
Tackling the growing market of horticultural lighting with LEDs

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Lighting for Horticulture

Horticulture is the science and art of growing plants and plant cultivars. It aims to improve qualities such as growth speed, yield, quality and nutritional value. Unlike agriculture which deals with the cycle of animal farming and strictly cultivates crops for human consumption, horticulture only involves the science of plant cultivation.^[1]

IN THE LATE 1800S, FRENCH

Botanist Charles Lucien Bonaparte built the first modern greenhouse in Leiden, Holland^[3]. This greenhouse popularised horticulture indoors. With technological advancements, electric lamps (also referred to as grow lights) were soon trialled to provide artificial lighting for horticulture in indoor spaces. Some early references of this were the works of Mangon in 1861 and Prilleux in 1869.^[4] Indoor horticulture has the ability to control an environment to assist with plant growth. Some advantages that grow lights offer are:

- The control of light exposure duration supplied to plants can replicate or counteract the varying daylight cycles which naturally occur during different seasons in the northern and southern hemispheres.
- Artificial lighting can tailor the light intensity and light spectrum output to the requirements of individual plants.

In turn, the plants benefit from artificial lighting by:

- Having a reduction of heat and light intensity, compared to outdoors, which can reduce the water requirements for plants.
- Allowing plants to be grown in places where the natural environmental conditions may otherwise be unsuitable.
- Controlling the light output which can promote faster growth, increase yield, and shorten the growth cycles of plants.
- Manipulating the characteristics of fruits and vegetables, such as the taste and colour.

Essentially, it separates the influence of natural climate to the growth of plants and creates an optimal environment. This means that plants can be cultivated through different seasons without interruption. A practical example of this benefit is the influence it has with the taste of basil.



Figure 1: Early Image of Horticulture, Circa 1920.^[2]

The taste of basil changes throughout the year with different seasons, making it challenging to create recipes. Basil grown in controlled environments can be in the same environmental conditions 365 days a year. In turn, the cultivated basil will have a consistent taste, requiring the same amount for recipes.^[5]

Plants require light as its main source of energy to promote growth through the process of photosynthesis. Light effects the developmental aspects of plants such as the size, flowering and fruiting phases, proportions of shoots to roots, and many other characteristics.

For most plants, leaves are green due to Chlorophyll. The light absorption acts as a catalyst to promote the chemical reaction of carbon dioxide and water which is converted to glucose and oxygen.

Chlorophyll

For most plants, leaves are green due to the chemical called chlorophyll. Chlorophyll absorbs specific wavelengths of light within the light spectrum of 380nm to 750nm. Within this waveband lies the Photosynthetically Active Radiation (PAR) at wavelengths of 400-700nm. Light in this range is the main promoter of photosynthesis. Chlorophylls absorb light in the red (long wavelength) and blue (short wavelength) regions, while reflecting a majority of the light in the green wavelength, making the leaves appear green.

Chlorophyll molecules serve three functions: to absorb light, to convert light energy via resonance energy transfer and to charge separation, leading to biosynthesis.^[7] Photosynthesis requires two main types of chlorophylls to absorb energy and activate the reaction, chlorophyll A and chlorophyll B.^[1] Chlorophyll A is present in vascular and non-vascular plants, while chlorophyll B is generally only present in vascular plants.

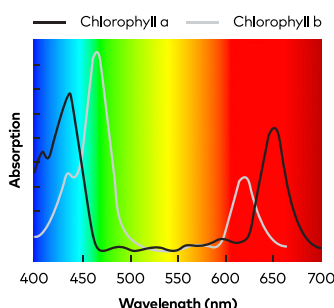


Figure 2: Absorption Spectra of Chlorophyll A & B.^[6]

Chlorophyll A

Chlorophyll A absorbs energy from wavelengths of blue-violet and orange-red light. Chlorophyll A is important in photosynthesis because its molecules are responsible for photosynthesis. It is the reaction centre for the absorbed energy.

Chlorophyll B

Chlorophyll B absorbs energy towards the green light wavelengths. It is an accessory pigment that collects energy and passes it on to Chlorophyll A. It is more absorbable than Chlorophyll A.

Photosynthesis is possible with chlorophyll A alone. However, this is not the case with only chlorophyll B, because as mentioned previously, chlorophyll A is the reaction centre. Additionally, the ratio of chlorophyll A to B in plants is typically 3:1. This is why most studies of the spectrum requirement of individual plants depend on the plant's Chlorophyll A light absorption and response.

Theories in Practice

Within the PAR region, various pigments and photosensitive compounds in plants peak in absorption and amount at different wavelengths^[8], but this is mostly in the red and blue regions.

The oldest and most commonly used method to determine the spectrum of light that all plants need is using the PAR curve which highlights these substances. It is important to note that the PAR curve is a general guide, since each plant has a unique spectrum absorption rate.

As seen in the PAR curve, most plants need light at the blue region of 440nm, peaking at 100% and peaks again at 95% in the red region at 675nm. The blue region of the spectrum is responsible for root, stem and leaf formation, while the red region is responsible for the flowering and fruiting phases of growth.

On the other hand, the study of Dr Keith J. McCree, which collected the most detailed plant light absorption data, was able to generalise a different plant light absorption curve using the same principles of the PAR curve.

The study concluded that plant species such as leafy greens prefer more blue light, while flowering and fruiting plants (like cucumbers and tomatoes) require more of the red light.

When designing grow lights, it is vital that the light output has the most energy in the blue and/or red regions of the light spectrum to have the maximum efficiency, according to the PAR and McCree Curves.

Although Chlorophyll B absorbs energy toward the green light wavelengths, its influence with photosynthesis is comparably lower compared to that of the red and blue lights. Having the same level of energy in the green light with the blue and red regions poses no issue with the plants since it will only absorb energy that it requires. However, since the absorption in this range is relatively small, addressing these areas will cause inefficiency.

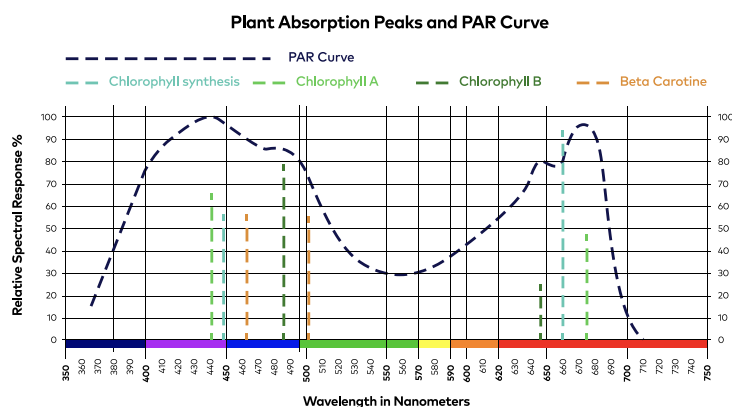


Figure 3: Plant Absorption Peaks and PAR Curve.^[8]

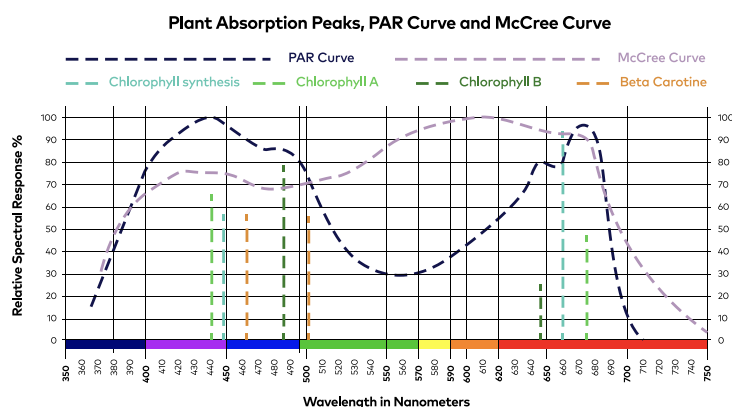


Figure 4: Plant Absorption Peaks, PAR and McCree Curve Comparison.^[8]



Photosynthesis is achieved in the wavelengths of 400-510nm (blue), and 610-700nm (red) according to the PAR curve. The wavelength range of 510-610nm, although has some benefits for plant growth, has little effect for photosynthesis, and is due to reflection of the green light.^[9]

For plants to grow indoors, the light sources must output light in the PAR range. The light output in this range is known as Photosynthetic Photon Flux (PPF). PPF is the total light (photons or light particles) emitted by the light source in the PAR range, in micromoles per second ($\mu\text{mol/s}$). Active PPF (A-PPF) is the concept of PPF of the light in the 400-510nm (blue), and 610-700nm (red) wavelengths only, which ignores the green light wavelengths. In short, A-PPF is the luminaire's output that is directly used by plants for photosynthesis. The commonly used variable for lighting comparison in horticulture is Photosynthetic Photon Flux Density (PPFD) which is a measure of photons that reach the target per area per second ($\mu\text{mol/m}^2\text{s}$).

However, with the growing popularity of efficiency, the concept of A-PPFD could certainly be the next step for horticulture lighting.

Plant lighting is different when compared to lighting for humans (Table 1). For plant light specification, we have to use the luminaire's PAR and PPFD. Apart from this, it is also important to address the amount of light that the plant receives within a day – sufficient for healthy plant growth.

This is called Daily Light Integral (DLI) ($\text{mol/m}^2\text{.day}$) which is the amount of light received during the photoperiod (light exposure duration).

	Human Light	Plant Light
Radiant Power 400nm-700nm	Lumens	Photosynthetically Active Radiation (PAR)
Light falling on a surface	Illuminance	Photosynthetic Photon Flux Density (PPFD)
Units	Lux	$\mu\text{mol/m}^2\text{s}$

Table 1: Human VS Plant Light.^[10]

Table 2 provides an example of PPFD levels required for optimum plant growth. Plant growth is determined by the daily PPF.

Type of Plant/ Condition	Approximate PPFD for Good Growth ($\mu\text{mol/m}^2\text{s}$)	Plant Light ($\text{mol/m}^2\text{.d}$)
House Plants	30-200	3-20
Leafy Crop Plants	200-600	10-30
Fruit Crops	400-1000	20-50

Table 2: PPF Levels for Good Plant Growth.

From this information, many grow lights have been designed and manufactured to be as efficient as possible, by having more PPFD, customised PAR spectrum output and requiring the least amount of energy.



Past Technology

Many indoor or closed type factories have been constructed since the 1970s in the USA such as GE's Genioponics in New York and Alaska, as well as General Mills' Phytofarm in Illinois.

These factories have ceased operation as of the early 1990s. However, plant production factories in Japan which started in the 1980s (such as Secom Herb Factory, TS Farm, and La Planta Co. LTD) are still operational as of 2006.^[11]

Among these plant factories, the most commonly used grow lights were High-Intensity Discharge (HID) light bulbs. The main HID types used are Metal Halide (MH) lamps and High-Pressure Sodium (HPS) lamps. The use of these light sources in controlled times mimics the condition of outdoor spaces to promote plant growth.

The HID types are used to shine a light on the plant in combination with a ballast and

hood or reflector to maximise the efficiency by reflecting light to where it is needed. Generally, a higher power HID means that a larger reflector is recommended. One disadvantage when using HID types is the amount of heat generated. So, the use of air or water-cooled hoods is also recommended.

As seen in figure 6, the HPS and MH lamps output light in the PAR range with the higher magnitudes of relative energy lying within the green light region. From these two light sources, there is more energy available with the MH bulb. However, this is still inefficient, since both bulb types output majority of its relative energy outside the A-PPFD range.



Figure 5: Horticulture Setup with HPS Lamps.^[12]

As stated by the study of Morrow, R.C.^[21], the main benefits of solid state (LED) lighting over gaseous discharge lamp technology are:

High light intensities

Low heat generation

Adjustable spectral quality to improve photosynthetic efficiency, plant form and function

Safer as they do not have high surface temperatures

Does not have breakable glass bodies that can cause injury to caretakers or plants

Some other HID types, such as mercury type lamps can cause contamination

Easily customisable lens and reflector technologies

Efficient driver configurations

HPS VS. Metal Halide Spectral Outputs

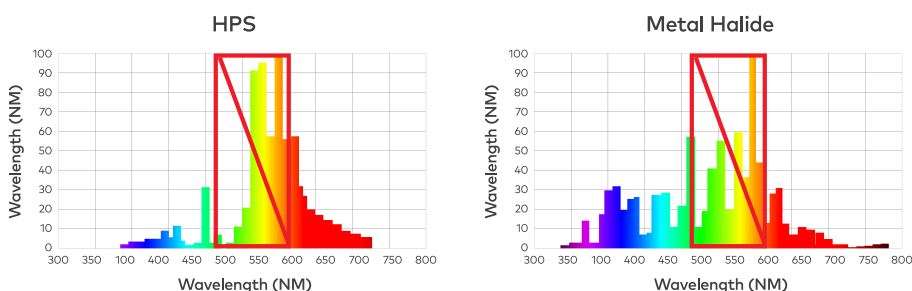


Figure 6: HPS & MH Lamp Spectrum.^[13]

LEDs VS HIDs

In 2000, Cosmo Plant Co. LTD introduced a plant factory, Cosmo Farm, which is the first commercially operational plant factory utilising LEDs as grow lights. The production of some of Cosmo's plant factories produced up to 7000 heads of lettuce per day.^[13]

Comparing figure 6 and figure 7, compared to the spectrum of MH and HPS lights, LED grow lights have been engineered to output the highest relative energy outside the green light region. This means that the majority of the light output of engineered Horticulture LEDs is directly beneficial to the plants.

Previously, the main limiting factor of LED-based plant factories was the cost. Along with this, early designs of LEDs had less optimised heat dissipation methods, where the heat generated from LEDs caused lower efficiency and life expectancy for the LEDs. However, due to the speed of technological development and as predicted by E. Ono and H. Watanabe in 2006^[15], the output of LEDs is increasing, and its costs are decreasing.

Fast forward to present day, LED technology has taken over the grow light industry for indoor horticulture due to its benefits and the minimisation of its previous limiting characteristics.

Compared to MH and HPS lamps which make use of gasses in the light bulb to produce light, LEDs generate light through electroluminescent principles.

Unlike HIDs, LEDs often have a smaller form factor and can be packaged in a larger array of housings. Additionally, the heat generation of LEDs is significantly lower than HIDs. From an experiment by Advanced LED Lights^[16] in the same control temperature and same cubic feet of growing area, the HPS lamp quickly overheated the space and reached a temperature of 36°C.

The test had to be immediately stopped for safety reasons. Meanwhile, the LED grow light was tested and sat at a comfortable 23°C by the end of the experiment. The low heat generation of LEDs allows the grow lights to be positioned closer to the plants as seen in figure 8, which would not be possible for HIDs.

Higher ambient temperatures mean that the plants will struggle to survive, lose nutrients, flavour and will incur more watering costs to hydrate overheated plants. Additionally, the ability to place LED grow lights in close proximity to the plants allows vertical farming. This means that the throughput of produce from LED versus HID lit horticulture setups in the same room volume can be marginally greater.

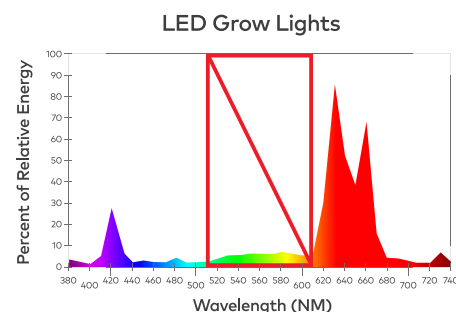


Figure 7: LED Grow Light Spectrum.^[14]



Figure 8: Modern Horticulture LED Setup.^[15]

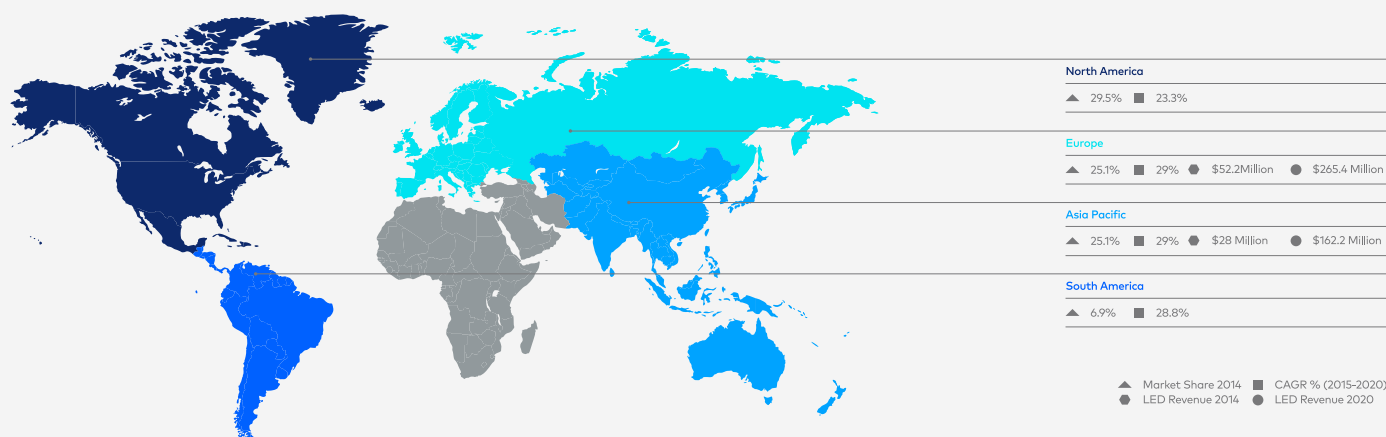


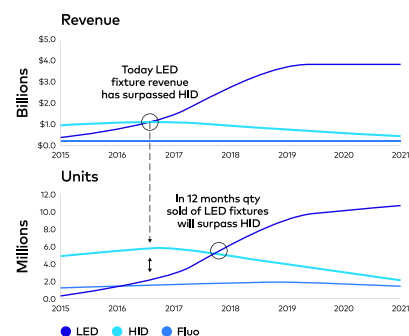
Figure 11: Global LED Grow Light Market [19].

Meeting the Demands of the Market

There has been tremendous growth in horticultural lighting using LEDs over the past few years. The market started growing in production size due to the demand and availability of horticultural LEDs.

There are significant benefits of LED horticultural lighting in comparison to past technologies. According to LEDs Magazine, LEDs are changing the horticulture market by increasing yields. It is understood that the initial price of LED lamps is higher than previous technologies, but it doesn't take long for the technology to pay for itself due to its many advantages.^[17]

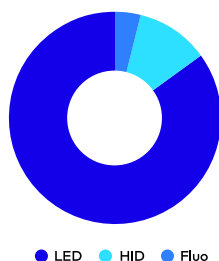
In the early 1980s, greenhouse tomatoes in the United States were merely 1% of the retail market. Today, 80% of tomatoes are grown in greenhouses.^[18] Using LEDs, the tomatoes only require 20% of the water required for field-grown tomatoes and have arguably superior quality and taste.^[17]

Figure 9: Navigant Research 2015 - HID VS LED.^[18]

From the Navigant Research 2015, by late 2016, the LED fixture revenues had surpassed HID in the global horticulture market, and it was speculated that in late 2017,

the quantity of horticulture LEDs sold would surpass HIDs. Furthermore, from the growth of horticulture LEDs in the market, it is predicted that by 2020 LED will have 85% of the market share for horticulture lighting – pushing HID and Fluorescent lights down to 11% and 4% respectively.^[17]

2020 Technology Share

Figure 10: Horticulture Technology Share in 2020.^[19]

Further statistics from the U.S. Department of Agriculture, International Artificial Grow Light Association, Investor Reports, and many more, state that for North America, Europe and Asia Pacific, the market share of LED Grow Lights in 2014 were 29.5%, 25.1% and 25.1% respectively. Studies suggest that there will be compound annual growth rates (CAGR) of 23.3%, 29% and 29% for North America, Europe and Asia Pacific respectively from 2015-2020. This means a growth in revenue from \$52.5m to \$265.4m for Europe, and from \$28m to \$162.2m for Asia Pacific.

One obstacle with the expansion and growth of horticulture using artificial lighting is the stereotype that horticulture is only for the purpose of plant and produce cultivation. However, the popularity of indoor plants due to its health and aesthetic benefits has been eliminating this barrier. The increasing demand for indoor plants in a wider range of applications ultimately increases the demand for horticultural luminaires not just for the functionality, but for the architectural design.

More than just aesthetics, studies from the University of Minnesota Extension^[20] for horticulture found that:

- Plants promote good health by removing up to 87% of toxins in a room
- Reduces stress in office spaces up to 60%
- Improves focus by 15%
- Increases creativity

In fact, when rating buildings for Green Star certifications, an internationally recognised sustainability rating system, the Green Building Council of Australia (GBCA) now includes indoor plants as part of their assessment for commercial buildings – up to two credit points towards Indoor Environment Quality (IEQ-15) office interiors rating^[19].

Unios Case Studies

Unios has developed lighting solutions for indoor horticultural lighting with the Flo Series Luminaires. From early prototyping until product release, Unios have meticulously monitored the effectiveness of horticulture LEDs to ensure the success of cultivation.

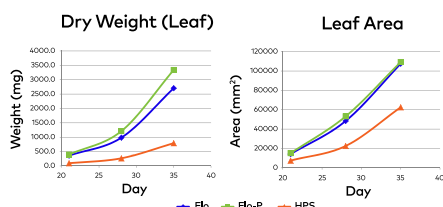


Figure 12: Dry Weight and Leaf Area – Flo Series LED Case Study.

A comparison of the growing ability of a HPS lamp, Flo and Flo-P chips were done using red leaf lettuce at the University of Yamanashi, Japan. In the research conducted, the Flo technology was configured with a wattage that would produce similar PPFD values to HPS technology. The results showed that the Flo technology outperformed HID when comparing A-PPFD values.

	lx	Irradiance	PPFD	A-PPFD
	(lm/m²)	(W/m²)	(μmol/m².s)	(μmol/m².s)
HPS	16122	43.5	216	83
Flo	9905	44.1	224	155
Flo-P	6858	44.1	226	185

Table 3: Performance of HPS VS Flo LED VS Flo-P LED Technology.

It is shown that although the PPFD of the HPS lamp was close to that of the Flo and Flo-P LEDs, LEDs present the advantage to customise the light spectrum output to be more suitable for plant growth. And although the PPFDs are close, the A-PPFDs of the LED chips are double that of the HPS lamps, proving the credibility of the A-PPFD concept for plant growth.

Laboratory tests were done to compare the performance of a typical 150W Metal Halide lamp to three 26W Kobe luminaires. The results are displayed in table 4 below.

	lx	PPFD	A-PPFD	A-PPFD: PPFD
	(lm/m²)	(μmol/m².s)	(μmol/m².s)	
Metal Halide (150W)	4729	77.6	45.7	0.59
Kobe 3000K (26W)	1754	28.9	17.9	0.62
Kobe Flo (26W)	2734	51.9	35.5	0.68
Kobe Flo-P (26W)	2452	69.7	57.5	0.83

Table 4: Performance comparison of a typical MH lamp, Kobe 3000K, Kobe Flo and Kobe Flo-P.

Looking at the test results, the Kobe Flo-P already has a PPFD value close to that of the MH. Delving deeper, the A-PPFD:PPFD of the MH is only 59% compared to the 83% that the Kobe Flo-P outputs. From a power consumption and A-PPFD efficiency point of view, it is easy to see that the Flo series outperforms the MH lamp. Not only does it supply a better quality light spectrum for plant growth, it also requires less power compared to MH lamps.

The benefits of the Flo series is not focused on the luminaire PPFD output. Its main advantage is the efficiency through a higher A-PPFD to PPFD ratio.

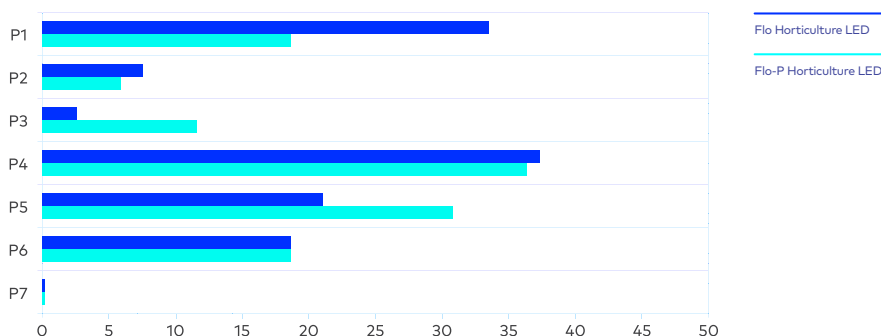
A practical comparison of Flo to a common MH lamp is that, to achieve the A-PPFD of 50 μmol/m².s, a Kobe Flo setup must have an average of 3847lx on the plant surface, while the HID must attain 5177lx. As seen here, the MH lamp would require almost 35% more illuminance on the plant surface than the Kobe Flo to have the same growing capacity; meaning more power consumption, more electricity cost, more heat generated and more visual discomfort.

The newly designed Flo Series is available in two distinct colour options – Flo-P and Flo. Flo-P delivers a more pronounced pink colour that is suitable for a range of flowering plant species. The Flo on the other hand, delivers a more neutral 2400K colour temperature to suit a broader range of applications such as office spaces and green walls.

Unios performed experiments in a controlled environment to investigate the growing performance of the Flo and Flo-P luminaires to a variety of plant types. This experiment is an important part of our research to have a first-hand experience of what is effective and what can be improved.

The green wall lighting setup in figure 13 uses two 26W Kobe Track Lights, the left side with the Flo-P LED Chip and the right side with the Flo LED Chip.

Plant Growth after 7 Weeks (cm)



The plants in the green wall are arranged as per figure 13. The order of the plants from the top to bottom level is as follows:

- W1. Liriope muscari “Evergreen giant”
- W2. Phormium tenax “Sweet mist”
- W3. Calibrachoa “Calipetite white”
- W4. Rhoen discolor “Moses in the cradle”
- W5. Viola hederacea “Native violet”
- W6. Myoporum parvifolium “Purpurea”
- W7. Dianella caerulea “Cassa blue”

The plants were all to be watered daily, using 4L of water for the whole setup. The green wall was also set to receive a 14 hour daily photoperiod from 6am to 8pm, to simulate Australian summer lighting conditions.

The growth of the plants was measured on a weekly basis, and by the seventh week, there was still significant growth in the plants, one case having up to 15cm of growth in one week. It was found that the areas with higher light intensity had better growth compared to those that did not. Uniformity is integral to the success of each plant as demonstrated by W7 receiving less light and consequently not growing as successfully.

Results show that both light sources are able to grow plants in the green wall, comparable to how they would outdoors. The growth was significant enough over the span of the experiment to prove the effectiveness of the luminaires, having slightly better growing plants with exposure to the Kobe Flo.

The conclusions of the experiment placed importance on the following factors to increase the success of indoor horticulture:

Plant selection – try to select plants which require the same environmental conditions

Simulating proper environmental conditions as required by the plant

Using the corresponding LEDs with respect to the PAR or McCree Curve requirements of the plant

Provide enough lighting to the whole green wall and attempt to keep the PPFD similar for the whole area, avoiding hot spots as much as possible

Promote proper distances from the luminaire to the plant

Understanding the plant or collection of plants will determine the light requirement needed

Throughout the case study that was conducted over the seven weeks, the Flo Series delivered on the two key objectives that were outlined in the initial development process. The first was successfully growing a variety of plants with LED horticultural technology. The second was blending the technology into a more design focused application such as green walls and indoor plants.



Figure 13: Unios Indoor Horticulture Setup

For more information about the Flo Series, get in touch with the team

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References

- [1] Difference Between, *Agriculture vs Horticulture*, 2009. [Online]. Available: <http://www.differencebetween.net/miscellaneous/difference-between-agriculture-and-horticulture/> [Accessed 05 April, 2018]
- [2] Manitoba Historical Society, *The Greening of The West: Horticulture on Canadian Prairies, 1870-1930*, 2009. [Online]. Available: http://www.mhs.mb.ca/docs/mb_history/31/prairiehorticulture.shtml [Accessed 05 April, 2018]
- [3] Dutta, I., Sen, V., *Greenhouse Farming in Gujarat: A March Towards Sustainable Agriculture*, 2013. Available: OIDA International Journal of Sustainable Development Vol. 06: 08. [Accessed 17 May, 2018]
- [4] Pfeiffer, N.E., *Microchemical and Morphological Studies of Effect of Light on Plants*, 2009. [Online]. Available: <https://www.journals.uchicago.edu/doi/abs/10.1086/333584> [Accessed 05 April, 2018]
- [5] LED Professional, *Trends in Horticulture Lighting*, 2017. [Online]. Available: <https://www.led-professional.com/resources-1/articles/trends-in-horticulture-lighting> [Accessed 22 March, 2018]
- [6] Biological Exceptions, *The Colors of Alien Plants*, 2013. [Online]. Available: <http://biologicalexceptions.blogspot.com.au/2013/06/the-colors-of-alien-plants.html> [Accessed 22 March, 2018]
- [7] Sciencing, *What Are the Roles of Chlorophyll A & B?* 2017. [Online]. Available: <https://sciencing.com/what-are-the-roles-of-chlorophyll-a-b-12526386.html> [Accessed 22 March, 2018]
- [8] Roberts, M., *What Light Do Plants Need*, 2016. [Online]. Available: <http://www.induluxtech.com/What%20Light%20Do%20Plants%20Need-Net.pdf> [Accessed 22 March, 2018]
- [9] Causes of Color, *Green plants and chlorophyll*. [Online]. Available: <http://www.webexhibits.org/causesofcolor/7A.html> [Accessed 22 March, 2018]
- [10] Agi32, *"Photosynthetic Photon Flux Density (PPFD) - Concepts"*, 2018. [Online]. Available: https://docs.agi32.com/AGI32/Content/adding_calculation_points/PPFD_Concepts.htm [Accessed 6 April, 2018]
- [11] Ono, E. Watanabe, H., *"Plant Factories Blossom", Engineering & Technology for Sustainable World*, 2012. [Online]. Available: <https://advancedledlights.com/blog/technology/operating-temperatures-hid-vs-led-grow-lights-infographic/> [Accessed 6 April, 2018]
- [12] Fran Gallo, *Fridheimar Greenhouse*, 2015. [Online]. Available: <https://frangallo.wordpress.com/2015/10/05/fridheimar-greenhouse/> [Accessed 22 March, 2018]
- [13] University of Utah School of Computing, *Jav-Botics: High Pressure Sodium vs Metal Halide Lighting Image*, 2017. [Online]. Available: <http://www.cs.utah.edu/~wakefiel/cs4710/> [Accessed 22 March, 2018]
- [14] RedLightMan, *LED vs HPS grow lights*, 2018. [Online]. Available: <https://redlightman.com/blog/led-vs-hps-grow-lights/> [Accessed 22 March, 2018]
- [15] Arch Lighting, *Lighting's Next Crop*, 2017. [Online]. Available: http://www.archlighting.com/industry/reports/lightings-next-crop_o [Accessed 22 March, 2018]
- [16] Advanced LED Lighting, *Operating Temperatures of HID VSLED Grow Lights*, 2012. [Online]. Available: <https://advancedledlights.com/blog/technology/operating-temperatures-hid-vs-led-grow-lights-infographic/> [Accessed 6 April, 2018]
- [17] LEDs Magazine, *LEDs are set to change horticulture by increasing yields*, 2017. [Online]. Available: <http://www.ledsmagazine.com/articles/2017/03/leds-are-set-to-change-horticulture-by-increasing-yields.html> [Accessed 22 March, 2018]
- [18] LUXEON LEDs for Horticulture, *LEDs for Horticulture*, 2015. [Online]. Available: <https://www.lumileds.com/horticulture/leds-in-horticulture/> [Accessed 22 March, 2018]
- [19] Green Building Council Australia, *"Indoor Environment Quality"*, 2008. [Online]. Available: <https://www.gbca.org.au/uploads/greenstar-submission/R1/2.%20Indoor%20Environment%20Quality/IEQ-15.pdf> [Accessed 6 April, 2018]
- [20] University of Minnesota Extension, *Plants Provide Benefits to your Office Space*, 2017. [Online]. Available: <http://www3.extension.umn.edu/county/benton/county-horticulture-educator/article/plants-provide-benefits-your-office-space> [Accessed 22 March, 2018]
- [21] Morrow, R.C., *LED Lighting in Horticulture*, 2008. Available: HortScience, Vol. 43(7). [Accessed 22 March, 2018]
- [22] Massa, G.D, et. al., *Plant Productivity in Response to LED Lighting*, 2008. Available: HortScience, Vol. 43(7). [Accessed 22 March, 2018]
- [23] Energy Rating, *Fact Sheet: A Consumer's Guide to Buying Quality LEDs*, 2016. [Online]. Available: <http://www.energyrating.gov.au/document/fact-sheet-led> [Accessed 22 March, 2018]
- [24] Texas Tropical Plants, *How Plants Can Help Improve Your Office Space*, 2017. [Online]. Available: <https://texastropical.com/news/plants-can-help-improve-office-space/> [Accessed 22 March, 2018]
- [25] Eureka Alert!, *Greener offices make happier employees*, 2008. [Online]. Available: https://www.eurekaalert.org/pub_releases/2008-05/asfh-gom051908.php [Accessed 22 March, 2018]
- [26] The Spruce, *What Is the Meaning of "Horticulture"*, 2018. [Online]. Available: <https://www.thespruce.com/what-is-the-meaning-of-horticulture-2131064> [Accessed 22 March, 2018]
- [27] Wheeler, R., *A Historical Background of Plant Lighting: An Introduction to the Workshop*, 2008. [Online]. Available: <http://hortsci.ashspublications.org/content/43/7/1942.full> [Accessed 22 March, 2018]
- [28] HortiDaily, *The effect of LED grow lights on human health*, 2017. [Online]. Available: <http://www.hortidaily.com/article/32458/The-effect-of-LED-grow-lights-on-human-health> [Accessed 22 March, 2018]
- [29] Active Grow, *Horticulture Lighting Terms*, 2018. [Online]. Available: <http://activegrowled.com/horticulture-lighting-terms/> [Accessed 22 March, 2018]
- [30] Planet LED, *LED History and General Information*, 2014. [Online]. Available: <https://www.planetled.com.au/led-history-general-information> [Accessed 22 March, 2018]