HIGH PPFD

Cultivation Guide

FLUENCE

BIOENGINEERING

INTRO

Thank you for purchasing your new Fluence Bioengineering lighting system. Our goal is to provide unsurpassed horticulture lighting technology and services to help our customers achieve their cultivation and research goals. In order to do this, at Fluence, we put education as the primary focus. You have already done the research and found the many benefits Fluence lighting systems have over high-pressure sodium, metal halide, fluorescent, and other LED lighting fixtures. You are now part of the Fluence family, and we strive to provide the most up-to-date, evidence-based information to keep you at the cutting edge of controlled environment agriculture.

As you know, light is the major environnmental variable used to drive photosynthesis in plants. However, if temperature, humidity, CO_2, nutrient, or media-moisture levels are outside the optimum range for the plant species you are growing, photosynthesis will be limited. There is a principle of limiting factors that has to be considered when cultivating plants. Understanding how each factor will influence plant growth and development, along with the relationship between each variable, will help you make optimal decisions regarding your environmental conditions. Cultivation under high photosynthetic photon flux density (PPFD) using LED technology is an emerging technique, and depending on your plant-growth facility, there may be some environmental variables you need to adjust in order to achieve your cultivation goals. We understand that every species requires different environmental conditions to optimize plant growth, and we encourage all growers to experiment and pursue their own cultivation strategies based on the crop being grown.

We have compiled this guide based on years of research and best-practice data from growers around the world to supplement your growing style and knowledge — and help you get healthier plants and higher yields.

> Short on time, but still want to get everything dialed in? Jump straight to page 16 for our recommended environmental conditions.

What is light?

Light is the single most important environmental variable concerning plant growth. Plants are autotrophs that evolved to use light energy from the sun to make their own food source via photosynthesis. Plants primarily use wavelengths of light within the visible light range of the electromagnetic spectrum (**Figure 1)** to drive photosynthesis, which is why light ranging from 400 - 700 nm is called photosynthetically active radiation (PAR). A triumph of physics in the early 20th century was the realization that light behaves both as a wave and a particle. These particles are known as photons or quanta, and the intensity that photons are absorbed by plants is critical to plant growth via photosynthesis.

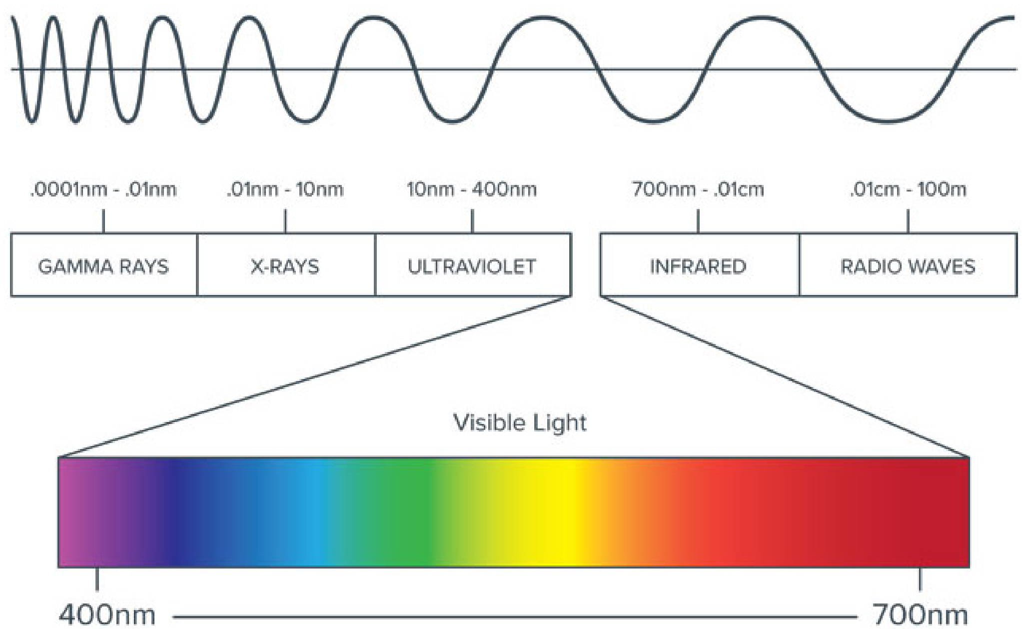

Figure 1: The electromagnetic spectrum

TABLE 1: **AVERAGE PPFD AT DEFINED MOUNTING HEIGHTS**

Distance from canopy	SPYDRX	SPYDRX PLUS	VYPRx*	VYPRx PLUS*	RAZRx	RAY44
6"	467	911	--	--	207	256
12"	387	745	--	--	142	171
18"	363	594	440	681	108	121
24"	264	477	333	510	83	88
30"	218	389	255	390	--	--
36"	183	321	200	303	--	--
42"	144	268	160	241	--	--
48"	139	224	130	196	--	--

Measurements taken at the center point of every 6'' square segment. SPYDRx and SPYDRx PLUS were over a 4' x 4' canopy, VYPRx and VYPRx PLUS were over a 4' x 3' canopy, and RAZRx and RAY44 were over a 4' x 2' canopy.

*VYPRx and VYPRx PLUS were designed to be mounted over a crop canopy with adjacent fixtures. Average PPFD will be significantly higher when mounted over a larger crop canopy with adjacent fixtures.

TABLE 2: **AVERAGE PPFD AT DEFINED DIMMING PERCENTAGES**

Dimming %	SPYDRX	SPYDRx PLUS	VYPRx*	VYPRx PLUS*	RAZRx	RAY44
100%	467	911	440	681	207	256
80%	374	729	352	545	166	204
60%	280	547	282	436	124	154
40%	187	364	225	349	83	102
20%	93	182	180	279	41	51

SPYDRx, SPYDRx PLUS, RAZRx, and RAY44 were mounted at 6"; VYPRx, VYPRx PLUS were mounted at 18". SPYDRx and SPYDRx PLUS were over a 4' x 4' canopy, VYPRx and VYPRx PLUS were over a 4' x 3' canopy, and RAZRx and RAY44 were over a 4' x 2' canopy.

*VYPRx and VYPRx PLUS were designed to be mounted over a crop canopy with adjacent fixtures. Average PPFD will be significantly higher when mounted over a larger crop canopy with adjacent fixtures.

Measuring Light Intensity

Throughout this guide we will frequently use the term photosynthetic photon flux density (PPFD) when we are discussing light intensity over a plant canopy. Quantum sensors measure the amount of PAR **(Figure 2)** landing on a specific location of your plant canopy, , with the unit μmol/m^2/s (number of photons of PAR landing on a square meter per second) being used to express values. If you do not have instruments available to measure PPFD, we have provided average PPFD values at different mounting heights (**Table 1**) and dimming percentages (**Table 2)** for single SPYDRx, SPYDRx PLUS, VYPRx, VYPRx PLUS, RAZRx, and RAY 44 lighting systems.

EQUIPMENT RECOMMENDATION

LI-COR LI-190R Quantum Sensor paired with a LI-250A digital readout LightMmeter or Apogee Instruments MQ-500 Full Spectrum Quantum Meter to meaure light intensity.

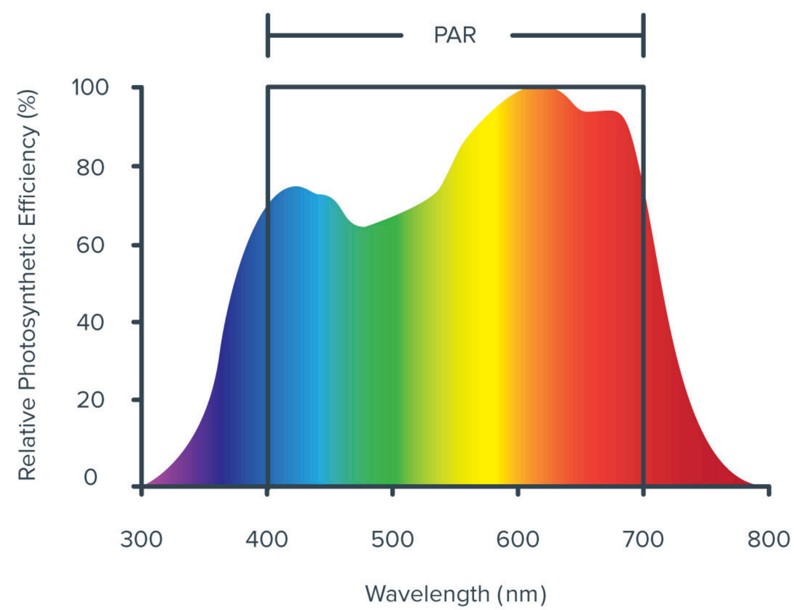

Figure 2: Average plant response to photosynthetically active radiation (PAR).

Differences Between Plant Growth and Development

Plant growth, defined as an irreversible increase in plant size, is a function of biomass production driven by photosynthesis, while plant development is the process by which plant organs (leaves, stems, flowers, etc.) originate and mature. It is important to understand the difference between plant growth and development when you make decisions regarding your growth environment.

It is also important to understand that plants have three distinct phases of growth (establishment, vegetative, and reproductive). Establishment growth occurs after seed germination or while you are rooting and establishing vegetative cuttings (clones). Vegetative growth occurs when leaves and stems are rapidly growing, while reproductive growth occurs as plants transition to produce flowers and subsequent fruit.

The initial goal for most crops is to establish large leaves and stems to provide plants with enough photosynthetic area to produce carbohydrates later used for the production of flowers and fruits. The allocation of photosynthates from 'sources' (active leaves) to 'sinks' (roots, shoots, flowers, and fruits) is an important balance influenced by environmental conditions. The principle of limiting factors also relates to photosynthate allocation. Plants are highly adaptive, due to their inability to relocate to an ideal environment. If an environmental variable is not favorable, plants allocate energy resources to increase their chance for survival. For example, in nutrient-limited conditions, a plant will allocate resources to expand root growth, while in light-limited conditions, resources will be allocated to stem and leaf growth. Depending on your cultivation goals and the crop being produced, environmental conditions will need to be adjusted during each growth phase. The remainder of this guide will outline the influence that environmental factors have on plant growth, and recommend ranges to optimize cultivation.

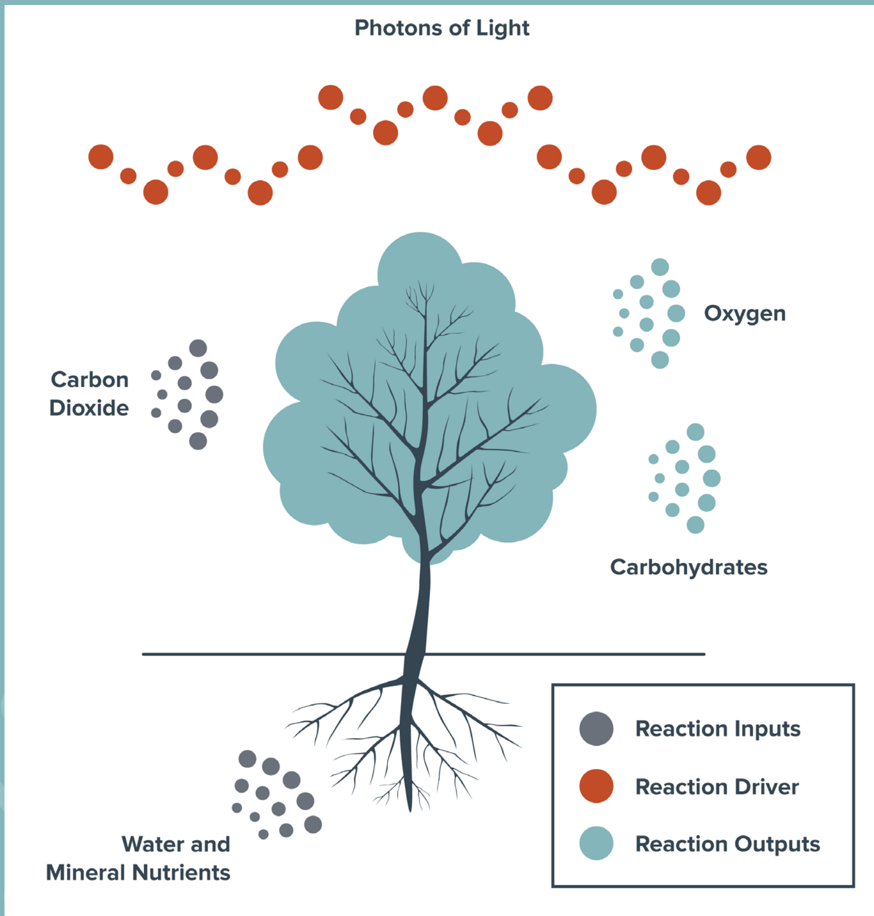

Figure 3: Photosynthesis reaction

Light Intensity

Photosynthesis occurs inside of specialized organelles known as chloroplasts, and is the process that uses light energy to split water (H_2O) and fix carbon dioxide (CO_2) to produce carbohydrates (CH_2O) and oxygen (O_2). The process is very complex; however, a simple diagram of the reaction is shown in **Figure 3**. As light intensity (PPFD) increases, photosynthetic rates also increase until a saturation point is reached. Every plant species has a light saturation point where photosynthetic levels plateau. Light saturation normally occurs when some other factor (normally CO_2) is limited (**Figure 4**).

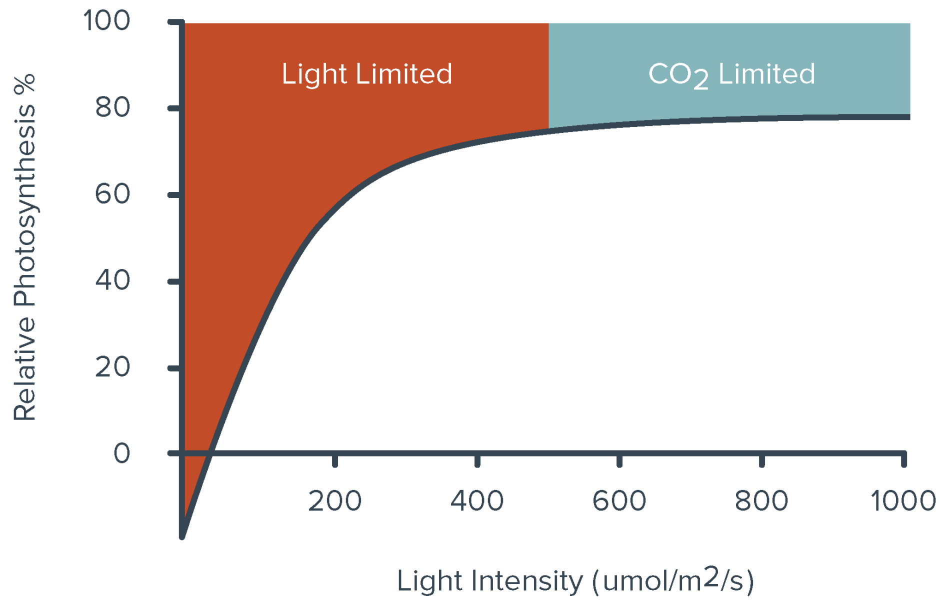

Figure 4: Influence of light intensity on the rate of photosynthesis

TABLE 3: **RECOMMENDED PPFD (μmol/m²/s)**

Species	Establishment		Vegetative	Reproductive
	Seed	Vegetative Cutting		
Cannabis	100-300	75-150	300-600	600+
Tomatoes	150-350	75-150	350-600	600+
Cucumbers	100-300	--	300-600	600+
Peppers	150-350	--	300-600	600+

Light Intensity (continued)

During establishment growth, light intensities need to be kept relatively low as the plant is developing leaves and stems that will be used to provide photosynthates during the vegetative growth phase. Increasing light intensity as you transition into the vegetative and reproductive growth phases will increase the rate of photosynthesis, which will provide the plant with more photosynthates used to develop flowers and subsequent fruit. Plants need time to acclimate to high light intensities (referred to as photoacclimation). If you expose plants to high light intensities too early in the crop cycle, you can damage chlorophyll pigments causing photo-oxidation (photo-bleaching), so we recommend slowly increasing your light intensity as your plant develops. Refer to **Table 3** for recommended PPFD ranges for establishment, vegetative, and reproductive growth of cannabis, tomatoes, cucumbers, and peppers.

TABLE 4: **RECOMMENDED CO_2 CONCENTRATION (ppm)**

Species	Establishment	Vegetative	Reproductive
Cannabis	400	400-800	800-1400
Tomatoes	400	400-800	700-1200
Cucumbers	400-600	400-800	800-1000
Peppers	400-600	400-800	800-1000

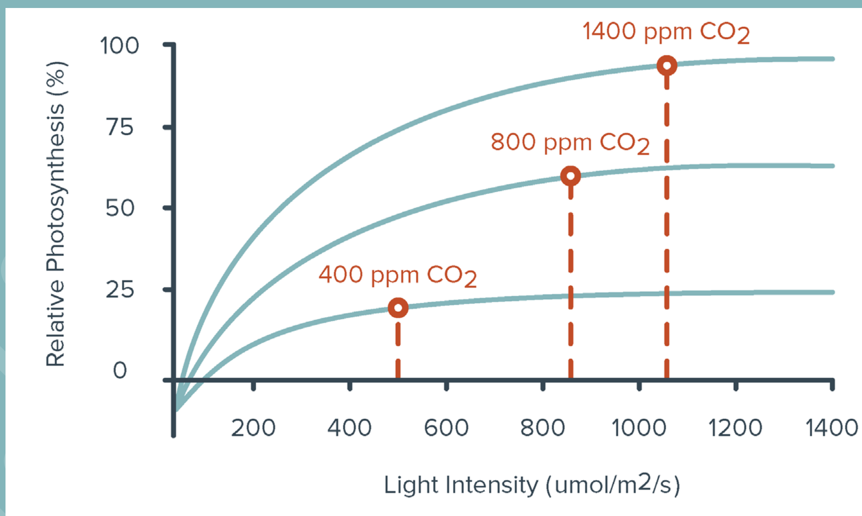

Figure 5: Influence of CO_2 concentration on the rate of photosynthesis.

Carbon Dioxide Enrichment: How Much CO_2 Should You Give Your Plants?

Carbon dioxide (CO_2) enrichment in your controlled environment will substantially improve the yield of your high PPFD crops. All plants have a light saturation point where the maximum rate of photosynthesis is reached at a specific light intensity. Maximum photosynthesis at ambient atmospheric CO_2 levels (~400 ppm) is normally limited by the amount of CO_2 available, not the intensity of light (**Figure 5**). Generally, optimum levels of CO_2 will be two to four times the normal atmospheric levels (800 – 1,400 ppm CO_2) when growing under high PPFD conditions. We recommend supplementing ≥ 800 ppm CO_2 into your controlled environment when you are providing your plants with ≥ 500 μmol/m^2/s. As you increase your light intensity, you can slowly increase your CO_2 levels as plants acclimate to increased PPFD. Refer to **Table 4** for recommended CO_2 concentrations during establishment, vegetative, and reproductive growth of cannabis, tomatoes, cucumbers, and peppers.

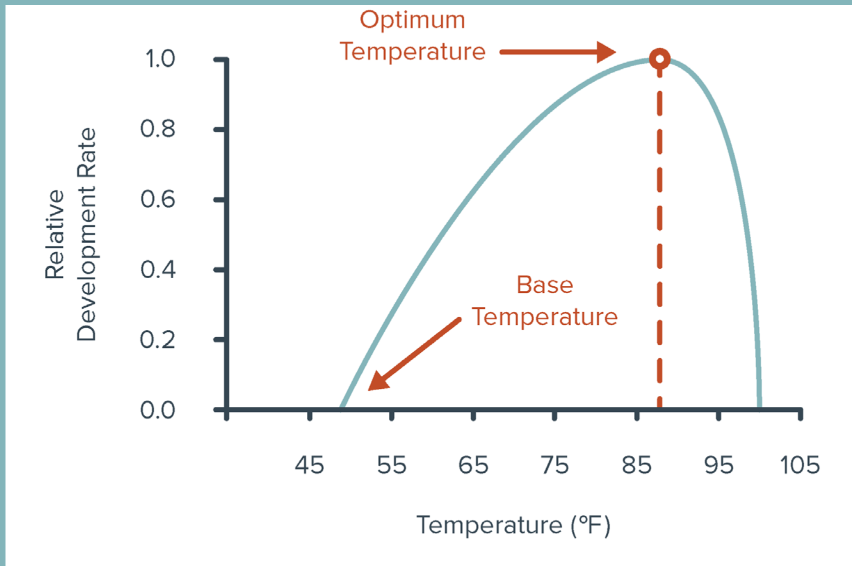

Figure 6: Influence of temperature on the rate of plant development.

How Does Temperature Affect Plant Growth and Development?

Plant growth and development is primarily influenced by temperatures at the growing points of plants (i.e., roots and shoot tips). When we are discussing temperature, it is important to understand that plant temperature (not air temperature) drives physiological responses in plants. Air temperature can differ by as much as 10° F from plant temperature, depending on your light source (HPS, MH, or LED), light intensity, humidity, and air speed. For example, HPS lights emit a large percentage of their energy in the infrared (IR) range (800nm–1000nm) which is not photosynthetically active yet significantly increases plant temperature. As a result, growers need to decrease their air temperature set-point to counter the additional radiant heat.

EQUIPMENT RECOMMENDATION

Fluke 59 Max+ Infrared Thermometer to measure plant temperature.

All crops have a species-specific base temperature, at which growth and development will not occur. Above the base temperature, growth and developmental rates increase with temperature until an optimum temperature is reached. Above the optimum temperature, plant development decreases (**Figure 6**). Light intensity primarily influences the rate of photosynthesis, while plant temperature primarily influences developmental rates. Net photosynthesis under increased

TABLE 5: **RECOMMENDED DAY/NIGHT TEMPERATURE (°F)**

	Establishment		Vegetative		Reproductive	
Species	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**
Cannabis	72-80	70-78	74-84	68-76	68-84	68-78
Tomatoes	68-72	68-72	70-79	61-65	68-73	62-65
Cucumbers	73-75	70-72	70-75	62-68	70-75	62-68
Peppers	72-73	72-73	72-74	64-65	72-74	66-68

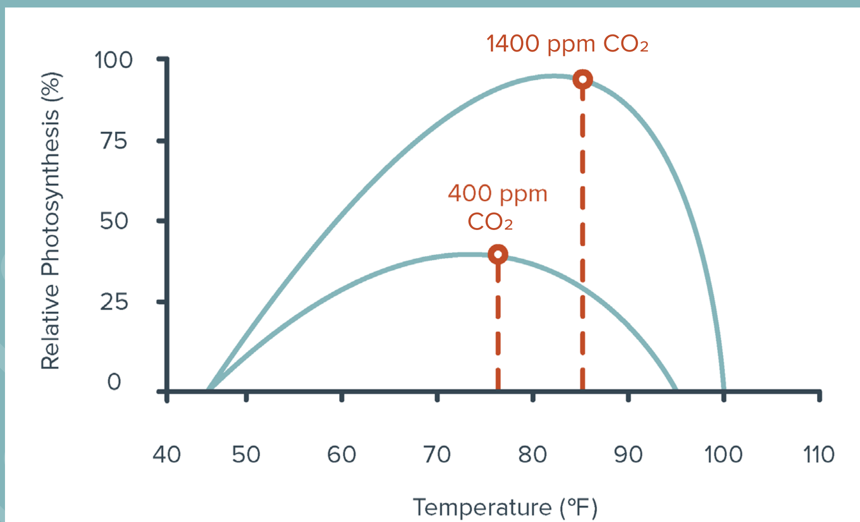

Figure 7: Influence of temperature and CO_2 concentration on the rate of photosynthesis.

Temperature (continued)

PPFD will increase as temperatures approach the optimum temperature for the species of plant you are growing; however, the optimum temperature for photosynthesis depends on the concentration of CO_2 (**Figure 7**); it is important to understand that as you increase temperature, you will also change the morphology of the plant by increasing developmental rates. The ratio between light intensity and temperature is known as the photothermal ratio. If you choose to grow at warmer temperatures, you need to ensure that you are providing an adequate light intensity, or you may produce plants that have increased internode distance, small stem caliper, and an overall spindly growth habit.

TIP

An air speed of 1.0 m/s is recommended in order to break the boundary layer and provide uniform air temperatures at the crop canopy.

EQUIPMENT RECOMMENDATION

Holdpeak 866B Digital Annenometor to measure wind speed.

The difference between day/night temperatures (DIF) will also significantly influence plant morphology. For example, if your day/night air temperature is 75°/65° F you have a +DIF of 10° F, which will promote stem elongation of most crops. Alternatively, if you have a warmer night temperature 65°/75 °F (day/night) you will have a -DIF, which will suppress stem elongation. Depending on the growth habit of your crop, you will need to find a balance between temperature and light intensity to achieve your desired plant architecture. We provide optimum temperature ranges for the cultivation of cannabis, tomatoes, cucumbers, and peppers (**Table 5**).

TABLE 6: **RELATIONSHIPS BETWEEN ENVIRONMENTAL VARIABLES**

Air temperature	Relative humid-ity	Vapor pressure deficit	Water demand	Evapotranspiration
↑	↓	↑	↑	↑
↓	↑	↓	↓	↓

TABLE 7: **RECOMMENDED RELATIVE HUMIDITY (%)**

Species	Establishment	Vegetative	Reproductive
Cannabis	60-80	55-75	50-60
Tomatoes	60-80	55-75	60-80
Cucumbers	60-80	55-75	60-80
Peppers	60-80	55-75	60-80

Relative Humidity and Vapor Pressure Deficit

Relative Humidity (RH) is the amount of humidity present at a given temperature and is expressed as a percentage. When air is completely saturated, it has a RH of 100%. Temperature and RH are the two main variables that influence water movement within a plant. Evapotranspiration is a process plants use to cool leaf surfaces. As the temperature of a leaf increases, plants will pull more water from the growing media. Water is evaporated from the leaf surface and as a result the leaf temperature decreases. We provided a table to show the influence that temperature and RH has on evapo-transpi-ration, and water demand (**Table 6**). As you can see, increasing the temperature in your controlled environment will reduce your RH, causing an increase in transpiration rates and water demand, while decreasing your temperatures will increase RH, causing decreased transpiration and water demand. Re-fer to **Table 7** for recommended RH ranges for establishment, vegetative, and reproductive growth of cannabis, tomatoes, cucumbers, and peppers.

A good tool to use when growing in a controlled environment is vapor pressure deficit (VPD). VPD is a good indicator of plant stress brought about by either excessive transpiration (high VPD values) or the inability to

TIP

During the finishing stages of cannabis flowering, you will want to maintain a relative humidity ≤ 55% to prevent fungal pathogens from colonizing on the flower. Depending on your temperature, this may or may not take you out of the optimum VPD range.

Relative Humidity and Vapor Pressure Deficit

(continued)

TABLE 8: **VAPOR PRESSURE DEFICIT (kPa)**

Temperature		Relative Humidity												
°C	°F	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%	45%	40%
15	59.0	0.00	0.09	0.17	0.26	0.34	0.42	0.51	0.59	0.68	0.76	0.85	0.94	1.02
16	60.8	0.00	0.09	0.18	0.27	0.36	0.46	0.06	0.64	0.73	0.82	0.91	1.00	1.09
17	62.6	0.00	0.10	0.19	0.29	0.39	0.49	0.58	0.68	0.78	0.88	0.97	1.06	1.16
18	64.4	0.00	0.10	0.21	0.31	0.41	0.51	0.62	0.72	0.82	0.93	1.03	1.13	1.24
19	66.2	0.00	0.11	0.22	0.33	0.44	0.55	0.66	0.77	0.88	0.99	1.10	1.21	1.32
20	68.0	0.00	0.12	0.23	0.35	0.47	0.59	0.70	0.82	0.94	1.06	1.17	1.28	1.40
21	69.8	0.00	0.12	0.25	0.37	0.50	0.62	0.74	0.86	0.99	1.11	1.24	1.37	1.49
22	71.6	0.00	0.13	0.26	0.40	0.53	0.66	0.79	0.92	1.05	1.19	1.32	1.45	1.58
23	73.4	0.00	0.14	0.28	0.42	0.56	0.70	0.85	0.99	1.13	1.27	1.41	1.54	1.68
24	75.2	0.00	0.15	0.30	0.45	0.60	0.74	0.89	1.04	1.19	1.34	1.49	1.64	1.79
25	77.0	0.00	0.16	0.32	0.48	0.63	0.80	0.95	1.11	1.27	1.43	1.59	1.74	1.90
26	78.8	0.00	0.17	0.34	0.50	0.67	0.84	1.01	1.18	1.34	1.51	1.68	1.84	2.01
27	80.6	0.00	0.18	0.36	0.54	0.71	0.89	1.07	1.24	1.42	1.60	1.78	1.96	2.13
28	82.4	0.00	0.19	0.38	0.57	0.76	0.95	1.14	1.33	1.51	1.70	1.89	2.07	2.26
29	84.2	0.00	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00	2.21	2.41
30	86.0	0.00	0.21	0.42	0.64	0.85	1.06	1.27	1.48	1.70	1.91	2.12	2.33	2.54
31	87.8	0.00	0.22	0.45	0.67	0.90	1.12	1.34	1.57	1.79	2.02	2.24	2.46	2.69
32	89.6	0.00	0.24	0.48	0.71	0.95	1.19	1.42	1.66	1.90	2.13	2.37	2.61	2.84
33	91.4	0.00	0.25	0.50	0.76	1.01	1.25	1.50	1.76	2.01	2.26	2.51	2.76	3.01
34	93.2	0.00	0.27	0.53	0.80	1.06	1.33	1.59	1.86	2.12	2.39	2.65	2.92	3.18
35	95.0	0.00	0.28	0.56	0.84	1.13	1.40	1.68	1.96	2.24	2.52	2.80	3.08	3.36

Key

- Optimal
- Moderate
- Sub-optimal

transpire adequately (low VPD values). When the VPD is too low (humidity too high) plants are unable to evaporate enough water to enable the transport of mineral nutrients (such as calcium), and in cases where VPD is extremely low, water may condense onto the plant and provide a medium for fungal growth and disease. **Table 8** provides VPD values based on temperature and humidity. Generally, you will want to grow your plants in the optimum VPD range. However, during establishment growth (especially vegetative cuttings), optimal VPD is around 0.3 - 0.5 kPa, which is outside of the optimal range in our VPD table.

TABLE 9: **EC TO PPM CONVERSION**

Electrical Conductivity (mS/cm)	Parts per million (ppm)		
	0.5 conversion	0.64 conversion	0.7 conversion
0.10	50	64	70
0.20	100	128	140
0.40	200	256	280
0.60	300	384	420
0.80	400	512	560
1.00	500	640	700
1.20	600	768	840
1.40	700	896	980
1.60	800	1024	1120
1.80	900	1152	1260
2.00	1000	1280	1400
2.20	1100	1408	1540
2.40	1200	1536	1680
2.60	1300	1664	1820
2.80	1400	1792	1960
3.00	1500	1920	2100

TABLE 10: **RECOMMENDED EC (mS/cm) OF NUTRIENT SOLUTION**

Species	Establishment	Vegetative	Reproductive
Cannabis	0.3-0.7	1.0-2.0	1.5-2.6
Tomatoes	0.3-0.6	1.0-1.8	1.2-2.4
Cucumbers	0.3-0.6	1.0-2.0	1.2-2.5
Peppers	0.3-0.6	0.8-1.6	1.0-2.4

Irrigation/Fertigation

Maintaining a balanced water, nutrient, and oxygen (O_2) supply to your root zone during all three phases of growth is critical in order to produce heathy, vigorous plants. There are hundreds of different fertilizer brands on the market, and whichever one you decide to use, make sure it provides balanced levels of macro- and micronutrients available to your crop. Follow the manufacturer's recommended fertilizer rates, and always monitor the pH and electrical conductivity (EC) of your nutrient solution. Many growers use parts per million (ppm) meters to measure nutrient solutions, however, ppm meters actually just measure EC and use a conversion factors of either: 0.5, 0.64, or 0.7 to express ppm values. Having different conversion factors (depending on the brand of your meter) can create confusion when making recommendations to growers (**Table 9**), which is why our preferred method of measuring fertilizer rates is using EC meters. Additionally, it is difficult to make recommended feed rates since EC varies not only with the concentration of fertilizer in solution, but also with the chemical composition of the nutrient solution. Keeping that in mind, we have provided general fertilizer rates during each phase of growth in **Table 10**.

Cultivation under increased PPFD generally causes increased transpiration rates. If you are feeding a high rate of fertilizer at each irrigation, plants will be taking up much more water than nutrients. This can cause soluble salts to build up in the root zone, resulting in increased osmotic pressure. This will make it difficult for your plants to uptake water and nutrients, and can lead to nutrient imbalances causing deficiencies or toxicities. A good practice to avoid salt buildup is to leach 15 to 20 % of your nutrient solution out of your root zone at each irrigation. Another practice to ensure you are not getting a salt buildup is to measure the EC of the solution going into the root zone and the EC of your leachate. If the EC of the leachate is ≥ 0.5 mS/cm of the input nutrient solution, you will want to decrease your feed rate, or flush the root zone with pH-adjusted water.

Monitoring the pH and EC of your growth media is a good tool growers can use to avoid many nutrient problems that can occur due to over- and under-fertilization. A simple method used to measure your pH and EC is called the pour-thru method. First, start by irrigating your crop with your nutrient solution until the soil is completely saturated (leachate is coming out of the bottom of the container). Wait 30 minutes, then place a saucer below the container and pour distilled water over the surface of the growing media until you collect a sample large enough (~50 mL) to be able to submerge your pH/EC meter in. Take your measurements, and record at least once weekly.

DEFINITION

Leachate: a liquid that extracts soluble or suspended solids as it passes through matter (i.e., growth media).

CONCLUSION

The take-home message is that plants require a dynamic environment to optimize growth and development. If any of the above variables fall out of the optimized range, those variables will become a limiting factor for important biological reactions, even if all other variables are at the optimum levels. If you maintain your growth environment in our recommended ranges, and use the information in this guide to supplement your growing style, **we believe you will have healthy crops, and overall higher yields** using Fluence Bioengineering horticulture lighting systems.

REFERENCE

RECOMMENDED ENVIRONMENTAL CONDITIONS FOR **ESTABLISHMENT** GROWTH

Crop	Light Intensity (μmol/m²/s)		Carbon Dioxide (ppm)	Temperature (°F)		Relative Humidity (%)	Electrical Conductivity (mS/cm)
	Seed	Vegetative Cutting		Day	Night		
Cannabis	100-300	75-150	400	72-80	70-78	60-80	0.3-0.7
Tomatoes	150-350	75-150	400	68-72	68-72	60-80	0.3-0.6
Cucumbers	100-300	--	400-600	73-75	70-72	60-80	0.3-0.6
Peppers	150-350	--	400-600	72-73	72-73	60-80	0.3-0.6

RECOMMENDED ENVIRONMENTAL CONDITIONS FOR **VEGETATIVE** GROWTH

Crop	Light Intensity (μmol/m²/s)	Carbon Dioxide (ppm)	Temperature (°F)		Relative Humidity (%)	Electrical Conductivity (mS/cm)
			Day	Night		
Cannabis	300-600	400-800	74-84	68-76	55-75	1.0-2.0
Tomatoes	350-600	400-800	70-79	61-65	55-75	1.0-1.8
Cucumbers	300-600	400-800	70-75	62-68	55-75	1.0-2.0
Peppers	300-600	400-800	72-74	64-68	55-75	0.8-1.6

RECOMMENDED ENVIRONMENTAL CONDITIONS FOR **REPRODUCTIVE** GROWTH

Crop	Light Intensity (μmol/m²/s)	Carbon Dioxide (ppm)	Temperature (°F)		Relative Humidity (%)	Electrical Conductivity (mS/cm)
			Day	Night		
Cannabis	600 +	800-1400	68-84	68-78	50-60	1.5-2.6
Tomatoes	600 +	800-1400	68-72	68-72	60-80	1.2-2.4
Cucumbers	600 +	800-1400	73-75	70-72	60-80	1.2-2.5
Peppers	600 +	800-1400	72-73	72-73	60-80	1.0-2.4

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