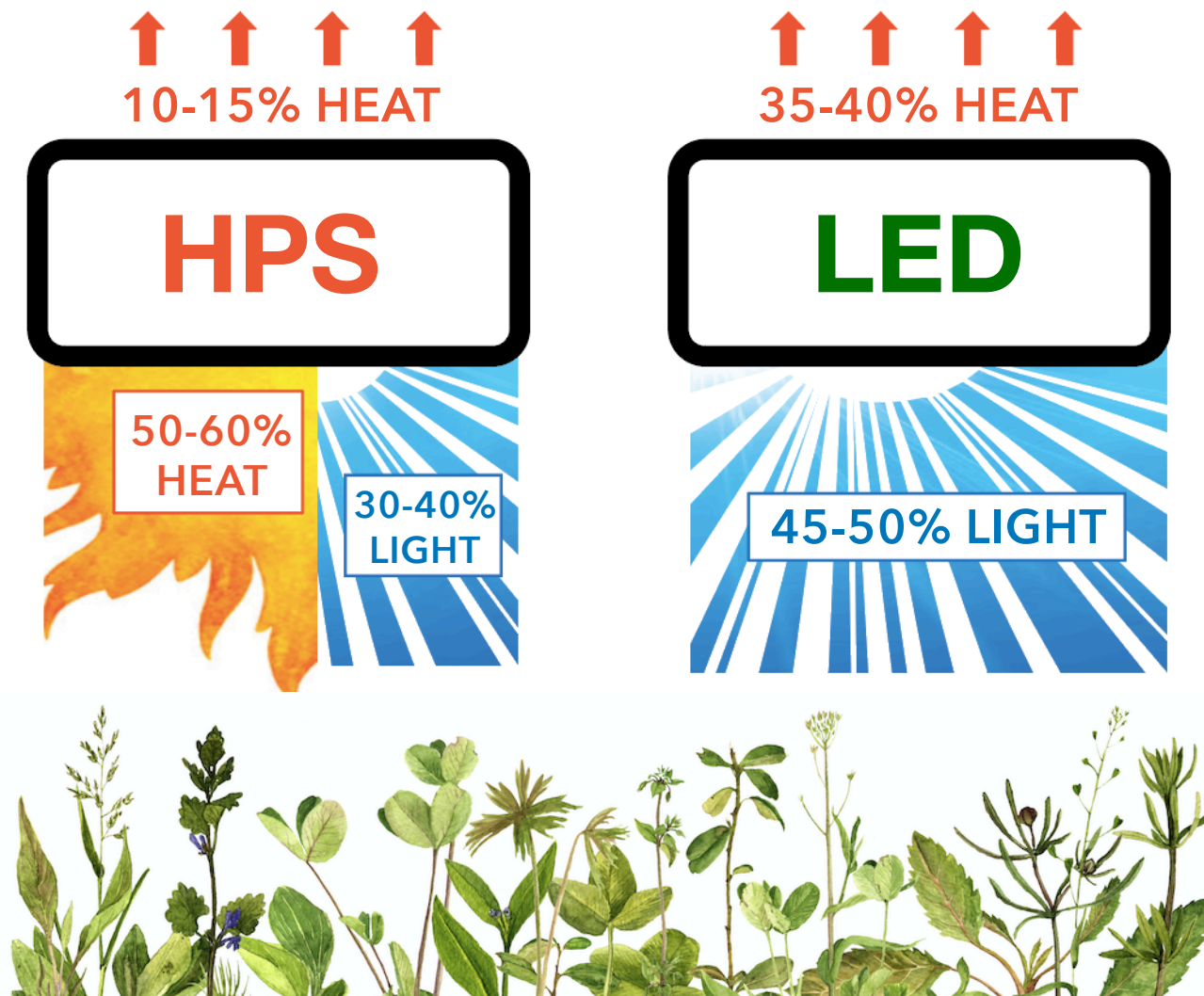


**LHC IN A GREENHOUSE**





Electric lighting can be the dominant source of heat in a grow room. As we know, LEDs are more efficient than traditional lighting technologies - they convert more electrical energy to light and less to heat. Energy supplied to an LED that isn't converted to light becomes heat that gets radiated into the air. In contrast, much of the heat generated by an HPS fixture is contained in the light beam in the form of infrared (IR) energy. The IR energy, which is absorbed by the plants, raises the leaf surface temperature and induces higher rates of transpiration. So, HPS lighting can lead to higher amounts of latent heat (via plant transpiration), while LED lighting creates more sensible heat by radiative heating. These differences can influence the strategies used to optimize temperature and humidity in a grow room.



# NUTRIENT STRATEGIES

In order to produce healthy and vigorous plants, it's important to understand how nutrient efficacy can be affected by upgrading to LED lighting. Growers are frequently surprised to discover the light intensity and uniformity on their canopies aren't what they thought. High pressure sodium (HPS) and ceramic metal halide (CMH) lights degrade in intensity fairly quickly. And in many cases the intensity and uniformity profiles are less than desirable, even with new bulbs. In contrast, a properly designed and installed LED solution should provide the right light intensity with excellent uniformity across the canopy. Furthermore, the spectral content of LEDs is different from traditional lighting technologies, and the change in spectrum may result in a variance in nutrient uptake by the plant. So how does this impact your nutrient strategy?

Drip irrigation using water soluble fertilizers, otherwise known as fertigation, is a common practice in controlled environment agriculture (CEA) - see photo to the right. The primary goal of fertilizing is to augment the nitrogen uptake in the plant, which should enhance fertility and productivity. Since nitrogen is a gas, ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ) is used in powder/crystal form and combined with water to supply nitrogen to the crop.

## FERTIGATION SYSTEM





When upgrading to LED lighting with different spectrum, intensity and uniformity profiles, fertigation strategies may need to be modified. We know that as light intensity (PPFD) increases, transpiration typically increases. Higher transpiration rates will pull more water out of the fertigation solution – leaving behind a relatively high concentration of mineral ions from the ammonium nitrate (nitrogen salts) in the media or root zone. This can make it difficult for the plant to take in water and nutrients, thereby creating nutrient imbalances.



The best way to ensure the ideal fertilizer concentration is to measure the pH and electrical conductivity (EC) of the nutrient solution and in the growing media. Since mineral ions in the fertilizer solution conduct electricity, measuring the EC is a perfect way to determine if the right amount of nutrients are being used to meet the needs of the plants without over fertilizing. It's important to measure both the nutrient solution and the soil/media near the root zone to determine the salinity level of each. An elevated EC reading means a high concentration of mineral ions (fertilizer). If the EC reading is too high in the nutrient solution, the solution should be diluted with additional water. If the EC is too high in the soil/media, it is best to perform a leaching operation to bring it back into balance. The photo on the left shows a typical meter that measures pH and EC.

Likewise, measuring pH of the soil/media is an indicator of salt build up. Ammonium-based fertilizers will acidify soil, meaning the pH will increase. For most commonly grown hydroponic crops, an optimal pH range is between 5.5 and 6.5.



There are a number of factors that determine the ideal EC value for a grow operation including, crop species, light intensity, temperature and humidity. However, some general guidelines for CEA grown cannabis are shown in the chart below. From the chart, the electrical conductivity, and hence the nutrient concentration, increases with increasing maturity of the plant. An EC meter measures electrical conductivity in units of millisiemens per centimeter (mS/cm).

CANNABIS GROWTH STAGE	EC OF NUTRIENT SOLUTION (mS/cm)
Propagation	0.25 - 0.75
Vegetative	1.0 - 2.0
Flowering	1.5 - 2.5

An incorrect nutrient concentration during fertigation can cause plant leaves to discolor, which is the result of a toxic effect commonly referred to as “fertilizer burn.” In the extreme, over fertilizing leading to a salt build up at the root zone can pull water out of the plant and cause it to wilt and die. To ensure an optimal harvest, the nutrient concentration may need to be adjusted to accommodate changes in light spectrum, intensity and uniformity from a lighting upgrade.





# RECOMMENDATIONS FOR CANNABIS GROWERS

Plant biology is a highly complex process that requires finely tuned inputs to achieve optimal production. Adjusting any one of the input parameters (light intensity, temperature, CO<sub>2</sub>, humidity, nutrients) can influence the ideal settings of other parameters. Further, as we have discussed, simply changing technology, such as HPS to LED, can alter the optimal settings of the input parameters. In the chart below, we offer recommendations for each of the input parameters to a cannabis grow operation assuming the lighting technology is LEDs.

INPUT PARAMETER	PROPAGATION	VEGETATIVE	FLOWERING
Light Intensity (PPFD)	100 - 250	300 - 450	700 - 1,200
Temperature*: Day (°F)	68 - 74	72 - 78	72 - 80
Temperature*: Night (°F)	66 - 72	68 - 74	70 - 76
CO <sub>2</sub> (PPM)	400	500 - 800	1,000 - 1,500
Relative Humidity (%)	70 - 80	55 - 70	45 - 60
Vapor Pressure Deficit (mbar)	5 - 8	8 - 12	10 - 15
Electrical Conductivity (mS/cm)	0.25 - 0.75	1.0 - 2.0	1.5 - 2.5

\*Note: Although recommendations are for ambient temperatures, it is important to understand the relationship between ambient temperature and leaf surface temperature to ensure the vapor pressure deficit remains within the ideal boundary conditions. Refer to the section on VPD for additional detail.







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