SMART GROW SYSTEMS

ORIGINAL RESEARCH
Published December 1, 2018

Title: The Importance of Daily Light Integral (DLI) for Indoor Cannabis Cultivation

Haley Bishoff - Smart Grow Systems Research Team
1. Bachelors of Science in Nutrition and Dietetics, Oregon State University

Hayden Burkett - Smart Grow Systems Research Team
2. Bachelors of Science in English, University of Oregon

ABSTRACT:

Daily light integral (DLI), represents the amount of photosynthetically active photons that are delivered to a given space over the course of a day. Plants respond to light that fall within the quantum response area of the visible light spectrum (between 400-700 nm). The quantum response area provides active photonic energy that allows photosynthesis to occur. Crops require different DLI amounts based on their grow cycle. In outdoor environments, DLI varies based on the season, weather and geographic location. These variables can be controlled much easier when growing indoor crops. Foot-candles are one of the most common light measurements. This measurement is less accurate for horticultural purposes, considering it measures light that is only visible to the human eye. Quantum meters measure precise PAR light (photosynthetic active radiation) in micromoles, versus just visible light alone. PAR readings are most accurate for measuring light when growing plants is the primary goal. When plants have a higher rate of photosynthesis, they have increased root development, growth and biomass production. Temperature, CO2 concentration and light are the main factors that affect the rate of photosynthesis. Large cannabis plants require a higher DLI of 65 mol m-2 d-1 in the last couple weeks of flowering, compared to fruits, vegetables and other flowering plants, which require around 15-40 mol m-2 d-1. Flowering cannabis in a sea of green application will require a lower DLI value, around 48 mol m-2 d-1.

Keywords: Photosynthetically active radiation, photosynthetic photon flux density, quantum response, photoperiod, micromoles, moles, foot-candle, quantum meter.

INTRODUCTION: UNDERSTANDING DAILY LIGHT INTEGRAL

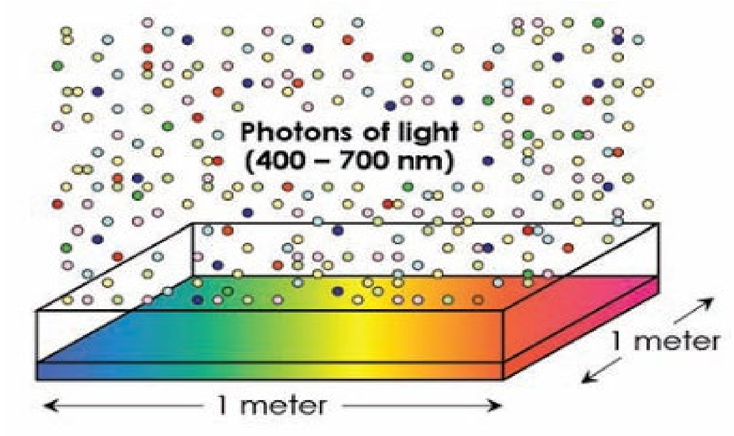

Figure: 1

In order to fully understand DLI, it is important to become familiar with photosynthetically active radiation (PAR light) and photosynthetic photon flux density (PPFD). Not all wavelengths of light can be utilized by plants for photosynthesis. Photosynthetic activity can be seen only when plants are able to utilize light with wavelengths of 400-700 nm, in what is called the quantum response area. Light that falls within the 400-700 nm range, or the quantum response area, is known as PAR light. PAR light is typically measured in PPFD, a measurement that describes the amount of photosynthetically active photons received in a square meter space during a single second interval. In other words, PPFD provides an instantaneous measurement of the density of PAR light in a given space. Daily light integral, or DLI, similarly measures the amount of photosynthetically active photons in a given space. Rather than providing an instantaneous, split-second measurement, DLI accounts for PAR light received over the course of a crop's photoperiod. Photoperiod refers to the amount of time that a plant receives light over a 24 hour span. DLI proves to be the more useful measurement of the two for this reason. Over the course of a day, outdoor light intensities vary due to changes in weather such as cloud coverage and the position of the sun. A PPFD reading in the morning will usually be different than a reading taken in the afternoon or in the evening. Therefore, a single PPFD measurement is not representative of the amount of PAR light received by a plant over a 24-hour period. In order to get an accurate representation, this requires a conversion of PPFD into DLI.

Figure 1: Illustration of PPFD, showing photons of light between 400-700 nm received by a 1 square meter space.

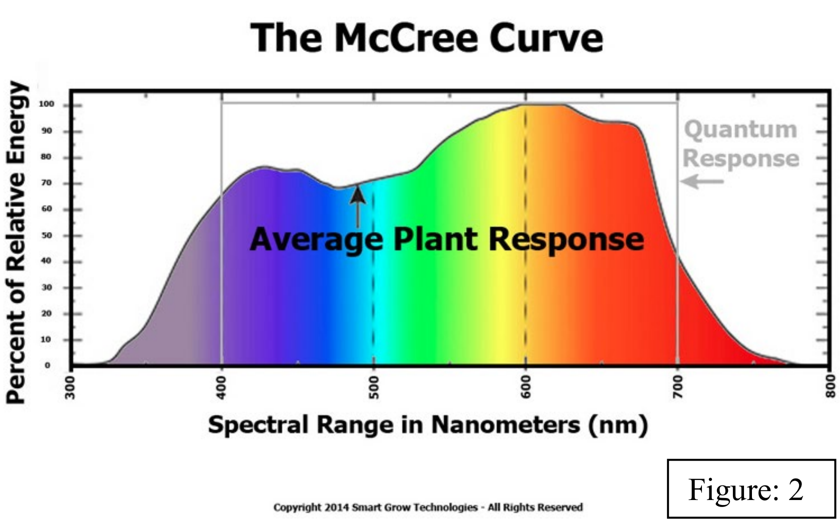

Figure: 2

Figure 2: The McCree Curve. This graph represents the Quantum Response area of the visible light spectrum that produces active, photonic energy between 400-700 nm.

PPFD is primarily measured in micromoles (µmol) while DLI is measured in moles (mol). A mole is a unit of measurement that describes the number of particles of any given substance. In this case the substance is light and the particles are photons. One mole is equal to approximately 6.02 x 10^23 particles, or Avogadro's number (Helmenstine), defined as the number of carbon atoms contained in 12 grams of carbon-12. A light that is measured emitting a PPFD of 1,500 µmol m-2 s-1 for 12 hours can be figured in terms of DLI with the calculation ((60sec/min)*(60min/hr)*(12hrs/day)*(PPFD))/1 million. When a PPFD measurement of 1,500 is plugged in, the DLI value comes out to be 64.8 mol m-2 d-1.

Figure 3: Image of a crop exposed to too much light that has been photodamaged.


Figure: 3

It is important to note that DLI requirements are crop specific. Every plant species has its own optimal light intensity that maximizes photosynthesis and growth. Knowing the optimal DLI value for the desired crop is essential for efficient growth. Too little light will limit development, while too much light may threaten the crop's metabolism if measurements exceed that crop's photosynthetic demand (Chandra).

MEASURING LIGHT

Figure 4: Representation of the foot-candle unit of measurement.

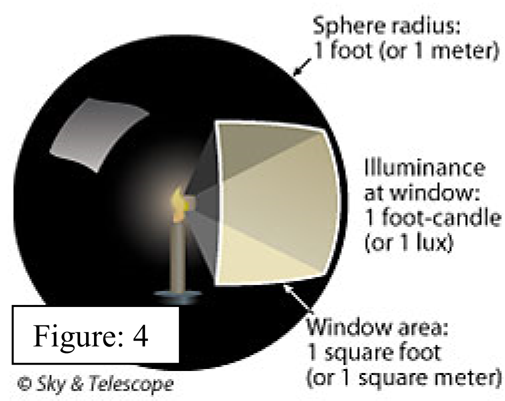

Figure: 4

In the U.S., light intensity is most commonly measured in foot-candles. A foot-candle is representative of the amount of illumination received by the inside surface of a one-foot radius sphere if a candle were placed one foot away at the exact center of the sphere. Like PPFD, this is an instantaneous measurement, describing the light intensity at only a single given second. As discussed before, this limits the usefulness of the measurement because a single second reading is not representative of the light received by a crop over the course of one photoperiod. The foot-candle is further limited in its horticultural usefulness in that it is a photometric unit, which measures the amount of light visible to the human eye, not the light that is helpful for photosynthesis (Torres). This leads the unit to often overestimate the necessary amount of light needed for plant growth. An alternative unit for measuring light uses the radiometric unit. Radiometry differs from photometry in that it is less concerned specifically with light as it relates to the human eye. Radiometric units instead measure the energy per time emitted by a

Figure: 5

light source and are expressed in watts. Because radiometric units are concerned with energy, they are better for measuring sunlight than photometric units, but are still not the most ideal way of measuring light as it pertains to plant growth. PPFD and DLI are measured in more plant-focused quantum units, which measure specifically the amount of photosynthetically active photons given off by a light source. PPFD and DLI are determined using a quantum meter. This tool is specially designed to measure the amount of PAR light received by an area. For this reason, it is recommended that quantum sensors are used to measure light in a horticultural space where plant growth is the primary concern.

Figure 5: Quantum meter, or PAR meter. Used to measure PPFD.

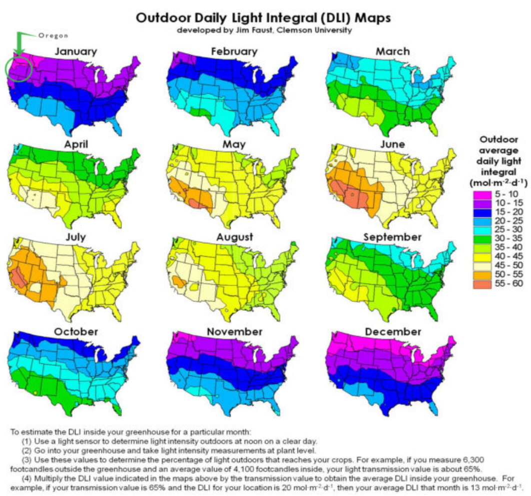

Figure: 6

OUTDOOR DLI NATIONWIDE

Over the course of a year, DLI measurements across the nation vary widely due to geographical differences in solar elevation angle, solar duration, surface elevation, and regional weather (Korczynski). This variation is so great that the average DLI throughout the Southwestern United States in June, at 55-60 mol m-2 d-1, is at certain points, ten times that of the Northern U.S. in December, at 5-10 mol m-2 d-1. For much of the year, from September to March, DLI differences occur primarily between the Northern and Southern U.S. Maximum quantum flux is higher in the Southern latitudes throughout the year due to a greater solar elevation angle in those latitudes. During the months of September through March, the South also sees a longer solar duration than the North, which results in the DLI disparity. Here we see that DLI is more or less a product of daylength, or photoperiod, and the quantum flux provided by the light source. Throughout the rest of the year, roughly May through August, DLI differences across the nation shift from a North-South disparity to an East-West one. While quantum flux in the Southern latitudes remains greater than those in the North, these months see a shorter solar duration in the South. Regional weather, fewer cloudy days and lower air humidity in the Southwest, as well as a higher quantum flux in the West due to elevation result in higher DLIs in the West, than in the East during the months May through August.

Figure 6: Topographical map of the United States describing monthly DLI distribution nationwide.

IMPORTANCE OF DLI FOR PLANT GROWTH

The goal for commercial growers of most crops is to maximize biomass and/or flower number while decreasing total production time. The photosynthetic rate of a plant has shown to affect each of these traits in a favorable way. When a plant has a high photosynthetic rate, we see greater biomass accumulation, faster rooting, and an overall increased quality of the crop (Torres). Photosynthetic rate is primarily affected by CO2 concentration, temperature, and most notably for the purposes of this paper, light intensity (RSC). While optimal light intensity varies from crop to crop, studies have shown that an increase in DLI directly and linearly increases the rate of photosynthesis to a point before effects plateau, depending on the crop. A mean DLI increase from 7 mol m-2 d-1 to 12 mol m-2 d-1 during the propagation of baby's breath saw the time to root cut in half. Similarly, when mean propagation DLI was increased from 1.2-7.5 mol m-2 d-1 in New Guinea impatiens and petunia, rooting, biomass, and crop quality all saw improvement (Torres).

DLI has been shown to have a particular effect on a crop's rate of flowering. Specifically, increased DLI for a number of different crops has influenced flower initiation more so than flower development (Korczynski). In petunias, an increase in DLI from 6.5 to 13 mol m-2 d-1 resulted in a decrease in time to flower from 67 days to 56. Similarly, cyclamen persicum saw its days to flower decrease substantially from 133 days to 75 days as DLI was increased from 1.4 to 17.3 mol m-2 d-1. The same trend in days to flower and increased DLI can be seen in a number of flowering crops including geranium, pansy, ageratum, and cannabis (Chandra, Oh, Korczynski).

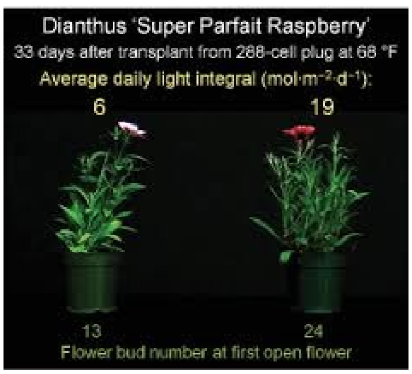

Figure: 7

Figure 7: The difference between two of the same plant grown at different DLI. Higher DLI shows more vibrant flower as well as increased flower bud number at an earlier time.

CROP SPECIFIC DLI

As mentioned previously, crop development and quality can be negatively influenced by too much or too little light. Because DLI requirements differ from crop to crop, it is important to be aware of what the desired plant requires for the most efficient growth. For this reason, Smart Grow Systems has begun to compile comprehensive requirements for various crops in order to ensure high quality product grown with maximum efficiency. Generally, ideal DLI amounts can be roughly found by determining the type of crop in question. Microgreens will typically require 6-12 mol m-2 d-1, leafy greens such as spinach and lettuce call for 12-17 mol m-2 d-1, and flowering crops thrive under DLIs of 15-40 mol m-2 d-1. It is worth noting that under controlled environments, these numbers can often be increased slightly for still greater positive effect.

While it is helpful to know general DLI requirements for a given type of plant, crop quality will benefit most if crop specific DLIs are known. Spinach and lettuce are closely related crops that share similar DLI specs, spinach grows best between 17-22 mol m-2 d-1. Meanwhile, lettuce requires slightly lower light intensities as close to 17 mol m-2 d-1 as possible. Flowering crops such as tomatoes, peppers, and strawberries generally call for higher DLIs. Strawberries prefer a DLI between 12-25 mol m-2 d-1, tomatoes and peppers require still greater intensities of approximately 20-30 mol m-2 d-1. In comparison with other crops, cannabis benefits from an exceedingly high DLI. Ideal PPFD for cannabis growth is 1500 μmol m-2 s-1, during flower, when a 12 hour photoperiod is recommended. Optimal DLI comes out to 65 mol m-2 d-1. Keep in mind, this high DLI is used in the last couple weeks of flower, for larger size cannabis plants and not used throughout the entire grow cycle.

Not only do various crop species have different optimal lighting requirements, DLI ranges throughout the entire grow cycle and for various methods of growing. Standard size cannabis plants requires increased light. For the sea of green (SOG) growing method, plants require a lower DLI value. Sea of green is the method that focuses on growing a large quantity of small plants. This is generally a style of growing that is incorporated into vertical racking systems to optimize square footage by high density planting and increasing yield. During the sea of green clone phase, DLI should be around 1-3 mol m-2d-1. During vegetation, DLI values increase to around 19 mol m-2d-1. Lastly, during flower, DLI will be around 48 mol m-2d-1.

METRICS INVOLVED IN PHOTOSYNTHESIS & PLANT GROWTH

Beyond DLI, there are other metrics to consider that affect plant growth. These include temperature, relative humidity, CO2 concentration and pH. Here, we will go through their individual roles and importance, relative to indoor horticulture.

One of the primary reasons why temperature is such a crucial factor, is that it controls the rate of plant growth by either allowing or inhibiting enzymes to function. There are numerous enzymes involved in biological processes such as photosynthesis. These enzymes will only function within a certain temperature range. When temperatures exceed or do not meet this range, chemical process can get either slowed or stopped. Relative humidity greatly influences the rate of transpiration: a measurement of how quickly water is absorbed, transferred through the plant and released through pores in the leaves into the atmosphere. Understanding how quickly transpiration occurs is telling of how efficiently photosynthesis is taking place. Humidity should also be tightly controlled in an indoor horticulture environment to prevent certain pests and diseases. Considering that carbon dioxide is a necessary reactant in the process of photosynthesis, greenhouse concentrations must meet a baseline level. Carbon dioxide concentrations of 1000-1500 ppm will help speed the growth of plants and rate of photosynthesis. Typically, CO2 concentrations will increase at the same rate that PPFD increases throughout the grow cycle.

One of the most important metrics is pH, which greatly affects the plant's nutritional status. pH stands for potential hydrogen and ranges on a 0-14 scale. This scale is broken into three categories: Acidic (0-6.9), neutral (7) and basic (7.1-14). Anything acidic is considered a "proton donor" and bases are "proton acceptors". This refers to the amount of hydrogen ions available within a solution, that are able to be given off or taken up. pH highly regulates the amount of available nutrients within soil or a nutrient solution. It's best to understand specific pH levels for different crops to ensure nutrients are distributed properly and taken up by the plant at their fullest potential.

DLI AND GROWING CONDITIONS FOR COMMON CROPS:

Figure: 8

	DLI (mol m-2 d-1)	pH	Air Temp. (C)	Relative Humidity	CO2 (ppm)
Spinach	17-22	5.6-6	24 C Day/ 19 C Night	50-70%	1000-1500
Lettuce	17	5.6-6	24 C Day/ 19 C Night	50-70%	1500
Cannabis	65	5.8-6	30 C	50-70 % veg. 50-60 % flow.	400-1500
Tomato	20-30	5.6-5.8	21-28 C Day/ 17-18 C Night	30-90%	200-1500
Strawberries	12-25	5.8-6.2	18-24 C Day/ 10-12 C Night	<85 % 95% 3 hrs. Night	400-900
Peppers	22-30	5.8-6.6	21-23 C Day/ 16-18 C Night	50-70 %	800-1000
Basil	>12	6.5-6.8	21-29 C	65-75%	1000-1500

Figure 8: Describing the optimal DLI, pH, air temperature, relative humidity, and CO_2 concentrations of various crops.

Cannabis specific DLI for Sea of Green Application
Clones: 18 hours on, 6 hours off
Baby Blue

Figure: 9

Week 1

Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
1.3 - 3.2 mol m-2d-1	1.3 - 3.2 mol m-2d-1	1.3 - 3.2 mol m-2d-1	1.3 - 3.2 mol m-2d-1	1.3 - 3.2 mol m-2d-1	1.3 - 3.2 mol m-2d-1	1.3 - 3.2 mol m-2d-1

Week 2

Day 8	**Day 9**	**Day 10**	**Day 11**	**Day 12**	**Day 13**	**Day 14**
1.3 - 3.2 mol m-2d-1	1.3 - 3.2 mol m-2d-1	1.3 - 3.2 mol m-2d-1	1.3 - 3.2 mol m-2d-1	1.3 - 3.2 mol m-2d-1	1.3 - 3.2 mol m-2d-1	1.3 - 3.2 mol m-2d-1

Vegetative Phase: 18 hours on, 6 hours off.
Baby Blue
Week 1

Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
17 mol m-2d-1	17 mol m-2d-1	17 mol m-2d-1	17 mol m-2d-1	17 mol m-2d-1	17 mol m-2d-1	17 mol m-2d-1

Day 8	**Day 9**	**Day 10**	**Day 11**	**Day 12**	**Day 13**	**Day 14**
17 mol m-2d-1	17 mol m-2d-1	17 mol m-2d-1	18 mol m-2d-1	18 mol m-2d-1	18 mol m-2d-1	18 mol m-2d-1

Week 2

Flowering: 12 hours on, 12 hours off
Golden Glow

Week 1

Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
15 mol m-2d-1	15 mol m-2d-1	15 mol m-2d-1	15 mol m-2d-1	15 mol m-2d-1	17 mol m-2d-1	17 mol m-2d-1

Week 2

Day 8	**Day 9**	**Day 10**	**Day 11**	**Day 12**	**Day 13**	**Day 14**
21 mol m-2d-1	21 mol m-2d-1	26 mol m-2d-1	26 mol m-2d-1	28 mol m-2d-1	30 mol m-2d-1	30 mol m-2d-1

Week 3

Day 15	**Day 16**	**Day 17**	**Day 18**	**Day 19**	**Day 20**	**Day 21**
32 mol m-2d-1	32 mol m-2d-1	32 mol m-2d-1	32 mol m-2d-1	32 mol m-2d-1	32 mol m-2d-1	32 mol m-2d-1

Week 4

Day 22	**Day 23**	**Day 24**	**Day 25**	**Day 26**	**Day 27**	**Day 28**
33 mol m-2d-1	33 mol m-2d-1	33 mol m-2d-1	33 mol m-2d-1	33 mol m-2d-1	33 mol m-2d-1	35 mol m-2d-1

Week 5

Day 29	**Day 30**	**Day 31**	**Day 32**	**Day 33**	**Day 34**	**Day 35**
35 mol m-2d-1	35 mol m-2d-1	35 mol m-2d-1	35 mol m-2d-1	35 mol m-2d-1	37 mol m-2d-1	39 mol m-2d-1

Week 6

Day 36	**Day 37**	**Day 38**	**Day 39**	**Day 40**	**Day 41**	**Day 42**
39 mol m-2d-1	39 mol m-2d-1	39 mol m-2d-1	41 mol m-2d-1	41 mol m-2d-1	41 mol m-2d-1	43 mol m-2d-1

Week 7

Day 43	**Day 44**	**Day 45**	**Day 46**	**Day 47**	**Day 48**	**Day 49**
43 mol m-2d-1	43 mol m-2d-1	48 mol m-2d-1	48 mol m-2d-1	48 mol m-2d-1	48 mol m-2d-1	48 mol m-2d-1

Week 8

Day 50	**Day 51**	**Day 52**	**Day 53**	**Day 54**	**Day 55**	**Day 56**
48 mol m-2d-1	48 mol m-2d-1	48 mol m-2d-1	48 mol m-2d-1	48 mol m-2d-1	48 mol m-2d-1	48 mol m-2d-1

Figure 9: Lighting requirements for Sea of Green cannabis cultivation throughout clone, propagation and flower.

SUPPORTING RESEARCH:

In a study completed by Niu et al., researchers looked at various environmental factors that affect the growth and flower development in pansies. A few variables were measured: CO_2 concentrations, DLI and temperature. Three DLI levels were studied (4.1, 10.6 and 15.6 mol m-2d-1). Plants were grown under two different CO_2 concentrations and nine combinations of temperatures varying from day to night time. Although multiple variables were taken into account, we will focus on the effects of DLI on growth and plant quality. Plant quality can be described as flower size, number of flower buds and plant height.

Overall, the developmental rate of flower and flower size increased as DLI increased from 4.1 to 10.6 mol m-2d-1. However, there was no statistical difference in these measurements from the change in DLI from 10.6 to 15.6 mol m-2d-1. DLI levels significantly influenced the dry weight of the plants. Under both CO_2 concentrations measured, dry weight increased 70% from DLI values ranging from 4.1 to 10.6 mol m-2d-1. There was no further increase in dry weight from 10.6 to 15.6 mol m-2d-1. The flower size increased by 25% when DLI was increased from 4.1 to 10.6 mol m-2d-1. Once again, there was no statistical significance in the flower size from DLI 10.6 to 15.6 mol m-2d-1. This shows that pansies, in particular, perform best under a DLI of around 10.6 mol m-2d-1.

A similar study by Oh et al., measured temperature and seven DLI levels ranging from 1.4 to 17.3 mol m-2d-1. This study was looking at crop characteristics of *Cyclamen persicum,* a flowering plant. Increasing the light intensity and DLI throughout the grow cycle showed improved plant quality by increased leaf number, flower number and total dry weight. The average leaf number increased from 8.7 to 28 and the average flower number increased from 0 to 14.7. These results were found as DLI increased from 1.4 to 11.5 mol m-2d-1. Above this DLI level, no major differences were seen. The dry weight and rate of photosynthesis showed similar trends. There was also a decreased time to flower as DLI increased. The first days to flower went from 133 to 75 as DLI increased from 1.4 to 17.3 mol m-2d-1.

Both of these studies show that various crop species have specific DLI requirements. DLI plays a major role in the quality of plants and the rate at which they develop. In addition, DLI, CO_2 and temperature together, can increase plant growth, development and overall plant quality.

CONCLUSION:

Daily light integral (DLI) is an important measurement when growing plants to ensure each crop is receiving a proper dosage of light. A benefit of indoor horticulture is that there are less factors to consider when measuring DLI, such as geographic location, season and weather. As various plants require different amount of lights throughout their grow cycle, it's important to tailor the lighting schedule accordingly. Crop specific DLI, in combination with CO_2 concentrations and temperature, can increase the rate of photosynthesis and plant quality. Higher rates of photosynthesis can lead to quicker root growth, plant development and an overall increased biomass. It is important to measure DLI using PAR and PPFD over the course of a day. Quantum sensors will provide the most accurate light measurement for horticultural purposes, finding the amount of photosynthetic active radiation over a canopy area.