LIGHT EMITTING DIODES FOR INDOOR GROWING OPERATIONS: A COMPARISON OF TRADITIONAL LIGHTING AND LEDS

Smart Grow Technologies

Modern, high-intensity LEDs are revolutionizing horticultural lighting. With well-studied and applied light recipes, growers are realizing increased growth rates and yields while reducing operating costs. A new phosphor blend based LED technology is now providing even more intense, better quality light.

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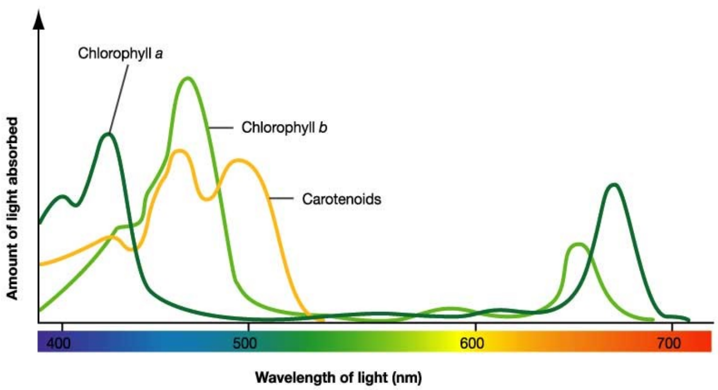
Introduction

To satisfy consumer demand for fresh, affordable produce and other horticultural products throughout the year, growers are increasingly turning to indoor growing operations. Such operations provide a grower the ability to more precisely control for temperature, humidity, water and lighting. Artificial lighting, is a key component of indoor growing facilities because it is crucial to healthy and rapid plant growth and can impact other aspects of the operation like temperature, space requirements and growth cycles. Traditionally, artificial lighting has been supplied by high intensity discharge (HID) fixtures with metal halide (MH) and high pressure sodium (HPS) lamps, and to a lesser extent, T5 or fluorescent bulbs all of which were sufficiently economic and readily available. Naturally, growers continue to search for ways to reduce operating costs while improving growth rates and yields of crops. A new phosphor blend based LED lighting technology is achieving these goals in Asia and is now available to U.S. growers.

Fig. 1



Absorption spectrum of chlorophyll and antenna pigments (Chen, 2014)

Among these traditional light sources, no one type of bulb has satisfied the needs of growers.

This is because plants use light to grow with the help of pigments, the most common of which and arguably most important to plant growth is chlorophylls a and b (Fig. 1).

Plants have other photosynthetic pigments, known as antenna pigments such as the carotenoids which also absorb light and have a significant role in photosynthesis (Fig. 2). The chlorophylls have two light absorption peaks – one in the red region (700nm wavelength) of the light spectrum and the other in the blue region (400 nm wavelength)—the range between these wavelengths is commonly referred to as the photosynthetically active radiation (PAR) range.

Fig. 2 **Two Stages of Photosynthesis**

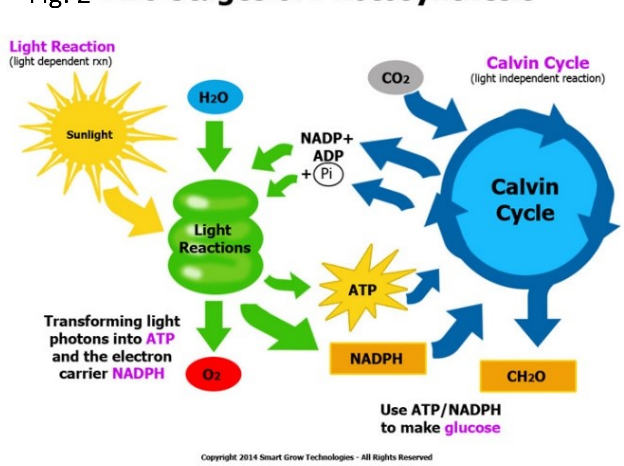
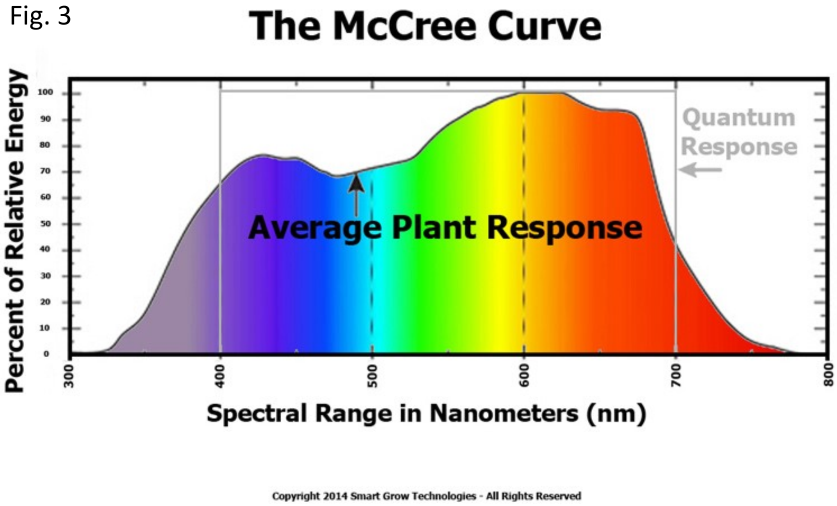


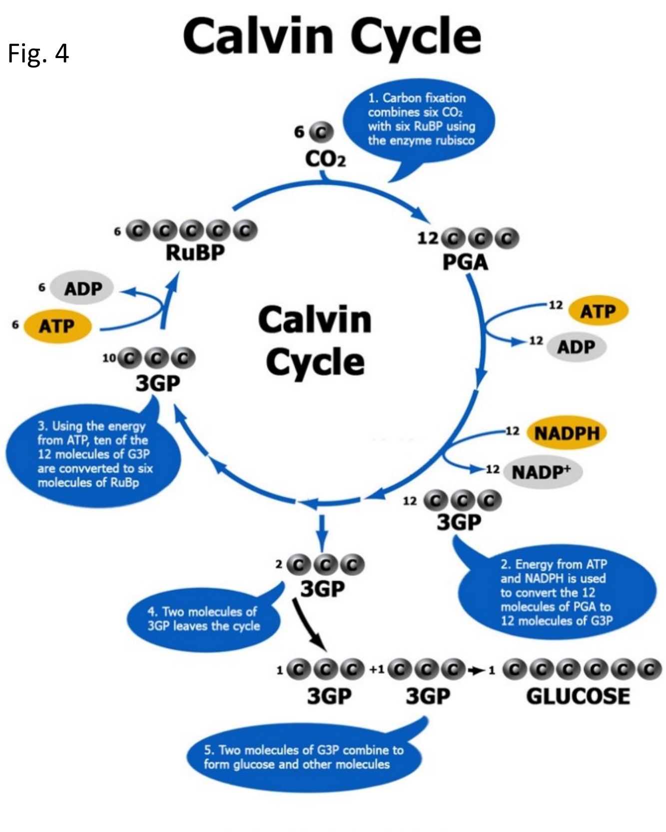
Fig. 3



While specific plants have specific light needs and responses to particular spectra, the McCree Curve represents the average photosynthetic response of plants to light energy. The McCree Curve, also known as the Plant Sensitivity Curve, begins at 360nm and extends to 760nm. This curve can be placed over a spectral distribution chart to see how well a light source can affect plant growth (Fig. 3). The quantum response begins at 400nm and extends to 700nm (Sager and McFarlane, 1997).

Plants turn absorbed light into sugar through a series of biochemical reactions known as the Calvin Cycle (Fig. 4). There are three phases to the reactions, carbon fixation, reduction reactions, and ribulose 1,5-bisphosphate (RuBP) regeneration. This process occurs only when light is available. Plants do not carry out the Calvin Cycle by night. Importantly, the quality of light can affect the Calvin Cycle. Light quality, or the amount of PAR light, alters plant photosynthesis by the effects on the activity of photosynthetic apparatus in leaves and the effects on the expression and/or activity of the Calvin cycle enzymes (Wang H, et al.)

Fig. 4



Unfortunately, no single type of traditional light is able to satisfy the ideal spectral needs of crop plants. For example, researchers have compared the spectrum of HPS lamps with chlorophyll absorption peaks. They showed that most of the light output from HPS lamps falls outside the peak

absorption ranges of chlorophyll, leaving only seven percent of light created by HPS lamps to be absorbed by plants.
(http://exhibition.sslchina.org/eng/news.9825fa1f0203ed47.htm)

To overcome the individual limitations, the combination of MH or T5 and HPS has been a less than ideal compromise growers have used or, even more cumbersome, they have rotated plants to sections of their growing facility where lights to suit particular parts of the plants' growth cycles are mounted. More recently, a new lighting technology, light emitting diodes or LEDs has been developed and is gaining acceptance among commercial growers. One reason is that LED colors can be optimized for specific plant needs and due to the compact size of the individual diodes, single fixtures can mount diodes of different colors to provide light recipes.

Another significant issue affecting HID lights is the heat they generate. This intense heat causes potential safety issues for operators and raises the ambient temperature of greenhouses and other enclosed growing structures. This added heat contributes to increased cooling costs. Not only is ambient temperature raised, also the potential for leaf burn is increased with HID lighting. As a result HID lights must be kept further from plants which reduces the effective intensity of the lights and contributes to inefficient utilization of growing space. In addition, increased heat translates to reductions in the life of filaments in any lighting technology. These heat related drawbacks also contributed to the adoption of LEDs.

Modern LEDs – A Revolution in Horticultural Lighting.

Since the early 1990s, LED technology has improved dramatically via focused research and manufacturing improvements. Modern LEDs provide several advantages over traditional HID horticultural lighting, including the ability to control spectral composition, the ability to produce very high light levels with low radiant heat output and no long-wave radiation. They also maintain useful light output for years without replacement (Morrow, 2008). LEDs provide spectral composition control permitting lighting recipes whereby wavelengths can be matched to plant photoreceptors for optimal production, plant morphology, pathology and composition. Thus, narrow-band LEDs avoid the inefficient energy burden of broad wavelength light, as a result energy is further saved. LEDs are solid-state devices, as such they can be integrated into digital lighting programs like intra-day, sunrise and sunset simulations as well as inter-day plant life-cycle programs (Yeh & Chung, 2009). They are safer to operate because they do not have glass envelopes or high surface temperatures and they do not contain mercury. (Morrow, 2008) Finally, they don't have massive ballasts that would otherwise block natural light.

Focused, Tailored Spectrum

An ideal lighting system must convert as much electricity as possible into PAR energy. The spectral output of an LED system can be matched to plant photoreceptors and optimized to provide maximum production within ideal spectrum without wasting energy on nonproductive wavelengths (Dougher and Bugbee, 2001; Sager et al., 1982). The light can be customized for specific crops or production protocols and even modified over the course of a day or growth cycle (Morrow, 2008). It is also possible that custom-designed lighting could significantly reduce insect, disease, or pathogen loads on crops (Massa et al., 2008) or used for disease visualization. Kevin Folta, University of Florida, Horticultural Sciences Department, reported that "In the lab we have exposed strawberry plants to LED lights and they don't get spider mites," he said. "We don't know if there is something that the LEDs are doing to change the development of the spider mite. Or the light maybe doing something to the plant that causes it to produce a chemical the spider mites don't like so they choose to go to a different plant. This is something that we still need to test." (http://hortamericas.blogspot.com//.../led-grow-lights-used-inleafy-green.html)

Increased Growth Rates and Yields

Given the tailored light advantages of LEDs, it is no surprise that research universities, governmental organizations and commercial growers who have begun using LED lighting systems are reporting increased growth rates, crop yields and desirable characteristics of particular crops. Specialty Greens in Lafayette, California and Hort Americas studied the effects supplemental LED lighting on growth rates and yields of lettuce and herb crops. They report that lettuce grown under the LEDs had accelerated growth going from seed to harvest within a 30-day crop cycle. In another experiment, the company forecasted two to three harvests of mizuna grown with LEDs within 30 days and similar results for kale, chard and some lettuces. (http://hortamericas.blogspot.com//.../led-grow-lights-used-in-leafygreen.html) Similarly, Clean Fresh Food of Wisconsin reported that they achieved an estimated 40 percent lettuce, chard and microgreen crop productivity gain with LED lighting compared to traditional HID lighting.

In evaluating plug quality after 28 days under various supplemental lighting treatments, researchers at Purdue University reported that plug quality of various species of ornamentals was statistically higher under particular red:blue LEDs than those grown under HPS lamps. LED grown plugs were generally more compact, sturdier and greener, and had thicker stems and higher dry mass (Randall W. and Lopez R.). In another study, researchers investigated the effect of LED lighting on the growth and yield of tomatoes. They reported that the growth of plants was better under LED lamps than with HPS lamps. Red and blue supplemental lighting from LEDs decreased harvesting time by 17 days and increased productivity by 2.6 fold when compared to no supplemental light (Lee S. et al, 2013).

This initial data is promising and supported by earlier studies that did not directly compare LEDs to other lighting options but did report results achieved with various spectrum produced with LEDs in an effort to provide data on ideal LED light spectra (Massa et al. 2008). Other organizations continue to research growth rate and yields of various crops grown under LEDs compared to traditional HID lighting and will continue to report their data in scientific and trade publications and presentations. At the 2012 OFA Annual Short Course in Columbus, Ohio, Cary A. Mitchell presented data showing comparisons of quality in seedlings and cuttings grown under narrow spectrum LEDs vs. HPS lamps. The LEDs provided higher finished plug quality in 5/6 species investigated and comparable growth in cuttings. Notably, energy costs, measured as kilowatt-hours per day, were 128% greater with the HPS lamps. (http://leds.hrt.msu.edu/research/)

In addition to the ability to provide narrow-spectrum or colored wavebands specific for desired plant responses, LEDs also cast off heat separately from light-emitting surfaces through active heat sinking (Bourget, 2008). This is significant for high intensity LEDs because it allows growers to place the LED lighting fixtures close to crop surface--even within the canopy of high growing crops like tomatoes--without the risk of overheating and stressing plants (Bourget, 2008).

Reduced Operating Costs

Regardless of this encouraging data, the question remains if farmers will recoup the upfront cost of new LED lighting systems. Devesh Singh and others at the Hannover Centre for Optical Technologies at the University of Hannover in Germany compared the life-cycle costs of traditional high pressure sodium lamps against those of LEDs for greenhouse lighting and they report that the advantages are clear (Singh et al., 2014). They calculate that the cumulative cost of high pressure sodium lamps surpasses that of LEDs. Similarly, in the sample return on investment (ROI) analysis presented below, simple payback of the initial investment to purchase and install LED lights to replace traditional lighting can be as quick as one year.

Commercial growers are also experimenting with LEDs and comparing them with traditional lighting. Clean Fresh Food of Wisconsin reported using 70 percent less energy than conventional high-intensity discharge (HID) greenhouse light fixtures.

Researchers at Purdue University experimented with LEDs to compare year-round tomato production with supplementing light vs. traditional overhead HPS lighting vs. high intensity red and blue LEDs (Kacira, 2011). The study demonstrated that growers could yield the same amount of tomatoes using LEDs as they could with HPS and consume only 25% of the energy of the HPS fixtures. Similar results were reported for cucumber and lettuce (Mitchell et al., 2012).

Comparison of LED and HPS Lighting Systems

For this comparison, intensity and efficiency is expressed in micromole photons per second (µmol/s). Research at universities and applied research stations demonstrated that the rate of photosynthesis is related to the amount of photons emitted between 400 – 700 nm, called 'Photosynthetic Photon Flux' (PPF) which is a way of measuring if a light source is suitable for photosynthesis. This is expressed in micromole photons per second (µmol/s). The higher the PPF value per Watt, the more efficient the light source for plant growth. In the table below, PAR FORCE LED lights are the most efficient, providing the highest PPF per watt.

Lighting System	Power † Total Input Wattage	Lifetime*	Intensity (PPF) *†	Efficiency
LED PAR FORCE Hybrid LED Pro Panel	260w	50,000 hrs	620 µmol/sec	2.38 PPF/w
LED Philips GreenPower LED Toplighting Module DR/B HB 400V	200w	25,000 hrs	440 µmol/sec	2.2 PPF/w
HPS Philips Master GreenPower CG 1000W	1035w	10,000 hrs	1850 µmol/sec	1.79 PPF/w

* Lifetime values are given at an ambient temperature of 25 °C rated life to 90% of initial photon flux = 25 khrs.
† Photon flux and Power consumption values are typical at stable operation at an ambient temperature of 25 ºC.

PAR FORCE LED lighting systems are able to provide higher intensity light at comparable power consumption levels because they are constructed with smaller, more efficient .05 milliamp LEDs that provide the intensity of larger two to three milliamp LEDs commonly used in competing products, and do so at lower, more light-quality stable operating temperatures. In addition, PAR FORCE LEDs use a superior combination of a single blue LED and proprietary phosphor coatings to maximize PAR spectrum. These key differences are why PAR FORCE LEDs are rated to provide the highest intensity by the United States Department of Energy. This higher intensity provides higher PPF which translates to increased efficiency at providing PAR. In so doing, PAR FORCE LED fixtures are providing larger yields and growth rates for the same energy consumption.

A New Milestone in LED Technology – Milliamp Sized, Phosphor Blend LEDs

The engineering team that developed the novel technology driving the intensity advantage of PAR FORCE LED panels is Greg Lai, PhD and Jessi Niou of Frequency LED. Together they have 50 years of working experience in the semiconductor industry. Dr. Lai has a PhD in material science from Michigan State University and developed the phosphors used in PAR FORCE LEDs. In addition he is the co-founder of a Taiwan based, indoor vegetable growing operation—VegFab--that has provided Asian markets fresh vegetables since 2010. Mr. Niou, holds a BSEE and MSEE and having co-founded Frequency LED with Dr. Lai, has worked with him since 2010 to develop phosphorous formulations that improve growth rates and yields for vegetables, berries and cannabis.

At VegFab, using the technology in phosphor blended PAR FORCE LEDs, the team has produced harvestable lettuce and crucifer in 42 and 35 days respectively. Their chosen system of tables and racks provides 37,500 individual growing holes. This setup typically produces 3.5 tons of lettuce and 5.6 tons of crucifer per month with approximately 36,000 kWh per month in electricity for lighting, HVAC and all other operating devices.

The Phosphor Blend Difference

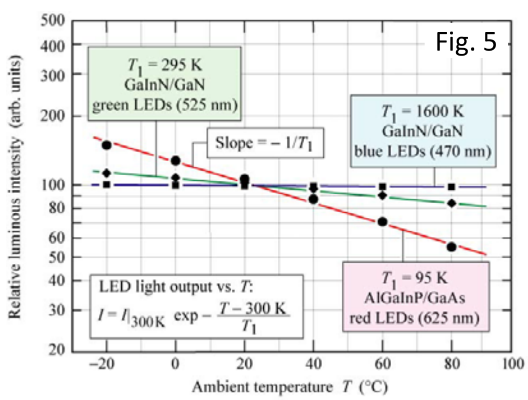


Fig. 5.7. Characteristic temperature T_1 of GaInN/GaN blue, GaInN/GaN green, and AlGaInP/GaAs red LEDs near room temperature (after data from Toyoda Gosei Corp., 2000). More recent data (Toyoda Gosei Corp., 2004) shows the following values for T_1: Blue GaInN LED, 460 nm, T_1 = 1600 K; Cyan GaInN LED, 505 nm, T_1 = 832 K; Green GaInN LED, 525 nm, T_1 = 341 K; Red AlGaInP LED, 625 nm, T_1 = 199 K.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

While it is beyond the scope of this paper to explain all of the technical differences between LED technologies, there are differences that are important to growers and that likely explain the poor performance of earlier LEDs for horticulture applications. Most horticultural LED lighting systems use the common method of mixing red, green and blue (RGB) LEDs to create light. Hence the method is called multi-color white LEDs (sometimes referred to as RGB LEDs). This technology is common to many uses because of the flexibility of mixing different colors and, in principle, this mechanism also has higher quantum efficiency in producing white light. However, important to horticulture applications that do not need white light, this type of LED's emission power decays exponentially with rising temperature (Schubert, E. and Kim, J.) resulting in a substantial change in color stability. Such problems inhibit its ability to maintain PAR light and likely resulted in disappointing results for growers who trialed this technology. Figure 5, presented by E. Fred Schubert, Department of Electrical, Computer, and Systems Engineering Department of Physics, Applied Physics, and Astronomy Rensselaer Polytechnic Institute supports this assessment of RGB LEDs. It shows the significant fall off of relative luminous intensity at increasing ambient temperatures for typical red LEDs found in RGB LED panels.

The blue diodes used in PAR FORCE LEDs are more stable despite temperature variations so light intensity and color stability is superior to RGB LEDs. PAR FORCE LEDs use phosphor blends to tailor light spectrum and because of this different approach to creating PAR spectrum, do not suffer this significant fall off in intensity. In addition, as mentioned above, they are much smaller than typical horticulture LEDs, which enables lower operating temperatures providing improved light quality stability. As a result, phosphor blended LEDs provide more PAR per watt than RGB LEDs. The lower operating temperature and inherent stability advantage enables PAR FORCE LEDs to provide more consistent and intense PAR light throughout an operating day and LED operating lifetime. More, and more intense PAR light provides increased yields, growth rates and crop quality.

LED Return on Investment (ROI) Analysis

Despite the many advantages of LEDs compared to traditional lighting, commercial growers are prudently weighing the costs to gain such benefits. In the interest of addressing such concerns, an ROI analysis is presented below which presents the economic benefits of replacing HPS fixtures with PAR FORCE Hybrid Pro Panel LED fixtures. PAR FORCE fixtures are available in three different wattage and corresponding lit areas:

1. 525 watts ideal for 5 foot by 5 foot or 25 square feet of lit area
2. 375 watts ideal for 5 foot by 4 foot or 20 square feet of lit area
3. 260 watts ideal for 4 foot by 4 foot or 16 square feet of lit area

Assumptions

For this analysis it is assumed that PAR FORCE 525 watt Hybrid LED Pro Panels which provide the most yield potential via the largest lit area (25 square feet) and highest concentration of light within that area of the three PAR FORCE options will be installed. These 525 watt LED fixtures will be installed in an indoor growing environment instead of 1000 watt HPS fixtures.

Assumptions include:

Lighting Costs:

- 525watt PAR FORCE Hybrid LED Pro Panel cost is $2000.00 each, complete
- 1000watt HPS fixture cost is $650.00 each including bulb, ballast hood and reflector unit

Plant area:

- A 1000w HPS, and similarly a 525w LED fixture, provide light to 25 square feet of growing space each (5 x 5 feet).

HVAC:

- Electricity costs $0.10 USD per kWH
- Energy Efficiency Ratio (EER) is 14
- HVAC is operated 360 days per year, 13 hours per day
- One 1000w HPS fixture creates 3,412 BTU/kW of heat which requires .28 tons of cooling where one ton of cooling equals 12,000 BTU/hour
- As a result, it takes $114.06 USD per year in HVAC costs to mitigate the excess heat produced by a single 1000w HPS fixture

Growing Area:

- Dimensions are 150 feet long x 5 feet wide x 15 feet high
- 112 crop cycle days; 56 vegetative propagation days; 56 bloom days
- 360 operating days per year
- 13 hours of light per day
- $0.10 USD per kWH electricity cost

Given these assumptions which are based upon actual product specifications and other industry information, 30 525w PAR FORCE Hybrid Pro Panel LED fixtures will replace the existing 30 1000w HPS fixtures. The simple payback of the initial investment of $60,000 USD minus the avoided HPS costs of $19,500 will be 22 months with an internal rate of return (IRR) of 34% calculated based upon a five year cash flow. Labor to replace bulbs and any incentives are not included in this analysis and, if included, will improve the ROI and IRR calculations.

The investment details are as follows:

Initial Investment	1000w HPS Fixtures	525w PAR FORCE HYBRID LED Fixtures	Net Investment
Purchase of Fixtures	$19,500	$60,000	$40,500

Annual Operating Costs	HPS Configuration	PAR FORCE Hybrid Pro Panel LED Configuration	Avg Annual Savings
Electricity	$17,462	$6,950	$10,512
Bulb Replacement	$11,475	-	$11,475
	$28,937	$6,950	$21,987

As mentioned above, PAR FORCE fixtures are available with different wattage levels. To be most efficient and cost conscious rather than pursue the highest potential crop yield, a grower could install $1800.00, 375 watt PAR FORCE fixtures instead of the 525watt models. If the ROI were to be calculated using 375 watt PAR FORCE fixtures instead of the 525 watt fixtures the simple payback would be approximately 17 months with an IRR of 56% per year.

As discussed, PAR FORCE LED technology provides flexibility in terms of light recipes specific to particular crop needs. PAR FORCE LEDs provide energy efficiency and other cost saving benefits that translate into reductions in operating costs and substantial returns on investment. Perhaps most importantly, LED related data is continuing to be amassed by research institutions and proactive commercial growers that show increase growth rates and yields of a variety of commercial crops.

Bourget, C. 2008. An introduction to light-emitting diodes. HortScience 43:1944-1946.

Chen P. Accessed 29 June 2014. Chlorophyll and other photosentives. In: LED grow lights, absorption spectrum for plant photosensitive pigments. http://www.ledgrowlightshq.co.uk/chlorophyll-plant-pigments/.

Dougher, T. and B. Bugbee. 2001. Differences in the response of wheat, soybean and lettuce to reduced blue radiation. Photochem. Photobiol. 73:199–207.

Lee S., Kwon J., Park K., Choi H. 2013. The Effect of LED Light Source On The Growth And Yield of Greenhouse Grown Tomato. ISHS Acta Horticulturae 1037: International Symposium on New Technologies for Environment Control, Energy-Saving and Crop Production in Greenhouse and Plant Factory - Greensys 2013

Kacira, M. 2011. Greenhouse Production in US: Status, Challenges, and Opportunities. Presented at CIGR 2011 conference on Sustainable Bioproduction WEF, September 19-23, 2011.

Massa G, Kim H, Wheeler R, Mitchell C. 2008. Plant Productivity in Response to LED Lighting. HortScience. 43:1951-1956.

Mitchell CA, Both A, Bourget CM, Kuboto C, Lopez RG, Morrow RC & Runkle S. 2012. LEDs: The future of greenhouse lighting. Chronica Horticulture. 55:6-12.

Morrow RC. 2008. LED lighting in horticulture. Hort Science. 43:1947–1950.

Ono, E. and H. Watanabe. 2006. Plant factories blossom—Production in Japan steadily flowers. Resource 13:13–14.

Randall W., and Lopez R., 2013. Comparing LED Lighting To HPS Lamps For Plug Production. Greenhouse Grower. November:32-38.

Sager, J., J. Edwards, and W. Klein. 1982. Light energy utilization efficiency for photosynthesis. Trans. ASAE 25:1737–1746.

Schubert, E. and Kim, J., 2005. Solid-State Light Sources Getting Smart. Science 308(5726): 1274.

Singh D, Basu C, Meinhardt-Wollweber M, Roth B. 2014. LEDs for Energy Efficient Greenhouse Lighting. Hannover Centre for Optical Technologies.

Steigerwald D., J. Bhat, D. Collins, R. Fletcher, M. Holcomb, M. Ludowise, P. Martin, and S. Rudaz. 2002. Illumination with solid state lighting technology. IEEE Journal on Selected Topics in Quantum Electronics 8:310–320.

Wang H., Gu M, Cui J, Shi K, Zhou Y, and Yu J. 2009. Effects of Light Quality On CO2 Assimilation, Chlorophyll-fluorescence Quenching, Expression of Calvin Cycle Genes and Carbohydrate Accumulation in Cucumis sativus. J Photochem Photobiol B. Jul 17;96(1):30-7. doi: 10.1016/j.jphotobiol.2009.03.010. Epub 2009 Apr 5.

Yeh N & Chung JP. 2009. High-brightness LEDs – energy efficient lighting sources and their potential in indoor plant cultivation. Renew Sust Energ Rev. 13:2175–2180.