FLUENCE BY OSRAM

PHOTOBIOLOGY GUIDE

INTRO

We compiled this high PPFD cultivation guide (defined as crops requiring ≥ 500 µmol/m2/s) based on years of research and best-practice data from commercial growers around the world to ensure your successful transition to Fluence lighting solutions.

Light is the major environmental variable used by plants to drive photosynthesis. However, if temperature, humidity, CO_2, nutrient, or media-moisture levels are outside the optimum range for the plant species being grown, photosynthesis will be limited. There is a principle of limiting factors that must be considered when cultivating plants, and when one variable is changed (such as light intensity and/or quality), all other variables need to be examined as they may also need to be adjusted to optimize production in your controlled environment.

This guide is not a prescriptive document, rather it is intended to supplement your cultivation knowledge to help you think critically regarding environmental conditions and optimize decision-making for your facility. Furthermore, we recognize that every species requires different environmental conditions to optimize plant growth, therefore we encourage all growers to experiment and pursue their own cultivation strategies based on the crop being grown.

Overall, we want to help you realize your potential of higher yields and healthier plants when using high PPFD Fluence solutions. If you have any specific questions regarding this guide or are seeking further cultivation support, please contact us at 512-212-4544.

WHAT IS LIGHT?

The term "light" represents only a portion of the larger range of electromagnetic radiation **(Figure 1).** Light has a unique characteristic where it behaves as a wave and a particle at the same time. Measuring the wavelength in nanometers (nm) provides information about the light quality while measuring the particle (also known as photon or quanta) in micromoles per meter squared per second (µmol/m²/s) provides information about the light quantity or "intensity".

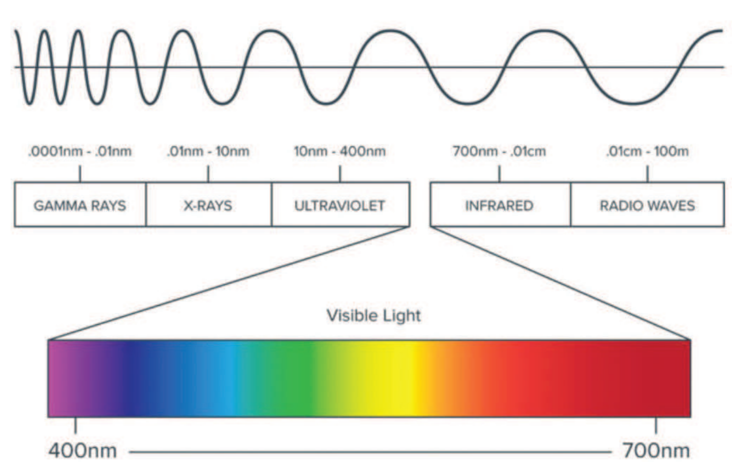


Figure 1: The electromagnetic spectrum

WHAT IS PHOTOBIOLOGY?

Photobiology is the study of the interaction between light and living organisms (for the purposes of this document (and our lighting solutions as a whole), we're solely focused on plants). Plants are autotrophs that evolved to use light energy from the sun to make their own food source via photosynthesis. Thus, light is the most critical environmental variable concerning plant growth – without it, plants simply cannot survive. Wavelengths of light that drive photosynthesis are primarily found within the range of 400 - 700nm – this range is aptly called photosynthetically active radiation (PAR). Within a plant leaf are various pigments and photoreceptors that respond to different wavelengths of PAR. Additionally, these pigments and photoreceptors perceive the intensity of photons that are absorbed which have an impact on the rate of photosynthesis and overall plant growth.

HOW IS LIGHT MEASURED?

Photosynthetic photon flux density (PPFD) refers to the amount of PAR landing on a specific location of your plant canopy. A quantum sensor is used to measured PPFD and the unit of measurement is µmol/m²/s (number of photons of PAR landing on a square meter per second).

It is critical as a cultivator to measure your environmental variables frequently and accurately; this enables you to better diagnose problems if/when they arise. Light levels are no exception, we strongly encourage you to use a high-quality PAR meter such as Li-Cor or Apogee (model numbers listed in recommended equipment section). However, if you do not have instruments available to measure PPFD, we have provided average PPFD values expected at different mounting heights and dimming percentages for single Fluence lighting systems.

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

Light Overlap

If you have two or more fixtures mounted closely to one another, the canopy under each fixture will receive light overlap from the adjacent fixture(s). Light overlap can add 15-40% more PPFD at the canopy and significantly improve light uniformity. If you have a single fixture, or multiple fixtures mounted more than 10 feet away from each other please refer to **Table 1** for applicable PPFD averages. If your fixtures are mounted in a grid to cover larger areas, please refer to **Table 2** for applicable PPFD averages.

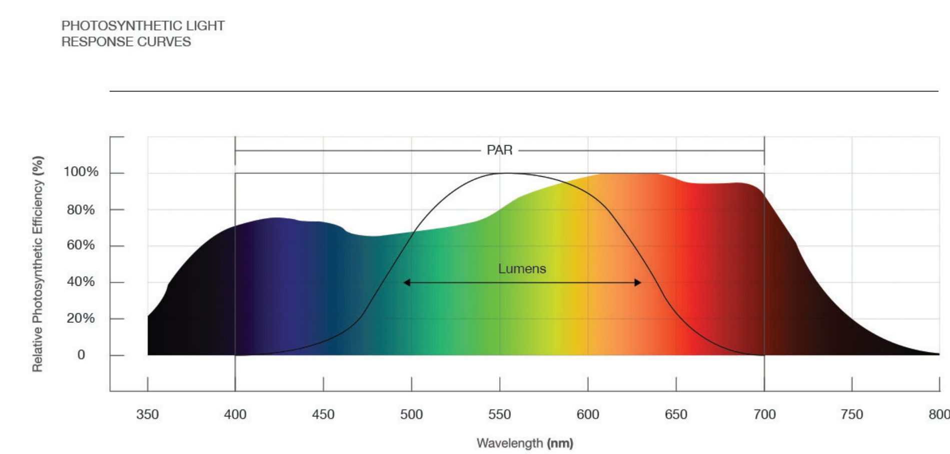


Figure 2: Average plant response to photosynthetically active radiation (PAR).

Reflectivity

For small grow environments using a single fixture, wall reflectivity can significantly influence PPFD levels at the canopy. A matte white wall has a reflectivity between 70% and 90%, while a typical grow tent lined with mylar can reflect up to 95% of light. Mounting height plays a role in reflectivity as well. For example, a light mounted six inches above canopy will have significantly less photon spread than a light mounted three feet above canopy. The higher the fixture is mounted, the more important wall reflectivity becomes by redirecting photons back towards your crop.

DIFFERENCES BETWEEN PLANT GROWTH AND DEVELOPMENT

It is important to understand the difference between plant growth and development when you make decisions regarding your growth environment.

- Plant growth: an irreversible increase in plant size is a function of biomass production driven by photosynthesis
- Plant development: process by which plant organs (leaves, stems, flowers, etc.) originate and mature.

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
- 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 that will be allocated to flowers and fruits during the reproduction phase. 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 development and provide you with recommend ranges to optimize cultivation under Fluence lighting systems.

LIGHT INTENSITY

Photosynthesis:

Photosynthesis occurs inside 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).**

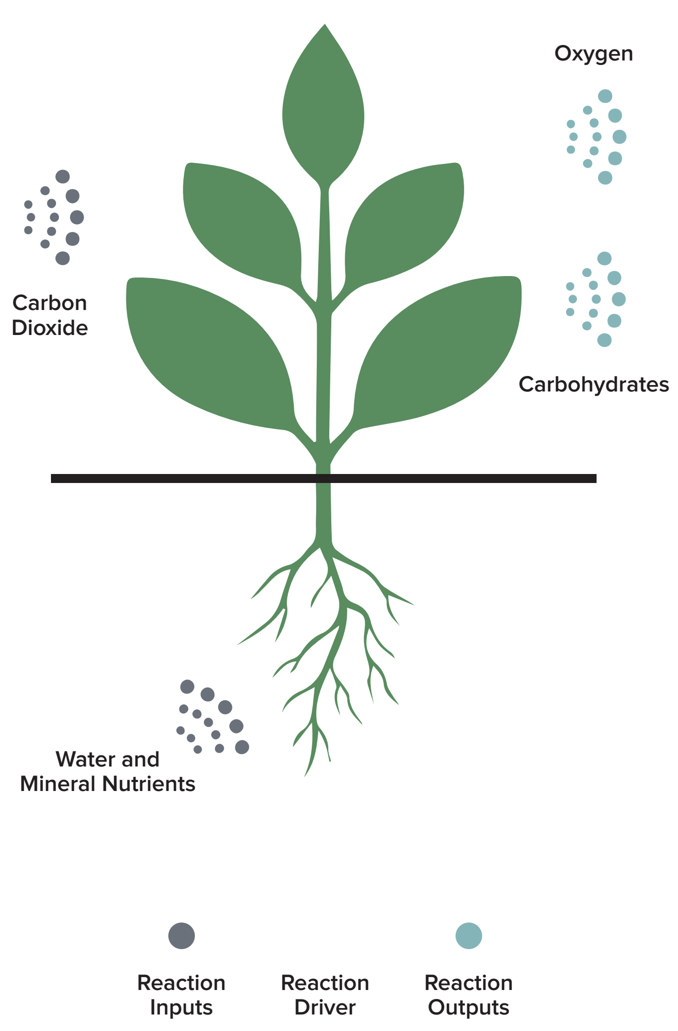


Figure 3: Photosynthesis reaction

Light Saturation:

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).**

Photoacclimation:

During establishment growth, light intensities need to be kept relatively low as the plant is developing roots, 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. As a general rule of thumb, increasing by 50 µmol/m^2/s or less per day, with frequent observation, is a good place to start. Refer to **Table 3** for recommended PPFD ranges for establishment, vegetative, and reproductive growth of cannabis, tomatoes, cucumbers, and peppers.

Photoperiodism

Photoperiodism has been investigated by the scientific community during the past century for its complex and ubiquitous "nature". Photoperiodism is a plant's response to the duration of the day (light period) in combination with the duration of the night (dark period). This phenomenon influences different plant responses such as flowering, vegetative reproduction and dormancy. This discovery lead to the creation of photoperiod classes of plants by their response to the daylength. Growers and scientists learn more about plants every year and this list continues to gain more classes. The following are the current classes of photoperiod:

- Short Day Plants (SDP)
- Long Day Plants (LDP)
- Day Length Neutral Plants (DLNP)
- Intermediate Day Length Plants (IDP)
- Dual Induction Plants (SLDP)

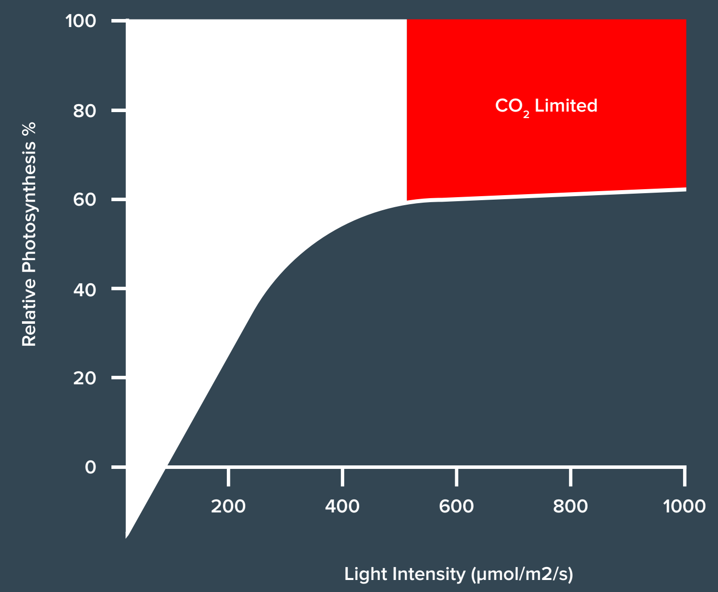


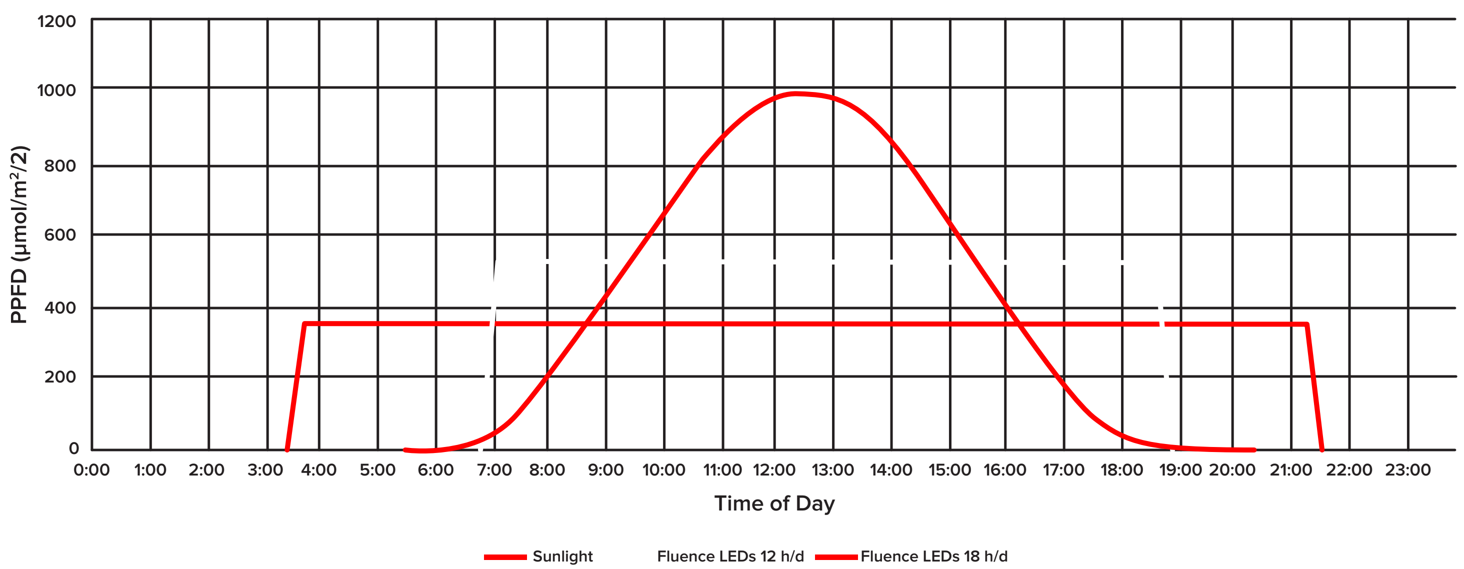
Figure 4: Influence of light intensity on the rate of photosynthesis

	Establishment			
Species	**Seed**	**Vegetative Cutting**	**Vegetative**	**Reproductive**
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+

Photoperiodism is discussed during growing by the term photoperiod. Photoperiod is the length of time light is exposed to a plant during a 24 hour period.

Daily Light Integral

The term *daily light integral* (DLI) is used to describe the total quantity of light delivered to a crop over the course of an entire day. The DLI is reported as the number of moles (particles of light) per day. The advantage of an integrated measurement over an instantaneous measurement can be best demonstrated with an analogy. If you want to know how much rain fell during the course of a day, you would place a bucket outdoors and record the volume of water collected. Whereas recording the intensity of rainfall at one instant, e.g., the raindrops per second, would be of little value. Similarly, knowing the quantity of light delivered throughout the day is a very useful measurement for estimating the effect of sunlight on plant growth. Many important plant growth responses, such as biomass accumulation, stem diameter, branching, root growth and flower number are closely correlated to DLI. Over the past decade, DLI has become widely adopted by professional horticulturists as a tool for managing the light environment to optimize plant growth. Refer to **Figure 5** below.



James E. Faust is an Associate Professor at Clemson University. His research focuses on solving real-world plant production problems. Current projects involve evaluating disease management practices for cut flowers, the use of calcium and silicon to improve the post-harvest performance of flowering plants, and fertilizer delivery methods during the production phase for the improvement of plant performance during the consumer phase.

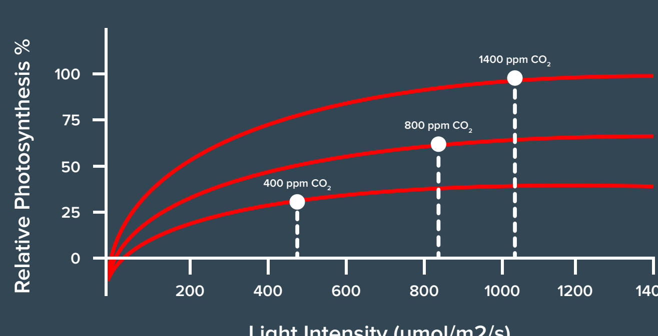


Figure 6: Influence of CO2 concentration on the rate of photosynthesis.

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

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. However, at ambient atmospheric CO_2 levels (~400 ppm) it is the limited availability of CO_2 that restricts photosynthetic activity, not the intensity of light **(Figure 6).** 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/m²/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.

Fluke 59 Max+ Infrared Thermometer to measure plant temperature.

TEMPERATURE: HOW DOES TEMPERATURE AFFECT PLANT GROWTH AND DEVELOPMENT?

Leaf Surface Temperature

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 (e.g. 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, whereas Fluence LED-based systems produce very little radiant heat. As a result, growers generally will decrease their air temperature set-point to counter the additional radiant heat from HPS and subsequently increase their air temperature compared to HPS when transitioning to Fluence.

Photothermal Considerations

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

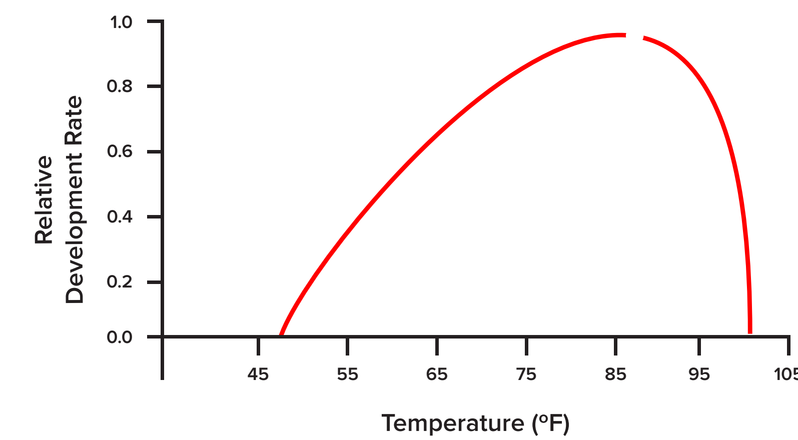


Figure 7: Influence of temperature on the rate of plant development

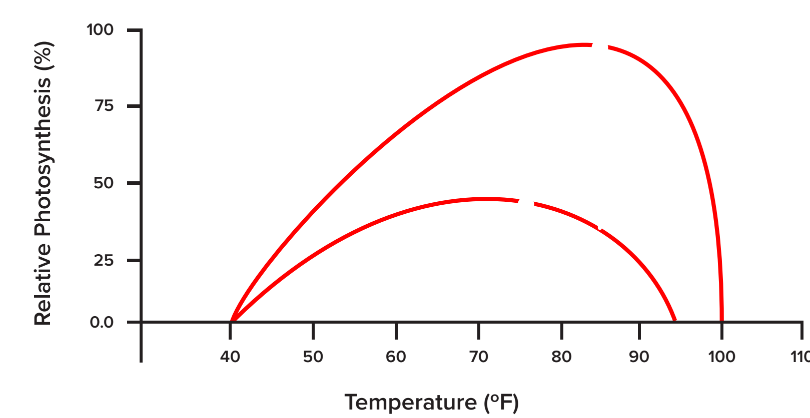


Figure 8: Influence of temperature and CO2 concentration on the rate of photosynthesis.

	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	68-68
Peppers	72-73	72-73	72-74	64-65	72-74	66-68

Air Temperature	Relative Humidity	Vapor Pressure Deficit	Water Demand	Evapotranspiration
↑	↓	↑	↑	↑
↓	↑	↓	↓	↓

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

until an optimum temperature is reached. Above the optimum temperature, plant development decreases **(Figure 7)**. Light intensity primarily influences the rate of photosynthesis, while plant temperature primarily influences developmental rates. Net photosynthesis under increased 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 in the growth environment **(Figure 8)**. However, 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 (≥ 80 °F), you need to ensure that you are providing an adequate light intensity (≥ 500 µmol/m²/s), or you may end up producing plants that have increased internode distance, small stem caliper, and an overall spindly growth habit.

Temperature Differential

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 of 10° F, 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)**.

RELATIVE HUMIDITY, VAPOR PRESSURE DEFICIT, AND AIR MOVEMENT

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, RH, and air movement are the three main variables that influence the movement of water throughout a plant. Evapotranspiration is the process plants use to cool leaf surfaces - as the temperature of a leaf increases, plants pull more water from the growing media and water is evaporated from the leaf surface, as a result, the leaf temperature decreases. We provide a table to show the influence that temperature and RH have on evapotranspiration 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. Refer to **Table 7** for recommended RH ranges for establishment, vegetative, and reproductive growth of cannabis, tomatoes, cucumbers, and peppers.

Vapor Pressure Deficit (VPD) is a valuable tool to use when growing in a controlled environment. Maintaining a proper VPD in your environment will help to reduce plant stress brought on by either excessive transpiration (high VPD values) or the inability to 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 on the plant surface 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 occurs around 0.3 - 0.5 kPa, which is outside of the optimal range in our VPD table.

Holdpeak 866B Digital Annenometer to measure wind speed.

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	0.55	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	0.13	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	1.10	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

**This is a guide generated for commercial greenhouse tomato production*

Optimal Moderate Sub-Optimal

Electrical Conductivity (mS/cm)	Parts per million (ppm) 0.5 conversion	0.65 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

Species	Establishment	Vegetative	Reproduction
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

Proper **Air Movement** is one environmental variable that is often overlooked in controlled environment agriculture. Air flow is critical to break the boundary layer around a leaf and allow transpiration and CO_2 uptake. It is also necessary to provide uniform temperature, humidity, and CO_2 concentrations in your environment. Therefore, we recommend maintaining an **air speed of 0.8 – 1.2 m/s** at the plant canopy to optimize plant growth and development.

IRRIGATION/FERTIGATION

Fertilizer pH and EC

There are hundreds of different fertilizer brands on the market, and whichever one you decide to use, make sure you're providing balanced levels of macro- and micronutrients to the crop being produced. Follow the manufacturer's recommended fertilizer rates, and always monitor the electrical conductivity (EC) of your nutrient solution and also maintain a pH of 5.2 – 6.8. Many growers use parts per million (ppm) meters to measure nutrient solutions, however, ppm meters just measure EC and use a conversion factor 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 to use 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. As a base line reference, we have provided general fertilizer rates during each phase of growth in **Table 10** - considering the variables described, it would be wise to start on the low end of the range and adjust upon close and frequent observation of your crops.

Leachate Testing

Cultivation under increased PPFD generally causes increased transpiration rates. This means if you are feeding a high rate of fertilizer at each irrigation, plants will be taking up much more water than nutrients. With more nutrients being left behind in the grow media, it is possible for soluble salts to build up in the root zone, resulting in increased osmotic pressure. This will make it difficult for your plants to uptake both 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 strategy that 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.

Root Zone Factors

Maintaining a balanced water, nutrient, and oxygen (O_2) supply to your root zone during all three phases of crop growth is critical to produce healthy, vigorous plants. Depending on the type of media (rockwool, peat based, coco, etc.) and irrigation system (drip, ebb and flood, deep water culture, etc.) used in cultivation, make sure you are maintaining the proper balance of water and air space around the root zone.

CONCLUSION

The take-home message is that plants require a dynamic environment to optimize growth and development. So while you are now providing your crops the best lighting possible (yes, we're biased), 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.

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