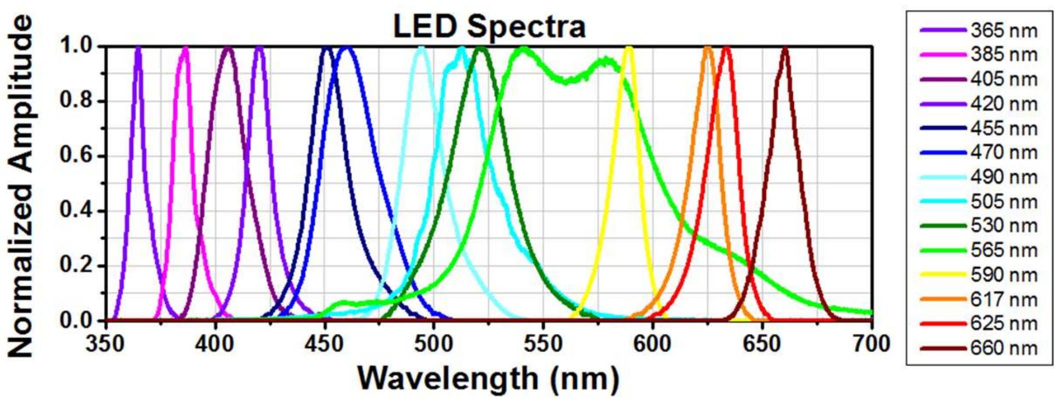

Specifying LED Colors for Horticultural Lighting

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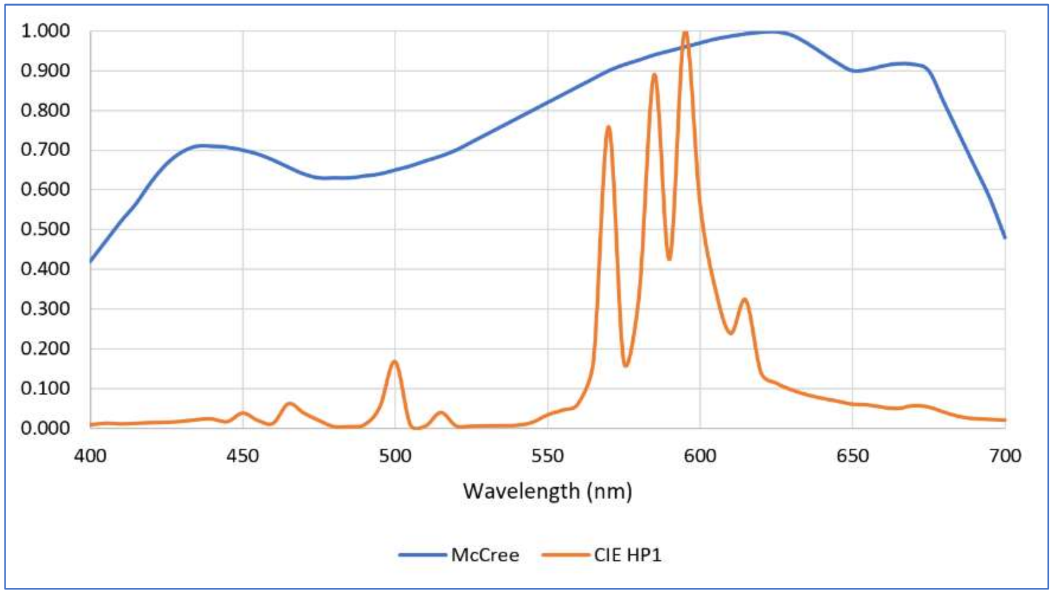
Senior Scientist

SunTracker Technologies Ltd.

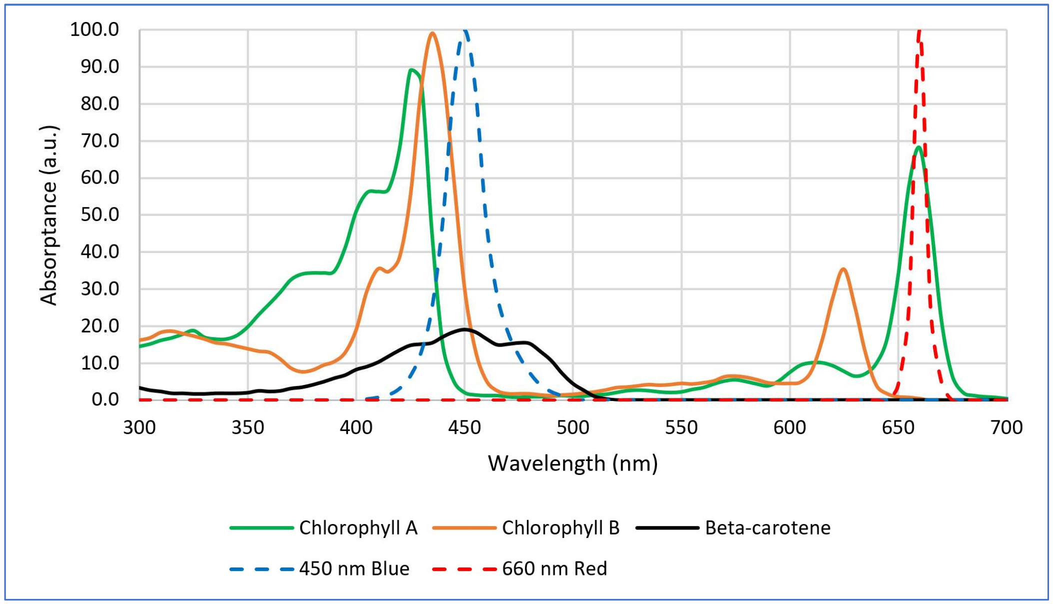
Image Credits: Maximum Yield, Thorlabs

High-Pressure Sodium Lamps



- Horticultural lighting for over 50 years
- 100 to 150 lumens per watt
- 400 to 1000 watts
- Withstand greenhouse heat and humidity
- Fixed spectral power distribution
- Well-suited for photosynthesis

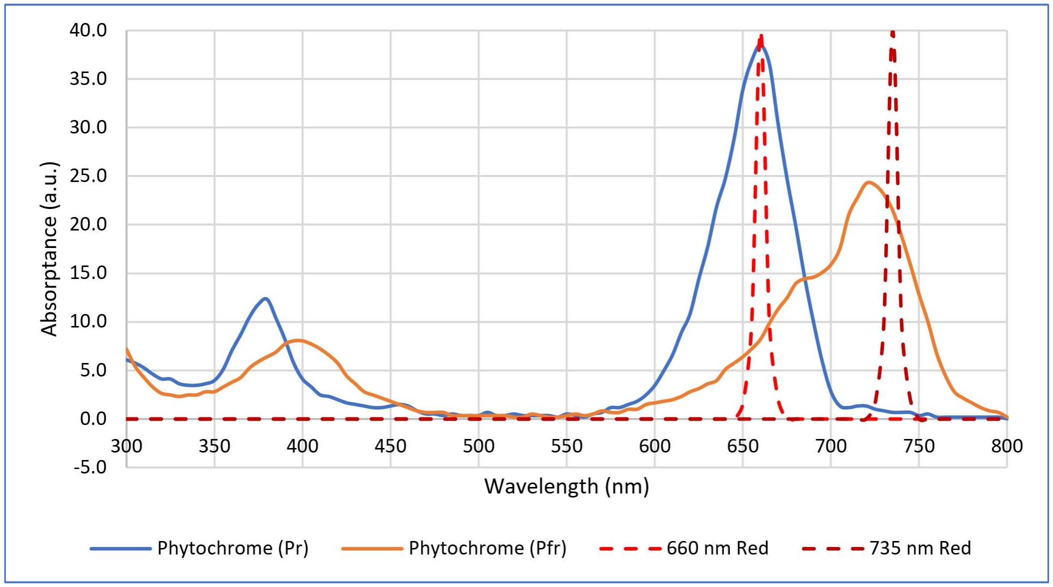
Photosynthesis and LEDs



- Photosynthesis driven by chlorophyll A/B and beta-carotene
- 450 nm blue and 660 nm red LEDs used for horticultural luminaires

Image Credit: Black Dog LED

Phytochrome and LEDs



- Isoforms of phytochrome (P_r and P_{fr}) act as biological switch to control many functions
- Relative concentration of isoforms dependent of red to far-red irradiance ratio (R:FR)
- 660 nm red and 735 nm far-red LEDs
- No formal definitions of “red” and “far-red”

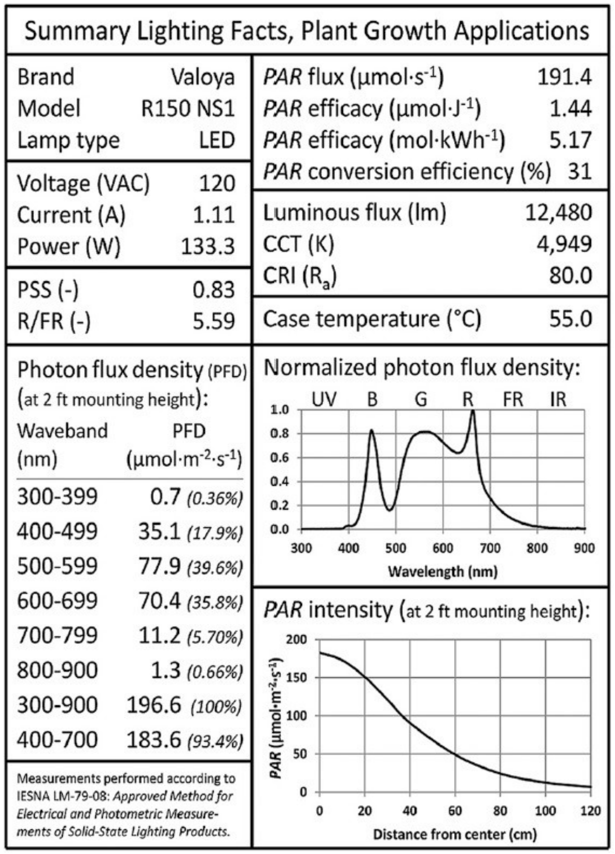
Plant Responses to Spectral Radiation

Wavelength Range	Color Name	Photopigments	Responses
280 nm – 315 nm	UV-B	UVR-8	Secondary metabolism Shade avoidance Phototropism
315 nm – 400 nm	UV-A	Chlorophylls Cryptochromes Phototropin Phytochromes Zeitlupe family	Secondary metabolism Photomorphogenesis
400 nm – 500 nm	"Blue"	Carotenes Chlorophylls Cryptochromes Phytochromes Zeitlupe family	Photosynthesis Secondary metabolism Shade avoidance Phototropism Photperiodism

Plant Responses to Spectral Radiation

Wavelength Range	Color Name	Photopigments	Responses
500 nm – 575 nm	Green	Cryptochromes	Photosynthesis Secondary metabolism Shade avoidance
575 nm – 620 nm	Yellow Orange	<Unknown>	Photosynthesis Secondary metabolism
610 nm – 700 nm	Red	Chlorophylls Phytochromes	Photosynthesis Secondary metabolism Shade avoidance Photomorphogenesis Photoperiodism
700 nm – 800 nm	Far-red	Phytochromes	Shade avoidance Photomorphogenesis Photoperiodism

Horticultural Lamp Label Proposal



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 (μmol·s^{-1})	191.4
PAR efficacy (μmol·J^{-1})	1.44
PAR efficacy (mol·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 (μmol·m^{-2}·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.*

- Divide 300 nm – 700 nm spectrum into arbitrary 100-nm width spectral bands
- Avoids use of color names and luminous flux (which are based on human visual system)
- Merges UV-B and UV-A into one band

Image Credit: Both, A.-J., et al. 2017. “Proposed Product Label for Electric Lamps Used in the Plant Sciences,” HortTechnology 27(4):544-549.

Plant Responses to Peak Wavelength

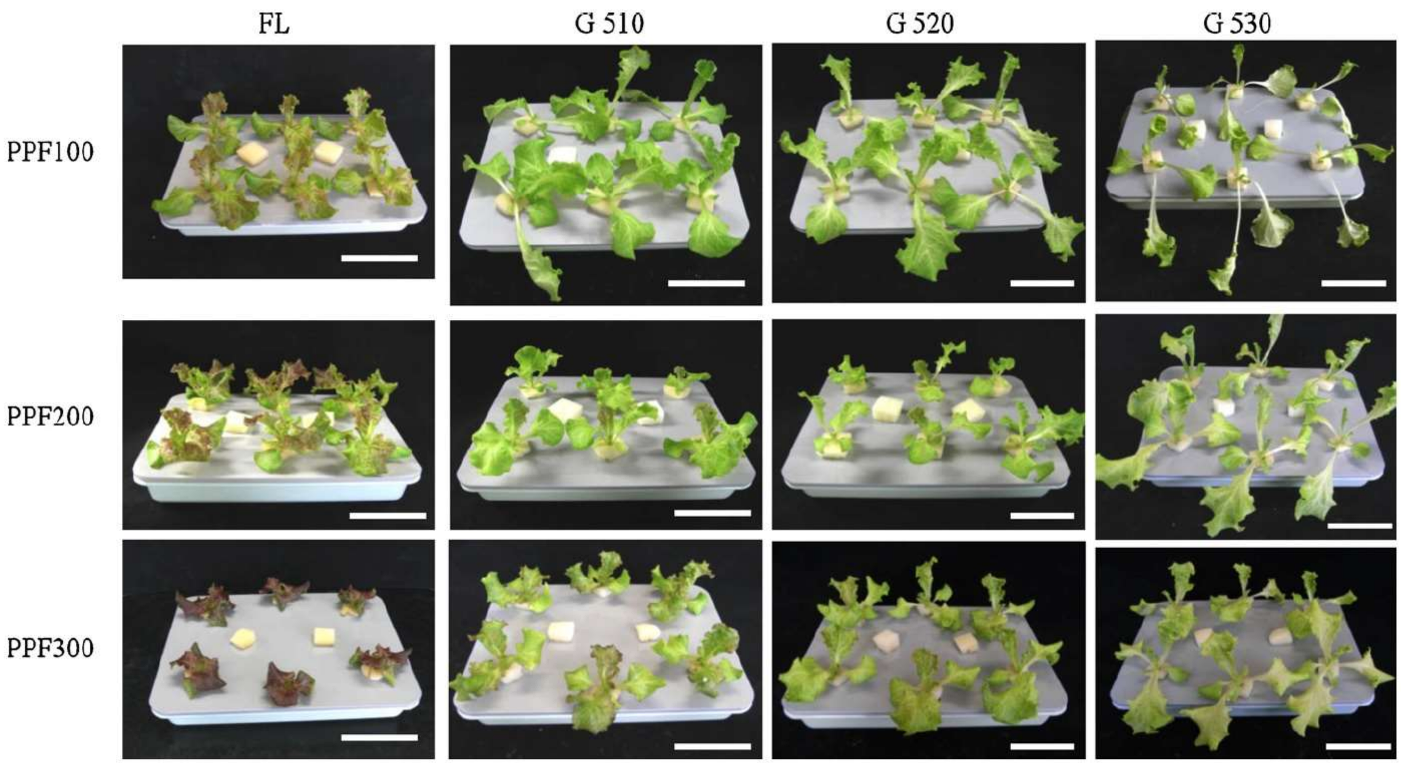
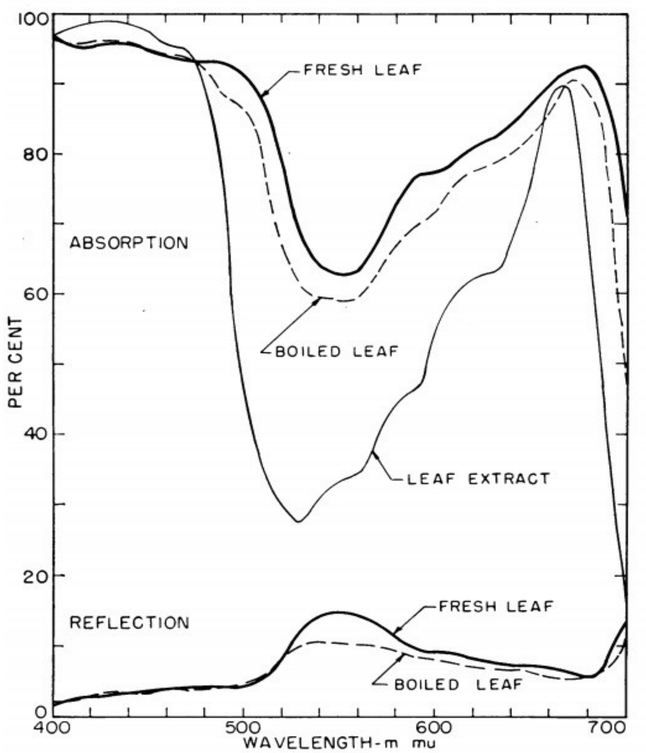


Fig. 2. Morphology of red leaf lettuce plants treated with light from a white fluorescent lamp (FL) and green light-emitting diodes (LED). Peak wavelength for each LED was 510 nm (G510), 524 nm (G520) and 532 nm (G530). Plants were photographed 17 d after sowing. Bars indicate 8 cm. Total photosynthetic photon flux was 100, 200 and 300 $\mu mol\ m^{-2}\ s^{-1}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

- Changes in peak wavelength of as small as 10 nm can have drastic effects on plant growth and health
- Secondary metabolites also important

Image Credit:Johkan, M. et al. 2012. “Effect of Green Light Wavelength and Intensity on Photomorphogenesis and Photosynthesis in *Lactuca sativa*,” Environmental and Experimental Botany 75:128-133.

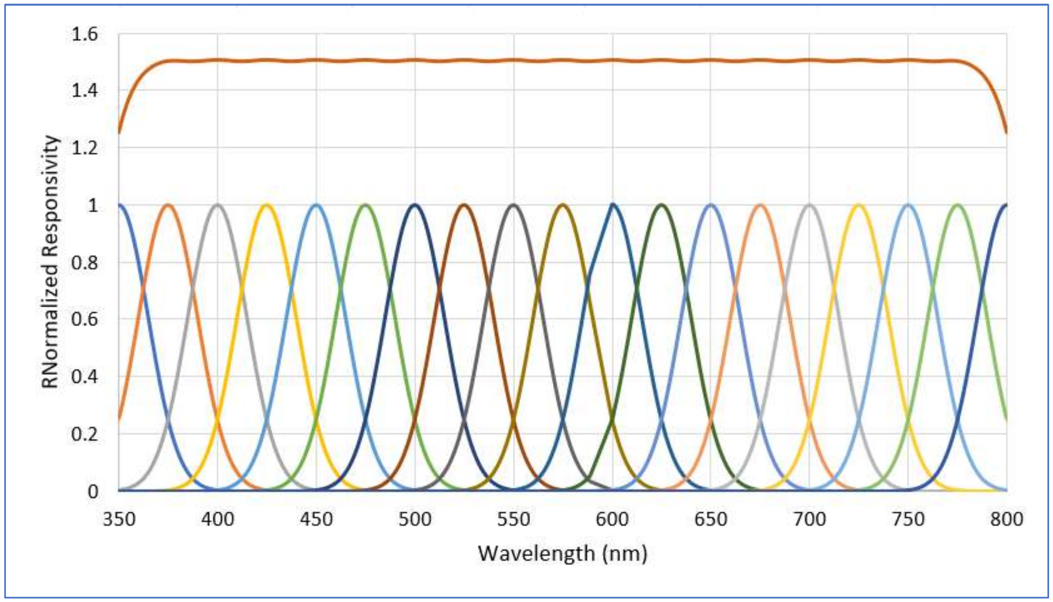
Plant Spectral Absorptance



- Plant photopigment spectral absorptances measured in solution (*in vitro*)
- Spectral absorptances *in vivo* broadened by:
  - Structural complexity of leaf
  - Screening by other photopigments
  - Presence of accessory photopigments
- Spectral reflectance distributions bandwidth-limited by:
  - Molecular interactions
  - Superimposed vibrational/rotational patterns
- Frequency limit of ~0.02 cycles per nm

Image Credit:Moss, R. A., and W. E. Lewis. 1952. "Absorption Spectra of Leaves. I. The Visible Spectrum," Plant Physiology 27(2):370-391.

Gaussian Radial Basis Function Approximation



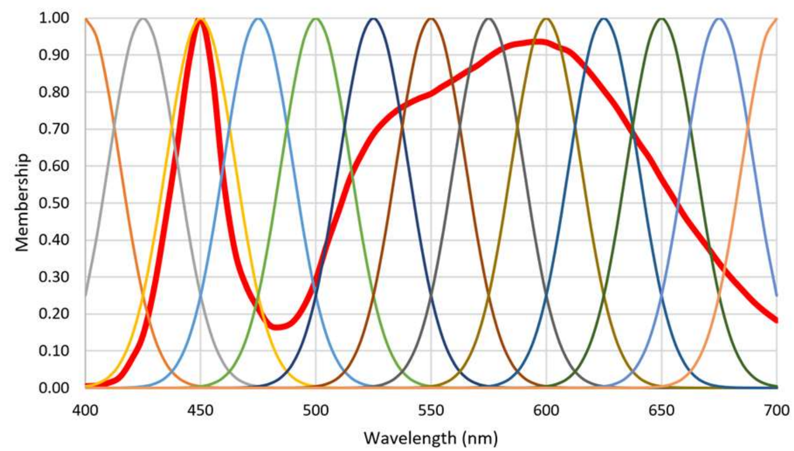
$$\varphi(r, x_i) = e^{-((r-x_i)/\varepsilon)^2}$$

$$\varepsilon = 12.5/\sqrt{-ln(1/\sqrt{2})} = 21.233$$

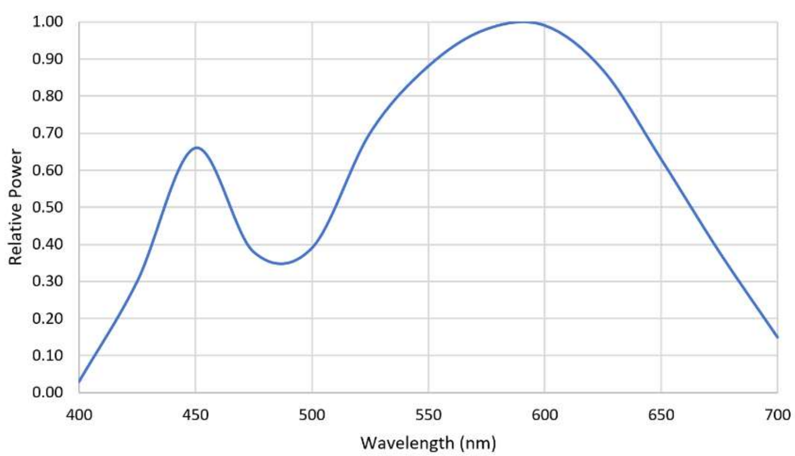
$$x_i = 350 + 25 * i \text{ for } i = 0, \ldots, 18$$

- Spectral power distribution approximated by sum of weighted Gaussian radial basis functions (RBFs)
- 18 functions sufficient to represent 350 nm – 800 nm spectral range
- 35 nm FWHM appropriate for horticultural applications
- Independent of human color vision

Gaussian Radial Basis Function Example

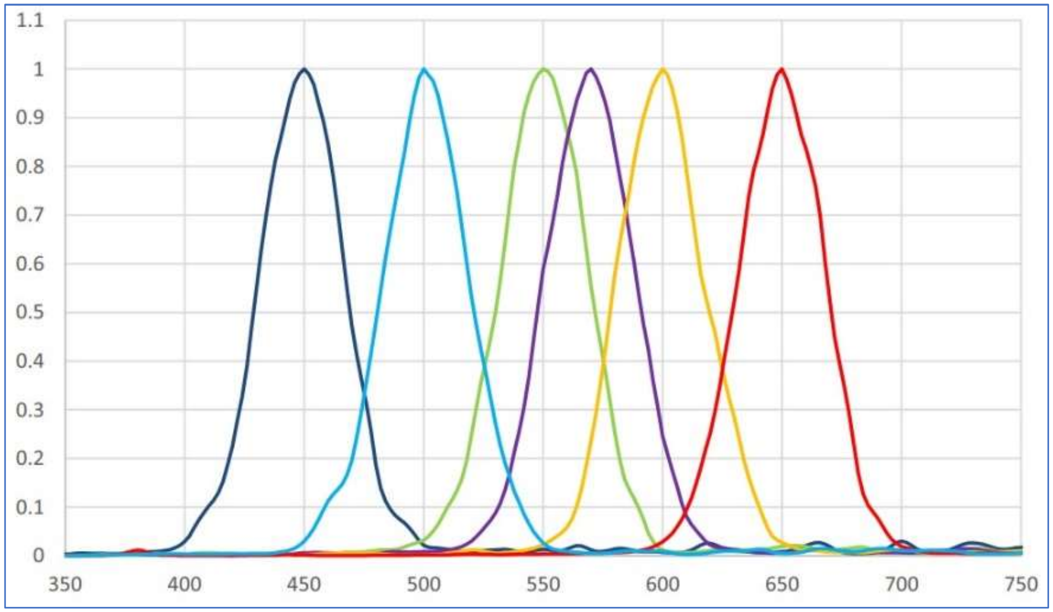


Wavelength	Weights
400	0.03
425	0.30
450	0.66
475	0.38
500	0.39
525	0.70
550	0.88
575	0.98
600	1.00
625	0.87
650	0.63
675	0.38
700	0.15



- Multiply 4000K white light LED spectrum by basis functions to obtain weights
- Cubic spline reconstruction using weights as knots
- Smoothed reconstruction adequately represents plant responses to spectral irradiance

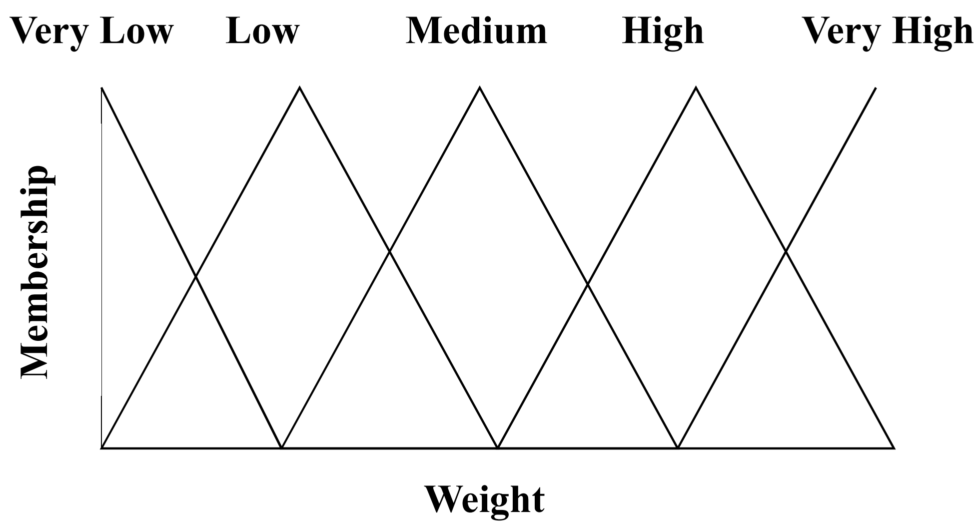
ams AS7262 6-Channel Spectral Sensor



- Commercial product implements approximate Gaussian RBF responses
- Possibility of inexpensive spectral sensor without need for spectroradiometer

Image Credit: ams AG. Premstaetten, Austria

Fuzzy Logic Classifier – Fuzzy Sets



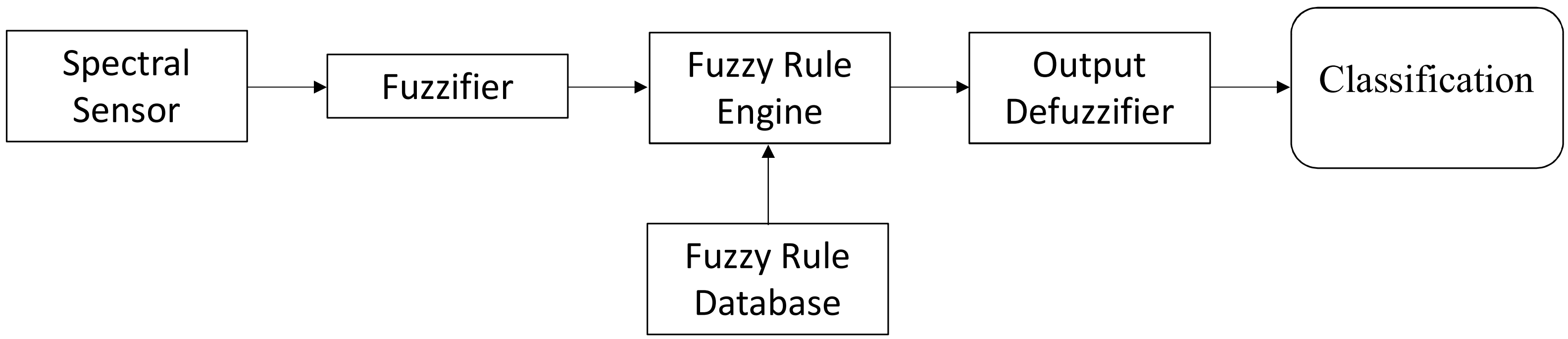
- Each RBF weight is "fuzzified" against membership functions
- Example only – triangular membership functions can also be trapezoidal or sigmoid

Wavelength	Weight	Very Low	Low	Medium	High	Very High
400 nm	0.03	0.88	0.12	0.00	0.00	0.00
425 nm	0.30	0.00	0.80	0.20	0.00	0.00
450 nm	0.66	0.00	0.00	0.36	0.64	0.00
475 nm	0.38	0.00	0.48	0.52	0.00	0.00

Fuzzy Logic Classifier – Fuzzy Rules

- Simplest possible fuzzy logic classifier
- Database of fuzzy *if-then* rules:
  - IF x_1 is low AND x_2 is high THEN output class is *Y*
- Each rule calculates a vote:
  - $\tau(x_1, x_2) = \mu_{low}(x_1)\ AND\ \mu_{high}(x_2)$
- Vote aggregation:
  - *output class* = $max\left(\tau_i(x_j, x_k)\right)$
- Other methods of calculating and aggregating votes available

Fuzzy Logic Classifier – System



- Framework for representing expert knowledge
- Represents effects of spectral power distributions on plant growth and health
  - Species and varietals
  - Growth stages
  - Environment conditions
- Classifies similar spectral power distributions

Summary

- Color names inappropriate for horticultural lighting
- Horticultural lighting SPDs represented by small number of RBF weights
- RBF functions smooth unimportant SPD details
- Fuzzy logic rules represent expert knowledge gained from horticultural research
- Fuzzy logic classifier resolves problem of determining similarity of two or more SPDs

Thank You