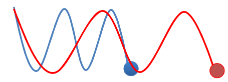
Plant Lighting Basics and Applications

Chieri Kubota
The University of Arizona
Tucson, AZ

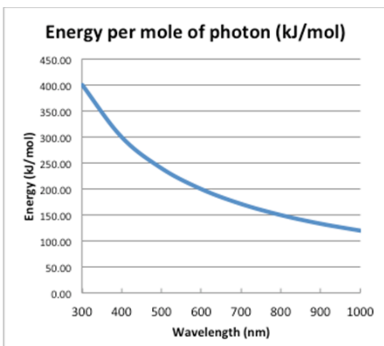
Keywords



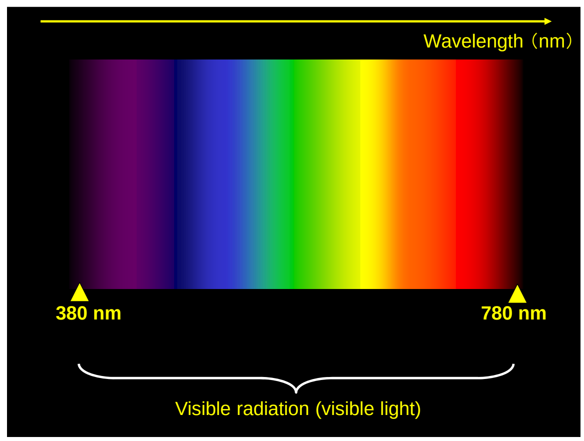
Light (radiation): electromagnetic wave that travels through space and exits as discrete energy packets (**photons**)
Each photon has its **wavelength**-specific energy level (*E*, in joule)

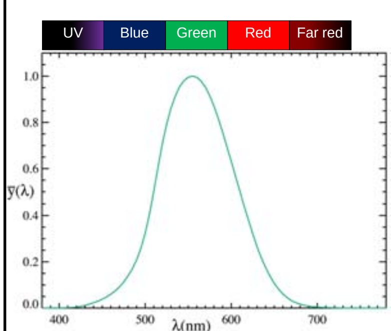
$$E = h \cdot c \ / \ \lambda$$

E: Energy per photon (joule per photon)
h: Planck's constant
c: speed of light
λ: wavelength (meter)



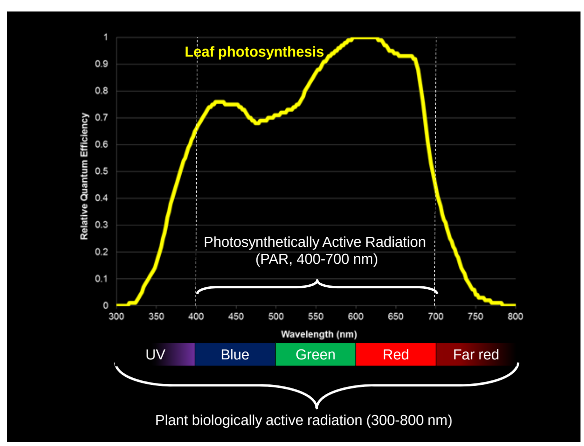
Energy per photon [J]: $E = h \cdot c \ / \ \lambda$
1 mole photons = 6.02×10^{23} photons

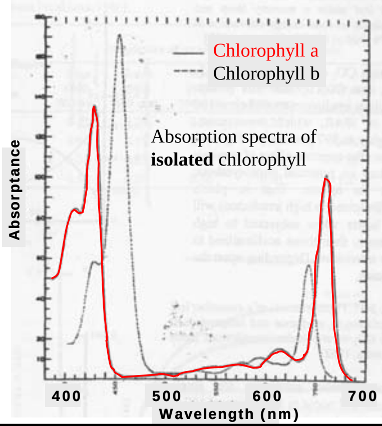




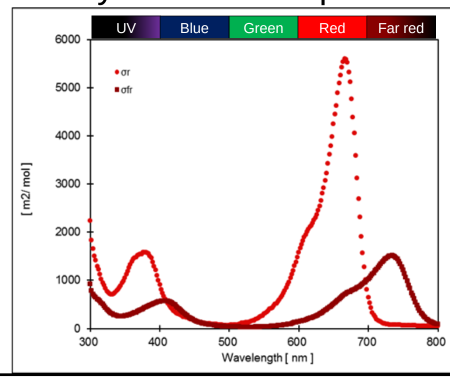
Human eye response peaks at green range.

Luminous intensity (footcandle or lux) does not work for plant light environment.





Phytochrome response

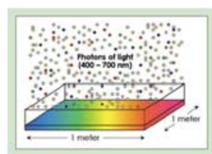


Light Unit and Terminology

	Radiation	Photons	Visible light
"Base" unit	Energy (J)	Photons (mol)	Luminous intensity (cd)
Flux [total amount received or emitted per time]	Radiant flux ($J\ s^{-1}$) or (W)	Photon flux ($\mu mol\ s^{-1}$)	Luminous flux (lm)
Flux density [total amount received per area per time]	Radiant flux density ($W\ m^{-2}$)	Photon flux (density) ($\mu mol\ m^{-2}\ s^{-1}$)	Illuminance, Luminous flux density (lux) or ($lm\ m^{-2}$) (fc) or ($lm\ ft^{-2}$)
Photosynthetic flux density [total amount potentially driving photosynthesis]	PAR (photosynthetically active radiation flux density) ($W\ m^{-2}$)	PPF (photosynthetic photon flux (density)) ($\mu mol\ m^{-2}\ s^{-1}$)	Not applicable

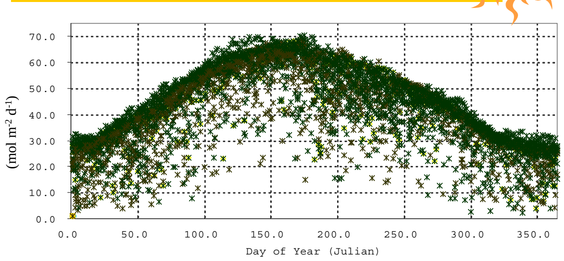
Daily light integral (DLI or Daily PPF)

- Total amount of photosynthetically active radiation (400-700 nm) received per sq meter per day
- Unit: mole per sq meter per day ($mol\ m^{-2}\ d^{-1}$)
- Under optimal conditions, plant growth is highly correlated with DLI.
- DLI = Potential growth
- "1% of light = 1% yield"



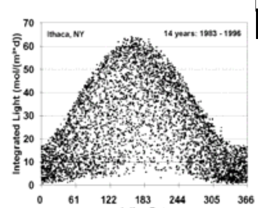
(Runkle 2006)

DLI in Tucson, AZ (1988-2001)

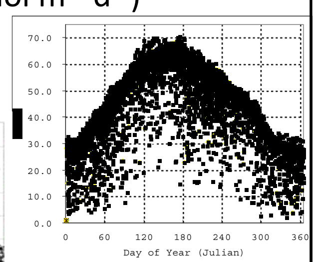


Kania and Giacomelli (2002)

DLI ($mol\ m^{-2}\ d^{-1}$)

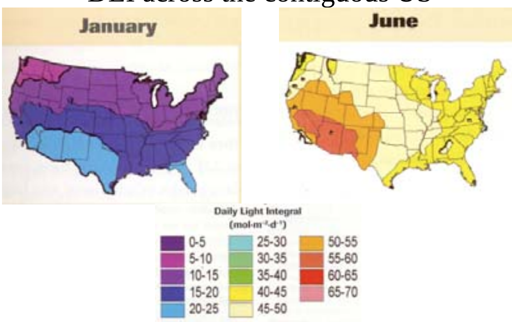


Ithaca, NY (1983-1996)



Tucson, AZ (1988-2001)

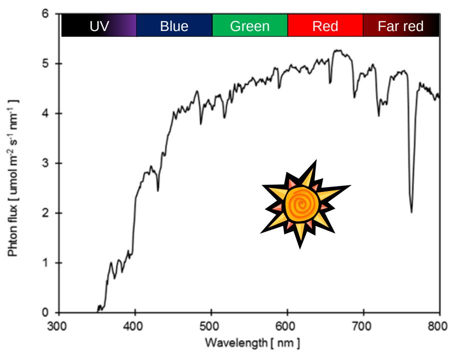
DLI across the contiguous US



(after Fisher and Runkle, 2004)

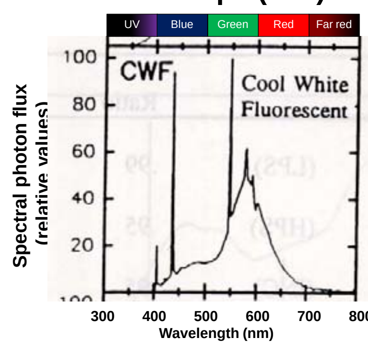
Solar radiation

- Intensity measured using two types of sensors
- Quantum sensor
  - Photosynthetic photon flux (PPF, 400-700 nm)
- Radiometer (pyranometer)
  - Actual sensing wavelength range varies depending on the sensor type (280 -2800 nm, 400 – 1100 nm etc.), but is designed to estimate the global solar radiation (300 – 3000 nm) in W m^{-2}.
  - When pyranometer is used, cumulative radiation level is expressed in MJ m^{-2}.

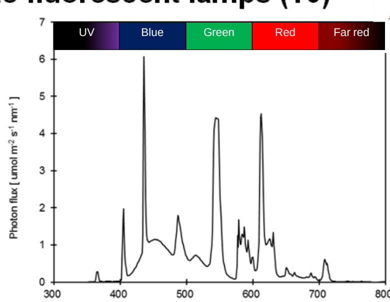


The full spectrum of sun light is 300 to 3000 nm!
(radiation in 800 – 3000 nm is nothing but heat)

Fluorescent lamps (T12)



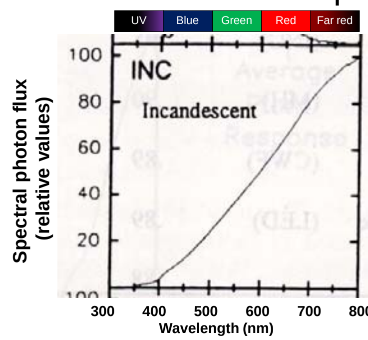
White fluorescent lamps (T5)



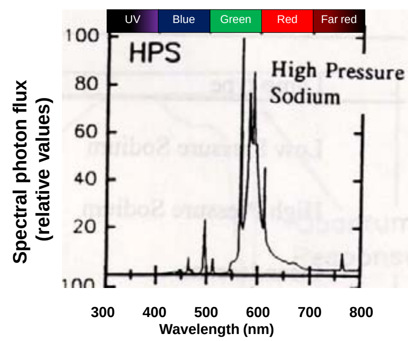
T5 white fluorescent lamp

Use of fluorescent lamps in rose propagation facility

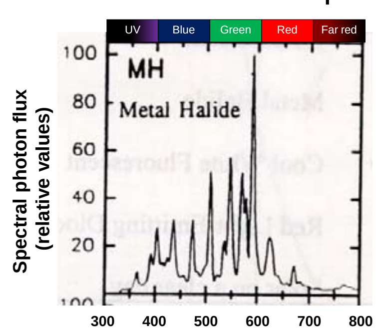
Incandescent lamps

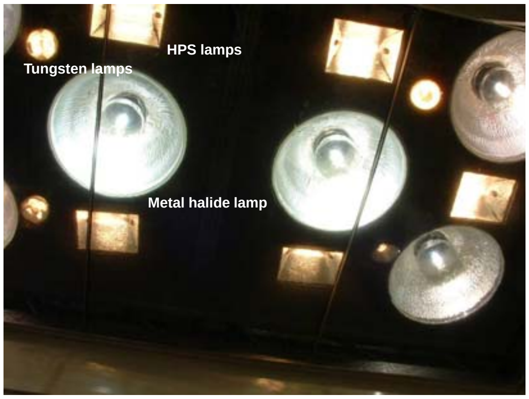


High Pressure Sodium lamps

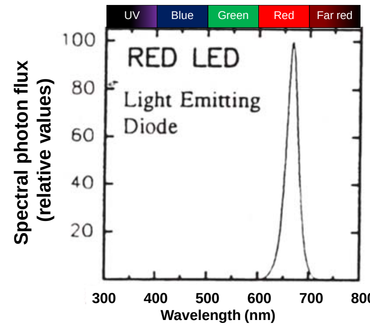


Metal halide lamps

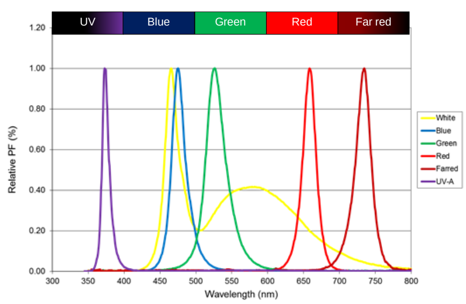




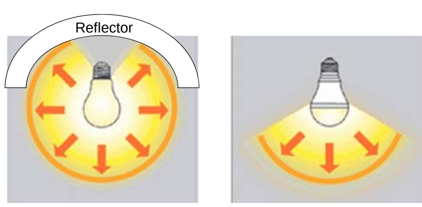
LED (Light Emitting Diodes)



LED of different colors (spectra)



Red and blue LEDs (courtesy of H.-H. Kim)



Conventional light distribution is wide
Advantage:
Uniformity
Disadvantage:
Significant loss at reflector

LED light distribution is narrow
Advantage:
Small reflector loss
Disadvantage:
Non-uniform light distribution

Important keys to evaluate artificial lighting

- Energy conversion efficiency
  - Watt to watt conversion
  - Watt to μmol s^{-1} conversion (Note: lm/W is useless information for plant lighting)
  - Spectral quality
  - Effective light flux per fixture (μmol s^{-1} per fixture)
  - Light distribution
- Plant response

Comparisons of different light sources

Lamps	Input (W)	Light flux (lm)	Effi-ciency (lm/W)	Life (h)	Price (Yen or $)	Price per lumen (Yen or $)
Hf-fluorescent lamps* (25.5 mm W x 1198 mm L)	32	3,520	110.0	12,000	1,470 yen	0.42 yen ($0.005)
LED lamps* (fluorescent lamp type) (25.5 mm W x 1198 mm L)	27.2	2,400	88.2	40,000	16,000 yen	6.67 yen ($0.083)
HPS (400 W lamp)	440**	44,000***	100	12,000	$150	$0.003

* Data after Kozai (2011)
**Power including ballast
***Effective light flux (after reflector loss)

Comparisons of different light sources

Lamps	Efficiency W/W %	Efficiency Photon flux /W (μmol s^{-1} W^{-1}) or (μmol J^{-1})
Hf-fluorescent lamps	25-28%	1.5*
LED (red)	22-32%	1.5-1.6**
LED (blue)	22-49%	
HPS	20-39%	1.4*
MH	22-30%	--

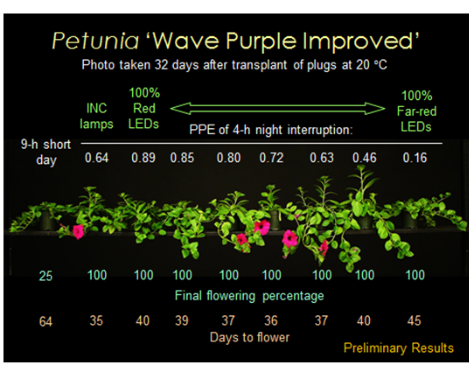
* Estimated from lumens converted to photons by factors reported by Thimijan and Heins (1983)
**Phillips catalogue data for GreenPower LED (Red + Blue)

LEDs in Horticulture

- Increasing interest worldwide
- Challenges
  - High fixture costs
  - Limited information on optimization (light quality, design and application methods)
- Opportunities
  - Maximizing photosynthesis
  - Photomorphology or photoperiodic control
  - New applications

Incandescent Lamps

- 100-year old technology
- Rich in yellow, red, and far-red in addition to thermal radiation.
- Widely used in horticulture for photoperiodic as well as supplemental photosynthetic lighting.
- The only widely available light source containing far-red radiation.
- Currently horticulture use is exempt from the phase-out, but the limited access may increase the price.



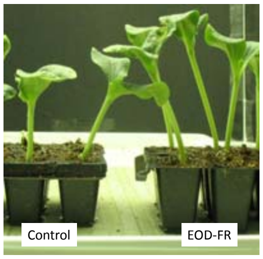
Runkle et al. Preliminary results using red and far-red LEDs at MSU. (PPE = phytochrome photo equilibrium or photostationary state)

Far-red LEDs

- Current LED market is for visible range (~380 – 680 nm), UV and NIR (>800 nm), leaving far-red (700 – 800 nm) without much development.
- Far-red (response peak at 735 nm) is a light quality relevant to plant growth/development.
- LED technology enables monochromatic far-red lighting.

End-of-day FR Light Treatment for Cucurbit Seedlings Grown under Artificial Lighting

Preliminary Experiment



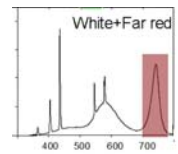
Plant species:
C. maxima x C. moschata 'Tetsukabuto'

Main light source:
Cool White fluorescent lamp
PPF: 150 µmol m^{-2} s^{-1} (400-700 nm)
Photoperiod: 12 hours

EOD FR treatment:
Intensity: 4 µmol m^{-2} s^{-1} (700-800 nm)
Duration: 30 min EOD for 3 days
FR Dose: 7200 µmol m^{-2} d^{-1}

Supplemental FR Lighting for Baby Leaf Lettuce under Artificial Lighting

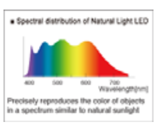
- Supplemental far-red light significantly increased the biomass of baby lettuce plants by 28%.
- This was due to the increased light interception caused by enhanced leaf elongation.
- Similar observation by Stutte et al. (2009).



(Li and Kubota, 2009)

Natural color LEDs

- Currently used for museums and retail stores
- Wavelength similar to sunlight
- Some products have very accurate color representation (Color Rendering Index: 98)
- Possible applications in certain types of plant factories
- Plasma lamps may have similar advantage.

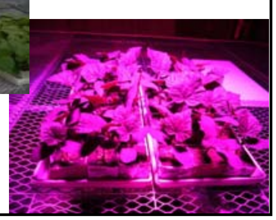


www.ccs-grp.com

(Nederhoff, 2010)

(Mitchell et al., 2012)

Testing supplemental LED lighting in greenhouse propagation



Developing LED Lighting Technologies and Practices For Sustainable Specialty-Crop Production

- **Funded by USDA SCRI Grants (2010-2014)**
- **Our overall goal is to enable specialty-crop growers working in CEA to successfully transition from traditional horticultural lighting sources to LED technologies.**
- **4 state universities, 15 supporting industry members**