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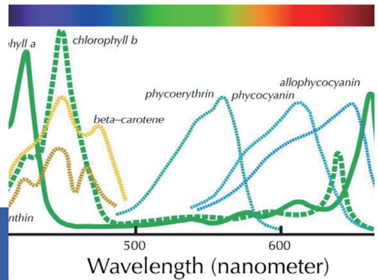
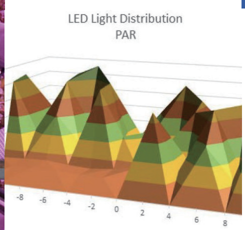
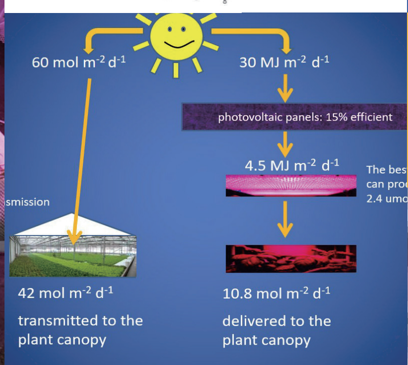




Global Solid State Lighting Special Report

2017 Volume Two



Applications of Solid State Lighting to Horticulture

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Abstract

The development of solid–state lighting offers many opportunities to design lighting systems that can accelerate the growth of plants for food and medicine. LED sources now offer equivalent or slightly better efficiency in producing light than the best traditional lamps, but the major advantage comes from the adaptability of LED systems to the dynamic needs of growing plants. This is accomplished through spectral tuning and light distribution. The potential for rapid growth of the market is constrained by the high initial cost of LED lights and the need for further study of the reaction of each specific plant to the intensity and spectrum of light.

1. Market Forecasts

LED Inside has estimated that the sales of LED systems for horticulture in 2017 will be about $193M out of a total market of $690M, representing a market share of 28%. They forecast that in 2020 LED sales will rise to $356M out of a total of $1424M. The market share of revenues would then be 25%, suggesting that increased unit sales penetration will be offset by reduced prices. In October 2017 Strategies Unlimited made the forecast shown in Figures 1 and 2, suggesting that total sales in 2020 will be above $5B, but that LEDs will capture only about $1B of these revenues.

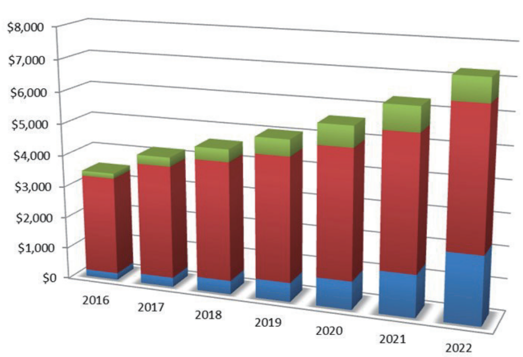


Figure 1. Sales of supplemental lighting systems for greenhouses 2016-2022 (Strategies Unlimited)

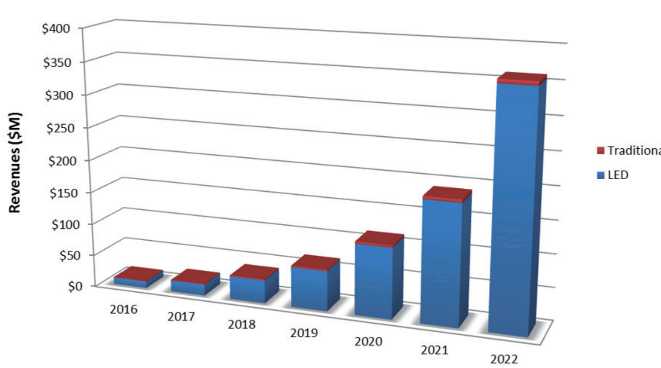


Figure 2. Sales of lighting systems for vertical indoor farming 2016-2022 (Strategies Unlimited).

Earlier forecasts from other companies have been based on much larger estimates for the current sales. For example, in 2015 Wintergreen Research stated "LED grow light module markets at $395 million in 2014 are forecast to reach $1.8 billion by 2021". Markets and Markets believes that the LED grow light market was already above $500M in 2015 and will rise to $1.9B in 2020.

Figure 3 gives a breakdown of the anticipated market for 2020, as seen by the European company Valoya.

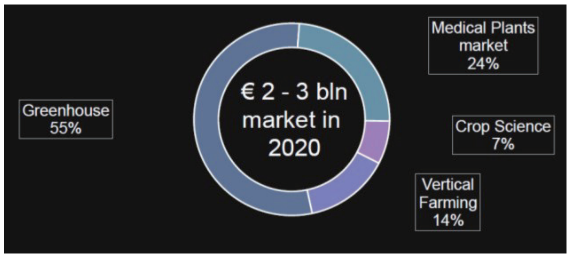
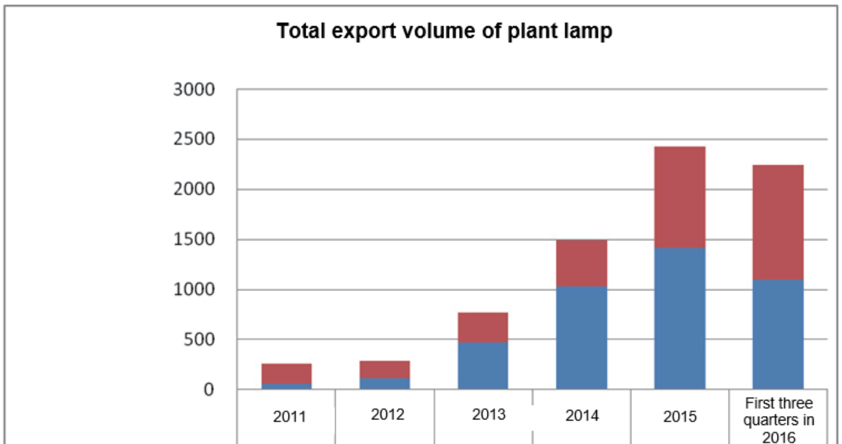


Figure 3. Sales of horticultural lights in 2020 by application (Valoya)

China is an important manufacturer of lamps for plants, mostly for export. Figure 4 shows recent data collected by the CSA.



	2011	2012	2013	2014	2015	First three quarters in 2016
Traditional plant lamp (10,000 yuan)	202.26	176.59	304.59	456.46	1015.29	1152.44
LED plant lamp (10,000 yuan)	53.61	115.32	467.68	1032.30	1413.94	1094.24

Figure 4. Export of plant lamps from China 2011-2016 in 10,000 RMB (CSA)

2.Performance of Plant Lights

The traditional method for measuring light output is the lumen. However, this measures the impact on the human eye and so is not appropriate for use in agricultural applications. One alternative is to measure the number of photons emitted. The most common unit is the micro–mole (1 μmol) which represents 6 x 10^{17} photons. An alternative is the optical Watt, which measures the energy carried by the photons.

2.1 Efficiency

Lamp output is often expressed in 1 μmol/s (second), while lamp efficacy is usually given in μmol/J (Joule). For a perfect lamp, 1 Joule could produce

- 5.5 μmol of deep red light (~660nm)
- 4.6 μmol of green light (~550nm)
- 3.8 μmol of royal blue light (~450nm)

Not all the wavelength spectrum is useful. Very low and very high wavelength light are not helpful, but there is not complete agreement on the appropriate range to be included. The following summary of terminology has been compiled by TUV–SUD.

Table 1. Common units used for plant lighting (TUV-SUD)

Parameter	Description
Photosynthetically active radiation (PAR)	The PAR ranges from 400 nm to 700 nm. Spectral range that plants are able to use in the photosynthesis process.
Photosynthetic photon flux (PPF) - μmol/s	PPF indicates how many photons of light are emitted by a light source each second.
Photosynthetic photon flux density (PPFD) - μmol/m²s	PPFD indicates how densely the fixture distributes the light photons on a one meter square target (i.e. your plants and corals) in one second.
Day light integral (DLI) - mol/m² /d	DLI amount of photons that were delivered to a one meter square target in a full photoperiod (i.e. a day).
Yield Photon Flux (YPF)	Photon flux weighted by the McCree quantum yield spectrum
PAR efficacy μmol/s W	Efficacy of the lighting system
Plant biological active radiation	PBR ranges from 280 nm to 800 nm. Spectral range that plants are able to use in the photosynthesis or photo morphogenesis process.
UV Radiation	UV ranges from 280 nm to 400 nm. Defined for UV-A and UV-B
IR Radiation	IR ranges from 700 nm to 800 nm

Many LED plant lights now offer efficacy around 2 μmol/J, which is close to that of the best high–pressure sodium (HPS) lamps. Figure 5 compares LED and HPS systems from a single vendor (Philips).

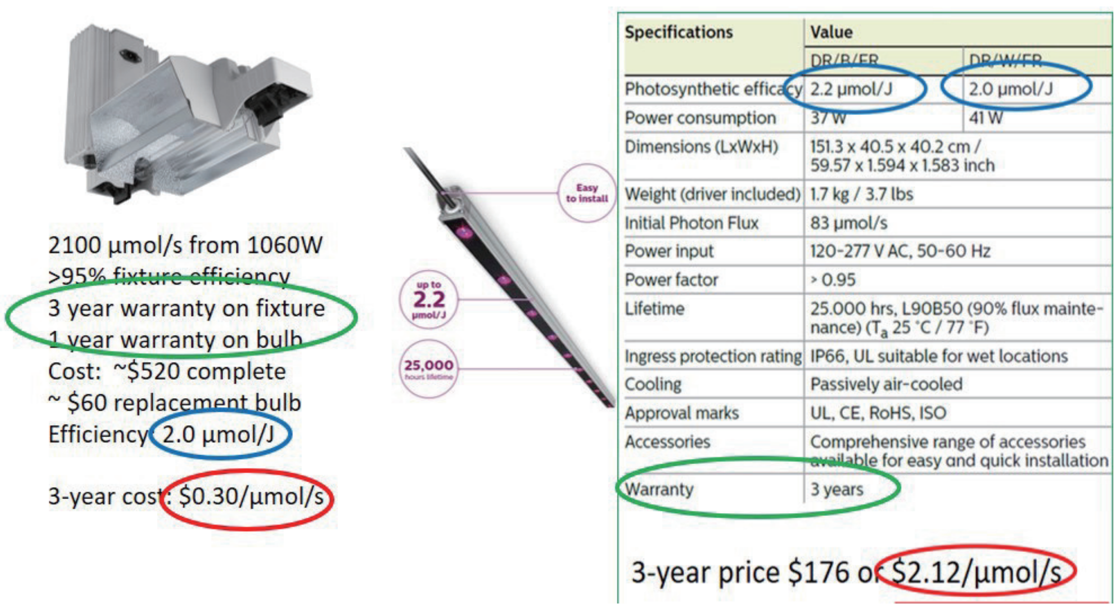


Figure 5. Comparison of HPS and LED systems from Philips

2.2 Lifetime cost

The major difference is in the purchase price for these systems. The warranties on the light sources are the same – at 3 years, but the HPS bulbs need to be replaced during this period. The price comparison in this figure assumes that 2 replacement bulbs are purchased for the HPS. It is possible that the lifetime of the LED system will be longer and that this will compensate for the higher initial price. But to assure the customer that this is the case, the warranty should be lengthened for the LED system.

Substantial efficiency gains can be made by owners of old systems. Many traditional lights have efficacy around 1 μmol/J or less. Some LED packages give efficacy around 3 μmol/J as shown in Figure 6.

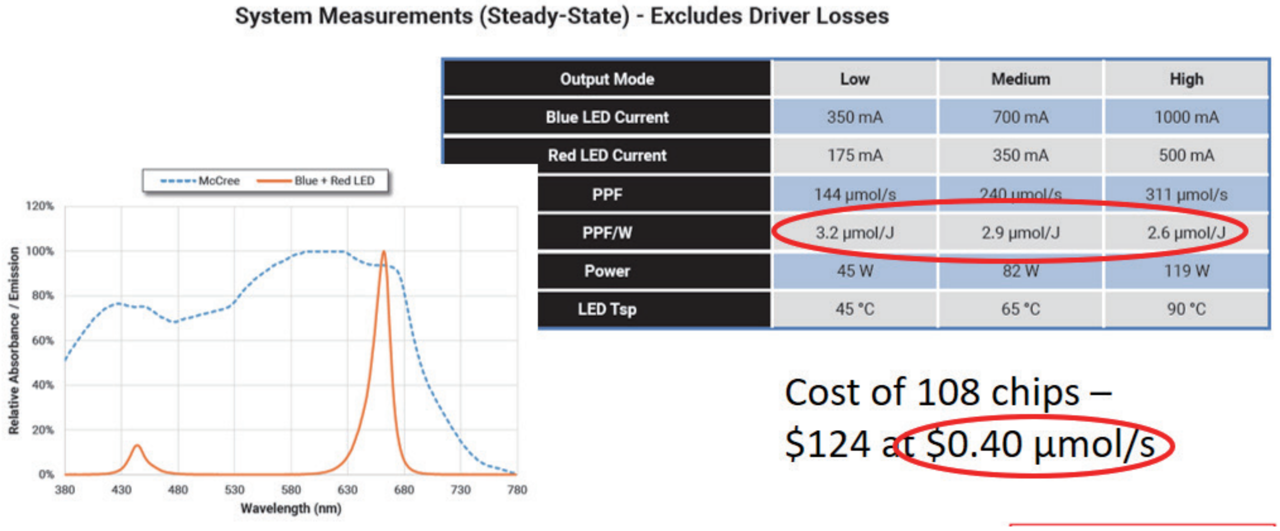


Figure 6. LED packages for horticultural lighting (Cree)

The performance of the chips is good, but the efficacy shown here does not allow for driver losses or optical losses in the luminaire. This case shows that the effective cost of the LED packages alone can exceed that of the whole HPS system.

LED plant lighting systems are clearly still in an early phase and substantial improvement can be expected. This could come in at least 4 ways.

- Extending the operating life of the system, backed by a longer warranty
- Price reductions through increased sales volume
- Optimized spectral spectrum

2.3 Spectral tuning

The photoreceptors in plants and animals differ significantly from that of the human eye. The action spectrum shown in Figure 7 was published in 1972 by McCree, based on studies of 22 crop species, and is often quoted as a standard.

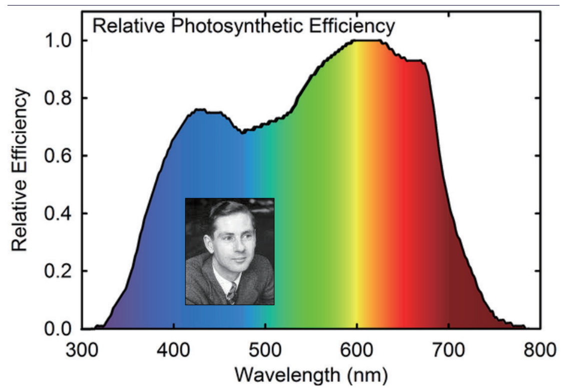


Figure 7. The relative photosynthetic response recorded by McCree (1972)

However, the plants contain many pigments with different absorption patterns, as shown in Figure 8, which is often cited in text books.

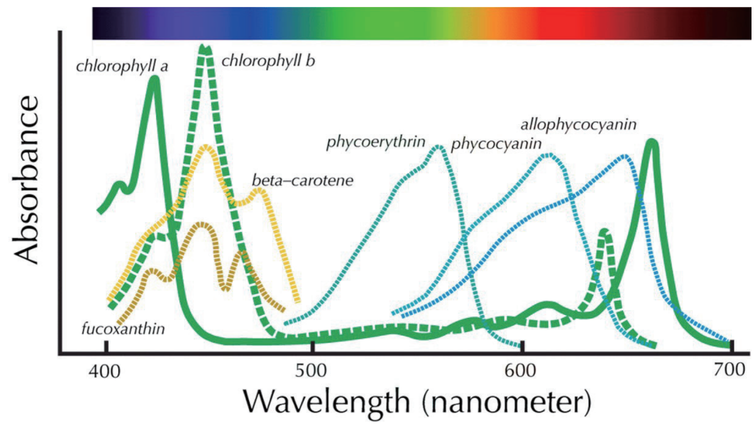


Figure 8. Absorption of different plant pigments

The focus of discussions is often on the relative importance of red and blue light. However, despite the fact that many plants reflect most of the incident green light, these figures show that the whole spectrum can contribute. For example, green light can penetrate more deeply into leaves than other portions of the spectrum.

Data on the value of spectral tuning vary substantially. Figure 9 from West Virginia University in the U.S. shows variations of 25% in the growth of lettuces under LED lights with differing spectra.

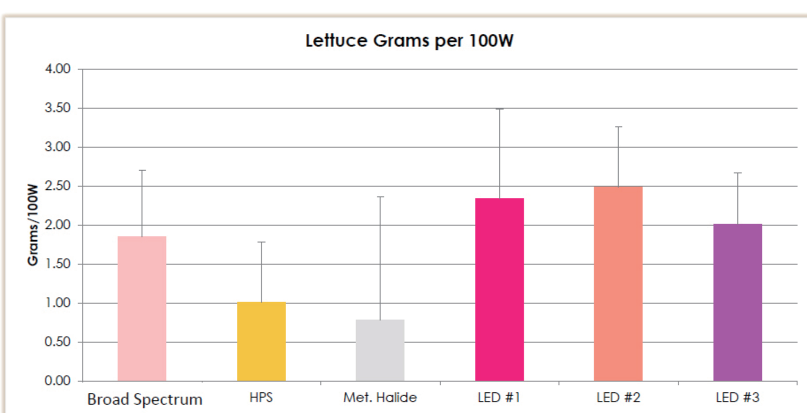


Figure 9. Growth rates for lettuce under different lighting systems (West Virginia University)

Studies of tomato growth at Wageningen University in the Netherlands show differences of only 8%, as shown in Figure 10.

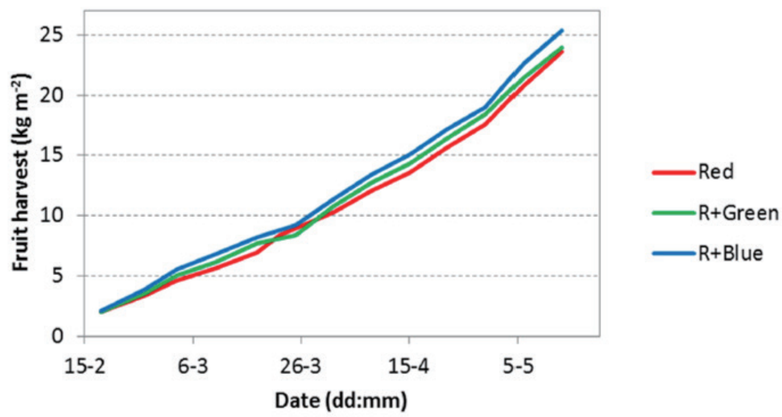


Figure 10. Growth rates for tomatoes under different color spectra (Wageningen University)

The fact that plants behave very differently is well illustrated in Figure 11, showing data from Utah State University.

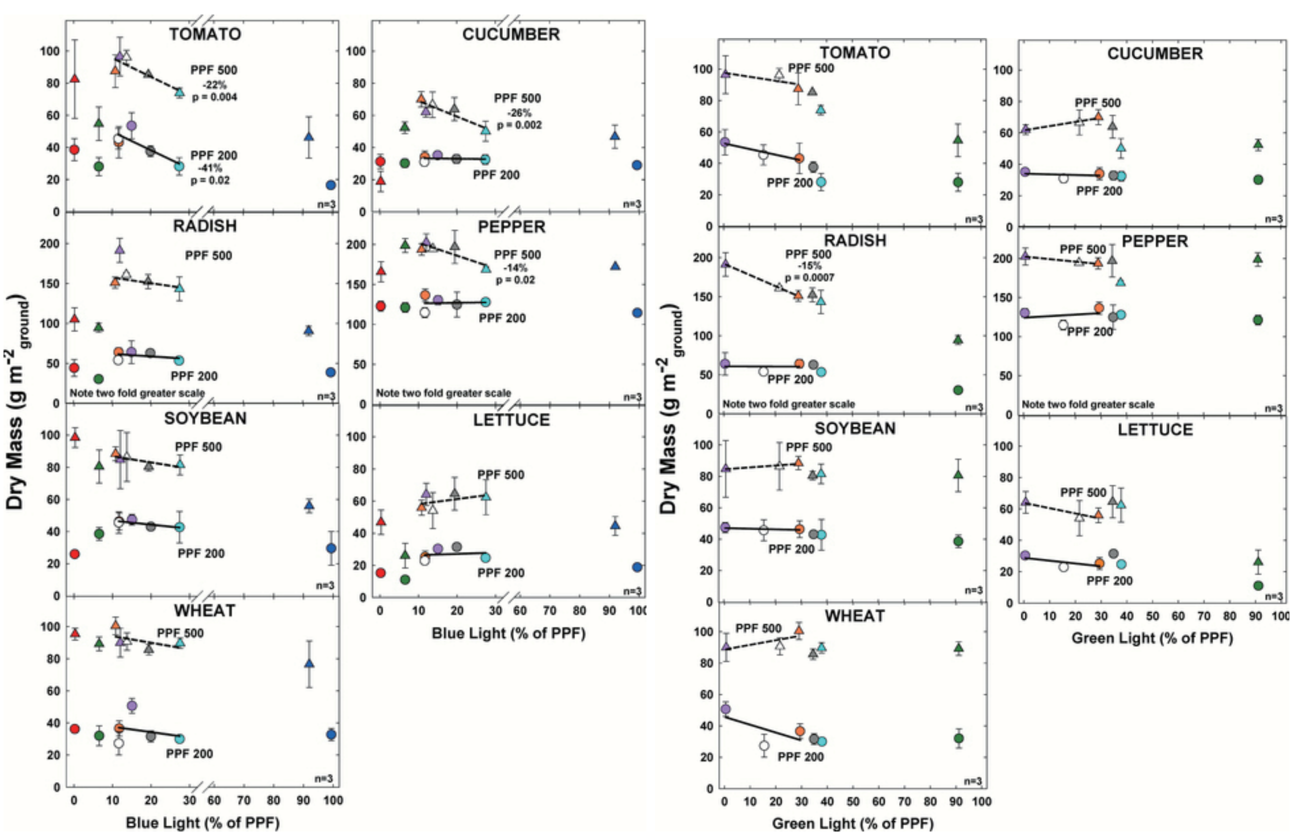


Figure 11. Growth rates for several plants as a function of blue and green content (Utah State University)

There are many other factors that must be taken into account in choosing the color spectrum

Figure 12 from West Virginia University shows some of the factors that influence plant health and nutritional value.

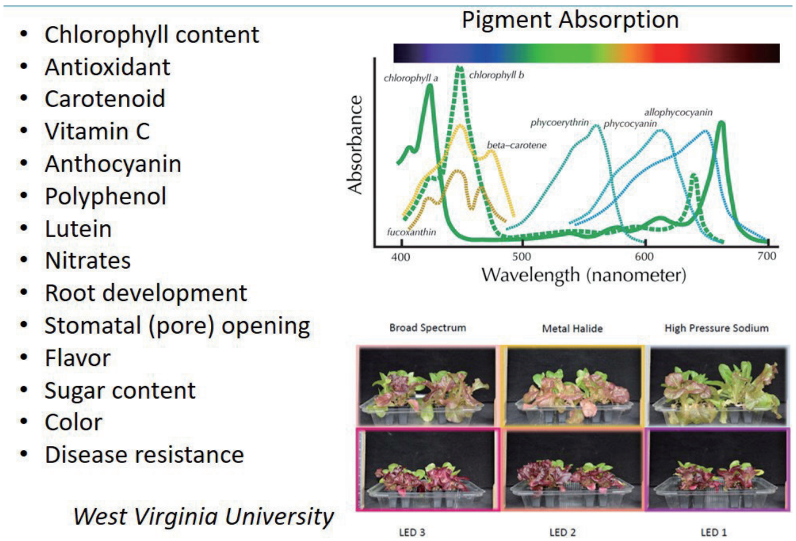


Figure 12. Factors influencing plant quality (West Virginia University)

There have been many studies to show that the quality and nutritional value of plants grown under LED lights is at least as good as those grown outdoors, but there as yet does not appear to be much convincing evidence for the use of specific spectra for improving plant quality. However, indoor farming does make it easier to control pests and other causes of disease.

The optical spectrum for a specific plant may change from one growth phase to the next. For example, many authors have suggested that blue light is more valuable in the early growth stage, producing a more robust plant, and red light is preferred in the later flowering phase. Thus, the capability to modify the spectrum during the growth is another advantage of using tunable LED lighting.

2.4 Spatial distribution

Assuring uniform illumination for all plant surfaces is clearly a major challenge, especially for point or linear sources. Figure 13 shows measurements made in a greenhouse by the Minnesota Department of Commerce, comparing an LED and HPS source.

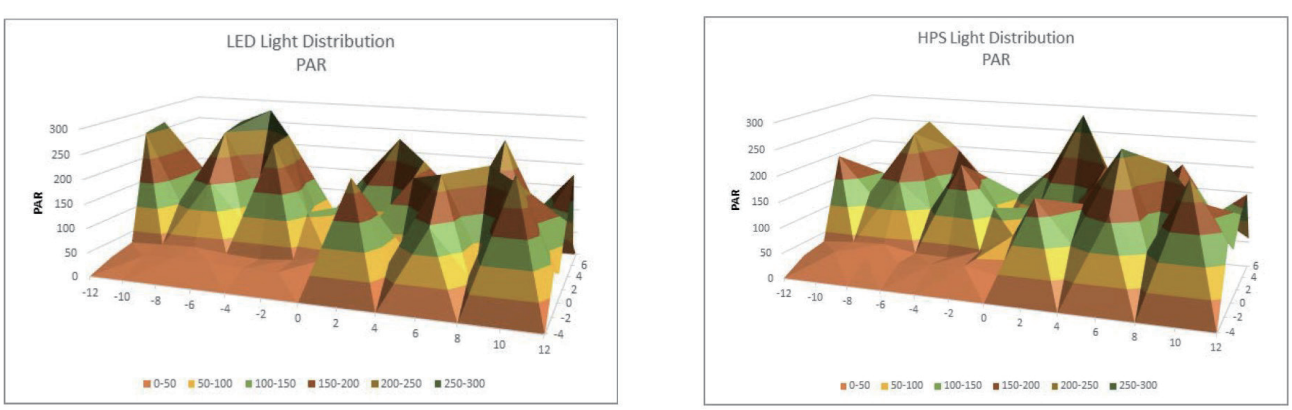


Figure 13. Spatial distribution of greenhouse illumination (Minnesota Department of Commerce)

Further evidence for the variation in uniformity is given in Table 2 and Figure 14. These are included not to recommend one manufacturer over another, but to show the importance of spatial uniformity in system design. Table 2 shows the results of computer simulations of illuminance across a horizontal plane, with the lamps placed at a height recommended by the manufacturer.

Table 2. Comparison of uniformity of illuminance for several sources (Cree Research)

	Reference Design	Gavita 1000W HPS	Typical LED 1 Spot Optic, 60deg	Typical LED 2 No Optic, 120deg
Height (ft)	4.9	3.2	2	0.5
PPFD Max	390	394	2335	934
PPFD Min	182	184	16	182
PPFD Avg	320	303	513	734
PPFD Uniformity* (min: max)	0.47	0.47	0.01	0.19
PPF / W	1.82	1.72	1.40	2.10
Power (W)	553	1064	600	660

When the lamps contain an array of point sources, optical elements can be introduced to spread the light more widely. A common pattern is the batwing distribution that is compared with a more standard distribution in Figure 14.

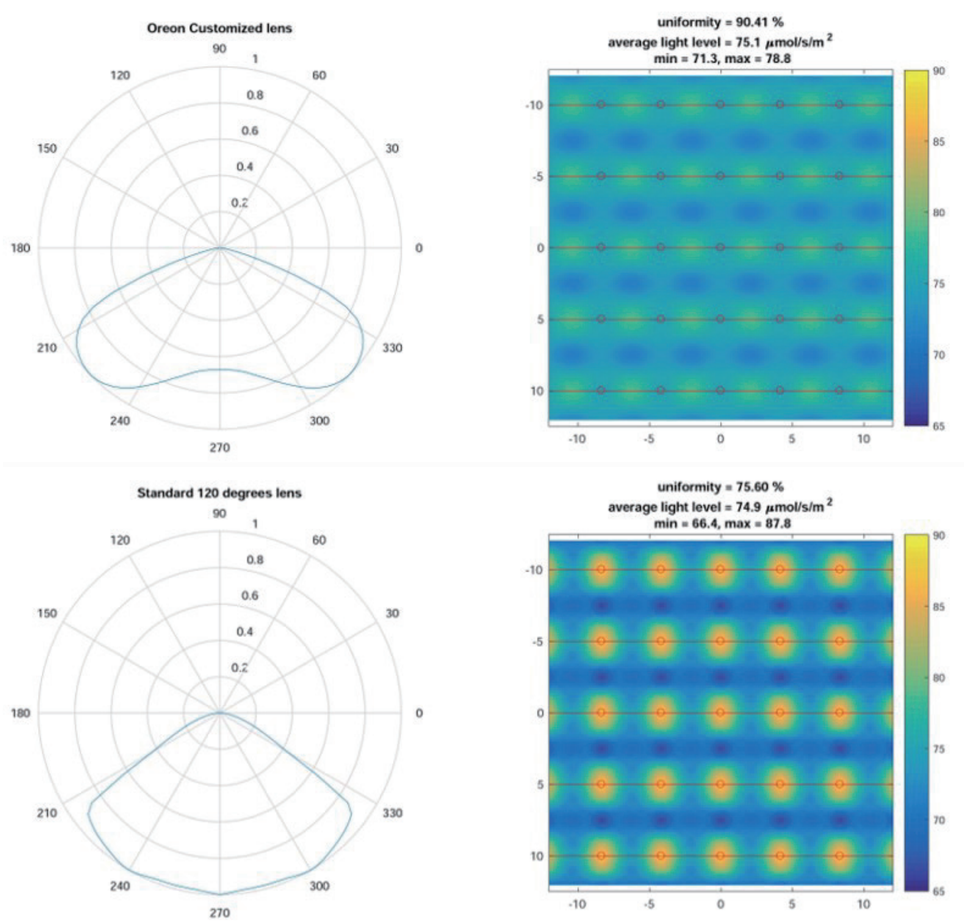


Figure 14. Comparison of the uniformity produced by batwing and traditional neam shapes (Lemnis-Oreon)

The fact that less heat is emitted from LED sources means that the lights can be placed closer to the plants. This is clearly valuable in vertical farming, as illustrated in Figure 15. Closely spaced strips of LEDs are used to improve uniformity, but perhaps a thin planar source with LEDs or OLEDs might be even better.

Figure 15. LED lighting for vertical farms (Lumileds)

For tall plants in greenhouses with ceiling lights, the lower leaves can be shaded by those above. This effect can be reduced by using inter–canopy lights, as shown in Figure 16 from the University of Purdue. Vertical strips of LEDs are used, so that only the lowest ones can be lit after planting and more switched on as the plants grow.

Figure 16. Inter-canopy lights with dynamic distribution (University of Purdue)

3. System Issues

In selecting the best light sources, the effect on the whole system must be considered. This is especially important when upgrading an existing operation. Figure 17 shows a slide presented by Nadia Sabeh at the Strategies in Light Meeting in 2017.

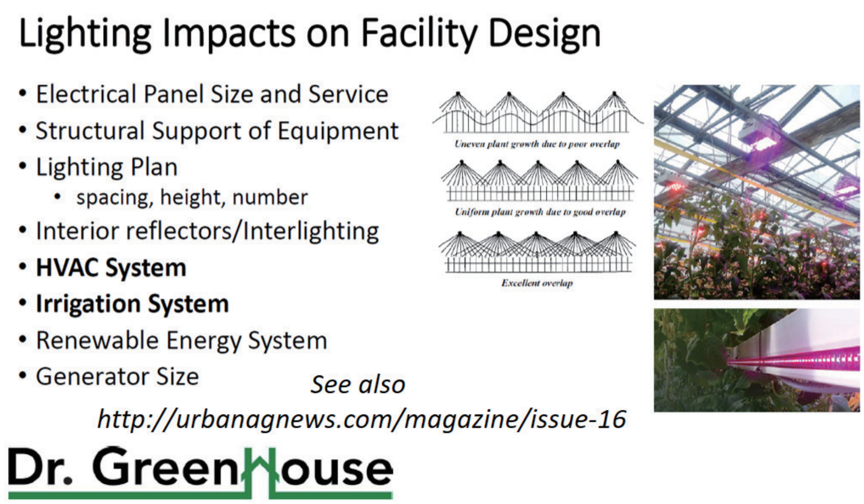


Figure 17. Impact of lighting on greenhouse design (Nadia Sabeh, Dr. Greenhouse)

A well–designed LED system can lead to savings in other cost elements, but the benefits vary substantially from case to case. Studies at Cornell University of various greenhouses and plant factories in the US found that heating costs often exceed cooling costs, as shown in Figure 18. So any reduction in energy bills for lighting might be partially offset by increased heating costs.

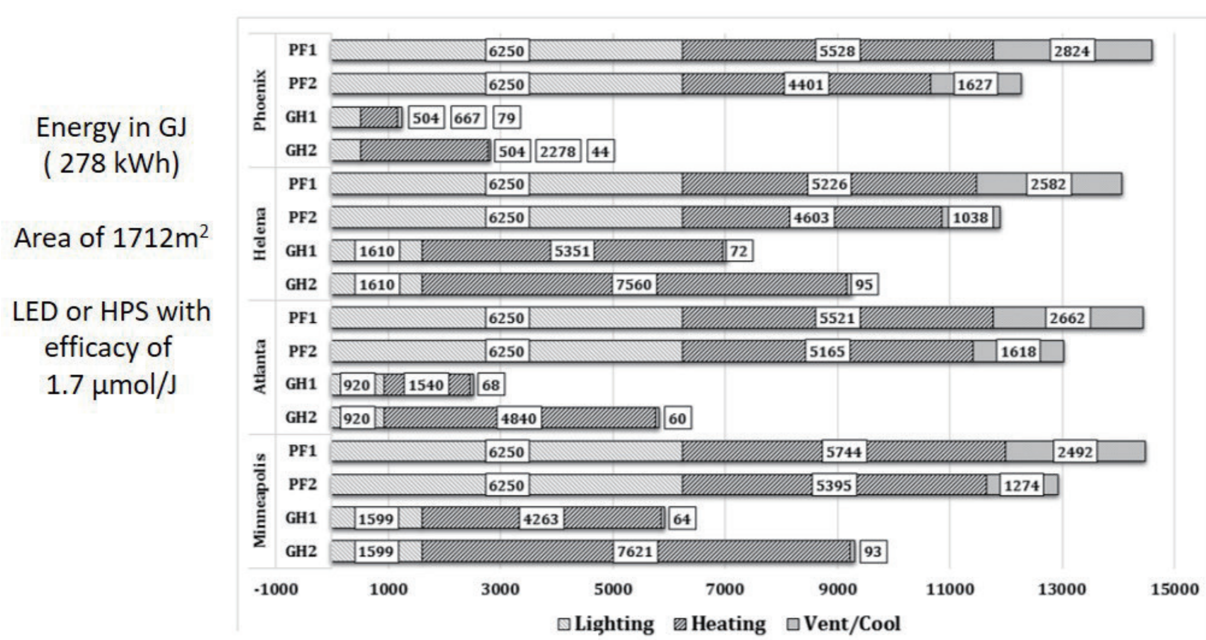


Figure 18. Energy use in greenhouses and plant factories (Cornell University)

The importance of the energy used in plant factories extends beyond the cost to the producer. One of the motivations for urban farming is to avoid the need to transport crops over large distances. In the US, a study by Iowa State University reported that the average distance travelled by tomatoes from grower to customer is 1500 miles. Many crops are transported over 2500 miles from California to east coast cities. However, an analysis by Cornell University suggested that the environmental damage of growing lettuce under artificial lighting in New York can be much greater than that of transporting the crop from California or Mexico, as shown in Figure 19.

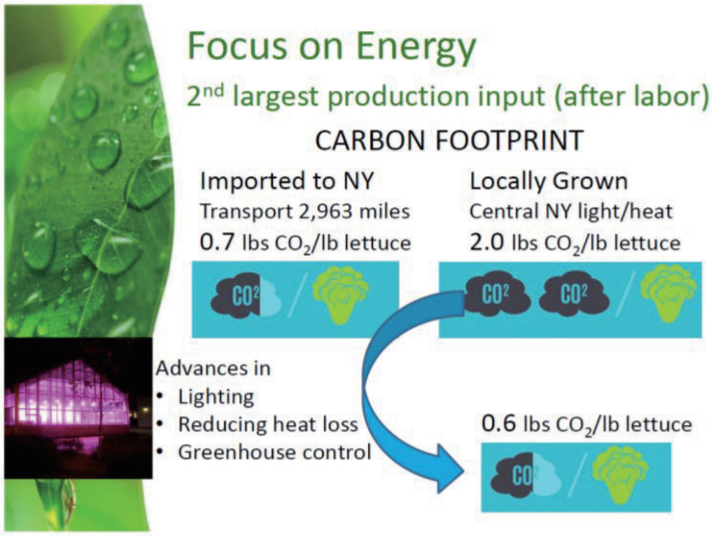


Figure 19. Comparison of CO^2 production under artificial lighting and in long-distance transport (Cornell University).

Figure 20 shows a similar analysis for tomatoes

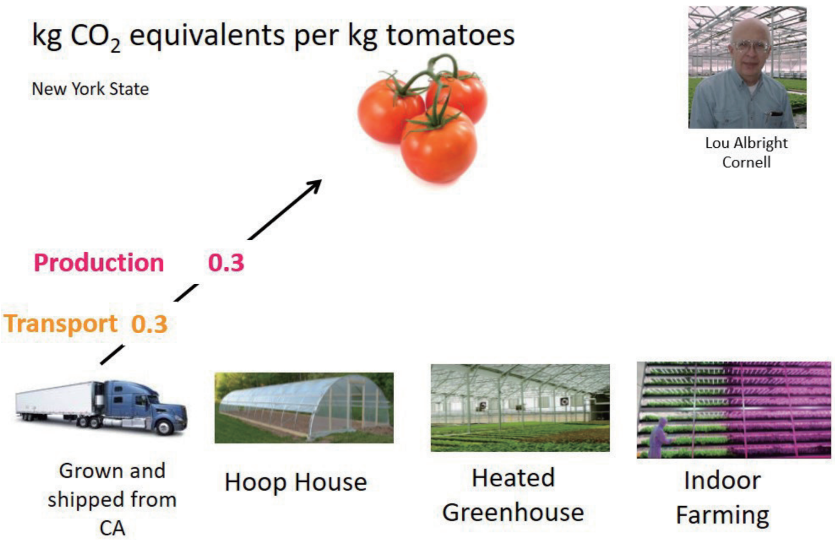


Figure 20. CO^2 production in various forms of tomato growing (Cornell University)

In addition to improving the efficiency of plant lighting systems, the environmental case for indoor agriculture is clearly stronger when the electrical power is created from renewable energy sources. However Figure 21, from Professor Bugbee of Utah State University, shows that significant improvement in LED lights and solar panels will be required to bring the efficiency of urban farming up to that of a traditional greenhouse.

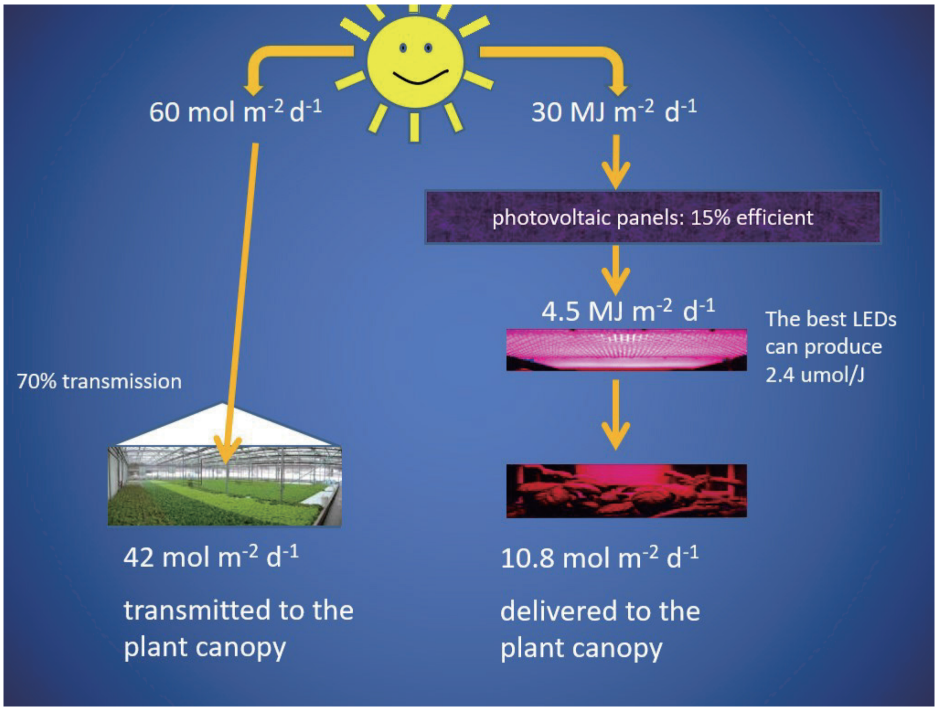


Figure 21. Efficiency of light production in a solar-powered plant factory and a greenhouse (Utah State University)

Reduction in water use is a clear environmental benefit to indoor farming. Agriculture is responsible for about 70% of total water use in the US. However, the cost of water is kept artificially low in many countries and the economic benefits of lower water consumption are usually minimal.

4.Standards and Labels

Standards for horticultural lighting are being developed across the world. Table 3 was assembled by TUV–SUD to summarize international efforts by the IEC and in North America by ANSI and ASABE. Table 4 describes efforts in China as summarized by the China Solid–State Lighting Alliance (CSA)

Table 3. Standards under development by International and North American organizations

Standard	Standard
IEC 60598 -2 -1 Particular requirements. Section One: Fixed general purpose luminaires	ASAE EP 344.3 Lighting Systems for Agricultural Facilities
IEC 60364-7-705 Requirements for special installations or locations – Agricultural and horticultural premises	ANSI/ASABE EP411.5 Guidelines for Measuring and Reporting Environmental Parameters for Plant Experiments in Growth Chambers
IEC 62471 Photo biological safety of lamps and lamp systems	ANSI/ASABE S640 Quantities and Units of Electromagnetic Radiation for plants.

Table 4. Standards under development in China (CSA)

Standard number	Standard name	Date of implementation
GB/T 32655-2016	*LED Lighting for Plant Growth-Terms and Definitions*	2016-11-1
CSA 032-2016	*General Technical Specification for LED Lamps for Plant Lighting*	Initiated in 2014, under formulation
CSA TR002	*Influence of Light Quality on Plant Growth and Development*	Initiated in 2015, under formulation
CSA 021-2013	*Performance Requirements for LED Panel Light for Plant Growth*	September 2013

The Lighting Facts Program of the US Department of Energy is considering the introduction of a label for horticultural lamps. An example of a suggested form is shown in Table 5. A discussion of this effort can be found at

https://www.controlledenvironments.org/wp-content/uploads/sites/6/2017/09/Both-et-al-Hortech-2017.pdf

Table 5. Example of a possible label for horticultural lamps (Lighting Facts Program)

Summary Lighting Facts, Plant Growth Applications

Brand	Valoya
Model	R150 NS1
Lamp type	LED
Voltage (VAC)	120
Current (A)	1.11
Power (W)	133.3
PSS (-)	0.83
R/FR (-)	5.59

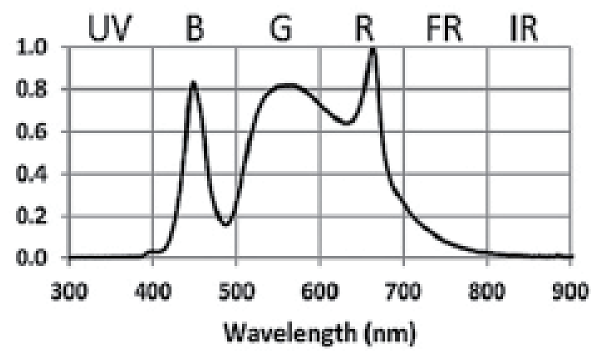
PAR flux ($\mu mol \cdot s^{-1}$)	191.4
PAR efficacy ($\mu mol \cdot J^{-1}$)	1.44
PAR efficacy ($mol \cdot kWh^{-1}$)	5.17
PAR conversion efficiency (%)	31
Luminous flux (lm)	12,480
CCT (K)	4,949
CRI (R_a)	80.0
Case temperature (°C)	55.0

Photon flux density (PFD) (at 2 ft mounting height):

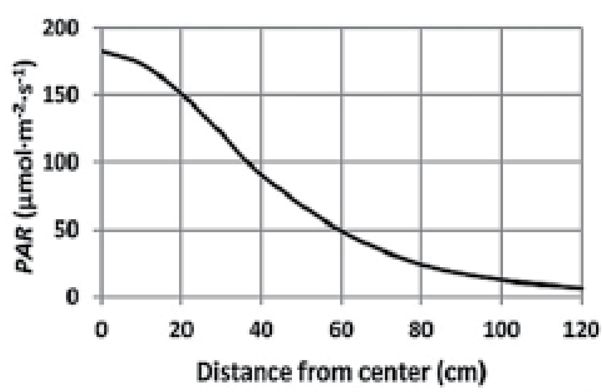
Waveband (nm)	PFD ($\mu mol \cdot m^{-2} \cdot s^{-1}$)
300-399	0.7 *(0.36%)*
400-499	35.1 *(17.9%)*
500-599	77.9 *(39.6%)*
600-699	70.4 *(35.8%)*
700-799	11.2 *(5.70%)*
800-900	1.3 *(0.66%)*
300-900	196.6 *(100%)*
400-700	183.6 *(93.4%)*

Measurements performed according to IESNA LM-79-08: *Approved Method for Electrical and Photometric Measurements of Solid-State Lighting Products.*

Normalized photon flux density:



PAR intensity (at 2 ft mounting height):



5. Conclusions

The major barrier to the wide adoption of LED lighting in horticulture is cost. For the production of most food crops, the profit margins are extremely thin and obtaining capital for expensive systems is very difficult for many owners of small and farmers medium–sized farms. Most urban farms for food production are profitable only when customers are willing to pay a premium for very fresh, high quality produce. Thus, the focus of many early adopters has been on high–value products, such as medicinal herbs. The World Health Organization has estimated that over 21,000 different plants are used in medicine, so optimizing the spectrum for each species is clearly a substantial challenge.

Reductions in the purchase cost of LED lighting systems will clearly come as the market volume grows and the technology improves, but this must not come through the sale of inferior products. On the contrary, the offering of longer warranties from the development of more reliable sources will be a major contribution to helping customers recover their investment.

The ease with which the intensity and spectrum of LED light can be controlled is a clear advantage of LED lighting. The lights can be programmed to dim during the daily rest periods or extra green light can be added to allow workers to enter with minimal impact on the growing cycle. The spectral balance can be adjusted during the growth phase or when the plant variety is changed. However, more research is needed to determine the optimal spectrum for each species, so that the added cost of these more complex systems can be recovered more quickly. Thus, this is an exciting field both for researchers as well as commercial suppliers and growers.

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