Horticulture Lighting with LEDs

OS SSL | 02.03.15 | Regensburg

Light is OSRAM

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Horticulture Lighting
What is horticulture lighting and how is it used?

- **Supplemental Lighting**
  To supplement natural daylight and raise grow light levels in order to enhance photosynthesis and thereby improve growth and quality of plants in greenhouses.

- **Photoperiodic Lighting**
  To control the light period by extending the natural day length with artificial light.

- **Cultivation without daylight**
  To totally replace daylight with artificial light for ultimate climate control.

Horticulture Lighting
How does light affect the plant growth?

• Light quantity

The amount of light affects the photosynthesis process in the plant. This process is a photochemical reaction within the chloroplasts of the plant cells in which CO2 is converted into carbohydrate under the influence of the light energy.

• Light quality regarding spectral composition of the light

The spectral composition of the different wavelength regions (blue, green, yellow, red, far red or invisible e.g. UV or IR) is important for the grows, shape, development and flowering (photomorphogenesis) of the plant. For the photosynthesis, the blue and red regions are most important.

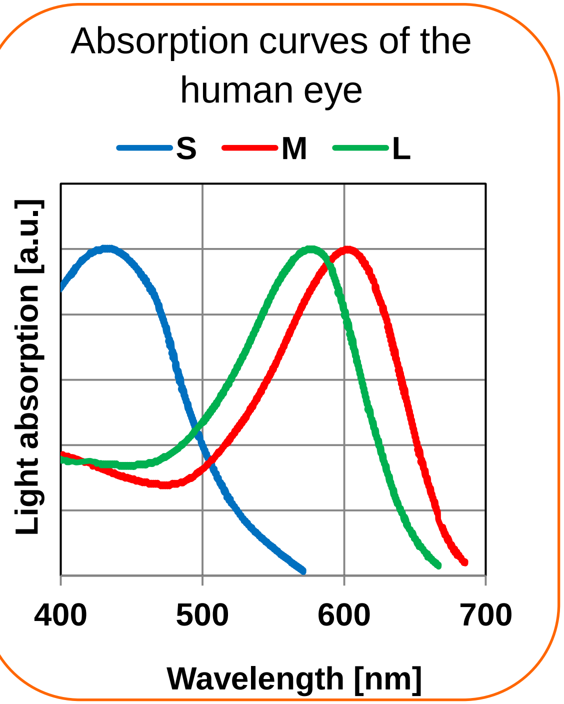
• Light duration

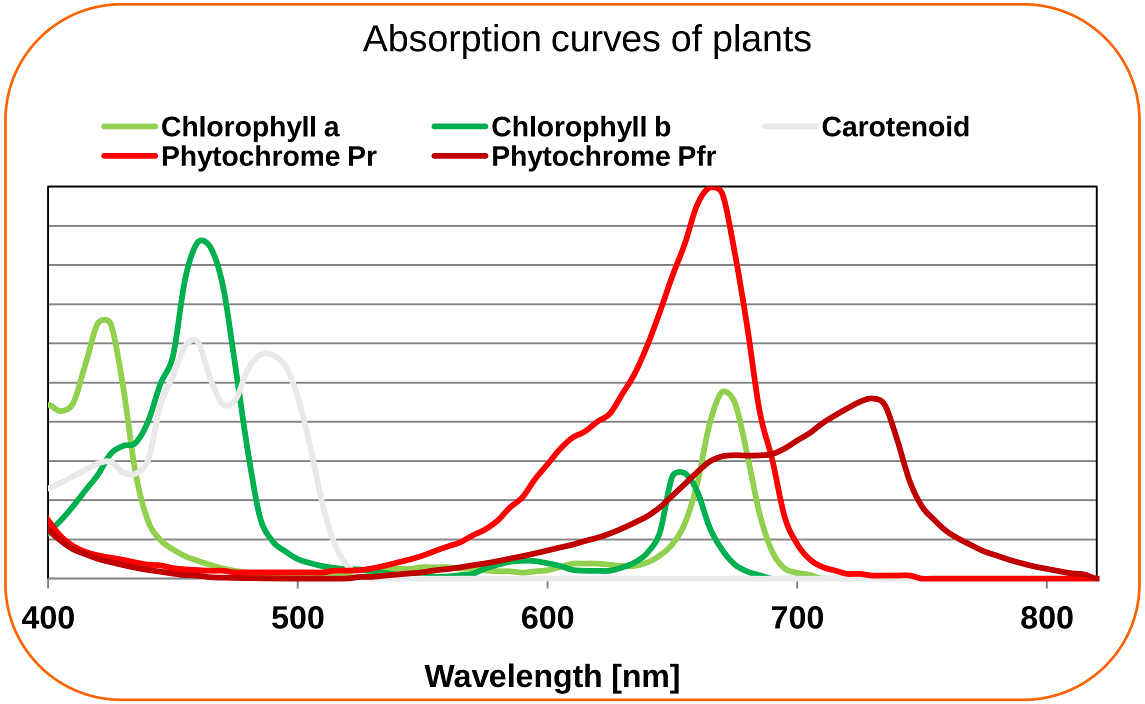
The timing / light duration which is also called photoperiod is mainly affecting the flowering of the plants. The flowering time can be influenced by controlling the photoperiod.

Source: [0];[18]

Difference in absorption curves for photochemical reactions between the human eye and plants

Light is generating a photochemical reaction. In our eye it is reacting with the photo receptor in different versions S, M and L. In plants, the light is reacting with Chlorophyll a and b.





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Effect of the different wavelength regions on plants

Different regions of the wavelength in the illumination spectrum have different effects on the plants:

Wavelength range [nm]	Photosyntesis	Further Effects	Further Effects	Further effects
200 – 280		Harmful		
280 – 315		Harmful		
315 – 380				
380 – 400	Yes			
400 – 520	Yes	Vegetative growth		
520 – 610	Some	Vegetative growth		
610 – 720	Yes	Vegetative growth	Flowering	Budding
720 – 1000		Germination	Leaf building and growth	Flowering
> 1000		Converted to heat		

Source: [0]

Photosynthetic efficiency is mainly driven by chlorophyll a and b

- **Chlorophyll a and b**

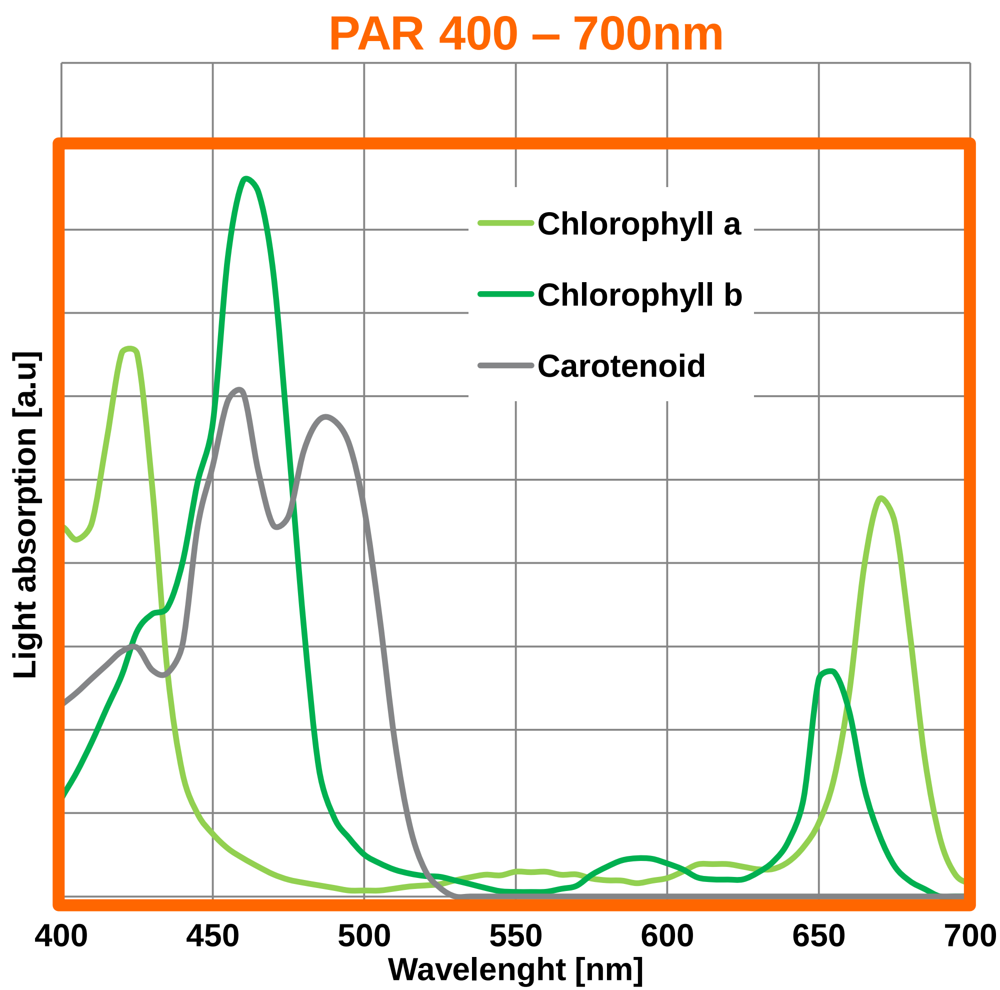
Mainly responsible for the photosynthesis and responsible for the definition of the area for the photosynthetically active radiation PAR.

- **Photosynthetically active radiation (PAR)**

Further photosynthetic pigments also known as antenna pigments like carotenoids □-carotene, zeaxanthin, lycopene and lutein etc.

- **Carotenoid**

Further photosynthetic pigments also known as antenna pigments like carotenoids β-carotene, zeaxanthin, lycopene and lutein etc.



Source: [18],[19]

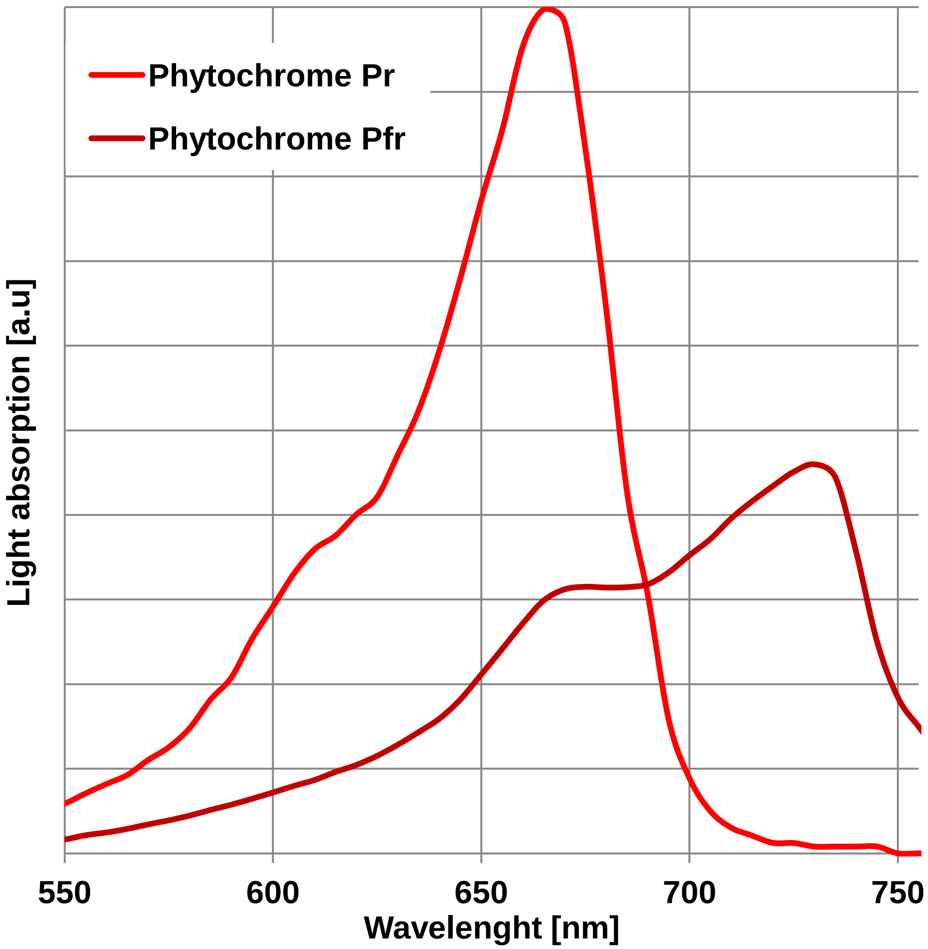
Photomorphogenic effects are mainly influenced by the phytochromes Pr and Pfr

- **Phytochrome Pr and Pfr**

The Phytochromes pr (red) and pfr (far red) are mainly influencing the germination, plant growth, leave building and flowering.

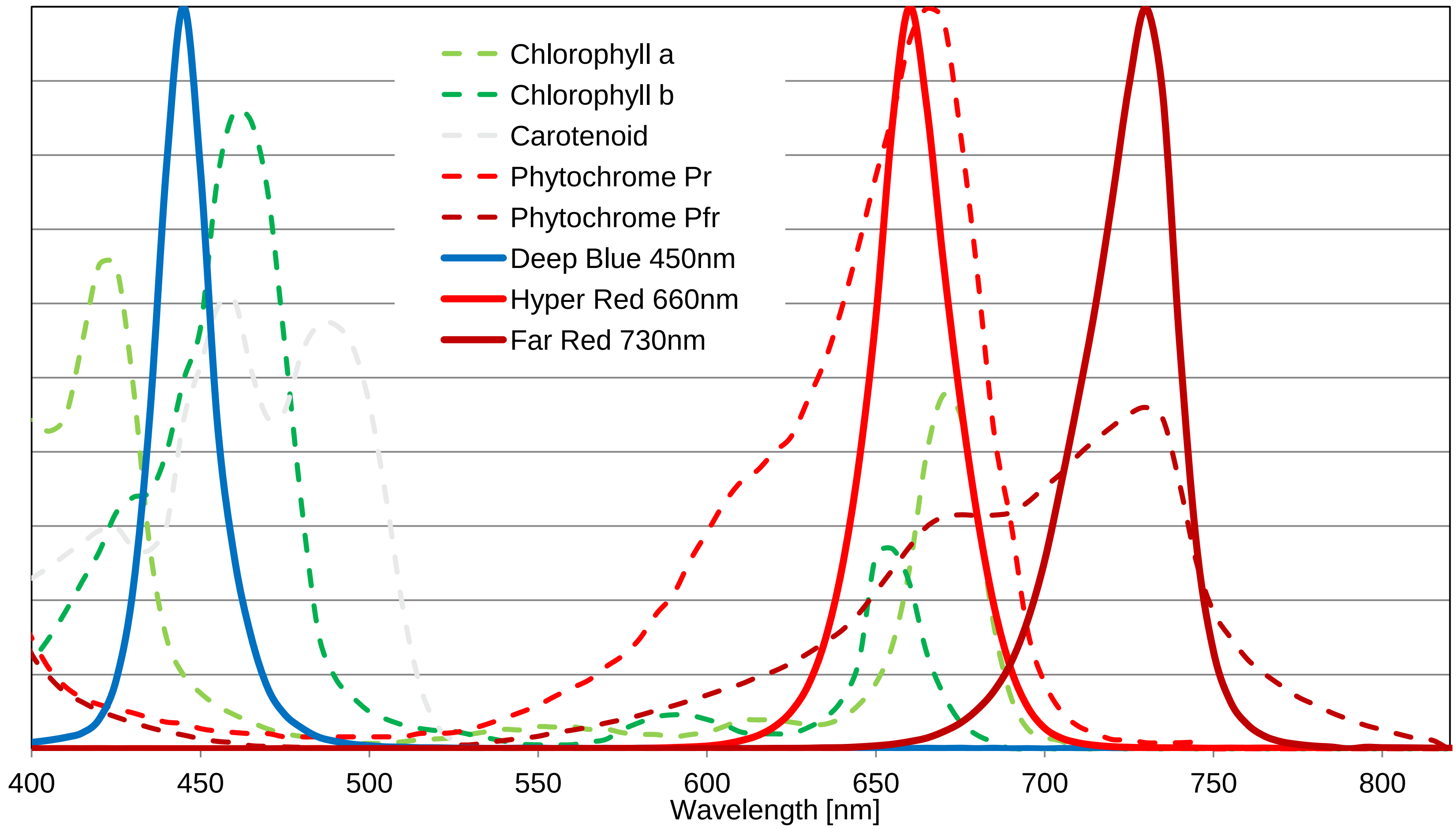
- **Phytomorphogenic effects**

The phytomorphogenic effects are controlled by applying a spectrum with a certain mix of 660nm and 730nm in order to stimulate the pr and pfr phytochromes.



Therefore we are focusing in horticulture lighting on the 450nm, 660nm and 730nm LEDs

All three important wavelength are available in the same LED package:



A typical application example for the use of 730nm: The shade escape reaction with

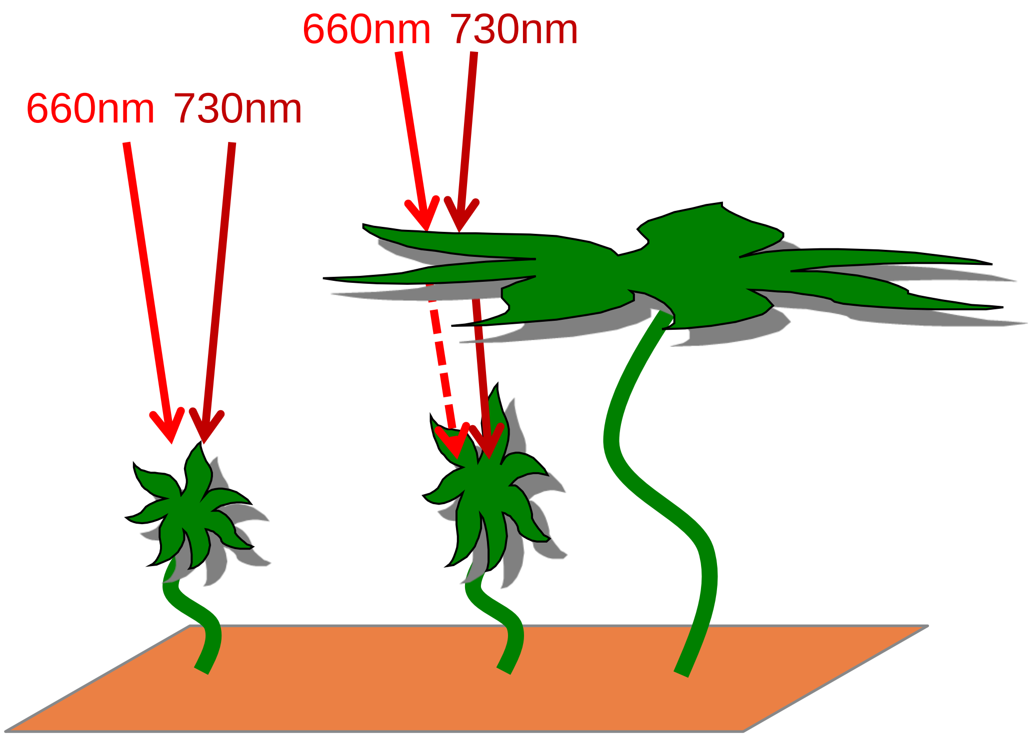
One of the most obvious influence of far red light on a plant is the shade escape reaction.

Illumination with 660nm:

If the plant is illuminated mainly with 660nm it feels like illuminated in the direct sun and growth normally.

Illumination with 730nm:

If the plant is illuminated mainly with 730nm it feels like growing in the shadow of another plant that shades the sun light. Therefore the plant is reacting with an increased length growth to escape the shadow. This leads to taller plants but not necessarily to more bio mass.



Source: [0]

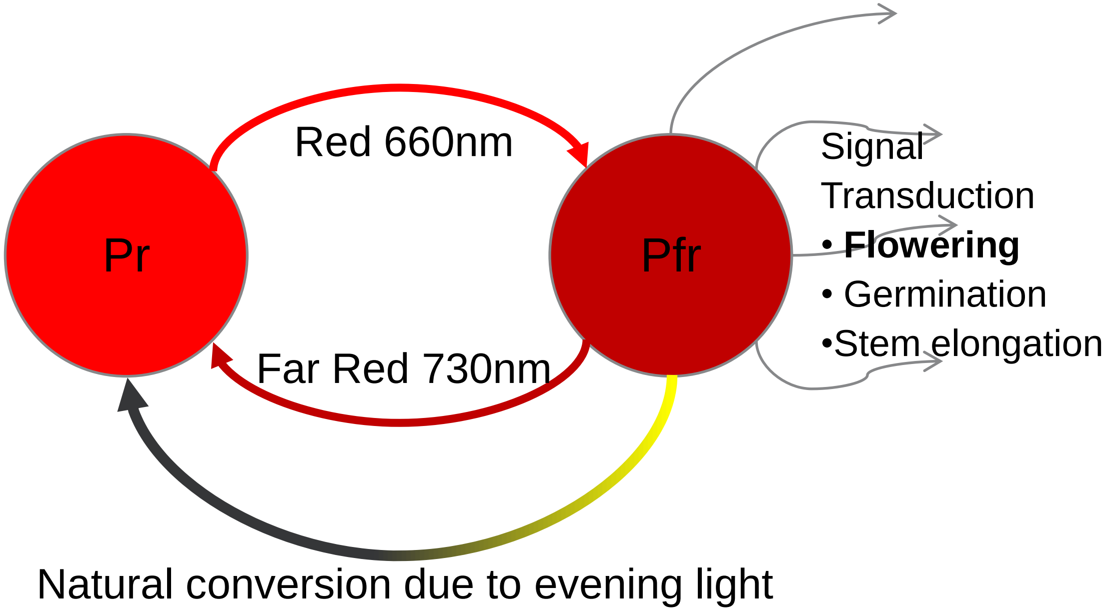
Special potential of LEDs in floriculture lighting

Traditionally ornamental plants are of high economic importance. The Red and Far-Red light mediates the conversion of phytochromes which can control the triggers for flowering.

Illumination with 730nm:

The cycle from Pr to Pfr is initiated by red light of 660nm which represents daylight. During the night time, the Pfr is converted back to Pr. This back conversion can also be actively be influenced by 730nm far red light.

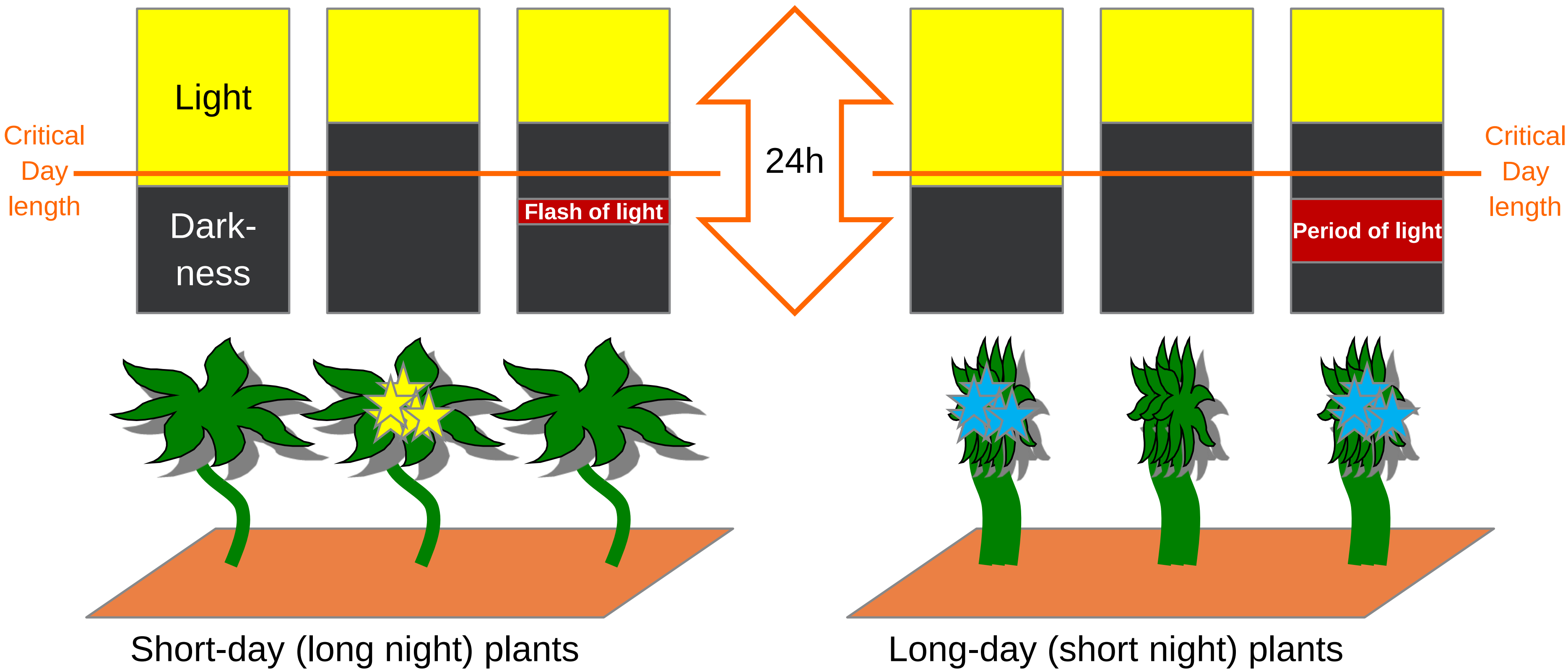
This enables a perfect control of the flowering timing independent of the seasons.



Source: [0]

Control of the flowering due to control of the critical night length by using any light

Due to the influence of the Pr and Pfr ratio the flowering can be controlled to adjust the timing to environmental or seasonal requirements.



Source: [0]

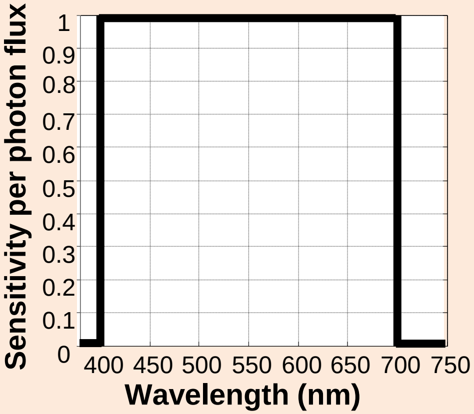
Background Knowledge
Photon counting

Today's method of weighing the spectrum is not really adequate

Situation today

- The whole spectrum is weighed equally by counting the photons in the photosynthetically active region (PAR)

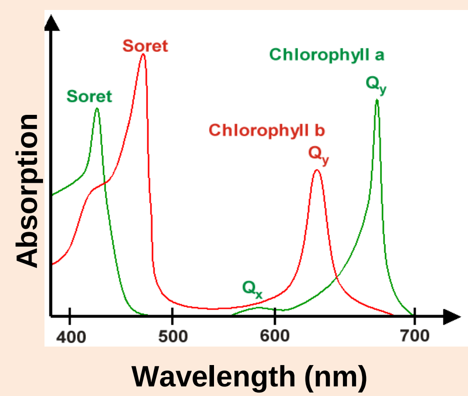
PAR sensitivity curve



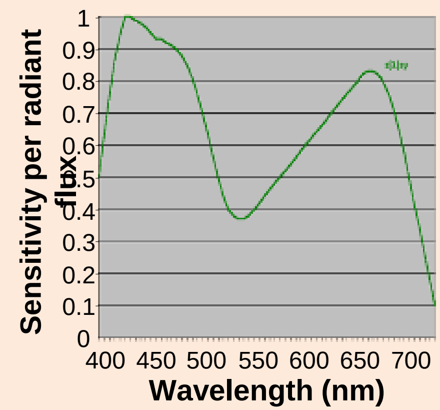
More realistic approach

- Weighing the emission spectrum of the light source with plants' spectral sensitivity curve ("plm/W")
- This curve is derived from the chlorophyll absorption spectrum taking into account internal energy transfer processes of the plant / leaves

Chlorophyll absorption spectrum



Plant sensitivity curve (DIN)*



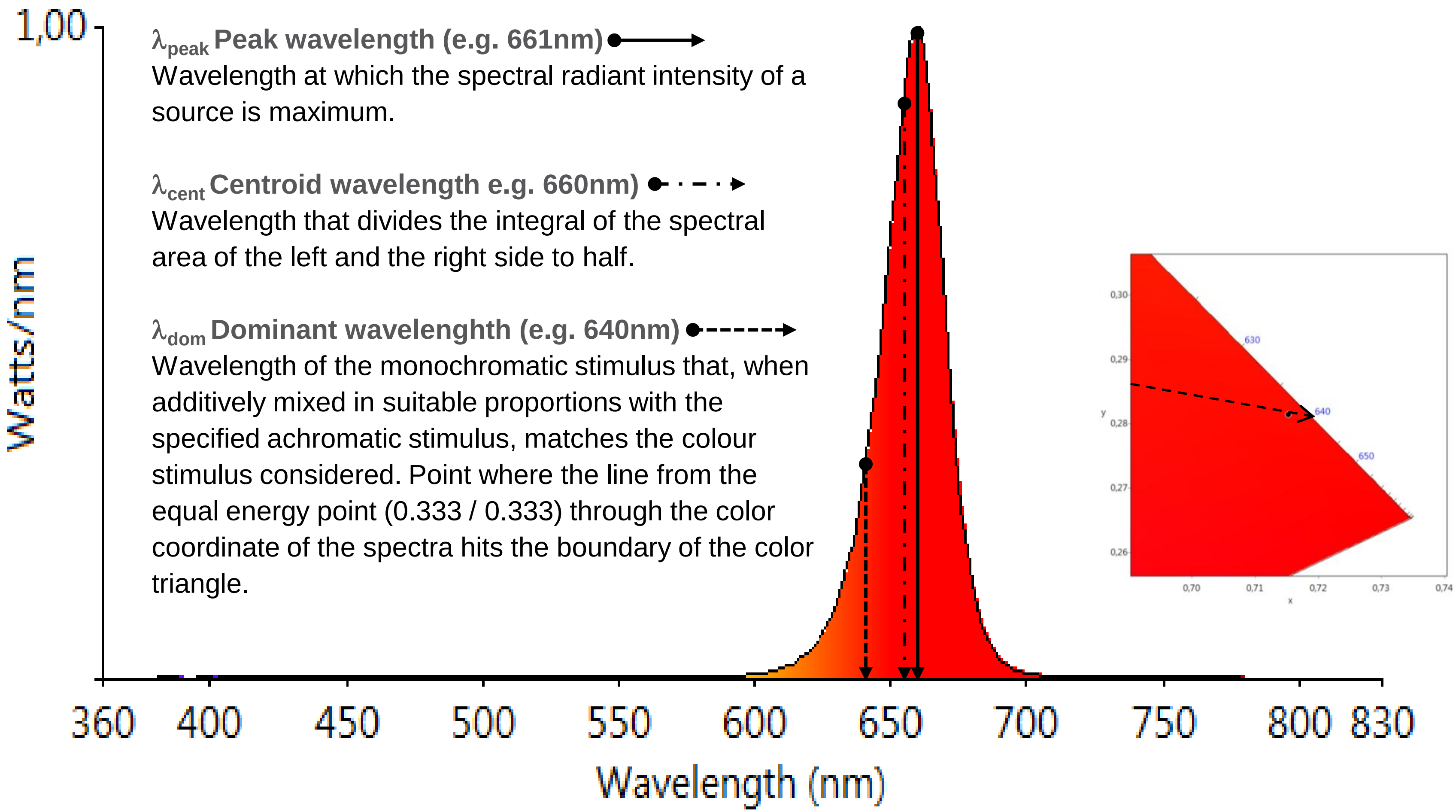
* DIN 5031-10

One spectrum and three different definitions of the wavelength

λ_{peak} **Peak wavelength (e.g. 661nm)**
Wavelength at which the spectral radiant intensity of a source is maximum.

λ_{cent} **Centroid wavelength e.g. 660nm)**
Wavelength that divides the integral of the spectral area of the left and the right side to half.

λ_{dom} **Dominant wavelenghth (e.g. 640nm)**
Wavelength of the monochromatic stimulus that, when additively mixed in suitable proportions with the specified achromatic stimulus, matches the colour stimulus considered. Point where the line from the equal energy point (0.333 / 0.333) through the color coordinate of the spectra hits the boundary of the color triangle.



What are typical µmol/s.m² values for horticulture lighting?

What light level for what cut flower?			
Plant	**min µmol/s.m²**	**max µmol/s.m²**	**typical µmol/s.m²**
Tomato	170	200	185
Pepper	70	130	100
Cucumber	100	200	150

What light level for what potted plant?			
Plant	**min µmol/s.m²**	**max µmol/s.m²**	**typical µmol/s.m²**
Orchid/Phalaenopsis	80	130	105
Dendrobium	130	260	195
Bromelia	40	60	50
Anthurium	60	80	70
Kalanchoë	60	105	82,5
Potted chrysanthemum	40	60	50
Potted rose	40	60	50
Geranium	40	60	50
Orchid/Phalaenopsis	80	130	105

What light level for what cut flower?			
Plant	**min µmol/s.m²**	**max µmol/s.m²**	**typical µmol/s.m²**
Chrysanthemum	105	130	117,5
Rose	170	200	185
Lily	80	100	90
Lisianthus	170	200	185
Alstroemeria	60	105	82,5
Anthurium / Orchid – cut	80	105	92,5
Freesia	70	105	87,5
Gerbera	80	105	92,5
Tulip	25	40	32,5

Source: http://www.hortilux.nl/light-technology

Effect of red light around 660nm on physiology of vegetables

Plant	Radiation source	Effect on plant physiology	Reference
Indian mustard (*Brassica juncea L.)* Basil (*Ocimum gratissimum L.)*	Red (660 and 635 nm) LEDs with blue (460 nm)	Delay in plant transition to flowering as compared to 460 nm + 635 nm LED combination	[38]
Cabbage (*Brassica olearacea var. capitata L.)*	Red (660 nm) LEDs	Increased anthocyanin content	[33]
Baby leaf lettuce (*Lactuca sativa L. cv.* Red Cross)	Red (658 nm) LEDs	Phenolics concentration increased by 6%	[7]
Tomato (*Lycopersicum esculentum L. cv.* MomotaroNatsumi)	Red (660 nm) LEDs	Increased tomato yield	[39]
Kale plants (*Brassica olearacea L. cv* Winterbor)	Red (640 nm) LEDs (pretreatment with cool white light fluorescent lamp)	Lutein and chlorophyll a, b accumulation increased	[36]
White mustard (*Sinapsis alba),* Spinach (*Spinacia oleracea), Green* onions (*Allium cepa)*	Red (638 nm) LEDs with HPS lamp (90 µmol m^{-2} S^{-1}), total PPF (photosynthetic photon flux) maintained at 300 µmol m^{-2} S^{-1}	Increased vitamin C content in mustard, spinach and green onions	[41]
Lettuce (*Lactuca sativa)* Green onions (*Allium cepa L.)*	Red (638 nm) LEDs and natural illumination	Reduction of nitrate content	[40]

Source: [0]

Effect of red light around 660nm on physiology of vegetables

Plant	Radiation source	Effect on plant physiology	Reference
Green baby leaf lettuce (*Lactuca sativa L.)*	Red (638 nm) LEDs (210 µmol m^{-2} S^{-1}) with HPS lamp (300 µmol m^{-2} S^{-1})	Total phenolics (28.5%), tocopherols (33.5%), sugars (52.5%), and antioxidant capacity (14.5%) increased but vitamin C content decreased	[42]
Red leaf, green leaf and light green leaf lettuces (*Lactuca sativa L.)*	Red (638 nm) LEDs (300 µmol m^{-2} S^{-1}) with HPS lamp (90 µmol m^{-2} S^{-1})	Nitrate concentration in light green leaf lettuce (12.5%) increase but decreased in red (56.2%) and green (20.0%) leaf lettuce	[43]
Green leaf 'Lolo Bionda' and red leaf 'Lola Rosa' lettuces (*Lactuca sativa L.)*	Red (638 nm) LEDs (170 µmol m^{-2} S^{-1}) with HPS lamp (130 µmol m^{-2} S^{-1})	Total phenolics and α-tocopherol content increased	[44]
Sweet pepper (*Capsicum annuum* L.)	Red (660 nm) and farred (735 nm) LEDs, total PPF maintained at 300 µmol m^{-2} S^{-1}	Addition of far-red light increased plant height with higher stem biomass	[34]
Red leaf lettuce 'Outeredgeous' (*Lactuca sativa L.)*	Red (640 nm, 300 µmol m^{-2} S^{-1}) and farred (730 nm, 20 µmol m^{-2} S^{-1}) LEDs.	Total biomass increased butanthocyanin and antioxidant capacity decreased	[30]

Source: [0]

Effect of red light around 660nm on physiology of vegetables

Plant	Radiation source	Effect on plant physiology	Reference
Red leaf lettuce ‘Outeredgeous’ (*Lactuca sativa L.)*	Red (640 nm, 270 μmol m^{-2} S^{-1}) LEDs with blue (440 nm, 30 μmol m^{-2} S^{-1}) LEDs	Anthocyanin content, antioxidant potential and total leaf area increased	[30]
Tomato seedlings ‘Reiyo’	Red (660 nm) and blue (450 nm) in different ratios	Higher Blue/Red ratio (1:0) caused reduction in stem length	[16]

Source: [0]

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Effect of blue light around 450nm on physiology of vegetables

Plant	Radiation source	Effect on plant physiology	Reference
Cherry tomato seedling	Blue LEDs in combination with red and green LEDs, total PPF maintained at 300 µmol m^{-2} S^{-1}	Net photosynthesis and stomatal number per mm^2 increased	[39]
Seedlings of cabbage (*Brassica olearaceae*var. *capitata L.)*	Blue (470 nm, 50 µmol m^{-2} S^{-1}) LEDs alone	Higher chlorophyll content and promoted petiole elongation	[33]
Chinese cabbage (*Brassica camprestis* L.)	Blue (460 nm, 11% of total radiation) LEDs with red (660 nm) LEDs, total PPF maintained at 80 µmol m^{-2} S^{-1}	Concentration of vitamin C and chlorophyll was increase due to blue LEDs applicatio	[32]
Baby leaf lettuce 'Red Cross' (*Lactuca sativa* L.)	Blue (476 nm, 130 µmol m^{-2} S^{-1}) LEDs	Anthocyanin (31%) and carotenoids (12%) increased	[7]
Cucumber 'Bodega' (*Cucumis sativus)* and tomato 'Trust' (*Lycopersicon esculentum)*	Blue (455 nm, 7-16 µmol m^{-2} S^{-1}) LEDs with HPS lamp (400-520 µmol m^{-2} S^{-1})	Application of blue LED light with HPS increased total biomass but reduced fruit yield	[45]
Transplant of cucumber 'Mandy F1'	Blue (455 and 470 nm, 15 µmol m^{-2} S^{-1}) with HPS lamp (90 µmol m^{-2} S^{-1})	Application of 455 nm resulted in slower growth and development while 470 nm resulted in increased leaf area, fresh and dry biomass	[46]

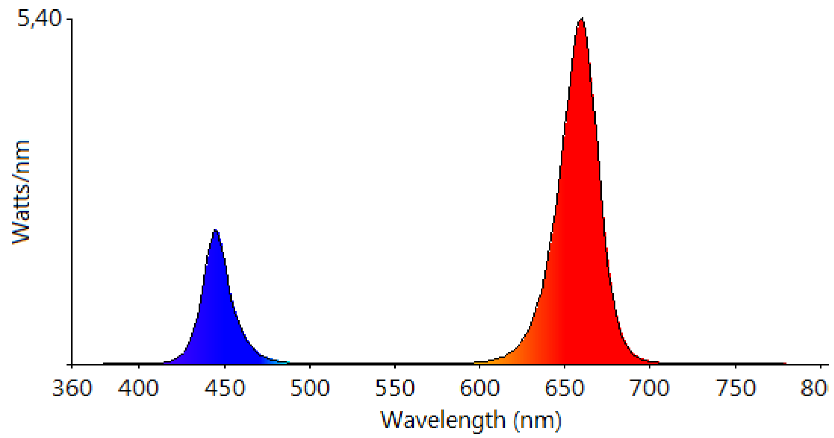
Source: [0]

Effect of green light around 520nm on physiology of vegetables

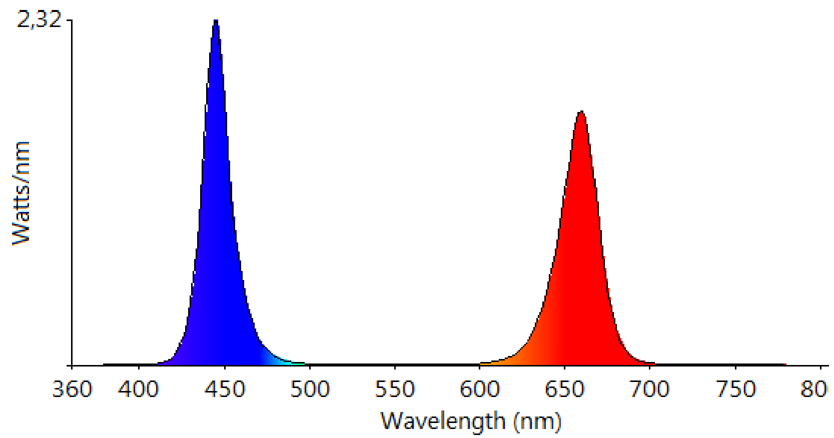
Plant	Radiation source	Effect on plant physiology	Reference
Red leaf lettuce (*Lactuca sativa L. cv* Banchu Red Fire)	Green 510, 520 and 530 nm LEDs were used, and total PPF was 100, 200 and 300 μmol m^{-2} S^{-1} respectively	Green LEDs with high PPF (300 μmol m^{-2} S^{-1}) was the most effective to enhance lettuce growth	[37]
Transplant of cucumber 'Mandy F1'	Green (505 and 530 nm, 15 μmol m^{-2} S^{-1}) LEDs with HPS lamp (90 μmol m^{-2} S^{-1})	505 and 530 nm both resulted in increased leaf area, fresh and dry weight	[46]
Red leaf lettuce (*Lactuca sativa L. cv* Banchu Red Fire)	Green 510, 520 and 530 nm LEDs were used, and total PPF was 100, 200 and 300 μmol m^{-2} S^{-1} respectively	Green LEDs with high PPF (300 μmol m^{-2} S^{-1}) was the most effective to enhance lettuce growth	[37]
Tomato 'Magnus F1' Sweet pepper 'Reda' Cucumber	Green (505 and 530 nm, 15 μmol m^{-2} S^{-1}) LEDs with HPSlamp(90 μmol m^{-2} S^{-1})	530 nm showed positive effect on development and photosynthetic pigment accumulation in cucumber only while 505 nm caused increase in leaf area, fresh and dry biomass in tomato and sweet pepper	[47]
Transplant of cucumber 'Mandy F1' **Source: [0]**	Green (505 and 530 nm, 15 μmol m^{-2} S^{-1}) LEDs with HPS lamp (90 μmol m^{-2} S^{-1})	505 and 530 nm both resulted in increased leaf area, fresh and dry weight	[46]

Horticulture Lighting
Example LED light ratios for different purposes

General purpose – high efficiency		
Type	Wavelength	mW Ratio
LD Cxxx	450nm	23%
LH Cxxx	660nm	77%
The highest efficacy of µmol/J from the spectrum can be achieved by using the 660nm Red LEDs combined with some 450nm Blue LEDs to maintain a reasonable ratio between the wavelengths		



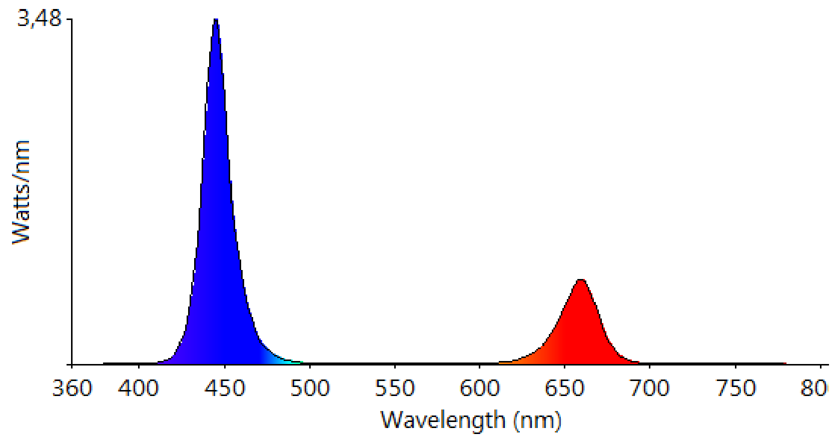
Vegetative Growth		
Type	Wavelength	mW Ratio
LD Cxxx	450nm	50%
LH Cxxx	660nm	50%
Especially for growth of the leafy green vegetable plants the vegetative growth ratio is used to achieve fastest growth where visible assessment of plant health is not important		



Source: http://www.illumitex.com/illumitex-leds/surexi-horticulture-leds/

Horticulture Lighting
Example LED light ratios for different purposes

Best for seedlings		
Type	Wavelength	mW Ratio
LD Cxxx	450nm	75%
LH Cxxx	660nm	25%
A high blue content in the spectrum is recommended for growth of the seedlings.		



Source: http://www.illumitex.com/illumitex-leds/surexi-horticulture-leds/

OSLON® SSL
Green House Lighting with LEDs

Toplighting

Toplighting is currently used with conventional light sources. The plants are illuminated from the top similar sun light.
The high power consumption and the heat of HPS luminaires are also demanding a distance between the light source and the plants.

Interlighting

Photo Interlighting: Courtesy of Netled Oy

Interlighting is enabled by LEDs as a light source! In this case the lighting is in between the plants and leaves. This should reduce the shadowing of the leafs which may occur by top lighting. This increases the amount of light even on the lower leafs.
Unlike the hot HPS Luminares, the comparatively low temperatures on the LED luminaire don’t damage the plants.

The incumbent –
High-Pressure Sodium (HPS) lamps

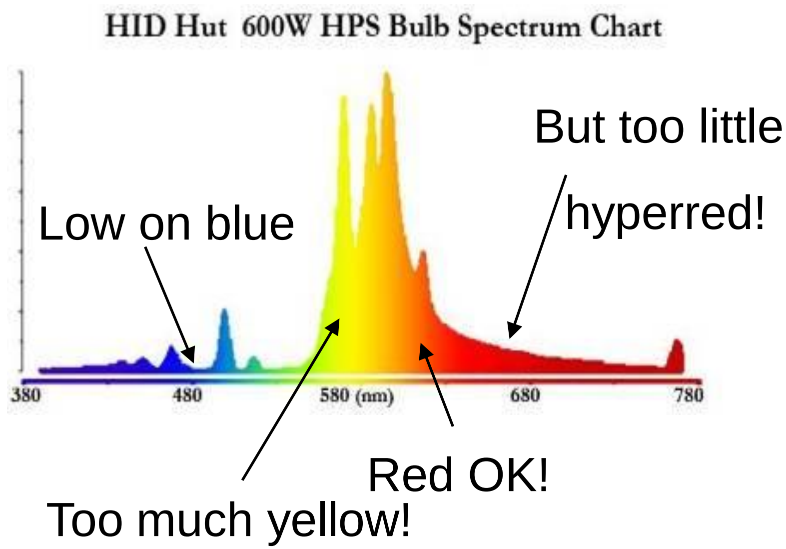
Today‘s widely used High-Pressure Sodium lamps produce over 100 lm/W, but over a wide wavelength range

Efficacy in Lumen per Watt is misleading, since plants don‘t have eyes

Typical lifetime is (only) ~8000h

Takes minutes to reach full power

Large lamps are most cost efficient



Products

Horticulture Lighting
current portfolio overview

well established OSLON SSL 450 nm and 660 nm portfolio available in unique 80° and 150° beam angle

	Blue	Deep blue	True green	Yellow	Amber	Red	Hyper Red	Far Red
	LB CPDP	LD CQxP	LT CPxP	LY CP7P	LA CPxP	LR CPxP	LH CPxP	GF CSxPM1
Dominant wavelength	464 - 476	449 - 461	513 - 537	583 - 595	612 - 624	620 - 632	646 - 666	730 (peak)
Viewing angle	150°	80°/150°	80°/150°	80°/150°	80°/150°	80°/150°	80°/150°	80°/150°
typ. Rth	7 K/W	7 K/W	7 K/W	7 K/W	7 K/W	7 K/W	7 K/W	7 K/W
Max. current	1 A	1 A	1 A	1 A	1 A	1 A	1 A	0.7 A
typ. Vf	3.1 V @ 350mA	3.1 V @ 350mA	3.2 V @ 350mA	2.25 V @ 350mA	2.20 V @ 350mA	2.15 V @ 350mA	2.10 V @ 350mA	1.85 V @ 350mA

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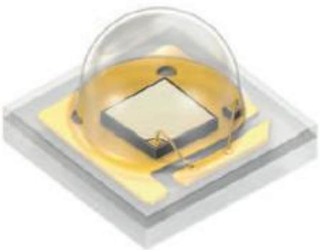
451 nm



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Horticulture Lighting
OSLON® SSL

LD CQ7P (80°)
LD CQDP (150°)

Product launched

Key Features

- λ_{peak} 451 nm
- Low thermal resistance @ 4.6 K/W
- Driving current condition up to 1A
- High reliable and high performance LED with superior corrosion robustness

Customer Benefit:

- 100% compatible to existing OSLON SSL devices
- Available in 80° and 150° viewing angle
- High performance and high reliable LEDs - perfectly addressed the Horticultural Lighting application needs

Values @ 25 °C	Binning current	Max. current	Viewing Angle	Typ. Radiant Flux	Typ. Forward Voltage	Typ. Radiant Efficiency
LD CQxP	350 mA	1000 mA	80 ° & 150 °	600 mW (350 mA) 1080 mW (700 mA)	2.95 V (350 mA) 3.15 V (700 mA)	59 % (350 mA) 48 % (700 mA)

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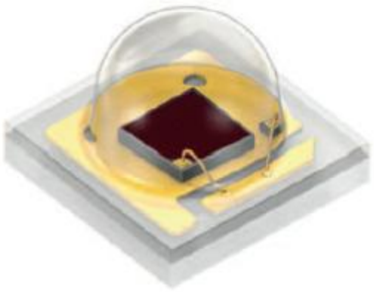
660 nm



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Horticulture Lighting
OSLON® SSL

LH CP7P (80°)
LH CPDP (150°)

Product launched

Key Features

- λ_{peak}: 660 nm
- Low thermal resistance @ 4.8 K/W
- Driving current condition up to 1A
- High reliable and high performance LED with superior corrosion robustness

Customer Benefit:

- 100% compatible to existing OSLON SSL devices
- Available in 80° and 150° viewing angle
- High performance and high reliable LEDs - perfectly addressed the Horticultural Lighting application needs

Values @ 25 °C	Binning current	Max. current	Viewing Angle	Typ. Radiant Flux	Typ. Forward Voltage	Typ. Radiant Efficiency
LH CPxP	350 mA	1000 mA	80 ° & 150 °	365 mW (350 mA) 709 mW (700 mA)	2.10 V (350 mA) 2.35 V (700 mA)	48 % (350 mA) 43 % (700 mA)

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730 nm

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Horticulture Lighting
OSLON® SSL

GF CS8PM1.24 (80°)
GF CSHPM1.24 (150°)

Product launched

Key Features

- λ_{peak}: 730 nm
- Low thermal resistance @ 6 K/W
- Driving current condition up to 1A
- High reliable and high performance LED with superior corrosion robustness

Customer Benefit:

- 100% compatible to existing OSLON SSL devices
- Available in 80° and 150° viewing angle
- High performance and high reliable LEDs - perfectly addressed the Horticultural Lighting application needs

Values @ 25 °C	Binning current	Max. current	Viewing Angle	Typ. Radiant Flux	Typ. Forward Voltage	Typ. Radiant Efficiency
GF CSxPM1.24	350 mA	1000 mA	80 ° & 150 °	231 mW (350 mA) 442 mW (700 mA)	1.85 V (350 mA) 2.10 V (700 mA)	36 % (350 mA) 30 % (700 mA)

Horticulture

LM80 status

OSLON® SSL
LM-80 Status by Type and Condition

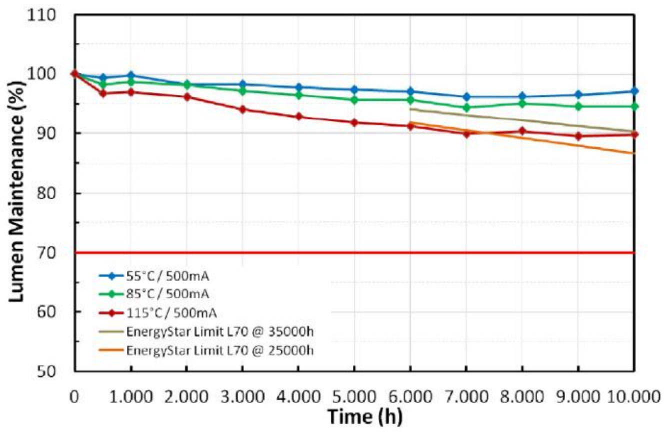
Product	Current	Temp (Ts)	3000 hr	6000 hr	9000 hr	Comments
GF CSxPM1.24	500mA	55°C	May'15	Sep'15	Jan'16	
		85°C	May'15	Sep'15	Jan'16	
		105°C	May'15	Sep'15	Jan'16	
	800mA	55°C	May'15	Sep'15	Jan'16	
		85°C	May'15	Sep'15	Jan'16	
		105°C	May'15	Sep'15	Jan'16	

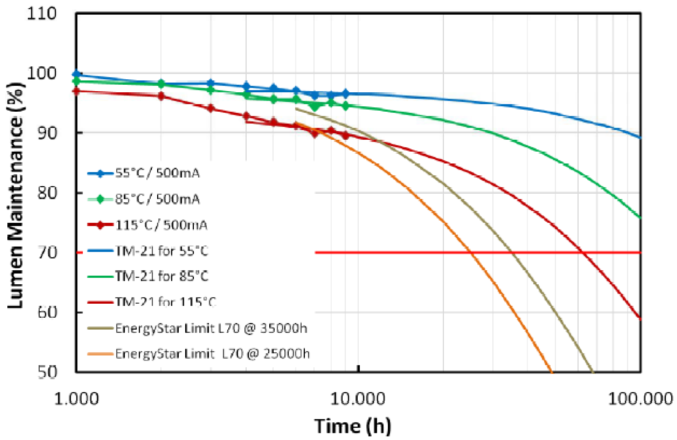
Product	Current	Temp (Ts)	3000 hr	6000 hr	10000 hr	Comments
LH CPxP	500mA	55°C			>60khs	
		85°C			>60khs	
		105°C			>60khs	
	800mA	55°C	May'15	Sep'15	Jan'16	
		85°C	May'15	Sep'15	Jan'16	
		105°C	May'15	Sep'15	Jan'16	

OSLON® SSL
unique selling point

LM80 Test overview 500 mA

Lumen Maintenance (I_F = 500 mA) – Normalized to 0 h





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OSLON® SSL
LM-80 Status by Type and Condition

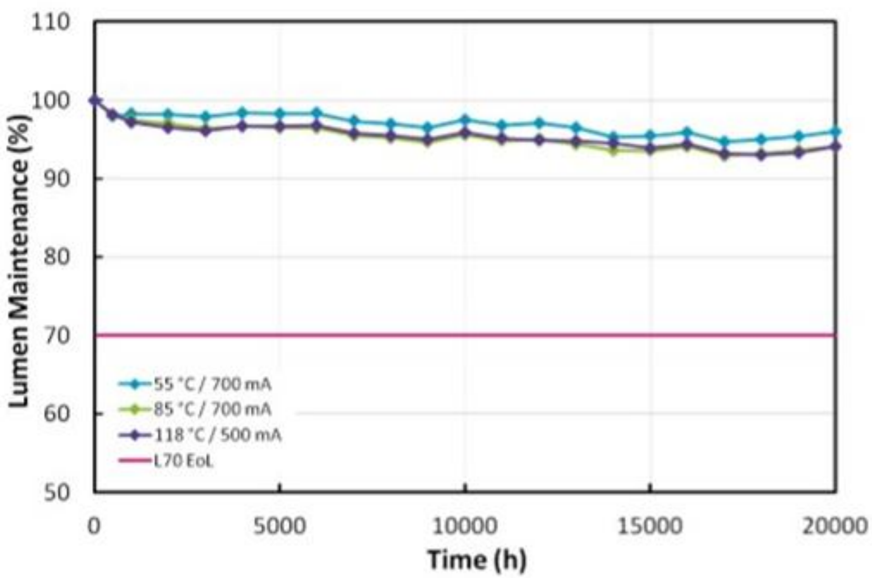
Product	Current	Temp (Ts)	3000 hr	6000 hr	10000 hr	Comments
LCW CxxP.EC 2400K – 6500K	350mA	55°C			L70(10k) > 60kh	
		85°C			L70(10k) = 54kh	
		114°C			L70(10k) = 41kh	
	500mA	55°C			L70(15k) = 76kh	
		85°C			L70(15k) = 51kh	
		118°C			L70(15k) = 39kh	

OSLON® SSL
unique selling point

LM80 Test overview

1. Graphic charts

Lumen Maintenance (I_F = 700 mA) – Normalized to 0 h



	I	II	III
Case temperature (solder point)	T_S = 55 °C	T_S = 85 °C	T_S = 118 °C
Device drive current	I_F = 700 mA	I_F = 700 mA	I_F = 500 mA
Number of samples	25	25	25
Test start	29.08.2009	29.08.2009	29.08.2009
Test duration	20,000 hours	20,000 hours	20,000 hours
Nr. of failures	0	2 (see section 10 for details)	0

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Appendix

Definitions

Radiometry: deals with the detection and measurement of electromagnetic radiation across the total spectrum

Photometry: subfield of radiometry; radiometric power scaled by the spectral response of the human eye

Photon Flux: number of photons in a spectral range per unit time. When limited to the range 400-700 nm, it is termed Photosynthetic Photon Flux.

Mol/mol/µmol: In chemistry, a unit of measurement counting the number of atoms/molecules/electrons/etc. in a substance (for horticulture, photons) By definition, the number of photons in a mol is 6.022×10^{23} (Avogadro's number)

Photon: Discrete bundle (quantum) of electromagnetic radiation (light). Can be considered to be a particle (although it displays properties of waves as well). The energy of a photon depends upon its wavelength. Conversely, if the energy & wavelength are known, the number of photons can be calculated

Photosynthetically Active Radiation (PAR): Radiation between 400 nm and 700 nm. Spectral region most useful to plants for photosynthesis

Photosynthetic Photon Flux Density (PPFD): Radiation between 400 nm and 700 nm. Radiation hitting a surface

Definitions

Photosynthesis: A process used by plants and other organisms to convert light energy into chemical energy that can be later released to fuel the organisms' activities. This chemical energy is stored in carbohydrate molecules, such as sugars, which are synthesized from carbon dioxide and water.

Germination: Germination is the process by which a plant grows from a seed. It is also known as sprouting of a seedling from a seed.

Vegetative Growth: Vegetative Growth is the period between germination and flowering. It is also known as vegetative phase of the plant development. During this phase the plants are performing photosysthesis and accumulating resources which will be used for the flowering and reproduction in the later stage.

Photomorphogenesis: Because light is the energy source for plant growth, plants have evolved highly sensitive mechanisms for perceiving light and using that information for regulating development changes to help maximize light utilization for photosynthesis. The process by which plant development is controlled by light is called photomorphogenesis. Typically, photomorphogenic responses are most obvious in germinating seedlings but light affects plant development in many ways throughout all stages of development.

Flowering: The transition to flowering is one of the major phase changes a plant makes during its life cycle. The transition must take place at a time that is favorable for fertilization and the formation of seeds. The right photoperiod is essential for the flowering.

Etiolatio: Abnormal shape of plants due to significantly accelerated length growths caused by insuficient illumination which can be used for photosynthesis.

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Thank you.

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