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Understanding LED Wavelength for Horticulture

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LED EVENT 2018

Ontwerp, toepassingen en techniek

CONGRESCENTRUM 1931
'S HERTOGENBOSCH

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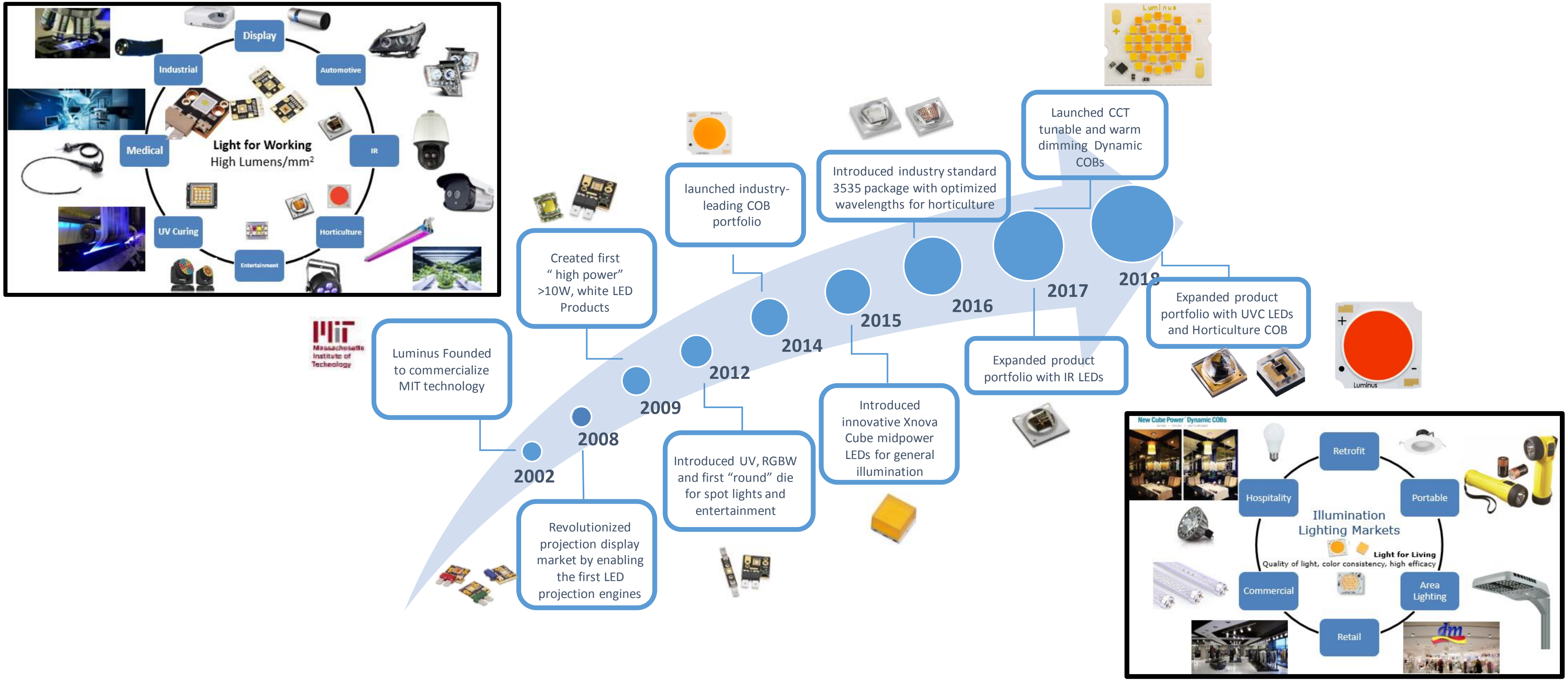
Luminus History and Milestones



Why Horticulture Lighting?

Growing Population

- Almost 10 billion people by 2050
- 60% increase in food production needed
- 46 Mega-Cities with >10m people in 2016

Scarce Natural Resources

- 80% of arable land already exploited
- 40% of the food in the US is never eaten
- 10% of our rainforests left by 2030

Change in customer demand

- Increase in urbanization
- New requirements for:
  - Fresh food
  - Organic agriculture
  - Local production

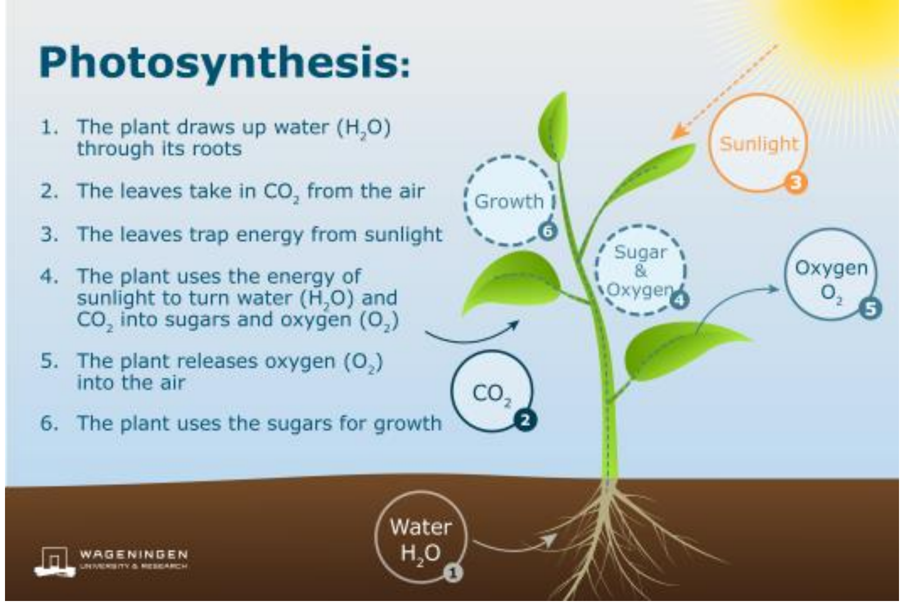
We need more food, closer to urban population, produced in an efficient way while respecting the environment and the need for healthier, better produce.

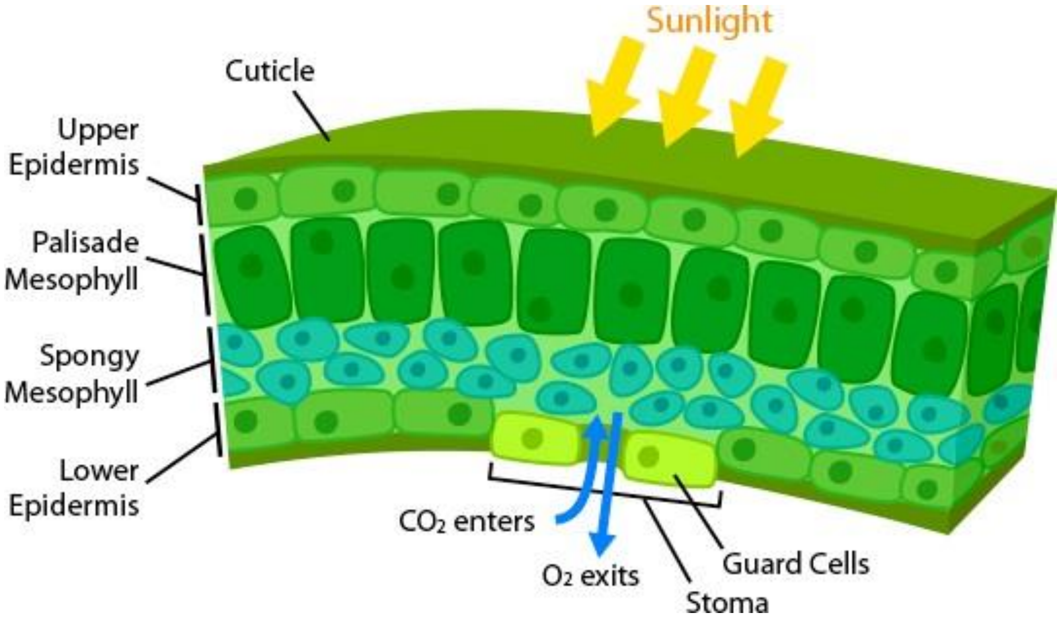
Why Horticulture Lighting?

$$6CO_2 + 6H_2O \xrightarrow{\text{with sunlight}} C_6H_{12}O_6 + 6O_2$$

Carbon dioxide, water, organic matter, oxygen

- Horticulture Lighting - Photosynthesis process

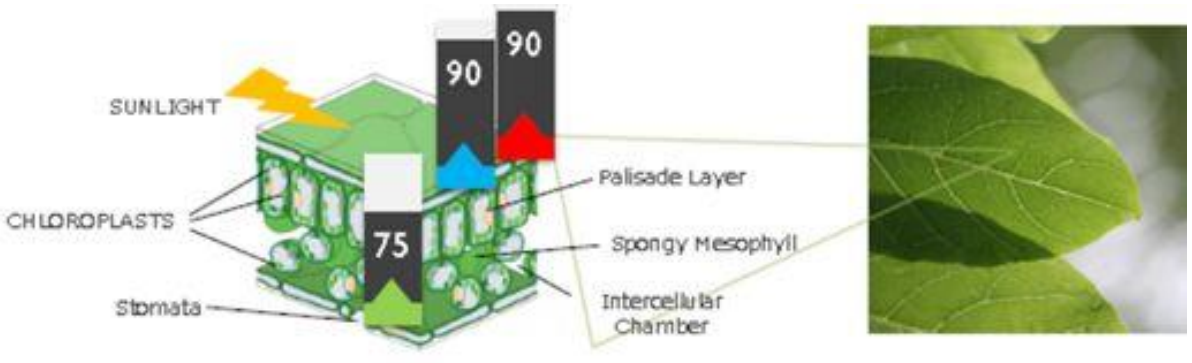




- Plants produce organic matter from air, water and light through photosynthesis
- Gas and water exchange take place through tiny holes in the plant leaves called stomata
- Photosynthesis takes place in mesophyll area inside the leaves
- Mesophyll cells contain chloroplast where the photosynthesis occurs
- Chlorophyll pigments in the chloroplast are responsible for the light absorption

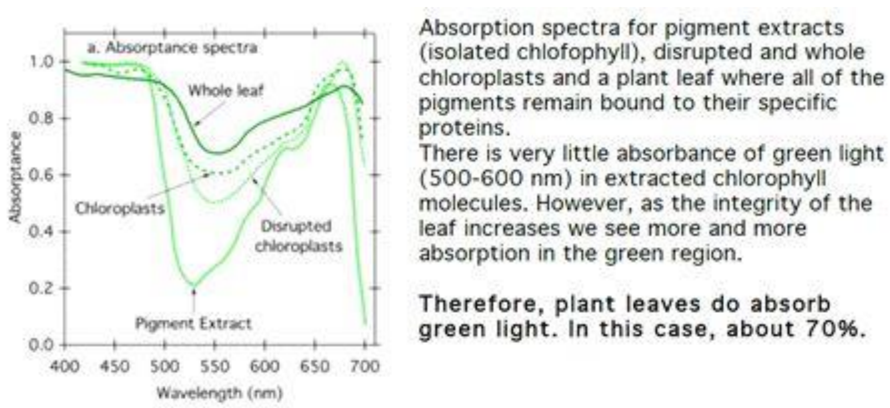
Where does photosynthesis take place?

- Light absorption of leaves



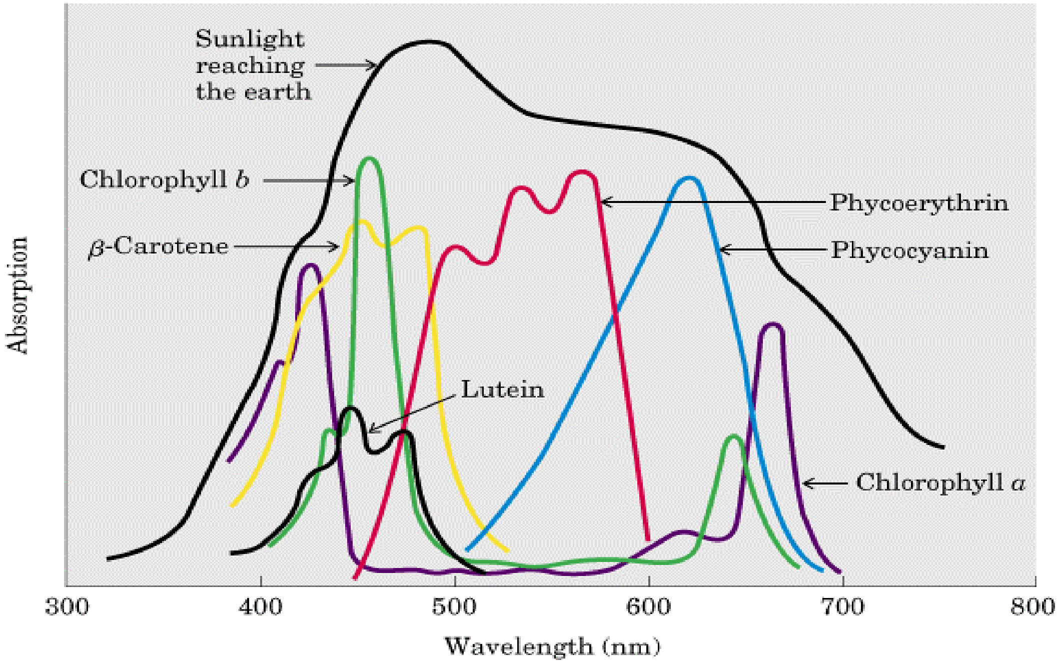
- Structure of a leaf:
  - Blue and Red wavelengths are absorbed in the vicinity of the surface
  - About 70% of the Green light is absorbed by the leaves but it reaches deeper regions
  - Green light scatters at inner region and is absorbed by chloroplast
  - IR light is reflected by the plant

All visible wavelengths are (partially) absorbed by the leaves



Plant Photo-pigments

- Hundreds of known photo-pigments covering UV to NIR
- Over 100 plant genes and 26 biochemical pathways are regulated by light
- Many functions still unknown
- Basis of “light recipes” development
- Trial-and-error approach



Photopigment Class	Functions (Non-inclusive)
Chlorophylls	Photosynthesis
Phytochromes	Photomorphology
Cryptochromes	Circadian / circannual rhythms
Carotenes	Photosynthesis
Xanthophylls	Light energy modulation / photosynthesis
Anthocyanins	Nutrient recovery / pollination attractant
Phototropin	Phototropism
UVR8	Ultraviolet protection

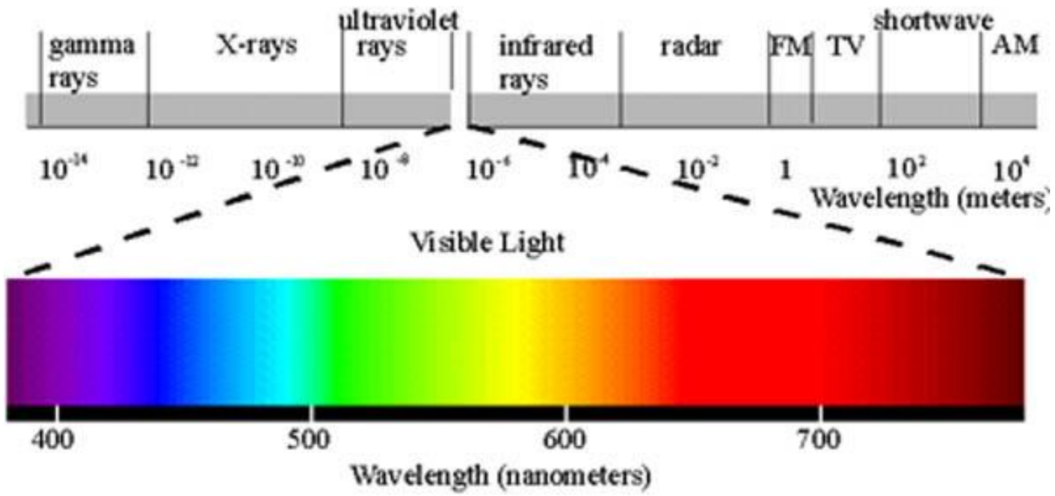
Is there an ideal light recipe?

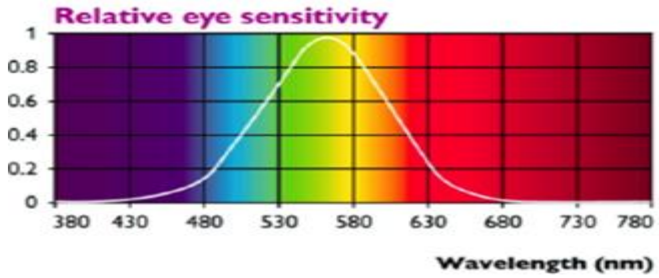
- Likely, no. Why?

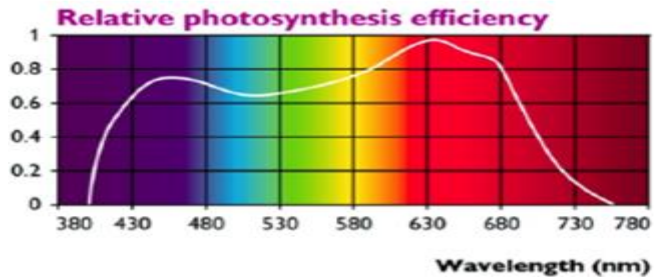
- Plant biodiversity:
    - 391,000 species of vascular plants currently known to science, of which about 369,000 species (or 94 percent) are flowering plants
- For comparison:
    - Insects: 1,000,000
    - Fish: 33,000
    - Birds: 10,000
    - Mammals: 6,495
- But, only 7,000 species of plants have been cultivated for consumption in human history
- Presently, only about 30 crops provide 95% of human food energy needs, four of which (rice, wheat, maize and potato) are responsible for more than 60% of our energy intake

Horticulture Metrics: background Information

- Plants are sensitive to a similar portion of the spectrum as is the human eye. This portion of the light spectrum is referred to as photosynthetically active radiation or PAR, namely about 400 to 700 nanometers in wavelength. Nevertheless, plant response within this region is very different from that of humans.
- The human eye has a peak sensitivity in the yellow-green region, at 555 nanometers. Plants, on the other hand, respond more effectively to red light and to blue light. The graphs below show the human eye response curve and the plant response curve.



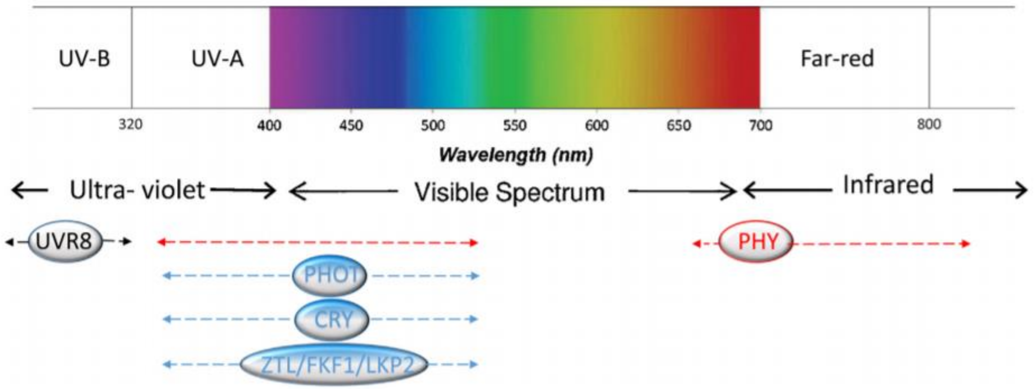


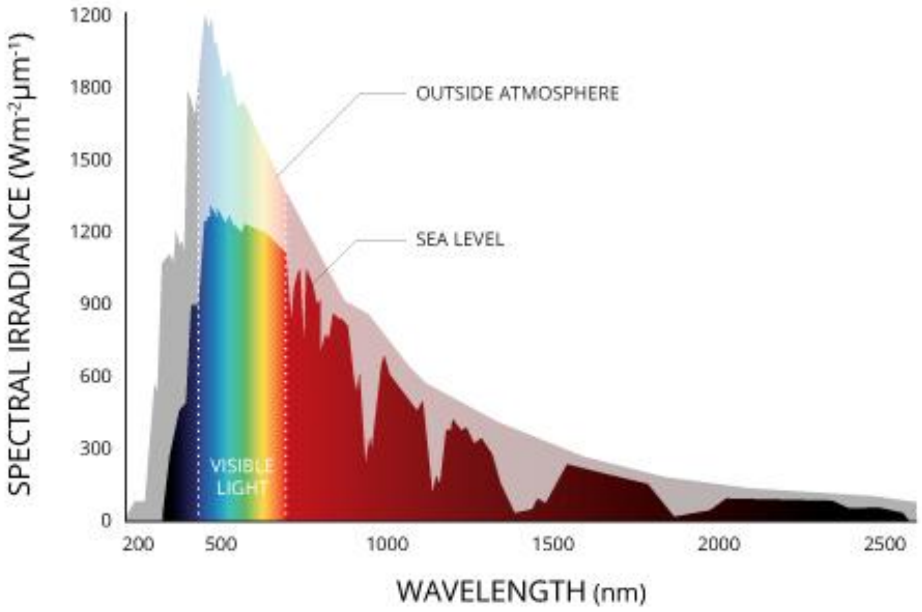


- Lumen output is not the correct metric to compare LEDs for horticulture applications

PAR definition and limitations

- PAR (Photosynthetically Active Radiation) is defined between 400nm to 700nm
- Sunlight radiation covers wavelengths from 280nm (UV-B) to 2500nm (Infrared)
- Wavelengths outside the PAR are also useful for plants
- Some plant photoreceptors have absorption outside of PAR. In particular:
  - UV-A (315nm to 400nm) and UV-B (280nm to 315nm):
    - These wavelengths have an effect on at least 4 known plant photoreceptors – see right figure below
    - They affect flowering time, plant shape and color, nutritional value,
    - UV-B increases plant resistance to insects and microbial pathogens
  - Far Red (720nm to 740nm):
    - In the phytochrome absorption range
    - Used as a “goodnight kiss” to signal the plants to go to sleep





Important Horticulture metrics

- Photosynthetic Photon Flux or PPF measures the "photosynthetically active photons emitted by a lighting system per second". This measurement is expressed in µmol/s. This is the "equivalent" of lumens for plants.

- Photon Efficacy or PPF/W refers to how efficient a horticulture lighting system is at converting electrical energy into photons. This measurement is expressed in µmol/J.

- Photosynthetic Photon Flux Density or PPFD is a measurement of the number of photosynthetically active photons that fall on a given surface each second. It is expressed in µmol/m^2/s.

- Day Light Integral or DLI is a cumulative measurement of the total number of photons that reach a given surface during the daily photoperiod. DLI is expressed in mol/m^2/d
  - Rule of thumb: 1% increase in DLI translates in 1% increase in plant growth yield

Photon Flux vs Wavelength

$$\Phi_p = \Phi_e \left(\frac{\lambda}{hcN_A}\right) 10^6$$

Φ_p: Photon Flux (µmol/s)

Φ_e: Radiant Flux (W)

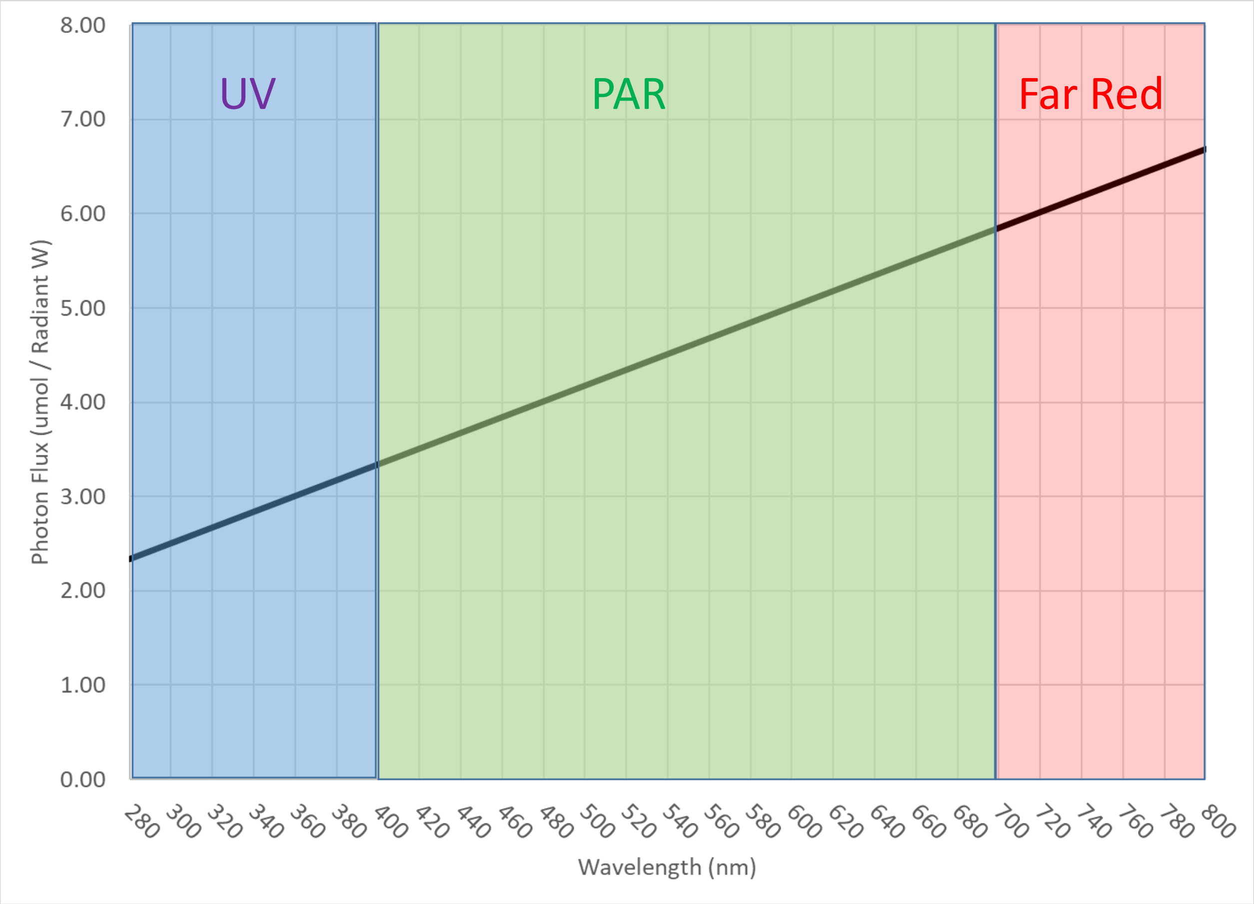
λ: Wavelength (m)

h: Planck's Constant ($6.626\text{x}10^{-34}$ m^2kg/s)

c: Speed of Light ($3.0\text{x}10^{-8}$ m/s)

N_A: Avogadro's Number ($6.022\text{x}10^{23}$)

$$\Phi_p = \Phi_e * 8.359 * 10^6 \lambda$$



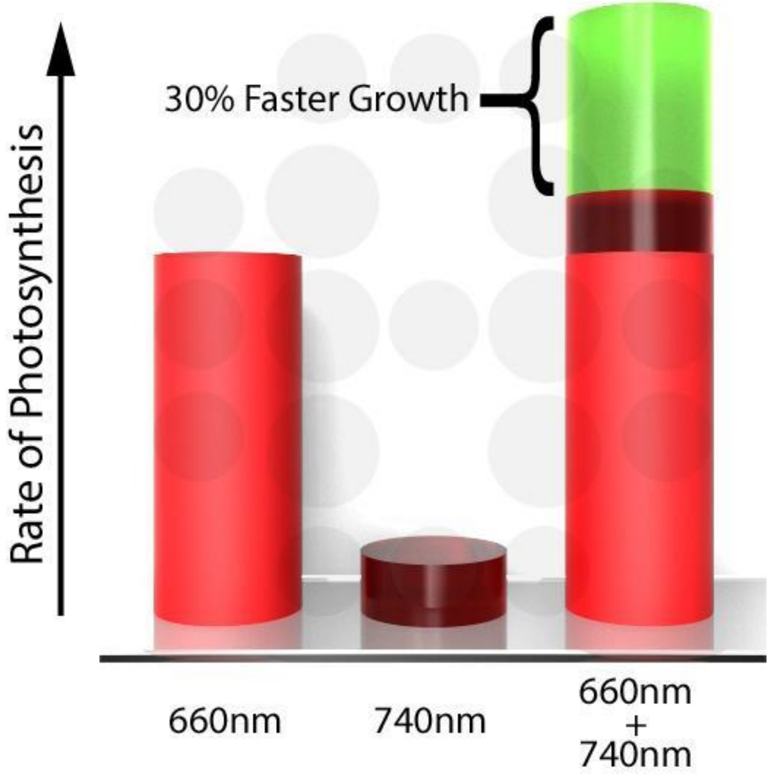
For the same radiant flux, Deep Reed and Far Red LEDs
offer much higher PPFs than Blue LEDs

Emerson Effect

- See graph on the right

a) shows the rate of photosynthesis after exposition to light of λ = 660 nm and λ = 740 nm, respectively.

b) when simultaneously exposed to both wavelengths, the rate of photosynthesis increased by 30%.



→ The addition of Far Red and Deep Red equals a greater rate of photosynthesis than the sum of the individual parts.

Why Use LEDs in Horticulture Lighting?

Power Consumption	Tunability / Light Control	Heat Management	Reliability / Maintenance
• Reduction of up to 70% compared to traditional light sources • LEDs come in different package sizes and power requirements that allow flexibility at the fixture level	• Spectral distribution can be controlled allowing broad range of spectrum composition from UV to Far Red • Multi-channel driver solutions allow fully tunable fixtures • Instant turn on/off and dimming capability	• Much lower fixture temperature allows new lighting configuration (inter-leaving lighting) and reduced distance between luminaires and plants • Stable temperature in growth chambers and greenhouses throughout the day	• Increased lifetime, reliability and compactness compared to traditional lighting solutions • Less maintenance (lamp change)

Other traditional lighting technologies

Light bulb

Flowering time control

Short lifetime

Low efficacy

Fluorescent tube

Closed indoor lighting

Efficacy

Undesirable emission

Metal Halide lamp

Hybrid with sunlight

No phosphor option

Heat

HPS lamp

Hybrid with sunlight

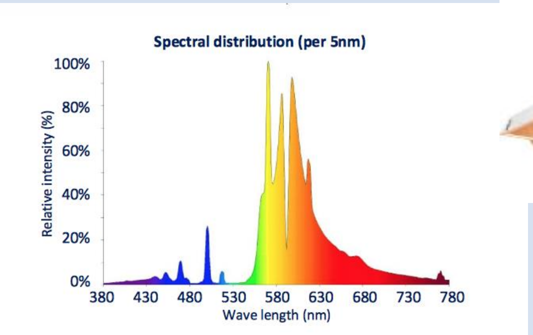
No phosphor option

Heat

Low Power ⟷ High Power

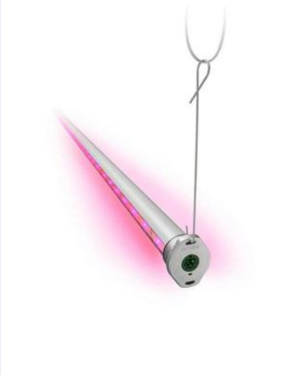
HPS vs LED fixtures

HPS lamp



- Developed for street lighting
- Spectrum covers PAR area, but the photon distribution is not adapted for plants
- 1000W is the standard and economic ($30 to >$100)
- 1700+ umol/s / **1.7 µmol/J**
- Warm white and cool white CCT
- 8,000 to 16,000 hours life expectancy but lamps are generally **changed every 5,000 to 10,000 hours**
- Excess heat dissipation, emits heat towards the plant making the temperature control very difficult
- The HPS spectrum is very poor in blue
- In a HPS spectrum green has the highest portion

LED



- Various power consumption (<100W) to 600+W
- Large price range - going down quickly
- Customizable spectrums
- **Up to 3.0 µmol/J** (fixture level)
- **>25,000 hours**
- Very little heat dissipation
- Wide spectrum covering wavelength from 380 – 780nm
- Has a high portion of blue light and can include some UVA

HPS vs LED fixtures (example cannabis)

HPS lamp	LED (Valoya NS1)
	
• Photon distribution > 600 nm lead to a low red to far-red ratio, supporting Shade Avoidance Syndrome responses. • General observed plant responses under HPS: stretched plants with elongated hypocotyls and internodes, lodging, reduced phenol expression, soft leave tissue. • Spectrum appears yellowish.	• General observed plant response under: compact growth (outdoor phenotype), no etiolation, promotion of phenol biosynthesis. • Plants have higher biomass, larger leaf area and higher number of leaves. • Plants under LED spectra were more compact and accumulated more dry weight.

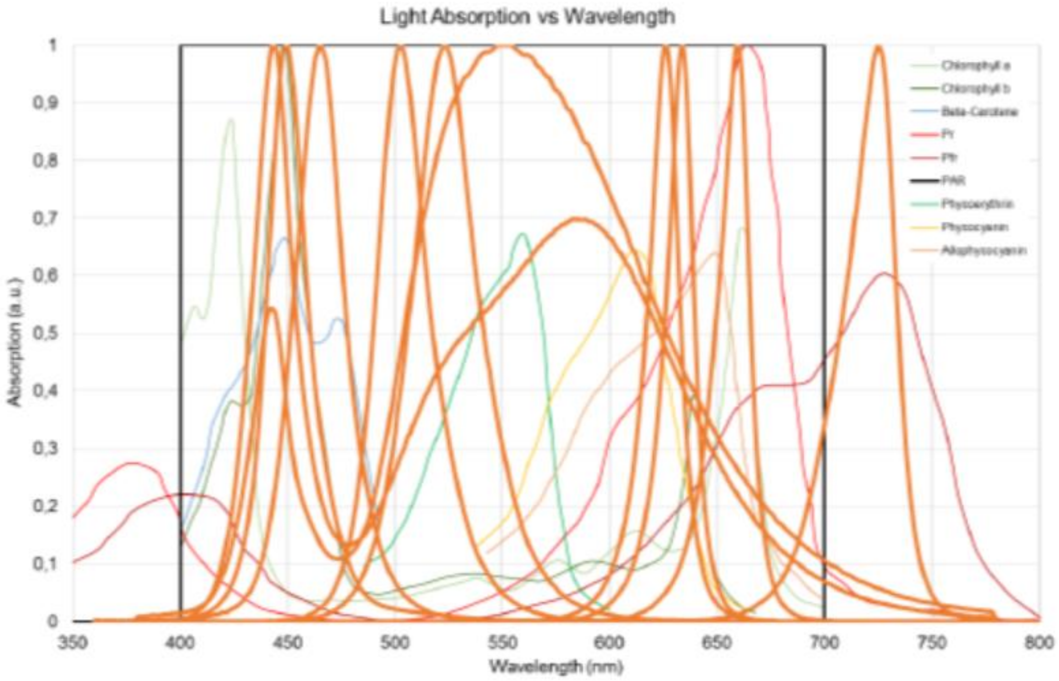
Source: Valoya Oy

What do LEDs offer in horticulture market?

- **Efficacy:**
  - Efficacy can be twice as good as with HPS lamps (>3.0 μmol/J)

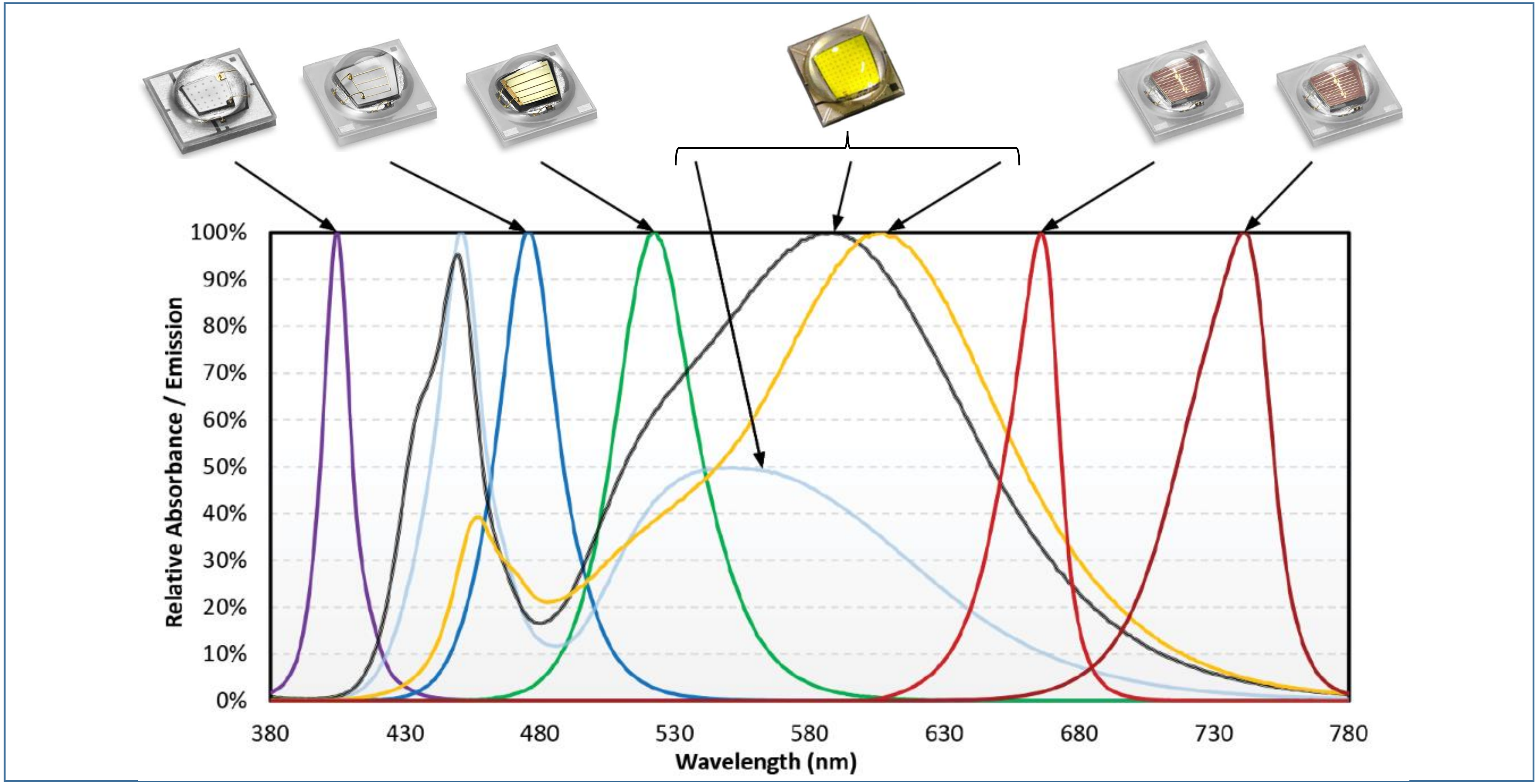
- **Reliability:**
  - Fixture-level reliability is limited by driver and other components.

- **Flexibility:**
  - Large range of visible spectrums can be covered.



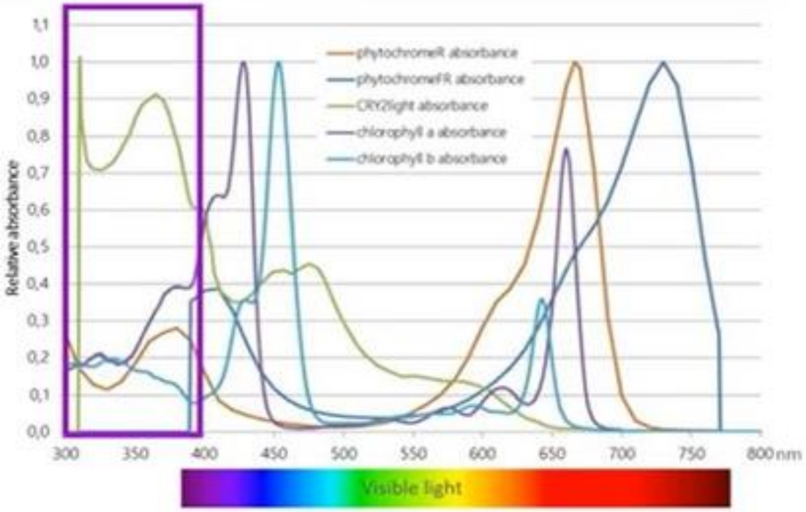
Source: Osram

Wavelengths of interest



Spectrum causing photoresponses

Source: Valoya Oy



UV Wavelenghts

UVA 315-400nm
UVB 280-315nm
UVC100-280

Mainly Absorbed by:

- UVR8
- Chryptochromes
- Phototropins

Plant responses:

- Reduced grow
- Degradation of DNA
- Reduced pollen fertility
- Thickening of leaves

Blue Wavelenghts

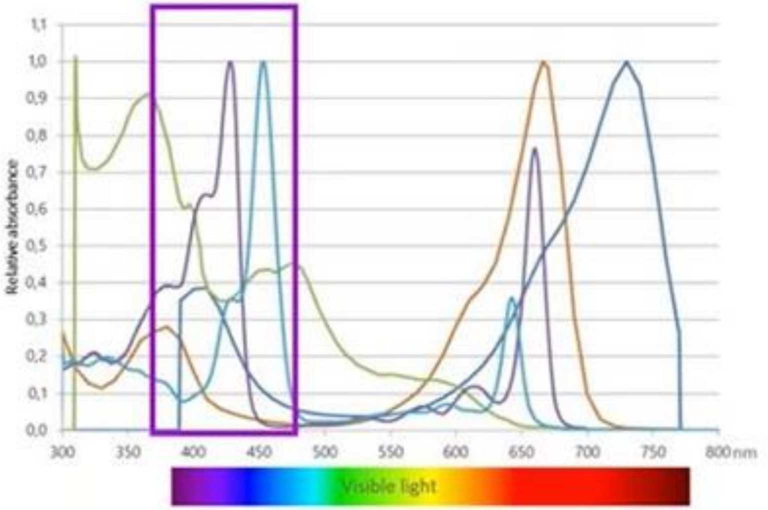
420-490nm (400-500nm)

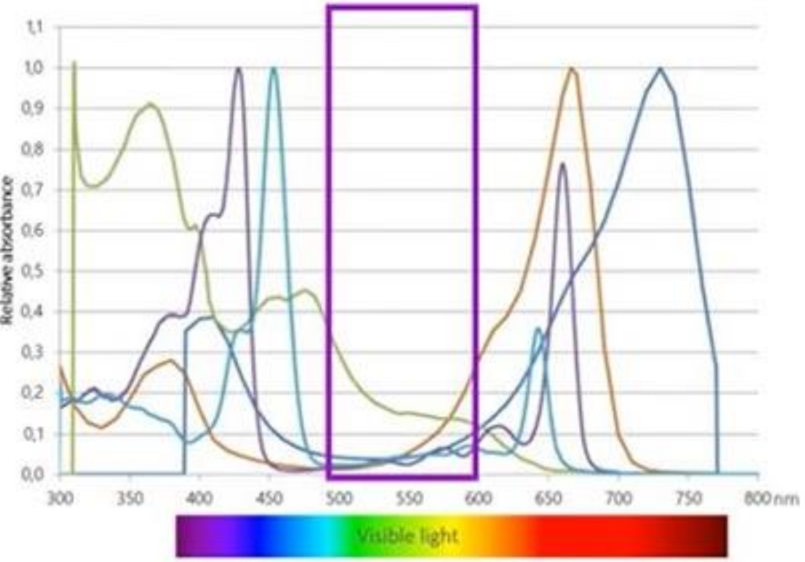
Mainly Absorbed by:

- UVR8
- Chryptochromes
- Phototropins

Plant responses:

- Leaf expansion
- Stomata opening
- Chloroplast movement
- Induce Photochemical responses





Green Wavelenghts

500-570nm (500-600nm)
UVB 280-315nm
UVC100-280

Plant responses:

- Root elongation
- Reduction of seeding biomass
- Intensifies **SAS**

SAS: Shade Avoidance Syndrome.
Symptoms are stretched hypocotyl (etiolation*), Longer internodes, Premature flowering, Narrow leaf shape resulting in smaller leaf area.

Red Wavelenghts

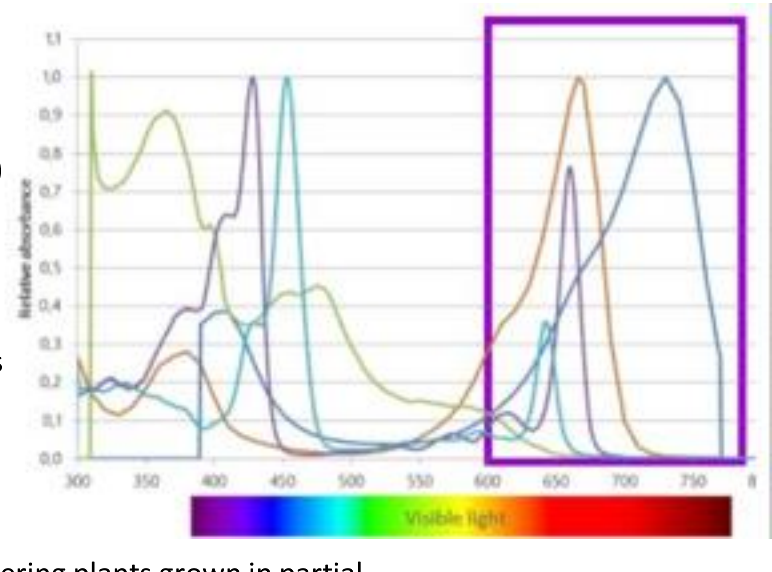
Red 620-680nm (600-700nm)
Far Red 700-750nm (700-800)
UVC100-280

Mainly Absorbed by:

- Phytochromes (Pfr and Pr)

Plant responses:

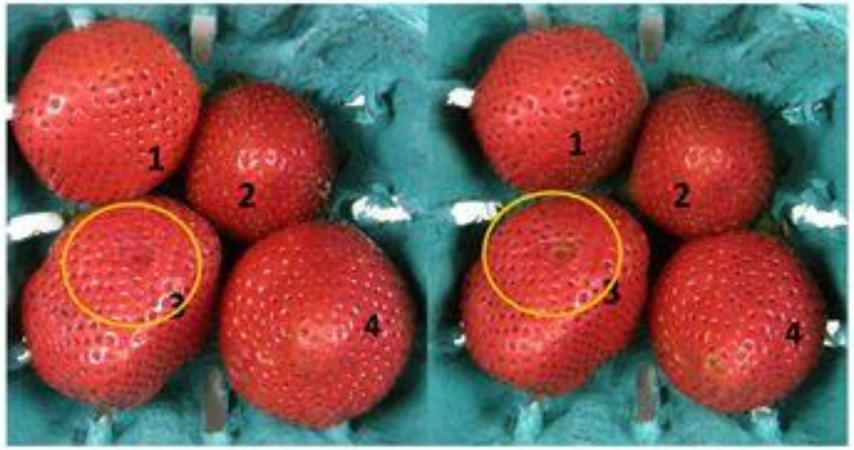
- mediated by phytochromes base on the spectrums red to far-red ratio
- Lower red to far-red ratios lead to **SAS**



*Etiolation is a process in flowering plants grown in partial or complete absence of light. It is characterized by long, weak stems, smaller leaves and a pale yellow color.

Use of UV-B (280nm) for shelf life extension

Dark Control: before test (left) and at end of test (right)



Illuminated with UVB: before test (left) and at end of test (right)

Source: "Deep Ultraviolet (DUV) Light-Emitting Diodes (LEDs) to Maintain Freshness and Phytochemical Composition During Postharvest Storage"

Read more at: https://phys.org/news/2013-06-day-fresh-strawberry-approach-berry.html#jCp

Use of UV-B (280nm) to change the color of lettuce

PAR | PAR+UVA | PAR+UVA/UVB

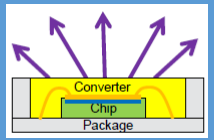
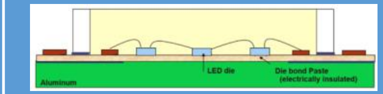
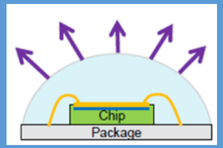
Figure 9. Red lettuce 'Lollo Rosso' after 7 days under the UV treatments.

Source: "The Effects of UV Radiation on the Content of Phenolic acid and Flavonoid, Stomatal Conductance and Taste in Red Lettuce 'Lollo Rosso", Dinalva Almeida De Oliveira, Master's Thesis - 2016

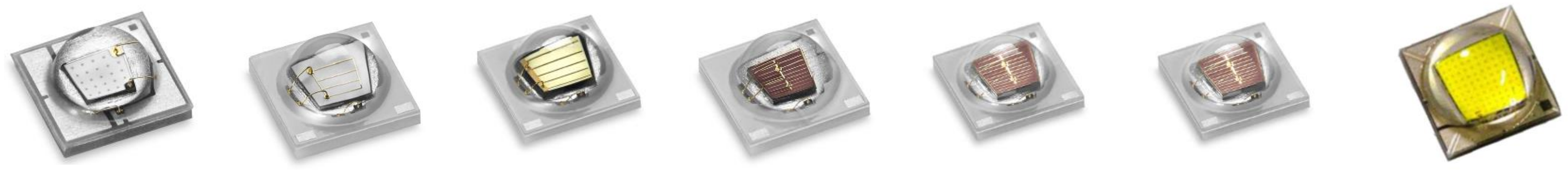
Visible Range

Wavelength (nm)	Effect on Plant Growth	State-of-the-art WPE (%)
280	Significantly reduces quantum yield rate of photosynthesis. UVR8 photoreceptor pathway. Use to increase THC potency in Cannabis	3-4%
315-400	Promotes pigmentation, thickens plant leaves. Some research indicates that it might be harmful to insects	50-60%
440-470	Chlorophyll absorption peaks at 439 and 469 nm. The blue spectrum is the most efficiently absorbed spectrum, promoting mainly vegetative growth.	>70%
510	Quantum absorption in the green spectrum. Little absorption in the yellow spectrum	25%
610	No chlorophyll benefit, but efficiently absorbed by phycocyanin receptors which initiate light signaling mechanisms for photoperiodism (onset of flowering)	45%
640-660	Chlorophyll absorption peaks at 642 and 667 nm. Speeds up germination and flower/bud onset. 660nm is the most vital wavelength for flowering.	>60%
690	Some research papers seem to indicate plant benefit at this wavelength – unclear.	40%
720-740	Emerson Enhancement Effect—quantum yield of red light and far red light, when shone simultaneously on a plant, increases the rate of photosynthesis.	47%
1000-1400	No plant activity detected in this wavelength range. Heat generated.	-

Main types of LEDs used in horticulture fixtures

	MP (Mid-Power) LEDs 	COB (Chip-On-Board) 	SMT (Surface Mount) LEDs 
Chip technology	Lateral die	Lateral die	Vertical die
Die size	2214 or smaller (0.2-0.5mm^2)	2235 (0.5mm^2)	Typically 42 mil (1mm^2)
Package Size (mm x mm)	2835 / 3030 / 5630	From 6mm to 32mm LES	Typically 3535
Emission type	Almost exclusivity phosphor converted	Almost exclusively phosphor converted	Direct and Phosphor-converted
PPF (μmol/s)	0.5-2	10-400	2-3 for 1mm^2 Up to 5 for 2mm^2 @ 660nm
Max PPF/W (μmol/J) at nominal drive current	2.7-2.9 @ 65mA for 3030	~1.8-2.0	3.0-3.5 for 1mm^2 & 5+ for 2mm^2 @ 660nm
Typ. PPF/$	40	~10	10-20

Performance metrics for 3535 LEDs



Device	Lens option	Test Current (mA)	Max rated current (A)	Forward Voltage (Vf)	Peak λ (nm)	Typ. lm at test	Typ. mW at test *	lm/W or WPE (%)	PPF (µmol/s)	PPF/W (µmol/J)
SST-10-Blue	90°/ 130°	350	1.5	3.00	450	20	630	60%	2.38	2.27
SST-20-Blue	130°	350	3	2.80	450	23	710	72%	2.68	2.73
SST-10-Green	90°/ 130°	350	1.5	3.10	530	148	270	136	1.21	1.12
SST-10-Red	90°/ 130°	350	1.5	2.10	630	71	320	97	1.67	2.27
SST-10-Deep Red	90°/ 130°	350	1.5	2.15	660	27	410	54%	2.24	2.98
SST-20-Deep Red	120°	350	3	2.00	660	27	410	59%	2.24	3.20
SST-10-Far Red **	90°/ 130°	350	1.5	2.10	730	-	320	44%	1.94	2.64
SST-10-Far Red Next Gen **	90°/ 130°	350	1.5	2.15	730	-	350	47%	2.13	2.84
SST-20-W27H	120°	350	3	2.80	-	89	340	35%	1.72	1.76
SST-20-W30H	120°	350	3	2.80	-	101	375	38%	1.88	1.92
SST-20-W35H	120°	350	3	2.80	-	112	405	41%	2.00	2.04
SST-20-W40H	120°	350	3	2.80	-	114	417	43%	2.03	2.07
SST-20-WCS	120°	350	3	2.80	-	184	600	61%	2.68	2.73
SST-10-UV-365	130°	500	1	3.60	365	-	875	49%	-	-
SST-10-UV-385	130°	500	1	3.40	385	-	1015	60%	-	-
SST-10-UV-395	130°	500	1	3.40	395	-	1015	60%	-	-
SST-10-UV-405	130°	500	1	3.40	405	-	930	55%	-	-

Performance based on datasheet test waveform – single pulse, 25oC
Photosynthetic Photon Flux (PPF) computed in the 400nm to 700nm range
* 130-degree lens for SST-10 products
** PPF computed in the 360nm to 830nm range
Note: 2018 Q2 data. For updated figures please contact Luminus Devices Inc.

Blue (450nm), Deep Red (660nm) and Far Red (730nm) are the most efficient direct-emission LEDs for horticulture

Performance metrics for MP & COB LEDs

Device	Lens option	Test Current (mA)	Max rated current (A)	Forward Voltage (Vf)	Peak λ (nm)	Typ. lm at test	Typ. mW at test *	lm/W or WPE (%)	PPF (μmol/s)	PPF/W (μmol/J)
MP-3030-1100-57-70	No lens	150	0.24	3.00		75	238	167	1.06	2.36
MP-3030-1100-56-95	No lens	150	0.24	3.00		60	219	133	1.03	2.29
MP-3030-2100-57-95	No lens	150	0.24	6.00		122	446	136	2.09	2.32
MP-3030-2100-22-90	No lens	150	0.24	6.00		114	435	127	2.24	2.49
MP-3030-2100-65-80	No lens	150	0.24	6.00		140	442	156	2.00	2.22
MP-1616-1103-18-90	No lens	150	0.2	3.00		38	166	84	0.88	1.96
MP-3030-12Z-35-80	No lens	65	0.4	2.69		35	106	200	0.491	2.81
MP-3030-110H-35-80	No lens	65	0.2	2.80		34	103	187	0.477	2.62
MP-3030-210H-35-80	No lens	65	0.24	5.65		69	210	188	0.968	2.64

Mid-Power LEDs are used for their high-efficacy

Device	Lens option	Test Current (mA)	Max rated current (A)	Forward Voltage (Vf)	Peak λ (nm)	Typ. lm at test	Typ. mW at test *	lm/W or WPE (%)	PPF (μmol/s)	PPF/W (μmol/J)
CXM-14-HS-11-36-AC30-P1-7	No lens	720	1.23	34.00		1160	10314	42%	45	1.84
CXM-14-HS-12-36-AC30-P1-7	No lens	720	1.23	34.00		1100	9842	40%	43	1.76
CLM-22-HS-11-36-AC30-P1-7	No lens	1100	1.86	33.80		1861	16930	46%	73	1.96
CLM-22-HS-12-36-AC30-P1-7	No lens	1100	1.86	33.80		1749	15749	42%	68	1.83
CXM-22-HS-11-54-AC30-P1-7	No lens	1100	1.86	51.00		2680	24492	44%	105	1.87
CXM-22-HS-12-54-AC30-P1-7	No lens	1100	1.86	51.00		2518	22838	41%	98	1.75

Performance based on datasheet test waveform – single pulse, 25oC
Photosynthetic Photon Flux (PPF) computed in the 400nm to 700nm range
* 130-degree lens for SST-10 products
** PPF computed in the 360nm to 830nm range
Note: 2018 Q2 data. For updated figures please contact Luminus Devices Inc.

COBs are used for their high PPF values

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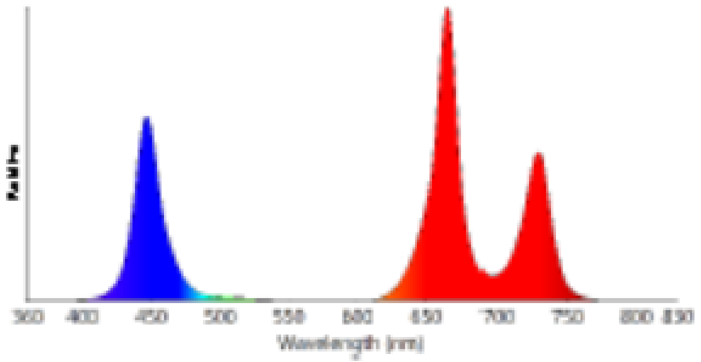
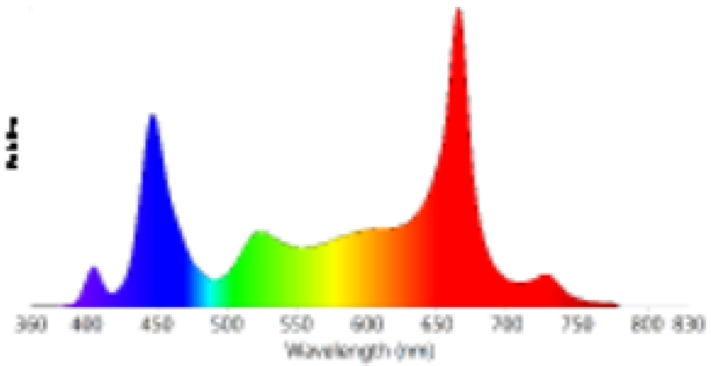
Various “universal” light recipes

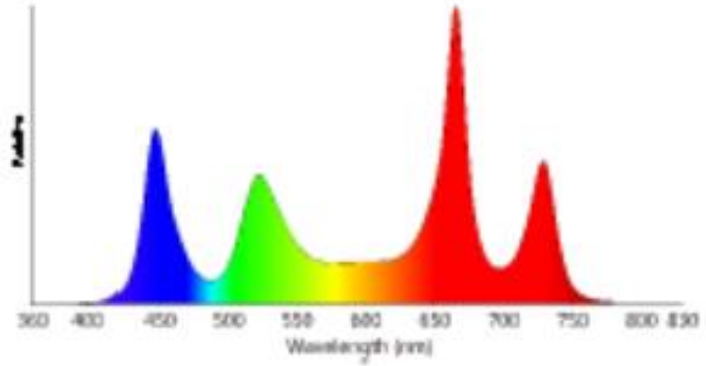


Young Plant

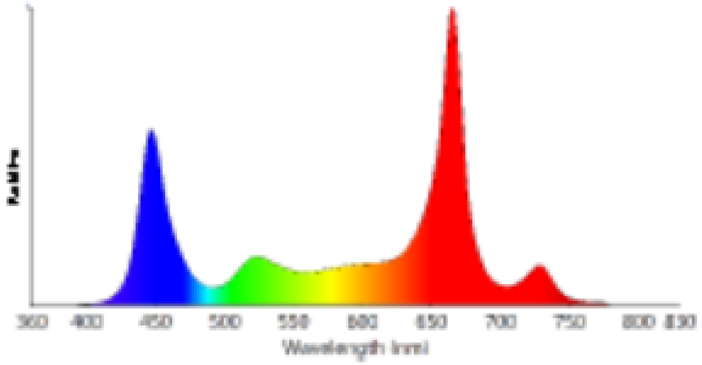


Fruit

Flower



Mature Plant



Which applications & drivers?


Vertical farming


Greenhouse


Multi-layer cultivation


Home farming

Horticulture applications


Inter-lighting


Stadium lawn maintenance


Space farming


Research farming

Indoor Farming

- Indoor farms are considered autonomous systems where energy, water, air, light are designed to optimize the growth and quality of the plant
- Light fixtures have to be optimized in conjunction of the design of the facility

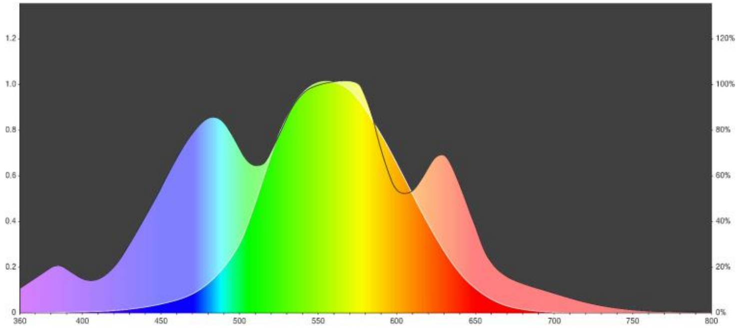
City farming

- City farming consists of growing crops in small interior areas, using multiple layers to maximize production.
- Conventional light solutions are not suitable for this application.
- LED technology provides the optimal light spectrum for indoor growth in a closed environment.

Beyond horticulture

Poultry farming

Insect traps



Photopic spectral response
of a person and a chicken

Fish farming

Conclusion

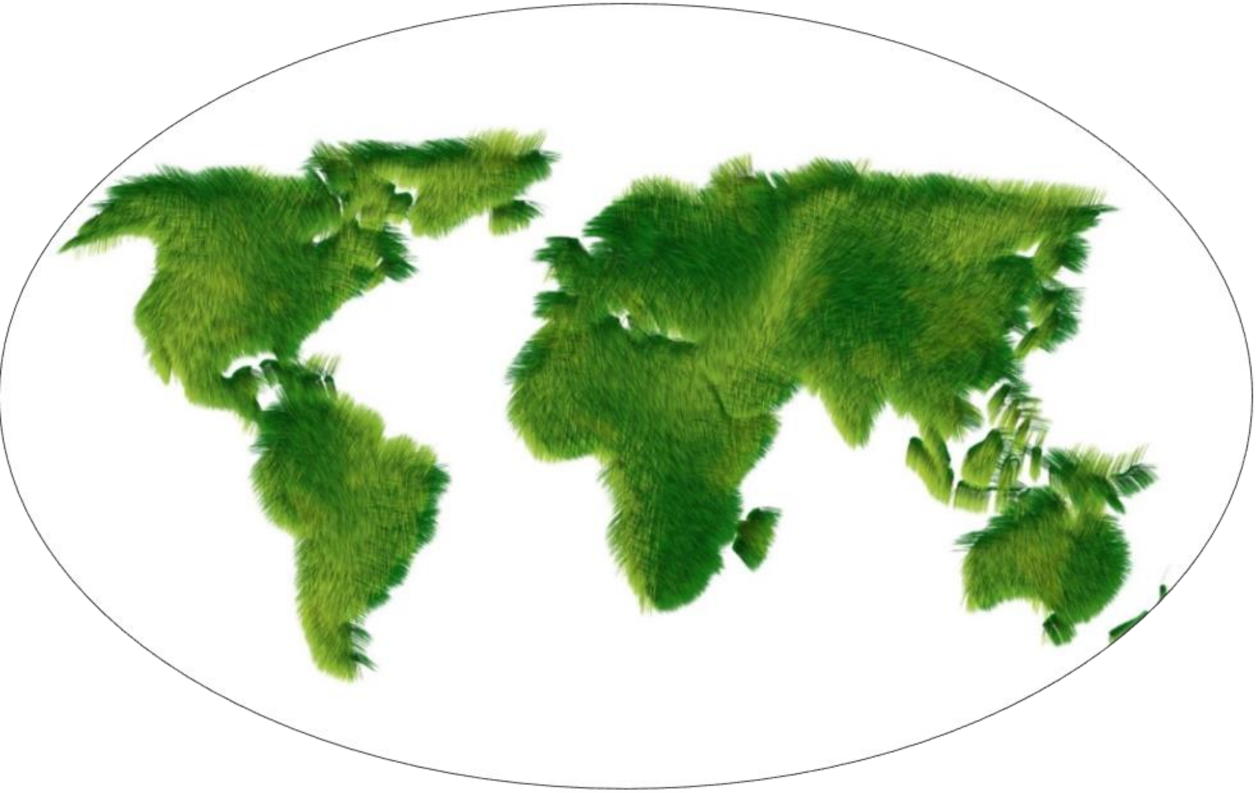
- LEDs are becoming more and more efficient – especially at the wavelengths of interest for the horticulture market (450nm, 660nm & 730nm)

- LED-based fixtures are being introduced with PPF/W values close to 3.0 μmol/J (for comparison the best HPS lamps are at 1.7 μmol/J)

- New packaging platforms need to be developed to take advantage of the current trends:
  - Increase ratio of emission area over package area
  - No? secondary optics

- Need to reduce cost even further to displace incumbent technologies

- Questions: Contact me at evanderzwart@luminus.com



Thank you!

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