# Measuring LED Lighting Systems and Developing Guidelines for Evaluation, Comparison and Use

SCRI-LED

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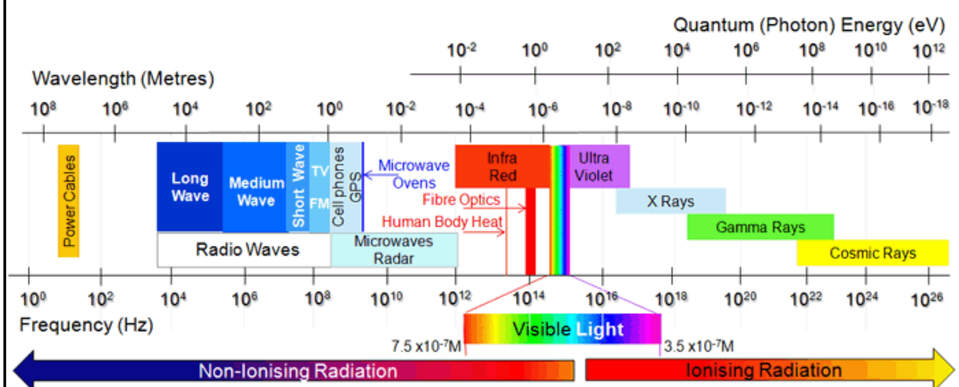
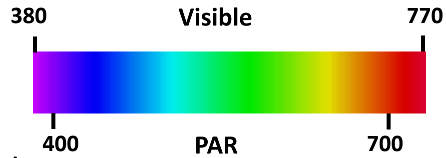
- Electromagnetic radiation spectrum




Ionizing radiation: able to detach an electron

http://www.sura.org

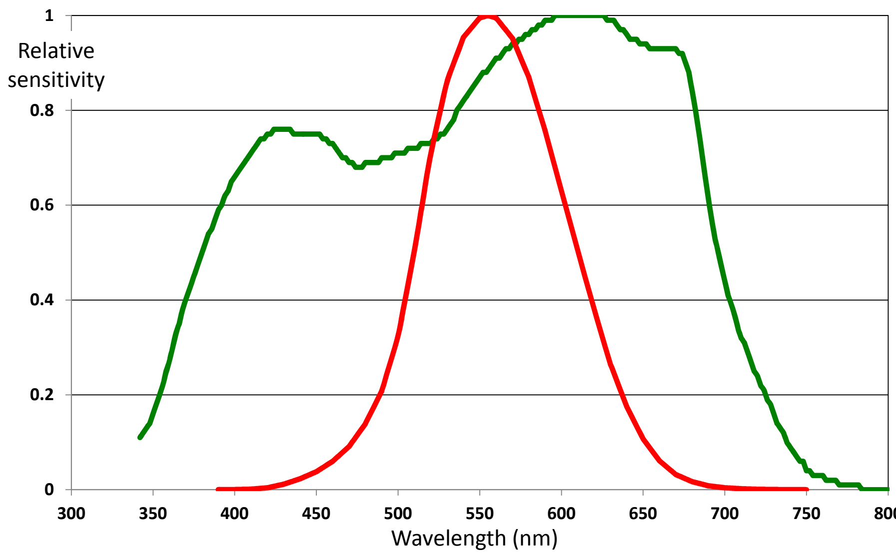
- Light, sensors, and units
  - Light:
    - Visible (380-770 nm)
    - PAR (400-700 nm)
    - Sunlight (280-2,800 nm)




  - Sensors:
    - Foot-candle or Lux meter (Visible)
    - Quantum sensor (PAR)
    - Pyranometer (Sunlight)
  - Units:
    - ft-cd or lux
    - $\mu mol/(m^2 * s)$ or $mol/(m^2 * d)$
    - $W/m^2$ (Note: radiant Watt)

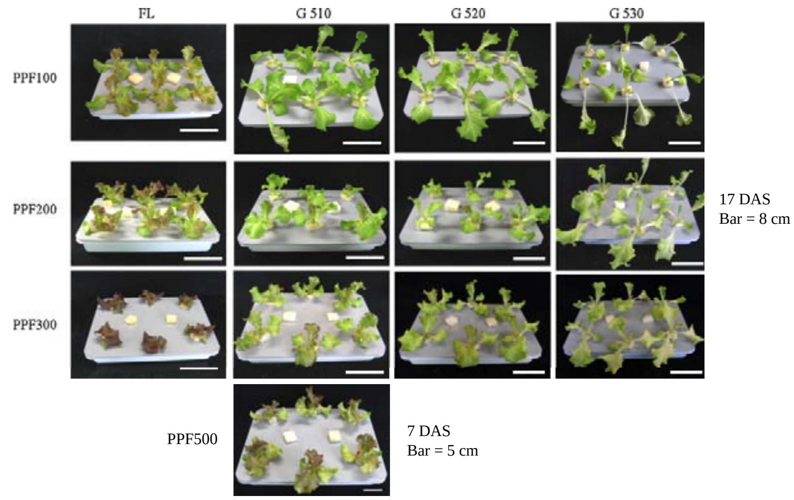
1 ft-cd = 1 $lumen/ft^2$
1 lux = $lumen/m^2$
1 ft-cd = 10.76 lux

- Comparing human and plant sensitivity to light




References: Sager et al. (1988) Transactions of the ASAE 31(6):1882-1889; CIE

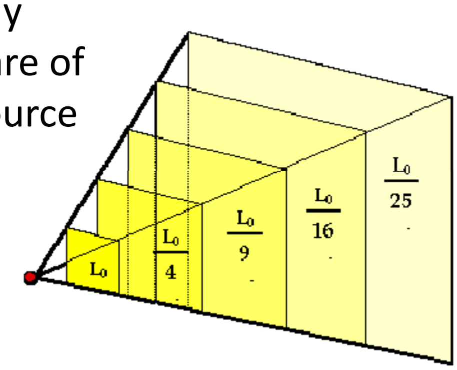
- Effect of green light on plants?




M. Johkan et al. 2012. Environmental and Experimental Botany 75:128–133

- Light measurements

- Photometric: Visible (lux, ft-c)
- Quantum: PAR (µmol/($m^2$s))
- Radiometric: Energy (W/$m^2$)
- Light intensity is inversely proportional to the square of the distance from the source




An example of the "one over r squared" relationship for light

http://imagine.gsfc.nasa.gov

- Directional light meters


**http://img.directindustry.com**

**http://img.directindustry.com**

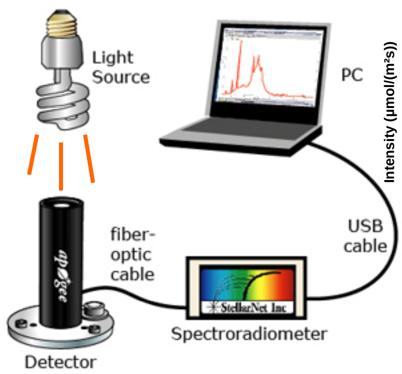
**http://www.envcoglobal.com**

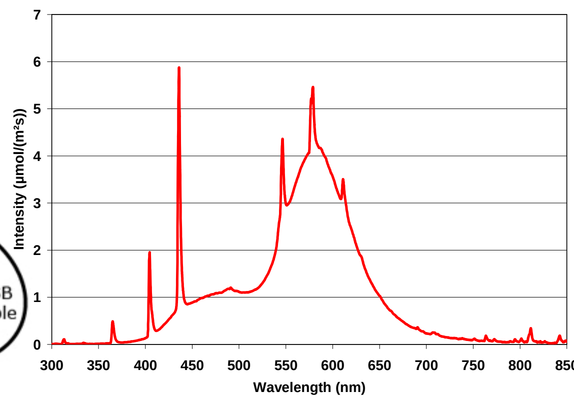
**http://img.directindustry.com**

- Omni-directional light sensor: integrating sphere

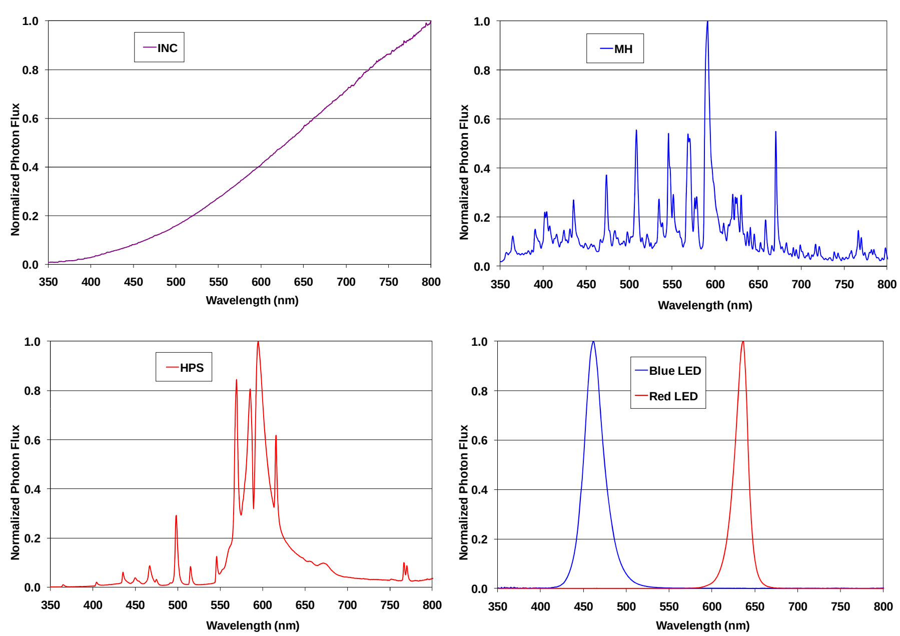
**http://www.nytimes.com**

- Measuring light spectrum: spectroradiometer



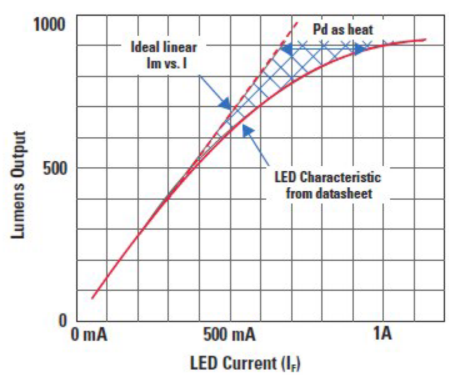




- Spectral output of various lamps



- Transitioning to LED lighting for horticulture

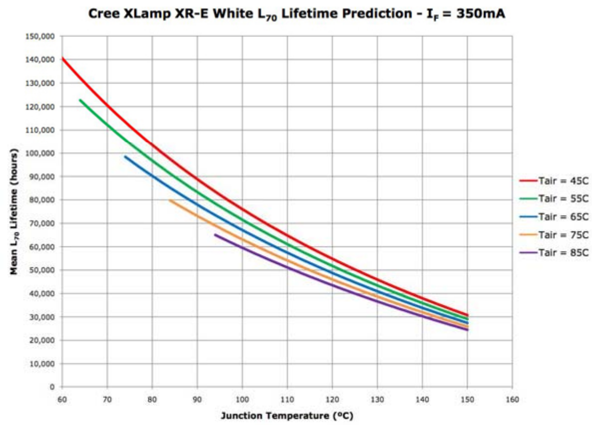
- Effects of LED dimming?
  - Is it desirable for horticultural applications?
  - What does it do the efficacy?
  - Does it change the spectral output?




http://www.electronics-lab.com

# • Effects of LED junction temperature (Is this an issue?)


**http://ewh.ieee.org**




**http://www.electronics-lab.com**

$L_{70}$ = lumen depreciation to 70% of initial lumen output
(By the way, is this acceptable for horticultural applications?)

# • Planned LED lighting system evaluations

- Supplemental lighting: Spectral distribution (350-800 nm; percentages of B, G, R, FR), luminaire location (above and/or within the canopy), PAR intensity (for targets of 50, 100, 150, and 200 $\mu mol/(m^2 s)$) and distribution (both these requirements vary by crop) for a specific mounting height and luminaire spacing pattern, directionality of the emitted light (evaluating for light pollution)
- Photoperiod lighting: R:FR ratio, intensity (target 1-2 $\mu mol/(m^2 s)$) and distribution for a specific mounting height and luminaire spacing pattern (continuous or cyclic operation)
- Electric power consumption per luminaire and supply voltage
- Luminaire dimensions and weight
- Luminaire life expectancy (estimated, based on equipment components and light depreciation)
- Design features that allow for operation in greenhouse environments (moisture, heat, chemicals)
- Cost (installation and operation)

## Additional considerations

### *Introduction*

Conditions in controlled environment plant growth rooms and chambers (CE units) should be reported in detail for comparison of results and duplication of experiments. The minimum guidelines table, along with these notes, should help meet these aims, indicating a required, minimum amount of information that should be reported. They may also highlight parameters that could be important, but that may not have been considered for measurement.

Average measurements should be reported, including their temporal standard deviation (s.d.).

All sensors should be calibrated regularly according to manufacturer's procedures and suggested frequency.

### *Radiation*

- Output of all electric radiation sources decreases with hours of operation e.g. for some fluorescent lamps output may drop 20% after the first five months of use.
- Irradiance varies significantly across the growing area in many CE units.
- Vertical radiation gradients occur in all CE units, depending on chamber size, lamp type, lamp distribution, and luminaire shape.
- Spectra from electric lamps generally differ from that of the sun. Unnatural red to far-red light ratios may affect morphogenesis in some plants and photomorphogenic effects should be considered when interpreting results.

### *Temperature*

- Differences may exist between the temperatures of the air and plant, especially under high radiation loads.
- Older on-off control systems can result in as much as ±5°C variation from the set point temperature.
- A vertical temperature gradient occurs in most CE units, depending on airflow rates and other factors.

### *Atmospheric moisture*

- Air humidity affects plants in CE units directly (via transpiration and gas exchange) and indirectly (via the plant's energy balance and physical and biological environment).
- Heating and cooling cycles lasting only 1 to 3 minutes can change absolute humidity by 1 to 2%, altering relative humidity by 20 to 40%.
- Air humidity is a challenging parameter to monitor, but is critical to plant water relations and infection by foliar pathogens. Relative humidity (RH) is acceptable for reporting humidity until CE units can control vapour pressure deficit (VPD), or portable instruments are available to measure and display VPD.

### *Carbon dioxide*

- Carbon dioxide ($CO_2$) is probably the least controlled environmental parameter in CE studies. Unfortunately, too little or too much $CO_2$ is hard to detect until plants start to show specific symptoms.
- Small variations in $CO_2$ can affect plant growth and development significantly. People in or around CE units, and even greenhouses, can increase $CO_2$, as may motor vehicles, heating systems, and other nearby sources that produce $CO_2$.
- Few CE units manufactured today have $CO_2$ control or monitoring equipment installed as a standard feature. However, most do have some degree of ventilation or air exchange, and good air exchange can moderate $CO_2$ build-up or depletion.
- Even if a CE unit is well ventilated, it is important to remember that the surrounding area with which it exchanges air should also be well ventilated.

### *Experimental design issues*

- Ideally, a single CE unit should be treated as a single replicate. True replication requires using multiple CE units, or repeating treatments in each unit with time, both expensive and time consuming options.
- Regular transfer of plants between CE units may be an alternative to avoid direct confounding of effects of an imposed environment with that of a CE unit.
- Repeating experiments in a CE unit with poorly controlled or monitored environmental parameters may lead to erroneous assumptions about treatment conditions and resulting data.

### *Example of a report suitable for publication*

The experiment was conducted in a 3 m by 4 m growth room equipped with cool white fluorescent lamps (Model 830, Philips) mounted above a clear glass barrier, and an upward airflow distribution system using sufficient outdoor make-up air to provide ambient $CO_2$ conditions inside the room. The room air temperature was maintained at 25/20°C (s.d. ±2/1°C) during the light/dark period. The photosynthetically active radiation (PAR) at the top of the canopy was maintained at 400 $\mu mol\ m^{-2}\ s^{-1}$ (s.d. ±10 $\mu mol\ m^{-2}\ s^{-1}$) during the 12-hour photoperiod. The relative humidity in the room was maintained at 70% (s.d. ±10%). The plants were grown in 1 L pots filled with a peat-vermiculite (2:1 volume ratio) mixture. The plants were hand watered daily with a freshly prepared nutrient solution (full strength Hoagland, pH 6).

International Committee for Controlled Environment Guidelines

## Minimum Guidelines for Measuring and Reporting Environmental Parameters for Experiments on Plants in Growth Rooms and Chambers

Sponsored by and published for the UK Controlled Environment Users' Group, the North American Committee on Controlled Environment Technology and Use (NCR-101), and the Australasian Controlled Environment Working Group

**March 2004**

## Minimum Guidelines for Measuring and Reporting Environmental Parameters for Experiments on Plants in Growth Rooms and Chambers

International Committee for Controlled Environment Guidelines

| Parameter to measure | | Units [1] | Where to measure | When to measure | What to report |
|---|---|---|---|---|---|
| *Radiation* | Photosynthetically active radiation (PAR) [2] | $\mu mol\ m^{-2}\ s^{-1}$ | Top of plant canopy in centre of growing area | At start and end, and every 2 weeks of the experiment | Average and standard deviation. Radiation source (type, model, and manufacturer) |
| *and* | Photoperiod | h | | | Duration of light and dark periods |
| *Temperature* | Air | °C | Top of plant canopy in centre of growing area | Daily during each light and dark period, at least 1 hour after light/dark change | Average and standard deviation |
| | Liquid culture | °C | Within solution under plants | As above for air temperature | Average and standard deviation |
| *Atmospheric moisture* | Water vapour pressure deficit (VPD) | kPa | Top of plant canopy in centre of growing area | Daily during each light and dark period, at least 1 hour after light/dark change | Average and standard deviation |
| *or* | Relative humidity (RH) | % | As above for VPD | As above fpr VPD | Average and standard deviation |
| *Carbon dioxide* [3] | | $\mu mol\ mol^{-1}$ | Top of plant canopy | At least hourly | Average and standard deviation |
| *Air velocity* [3] | | $m\ s^{-1}$ | At one or more representative canopy locations | At least once during the experiment | Average and standard deviation |
| *Watering* | | litre (L) | | Daily | Frequency, amount and type of water added |
| *pH* | Liquid culture | pH | In the bulk solution | Before and after pH correction | Average and standard deviation |
| *Electrical conductivity (EC)* [3] | Liquid culture | $S\ m^{-1}$ | In the bulk solution | Before and after EC correction | Average and standard deviation |
| *Substrate* | | | | At start of the experiment | Type and volume per container, components of soil-less substrate, container dimensions |
| *Nutrition* | Solid media | $mol\ kg^{-1}$ (dry) | | When added or replenished | Nutrients and their form added to soil media |
| | Liquid culture | $mmol\ L^{-1}$ | | Daily, or when replenished | Ionic concentration in initial and added solution. Aeration if any. Volume of initial solution |
| *Room or chamber properties* | Specifications | | | | Floor area. Manufacturer and model if available |
| | Barrier beneath lamps | | | | Indicate if present and its composition |
| | Air flow | | | | Indicate whether up, down or horizontal |

1 Report in other multiples or sub-multiples of indicated units if more convenient.
2 Referred to as photosynthetically active radiation (PAR: 400-700 nm) for general usage and described as photosynthetic photon flux density (PPFD) by many journals, professional societies, and manufacturers of quantum sensors. When diurnal PAR is ramped, integrals should be reported, e.g. in $mol\ m^{-2}\ d^{-1}$.
3 This parameter should be reported if records are available and always when it is a variable under investigation. For more information, consult the detailed guidelines published as ANSI/ASAE Engineering Practice EP411.4 (2002) 'Guidelines for measuring and reporting environmental parameters for plant experiments in growth chambers'. ASAE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA.