Solutions for Horticulture Lighting

LEDs for efficient and reliable luminaire design - ensure sustainable growth of plants

OS S EEM DM | LED EVENEMENT | Thomas Brandes

Light is OSRAM

Motivation
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 control of the growing process.
  Target: understand the influencing factors and correlations - define the main process parameters and set-up a control loop.

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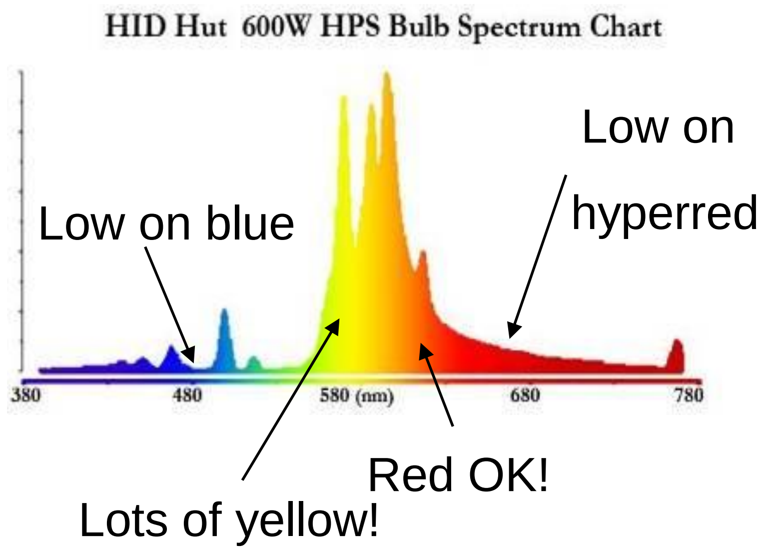
Where it all began: High-Pressure Sodium HPS lamp

High-Pressure Sodium lamps: above 100 lm/W, @ wide wavelength range

Plants don‘t have eyes: Efficacy in Lumen per Watt is misleading

Typical lifetime is ~8000h
Takes minutes to reach full power
Large lamps are most cost efficient
Established & well known

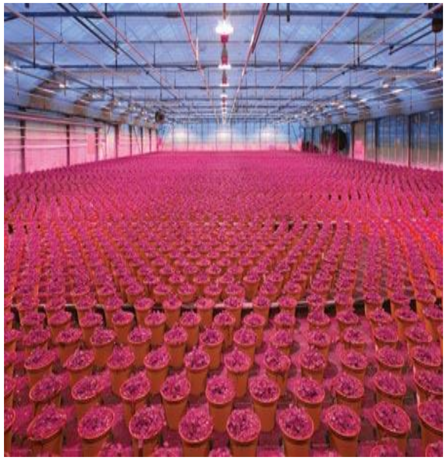


Improving the process and system life-time by dedicated control of spectrum and intensity with LEDs

LED opens new doors for horticulture lighting

LED Light is the efficient solution for Horticulture lighting - used to support, increase and enable the growth of plants by illuminating where and when needed:

Top Lighting



Inter Lighting

Vertical Farming

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 influencing the growing, shape, development and flowering => photomorphogenesis of the plant. For the photosynthesis, the blue and red regions are most important. Get more details in a moment.

- **Light duration**

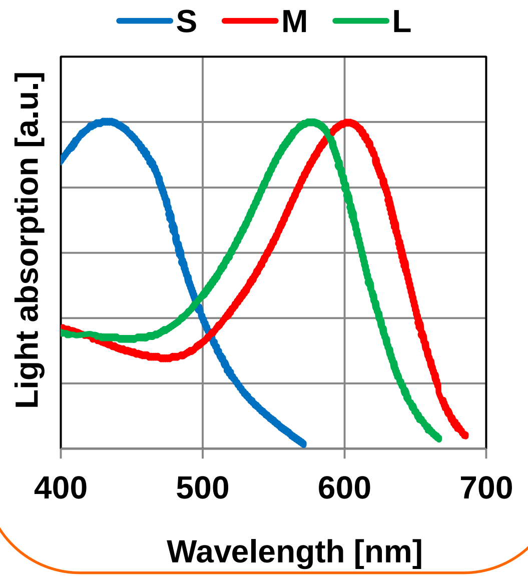
The timing / light duration which is also called photoperiod is mainly affecting the flowering of the plants. The flowering time can be influenced by controlling the photoperiod.

For more info: see the sources: [0];[18]

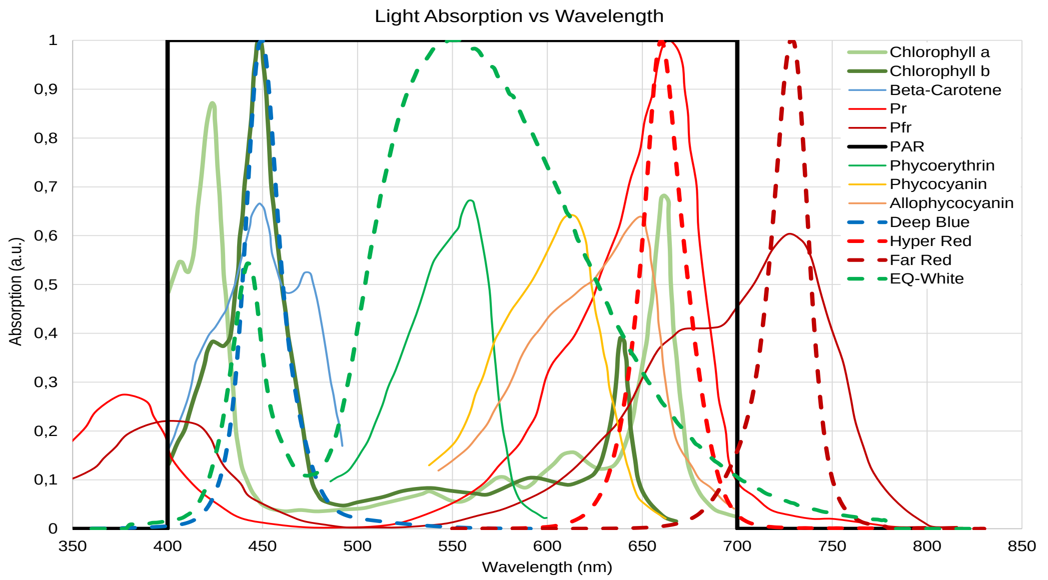
Difference in absorption curves for photochemical reactions between the human eye and plants

Light is generating a photochemical reaction.
In the eye, it reacts with our different photo receptors: version S, M, L
In plants, the light is reacting with Chlorophyll a and b.

Absorption curves of the human eye



Absorption curves of plants



Effect of the different wavelength ranges 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]

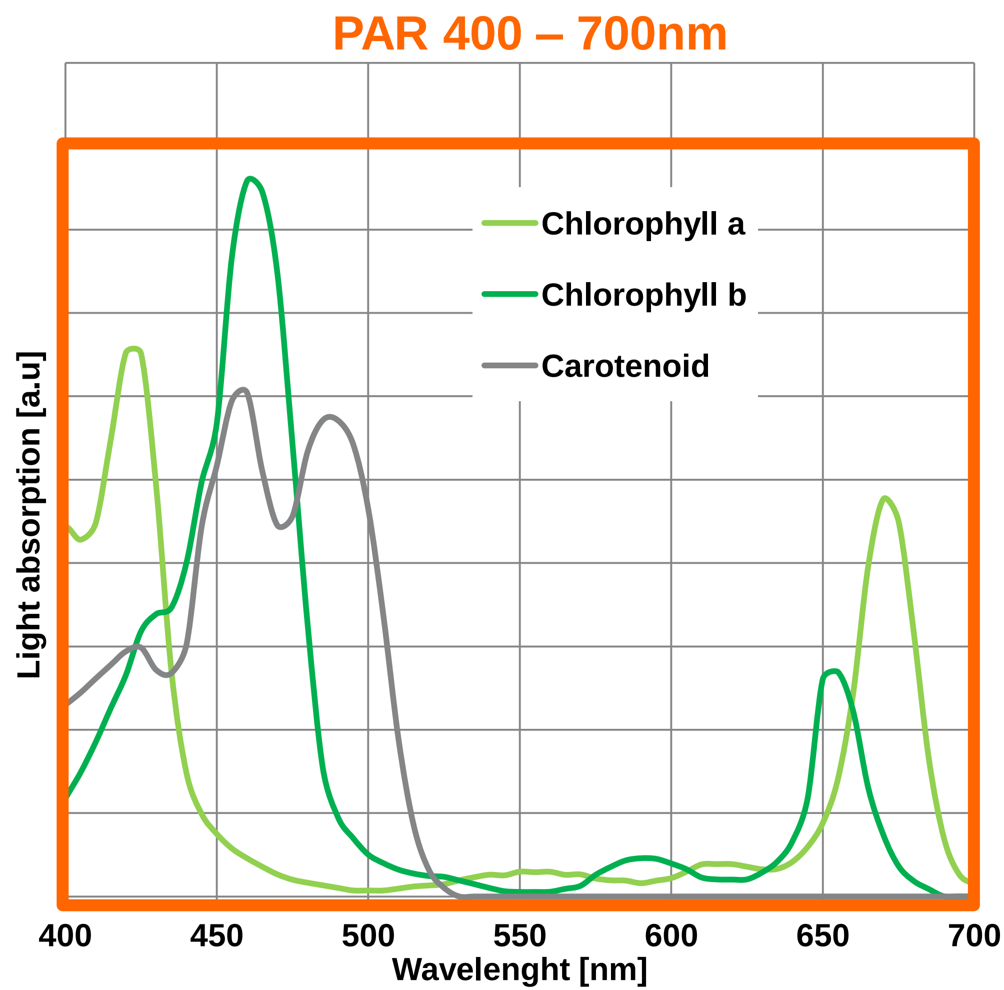
Photosynthetic efficiency is mainly driven by Chlorophyll a and b

- **Chlorophyll a and b**

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

- **Carotenoid**

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



Source: [18],[19]

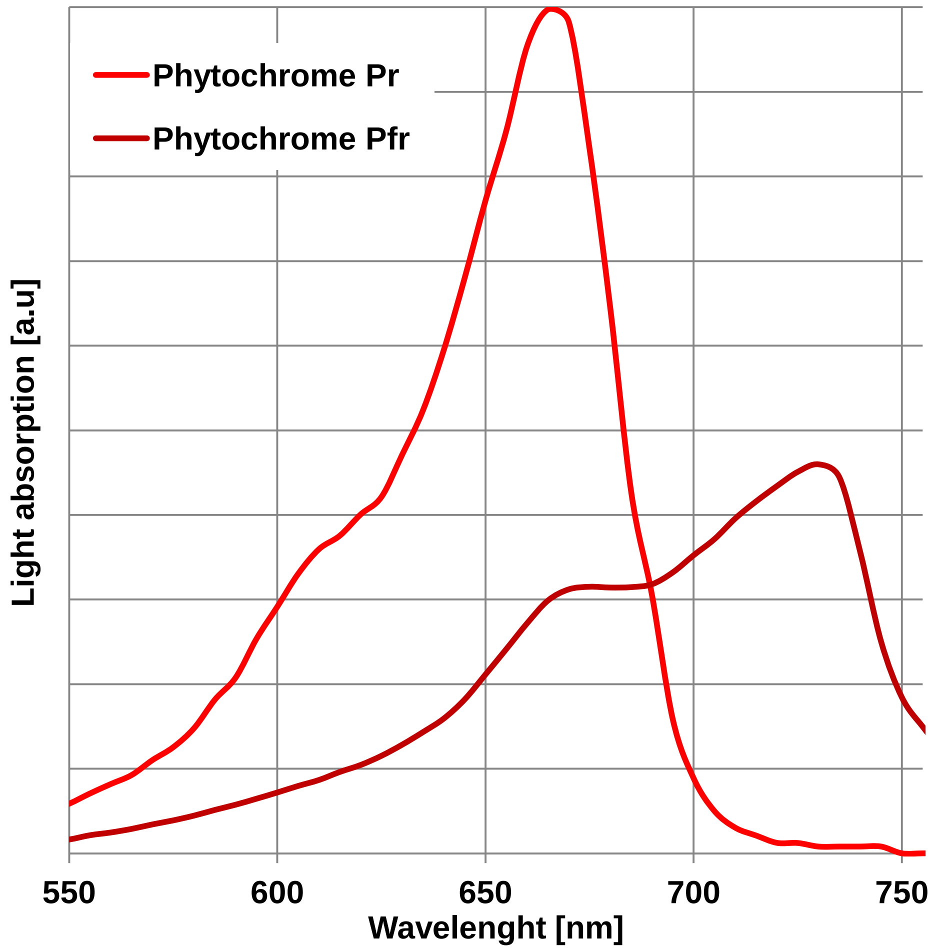
Photomorphogenic effects are mainly influenced by Phytochromes Pr and Pfr

• Phytochrome Pr and Pfr

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

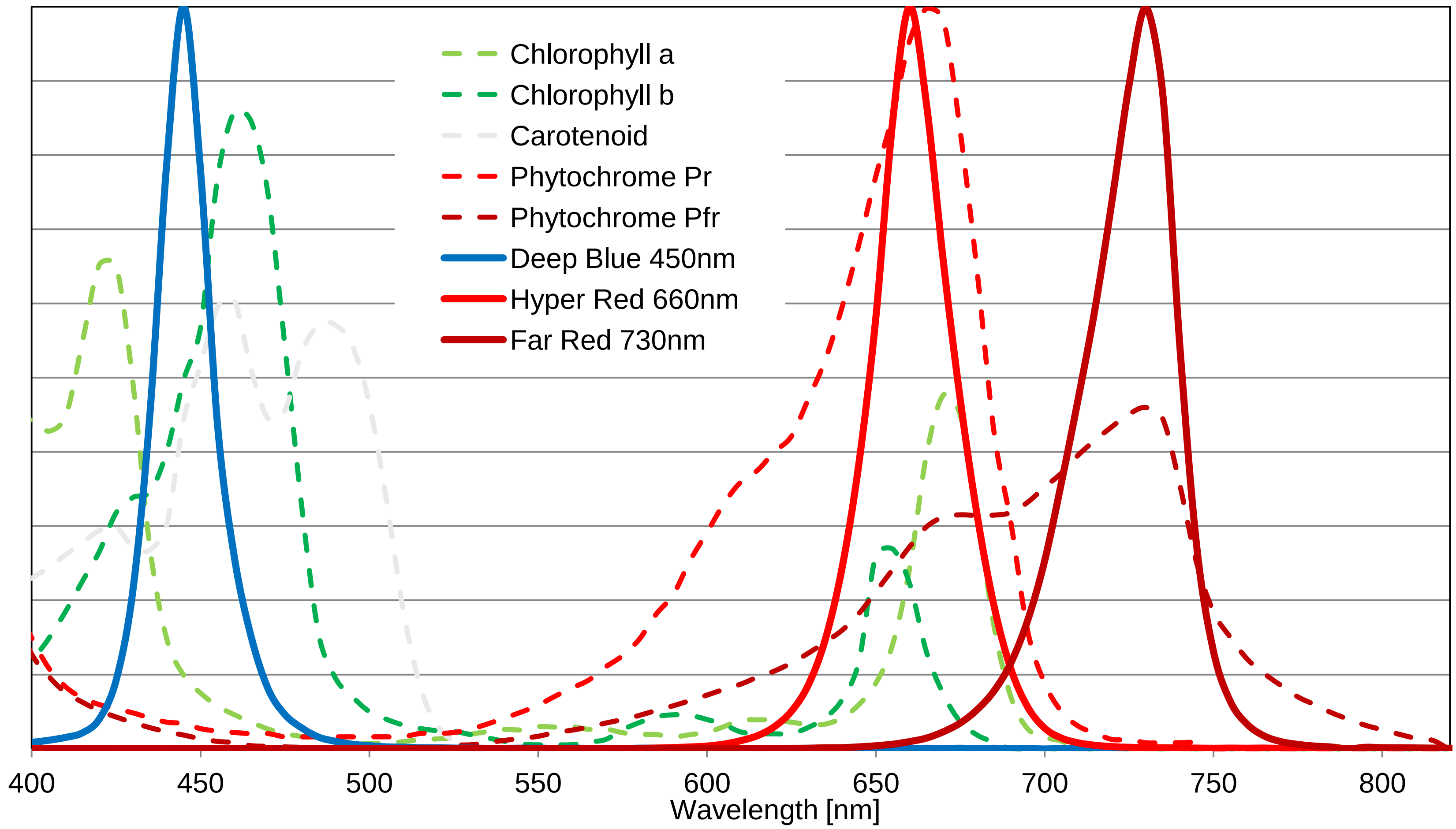
•Phytomorphogenic effects

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.



Today: Empiric focus in LED horticulture lighting on 450nm, 660nm and 730nm

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



Escaping the shadow - using far red 730nm

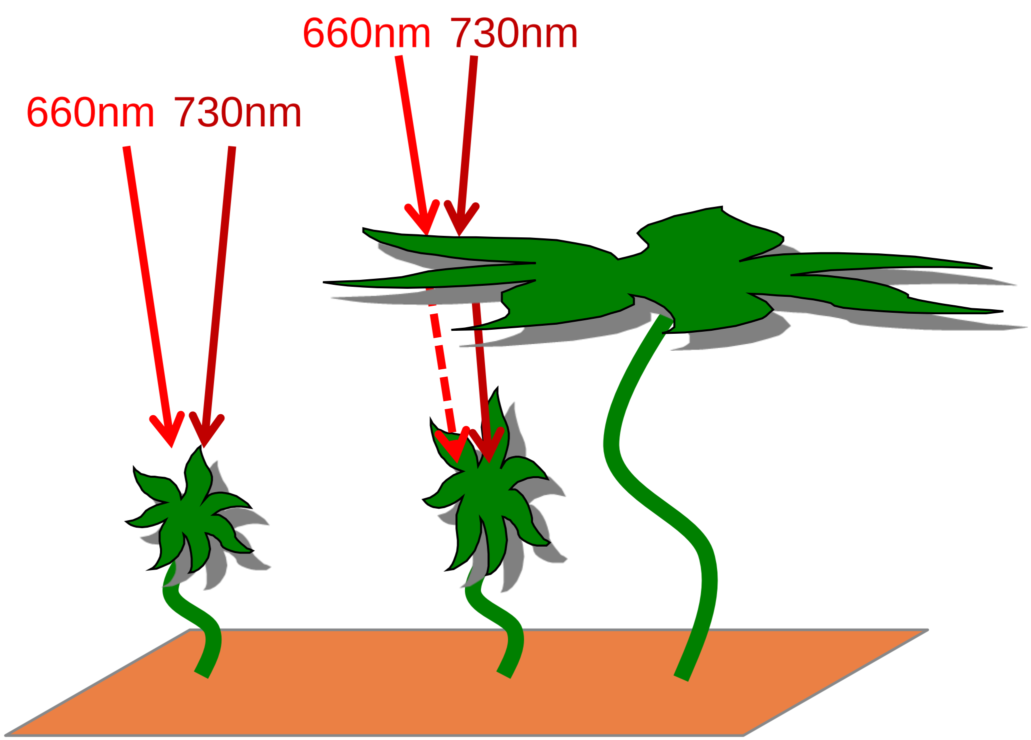
Plants react: One obvious influence of far red light on a plant is the active shade escape reaction.

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 – not necessarily impacting the cumulated bio mass.



Source: [0]

Special potential of LEDs in floriculture lighting 660nm and 730nm: Season Control

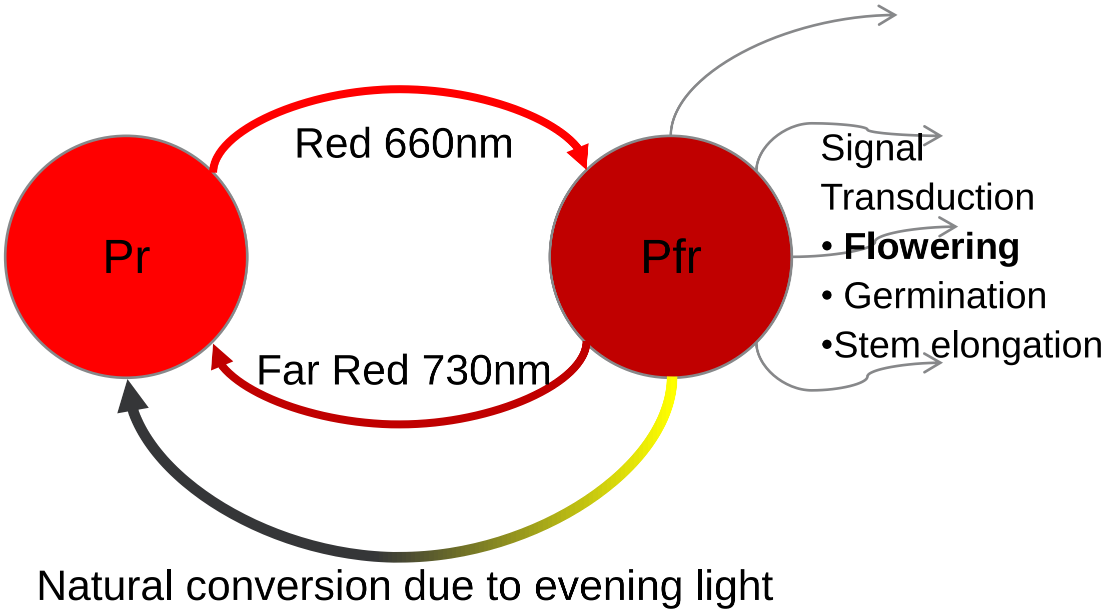
Traditionally ornamental plants are of high economic importance. The Red and Far-Red light mediates the conversion of phytochromes which can control the triggers for flowering.

Day & Night Cycle

Representing Daylight:
The cycle from Pr to Pfr is initiated by red light of 660nm

Representing Night:
Pfr is converted back to Pr.
This back conversion is actively influenced adding 730nm far red.

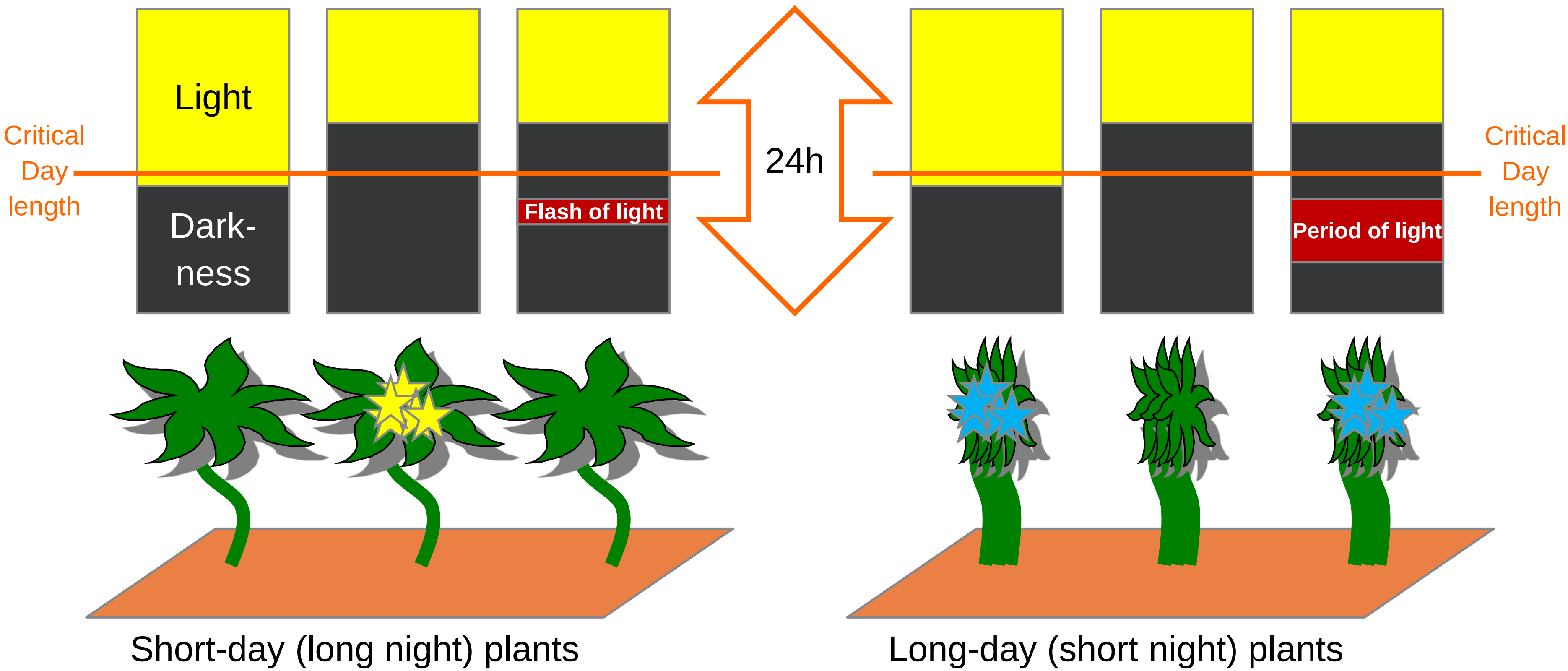
This enables a perfect control of the flowering timing independant of seasons.



Source: [0]

Control of the flower blossom: control the night length

It can make the flowers blossom in winter time or even prevent the blossoming in summer time. => Have the 730nm LED dimmable in the luminaire



Source: [0]

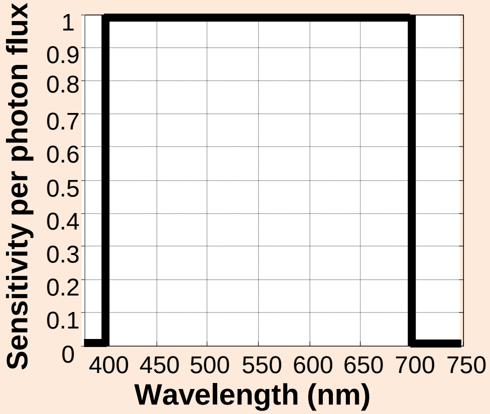
Background Knowledge Photon counting

Current method of weighing the spectrum is not adequate to actual plant absorption

Situation today

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

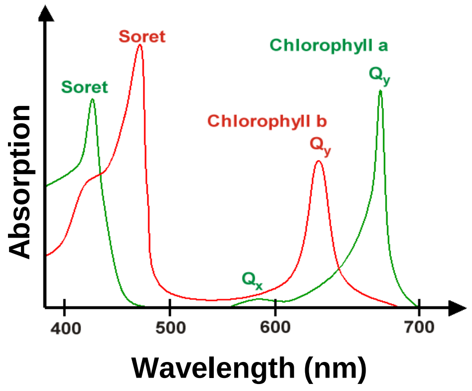
PAR sensitivity curve



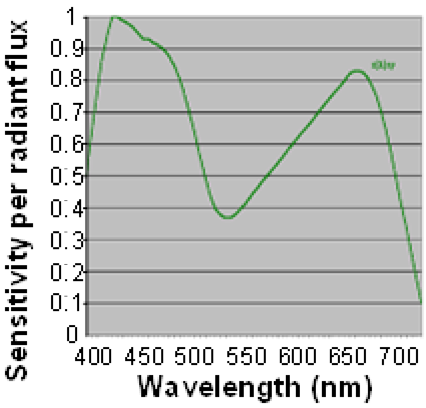
More realistic approach

- 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)*



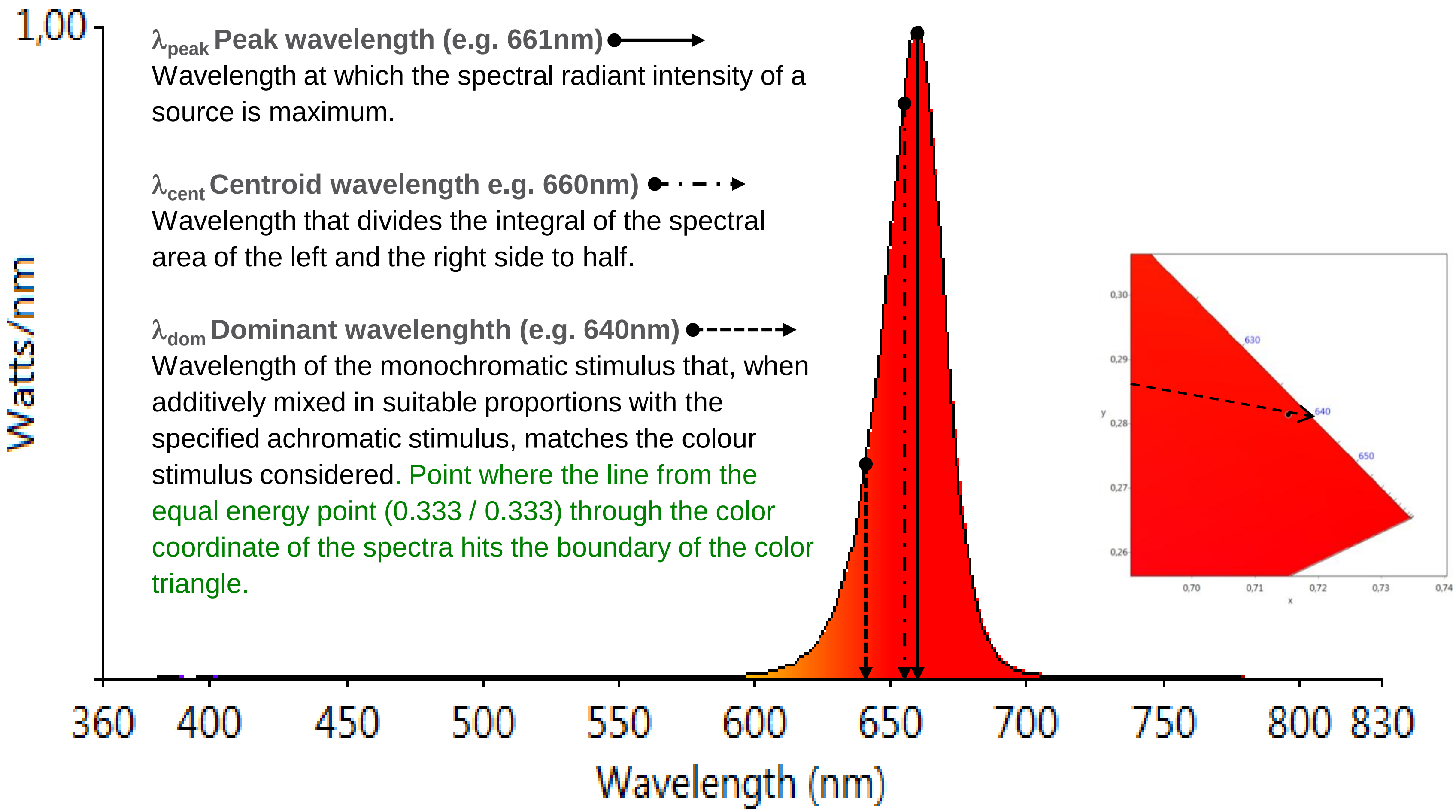
* DIN 5031-10

One spectrum and 3 wavelength definitions: Peak - Centroid - Dominant

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.



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Light level to apply - sorted by crop / plant / flower
Typical µmol/s.m² values for horticulture lighting

What light level for what type of crop?			
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 1/3

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 2/3

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 3/3

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]

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 olearacea*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]

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Effect of green light around 520nm on physiology of vegetables

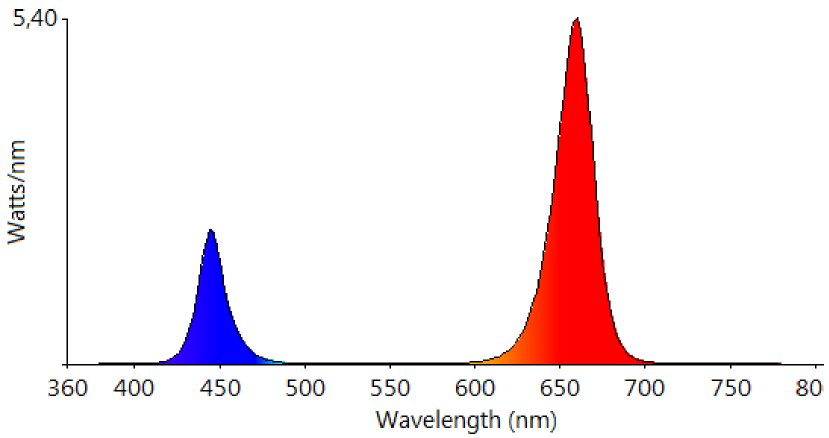
Plant	Radiation source	Effect on plant physiology	Reference
Red leaf lettuce (*Lactuca sativa L. cv* Banchu Red Fire)	Green 510, 520 and 530 nm LEDs were used, and total PPF was 100, 200 and 300 µmol m^{-2} S^{-1} respectively	Green LEDs with high PPF (300 µmol m^{-2} S^{-1}) was the most effective to 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'	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]

Source: [0]

Horticulture Lighting
Example LED light ratios for different purposes

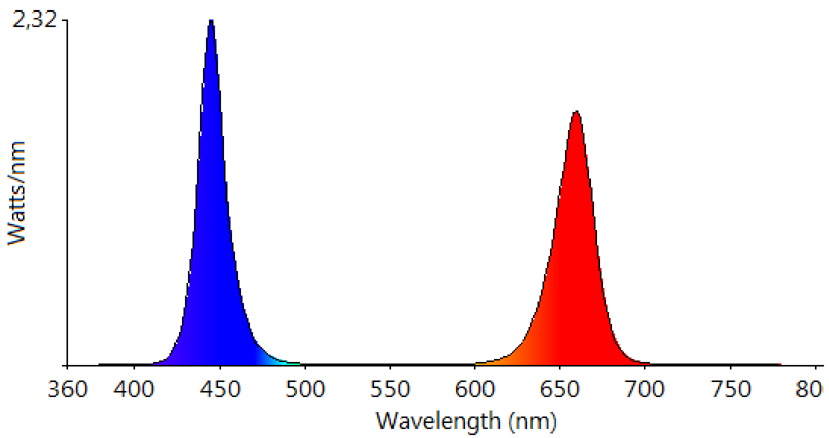
General purpose – high efficiency		
Type	Wavelength	mW Ratio
LD Cxxx	450nm	23%
LH Cxxx	660nm	77%

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%

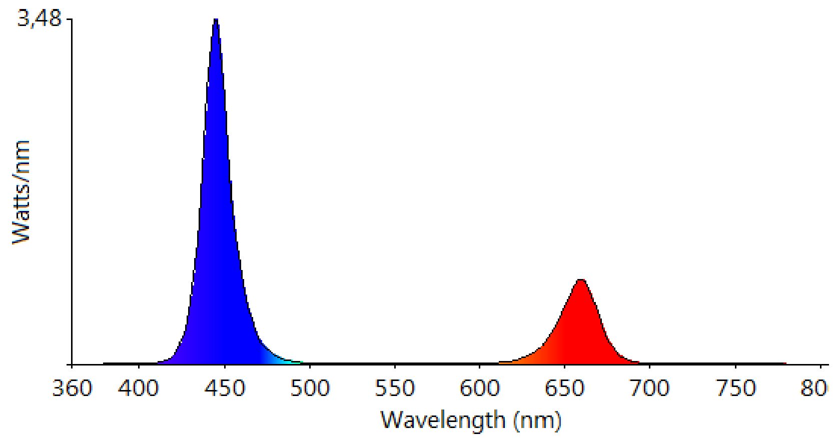
Especially for growth of the leafy green vegetable plants the vegetative growth ratio is used to achieve fastest growth where visible assessment of plant health is not important



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/

A few System considerations…

- Optics – Homogeneous light is needed for even crop growth and efficient energy use
- Thermal - Lighting should not cause plants to exceed optimal grow temperature
- Mechanical – Slim and semitransparent fixtures use less space and allow natural sunlight to reach plants
- Quality – Components with humidity robustness and fixtures with proper ingress protection are recommended

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Horticulture Lighting - OSLON® Family – current versions

Features

- 3 Different radiation angles: 80°, 120° 150°
- EQ White to add green content
- High reliable ceramic package with superior lifetime and corrosion stability

Applications

- Top Lighting, inter lighting and multilayer cultivation
- Urban Farming
- Algea Growth and agriculture lighting

LED Portfolio	Horticulture Lighting Colors			Horticulture White		
						
LED Type	OSLON SSL	OSLON SSL	OSLON SSL	OSLON SSL	OSLON SQUARE	OSLON SSL
Color	Deep Blue	Hyper Red	Far Red	EQW	CRI 90 5,700 K	CRI 70 5,000 K
Wavelength	450 nm	660 nm	730 nm	-	5,700K	5,000K
Radiation Angle 80°	GD CS8PM1.14	GH CS8PM1.24	GF CS8PM1.24	LUW CR7P		GW CS8PM1.PM
Radiation Angle 120°	GD CSSPM1.14	GH CSSPM1.24	GF CSSPM1.24	LUW CQAR	GW CSSRM1.CC	GW CSSRM2.PM
Radiation Angle 150°	GD CSHPM1.14	GH CSHPM1.24	GF CSHPM1.24	LUW CRDP	-	GW CSHPM1.PM

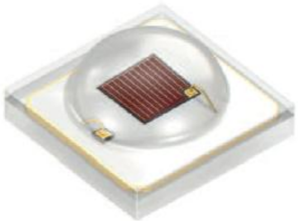
Horticulture Lighting
OSLON® Family – improved & NEW versions

Key Features

- Efficacy upgrade with latest technology
  - 450nm: **+5%** lm/W
  - 660nm: **+15%** lm/W
  - 730 nm: **+8%** lm/W
- High reliable and high performance LED with superior corrosion robustness

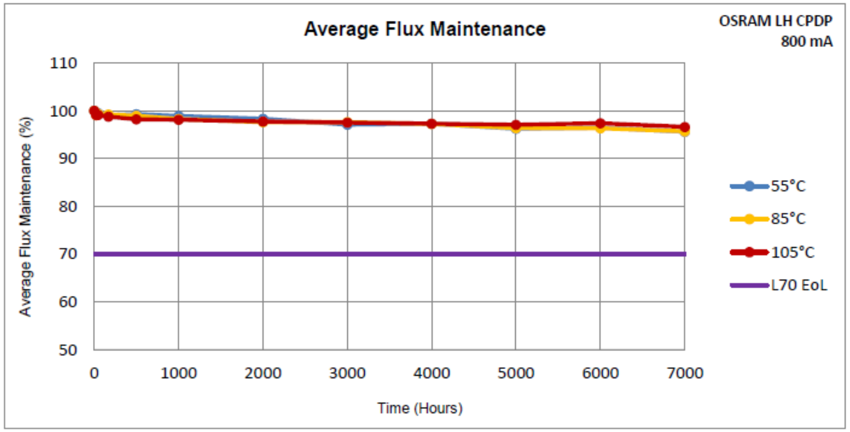
Customer Benefit

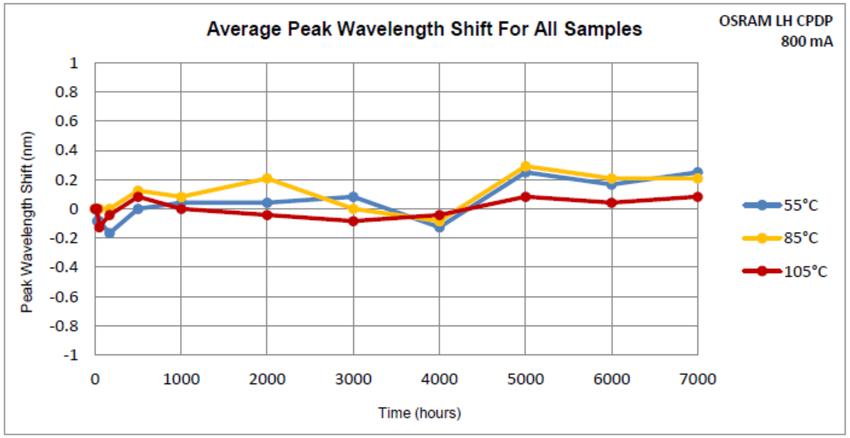
- In preparation: 660nm 2mm²
- Footprint compatible OSLON family
- **Info**: Polarity 660nm and 730nm has changed compared to LH CP



Values @ 25 °C	Binning current	Max. current	Viewing Angle	Typ. Radiant Flux	Typ. Radiant Efficiency	
GD CSxPM1.14	350 mA	1000 mA	80°& 150°	690mW	2,48 µmol/J	
GH CSxPM1.24	350 mA	1000 mA	80°& 150°	425mW	3,08 µmol/J	
GF CSxPM2.24	350 mA	1000 mA	80°& 150°	270mW	2,52 µmol/J	
GD CSSPM1.14	350 mA	1000 mA	120°	690mW	2,48 µmol/J	
GH CSSPM1.24	350 mA	1000 mA	120°	425mW	3,08µmol/J	
GF CSSPM1.24	350 mA	1000 mA	120°	270mW	2,52 µmol/J	

OSLON® SSL Quality & Reliability 2/3
LH CPDP 800mA





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OUTLOOK: What is next - Set the feedback loop !

Near IR spectroscopy may open new doors

Near-infrared spectroscopy (NIRS)

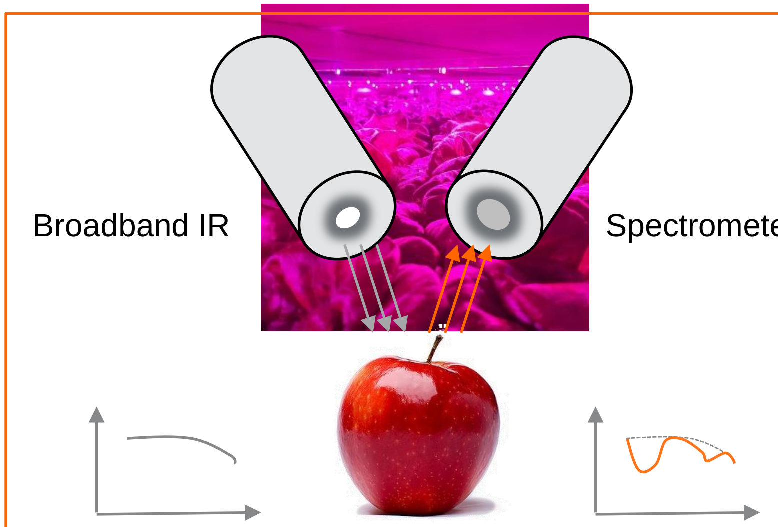
Detects molecular fingerprint of substances

Technology

- A broadband IRED with 700nm to 1050nm spectrum is used to illuminate a sample.
- The reflected light is received by a sensor.
- Based on the spectrum of the reflected light the molecular structure of the sample is analyzed

Why

- Measure the plant or blossom status
- Set the control to optimize the growing process

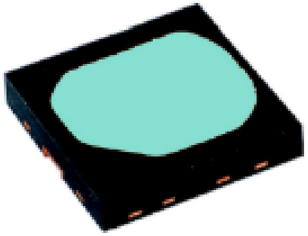


This opens new opportunities and new potential using a closed control loop in horticultural lighting

Effective definition of growth patterns condensed in dedicated algorithms for optimised plant growing.

Broadband IR emitter is a vital part of the control system

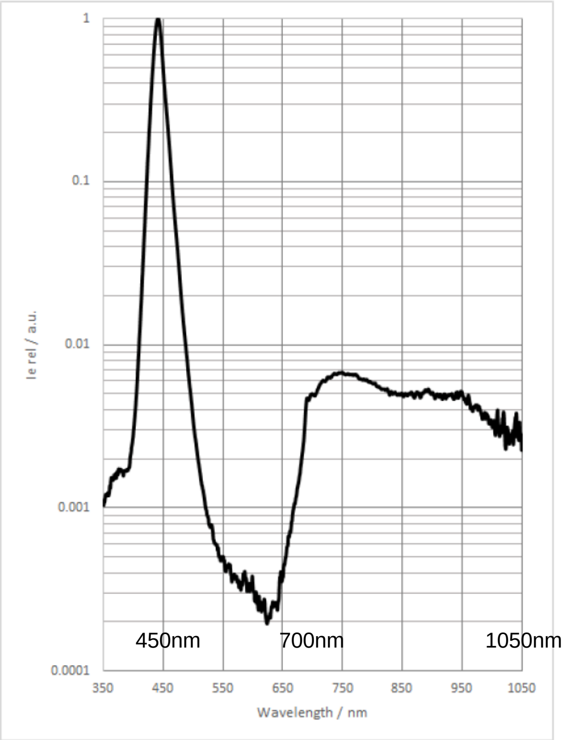
SFH 4735 OSLON black flat



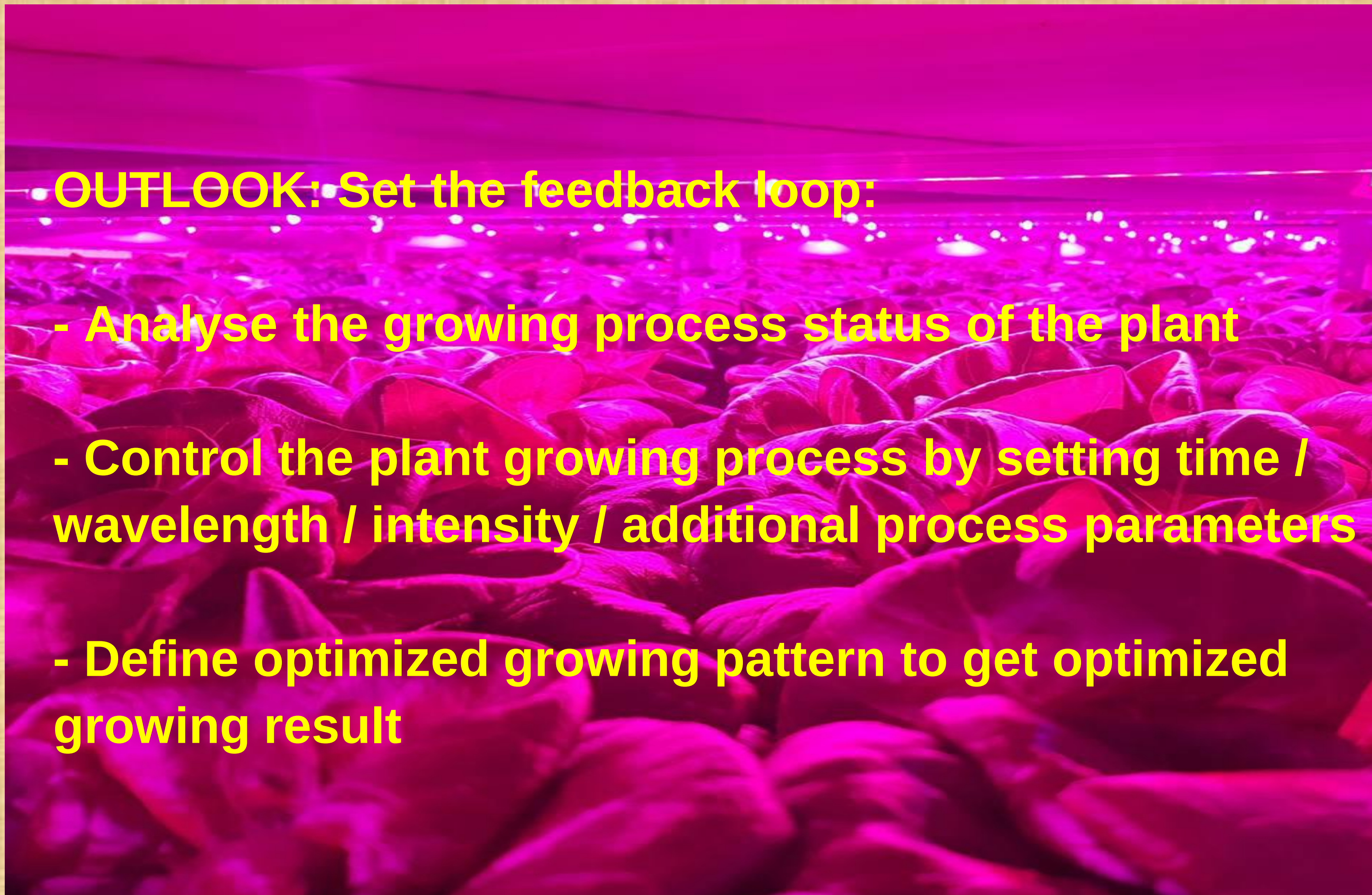
- broadband IR emitter for IR spectroscopy
- Blue chip converted into broad band IR 700nm – 1050 nm
- Blue peak desired as indicator/ target point
- OSLON black flat with ±60°
- New parts to follow: SFH 4736: with +/-45°

Relative Spectral Emission [1] *page 11*

$I_{rel} = f(\lambda)$, $T_A = 25$ °C, $I_F = 350$ mA, $t_p = 10$ ms



Samples available


OUTLOOK: Set the feedback loop:
- Analyse the growing process status of the plant
- Control the plant growing process by setting time / wavelength / intensity / additional process parameters
- Define optimized growing pattern to get optimized growing result

Invitation: Please have a look to the stand !

Thank you for your attention !

Contact your local distributor

RUTRONIK
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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.

References

References
0. Singh, Devesh, et al. "LEDs for Energy Efficient Greenhouse Lighting." arXiv preprint arXiv:1406.3016 (2014).

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

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

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

4. Tennessen DJ, Singsaas EL & Sharkey TD. Light-emitting diodes as a light source for photosynthesis research. Photosynth Res. 1994;39:85–92.

5. Barta DJ, Tibbits TW, Bula RJ & Morrow, RC. Evaluation of light emitting diode characteristics for a space-based plant irradiation source. Adv Space Res. 1992;12:141–9.

6. Olle M & Virsile A. The effect of light-emitting diode lighting on greenhouse plant growth and quality. Agric Food Sci. 2013;22:223-234.

7. Li Q & Kubota C. Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. Environ Exp Bot. 2009;67:59–64.

8. Lin KH, Huang MY, Huang WD, Hsu MH, Yang ZW & Yang CM. The effects of red, blue, and white light-emitting diodes on the growth, development, and edible quality of hidroponically grown lettuce (Lactuca sativa L. var. capitata). SciHortic-Amsterdam. 2013;150:86–91.

9. Massa GD, Kim HH, Wheeler RM & Mitchell CA. Plant productivity in response to LED lighting. Hort Science. 2008;43:1951–1956.

10. Vänninen I, Pinto DM, Nissinen AI, Johansen NS & Shipp L. In the light of new greenhouse technologies: Plant-mediates effects of artificial lighting on arthropods and tritrophic interactions. Ann Appl Biol. 2010;157:393–414.

References

11. Bourget CM. An introduction to light-emitting diodes. Hort Science. 2008;43:1944–1946.

12. Brumfield R. Dealing with rising energy costs. GPN. 2007;17:24-31.

13. Langton A, Plackett C & Kitchener H. Energy saving in poinsettia production. Horticultural Development Council Fact sheet. 2006;7:1-12.

14. Opdam JG, Schoonderbeek GG, Heller EB & Gelder A. Closed greenhouse: a starting point for sustainable entrepreneurship in horticulture. Acta Hort. 2005;691:517-524.

15. Ieperen VW & Trouwborst G. The Application of LEDs as Assimilation Light Source in Greenhouse Horticulture: a Simulation Study. Acta Hort. 2008;33:1407-1414.

16. Nanya K, Ishigami Y, Hikosaka S & Goto E. Effects of blue and red light on stem elongation and flowering of tomato seedlings. Acta Hort. 2012;956:261–266.

17. Keefe TJ. "The Nature of Light".Archived from the original on 2012-07-24. Retrieved 2007-11-05 Tower Hall Funabori, Tokyo, Japan.

18. Nishio JL. Why are higher plants green? Evolution of the higher plant photosynthetic pigment complement. Plant Cell Environ. 2000;23:539–548.

19. Chen P. Chlorophyll and other photosentives. In: LED grow lights, absorption spectrum for plant photosensitive pigments. http://www.ledgrowlightshq.co.uk/chlorophyll-plant-pigments/. Accessed 12 March 2014.

20. Bula RJ, Morrow RC, Tibbits TW, Barta RW, Ignatius RW & Martin TS. Light emitting diodes as a radiation source for plants. Hort Science.1991;26:203–205.

21. Tanaka Y, Kimata K & Aiba H. A novel regulatory role of glucose transporter of Escherichia coli: membrane sequestration of a global repressor Mic. EMBO J. 2000;19:5344-5352.

References

22. Tripathy BC & Brown CS. Root-shoot interaction in the greening of wheat seedlings grown under red light. Plant Physiol. 1995;107:407–411.

23. Yanagi T & Okamoto K. Utilization of super-bright light emitting diodes as an artificial light source for plant growth. Acta Hort. 1997;418:223-228.

24. Barreiro R, Guiamet JJ, Beltrano J & Montaldi ER. Regulation of the photosynthetic capacity of primary bean leaves by the red: far-red ratio and photosynthetic photon flux density of´incident light. Physiol. Plant. 1992;85:97–101
.

25. Sims DA & Pearcy RW. Response of leaf anatomy and photosynthetic capacity in Alocasiamacrorrhiza (Araceae) to a transfer from low to high light. Am J Bot. 1992;79:449–455.

26. Akoyunoglou G & Anni H. Blue light effect on chloroplast development in higher plants. In: Senger H. (ed.), Blue Light Effects in Biological Systems. Springer-Verlag, Berlin: 1984. pp. 397–406.

27. Saebo A, Krekling T & Appelgren M. Light quality affects photosynthesis and leaf anatomy of brich plantlets in vitro.Plant Cell Tiss Org. 1995;41:177–185.

28. Senger H. The effect of blue light on plants and microorganisms. Phytochem Photobiol. 1982;35:911–920.

29. Yorio NC, Goins GD, Kagie HR, Wheeler RM & Sager JC. Improving spinach, radish and lettuce growth under red light emitting didoes (LEDs) with blue light supplementation. Hort Science. 2001;36:380–383.

30. Stutte GW, Edney S & Skerritt T. Photoregulation of bioprotectant content of red leaf lettuc with light-emitting diodes. Hort Science. 2009;44:79–82.

31. Goins GD, Ruffe LM, Cranston NA, Yorio NC, Wheeler RM & Sager JC. Salad crop production under different wavelengths of red light-emitting diodes (LEDs). SAE Technical Paper, 31st International Conference on Environmental Systems, July 9–12, 2001, Orlando, Florida, USA: 2001. p. 1–9.

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References

32. Li H, Tang C, Xu Z, Liu X & Han X. Effects of different light sources on the growth of nonheading chinese cabbage (Brassica campestris L.). J Agr Sci. 2012;4:262–273.

33. Mizuno T, Amaki W & Watanabe H. Effects of monochromatic light irradiation by LED on the growth and anthocyanin contents in laves of cabbage seedlings. Acta Horticulturae. 2011;907:179–184.

34. Brown C, Shuerger AC & Sager JC. Growth and photomorphogenesis of pepper plants under red light-emitting diodes with supplemental blue or far-red lighting. J Am SocHortic Sci. 1995;120:808–813.

35. Goins GD, Yorio NC, Sanwo MM & Brown CS. Photomorphogenesis, photosynthesis and seed yield of wheat plants grown under red light-emitting diodes (LEDs) with and without supplemental blue lighting. J Exp Bot. 1997;48:1407–1413.

36. Lefsrud MG, Kopsell DA & Sams CE. Irradiance from distinct wavelength light-emitting diodes affect secondary metabolites in kale. Hort Science. 2008;43:2243–2244.

37. Johkan M, Shoji K, Goto F, Hahida S & Yoshihara T. Effect of green light wavelength and intensity on photomorphogenesis and photosynthesis in Lactuca sativa. Environ Exp Bot. 2012;75:128–133.

38. Tarakanov I, Yakovleva O, Konovalova I, Paliutina G & Anisimov A. Light-emitting diodes: on the way to combinatorial lighting technologies for basic research and crop production. ActaHorticulturae. 2012;956:171–178.

39. Lu N, Maruo T, Johkan M, Hohjo M, Tsukakoshi S, Ito Y, Ichimura T & Shinohara Y. Effects of supplemental lighting with light-emitting diodes (LEDs) on tomato yield and quality of single-truss tomato plants grown at high planting density. Environ Control Biol. 2012;50:63–74.

40. Samuolienė G, Urbonavičiūtė A, Duchovskis P, Bliznikas Z, Vitta P & Žukauskas A. Decrease in nitrate concentration in leafy vegetables under a solid-state illuminator. Hort Science. 2009;44:1857–1860.

References

41. Bliznikas Z, Žukauskas A, Samuolienė G, Viršilė A, Brazaitytė A, Jankauskienė J, Duchovskis P & Novičkovas A. Effect of supplementary pre-harvest LED lighting on the antioxidant and nutritional properties of green vegetables. Acta Hort. 2012;939:85–91.

42. Samuolienė G, Sirtautas R, Brazaitytė A, Viršilė A & Duchovskis P. Supplementary red-LED lighting and the changes in phytochemical content of two baby leaf lettuce varieties during three seasons. J Food Agric Environ. 2012a;10:701 – 706.

43. Samuolienė G, Brazaitytė A, Sirtautas R, Novičkovas A & Duchovskis P. Supplementary red-LED lighting affects phytochemicals and nitrate of baby leaf lettuce. J Food Agric Environ. 2011;9:271–274.

44. Žukauskas A, Bliznikas Z, Breivė K, Novičkovas A, Samuolienė G, Urbonavičiūtė A, Brazaitytė A, Jankauskienė J & Duchovskis P. Effect of supplementary pre-harvest LED lighting on the antioxidant properties of lettuce cultivars. Acta Hort. 2011;907:87–90.

45. Ménard C, Dorais M, Hovi T & Gosselin A. Developmental and physiological responses of tomato and cucumber to additional blue light. Acta Hort. 2006;711:291–296.

46. Novičkovas A, Brazaitytė A, Duchovskis P, Jankauskienė J, Samuolienė G, Viršilė A, Sirtautas R, Bliznikas Z & Žukauskas A. Solid-state lamps (LEDs) for the short-wavelength supplementary lighting in greenhouses: experimental results with cucumber. Acta Hort. 2012;927:723–730.

47. Samuolienė G, Brazaitytė A, Duchovskis P, Viršilė A, Jankauskienė J, Sirtautas R, Novičkovas A, Sakalauskienė S & Sakalauskaitė,J. Cultivation of vegetable transplants using solid-state lamps for the short-wavelength supplementary lighting in greenhouses. Acta Hort. 2012c ;952:885–892.

48. Folta KM. Green light stimulates early stem elongation, antagonizing light-mediated growth inhibition. Plant Physiol. 2004;135:1407–1416.

49. Kim HH, Goins GD, Wheeler RM & Sager JC. Green- light supplementation for enhanced lettuce growth under red and blue light-emitting diodes. Hort Science. 2004;39:1617–1622.

50. Simpson GG & Dean C. Arabidopsis, the Rosetta stone of flowering time? Science. 2002; 296:285–289.

References

51.Yanovsky MJ & Kay SA. Molecular basis of seasonal time measurement in Arabidopsis. Nature. 2002;419:308–312.

52. Downs RJ & Thomas JF. Phytochrome regulation of flowering in the long-day plant, Hyoscyamusniger. Plant Physiol. 1982;70:898–900.

53. Evans LT. Inflorescence initiation in Loliumtemu lentum L. XIV. The role of phytochrome in long day induction. Austral. J. Plant Physiol. 1976;3:207–217.

54. Shinomura T, Uchida K & Furuya M. Elementary processes of photoperception by phytochrome A for high-irradiance response of hypocotyl elongation in Arabidopsis. Plant Physiol. 2000;122:147–156.

55. Smith H. Light quality, photoperception, and plant strategy. Annu Rev Plant Physiol. 1982;33:481–518.

56. Runkle ES & Heins DR. Specific functions of red, far-red and blue lights in flowering and stem extension of long-day plants. J Amer Soc. Hort Sci. 2001;126:275–282.

57. Meng Q & Runkle ES. Control flowering with LEDs. Lighting Research.Growers Talk 62., http://www.ballpublishing.com/GrowerTalks/ViewArticle.aspx?articleid=20604 Accessed 15 Feb 2014.

58. Gomez C, Morrow RC, Bourget CM, Massa GD & Mitchell CA. Comparison of intracanopy light-emitting diode towers and overhead high-pressure sodium lamps for supplemental lighting of greenhouse-grown tomatoes. Hort Technology. 2013;23:93–98.

59. Voss J. Market special: greenhouse farming in Germany. The ministry of Economics Affairs, Agriculture and Innovation, NL, EVD International. 2011. http://duitsland.nlambassade.org/binaries/content/assets/postenweb/d/duitsland/ambassadeberlijn/zaken-doen/20110507-marktverkenning-greenhouse-farming-germany.pdf Accessed 16 Feb 2014

60. Kacira, M. Greenhouse Production in US: Status, Challenges, and Opportunities. Presented a CIGR 2011 conference on Sustainable Bioproduction WEF 2011, September 19-23, 2011. 61. Nelson AJ & Bugbee B. 2013. Supplemental greenhouse lighting: Return on investments for LED and HPS fixtures. http://cpl.usu.edu/files/publications/factsheet/pub__4338884.pdf

Thank you.

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