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www.strategiesinlight.com

2013 Strategies in Light

Photons and Plant Physiology

The Potential of Photomorphogenesis and Healthier Food with LEDs

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Selected Milestones in Applied Photobiology

1779
J. Ingenhousz discovers photosynthesis

1883
T. Englemann finds PAR region

1940s…
Multidisciplinary studies of photosynthesis

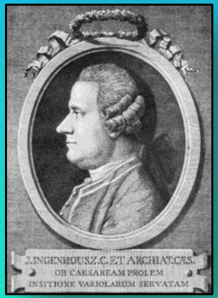
1700 **1800** **1900** **2000**

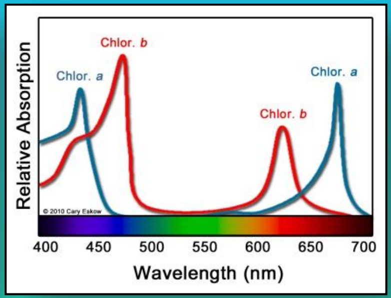
LED plant factories

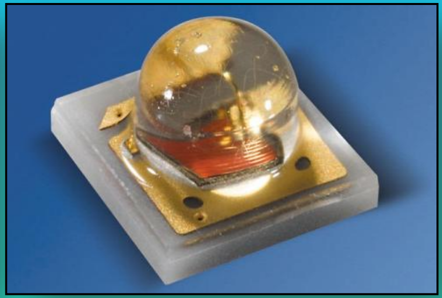
1773
J. Priestly associates light with energy in plants

1920s…
Photoperiodism SDP, LDP, etc.

1970s…
Photomorphology, action spectra



Plant Factories

Production-scale optimized greenhouses

- The plant factory concept developed in the 1980s
- Continuous, high-yield production (2X – 5X)
  - Controlled, automated environment
  - Seasonally invariant; stabilized costs
  - Highly efficient space/land utilization
  - Typically pesticide/chemical free
- Accelerating market for specialized PF grow lights
  - 2009: **$127 M**
  - 2011: **$741.6 M**
  - 2018 forecast: **$4 B**
  - Substantial opportunity for IP development by leveraging LEDs, photoperiodicity and photomorphogenesis

Ozu Corporation, Japan

Sources: WinterGreen Research, *Plant Factory and Grow Lights Market Shares, Strategies, and Forecasts, Worldwide, 2012 to 2018*

Agenda

- Photosynthetically active region (PAR)
- Photoperiodicity and photomorphogenesis
- Leaf spectral analysis – Avnet LightLab
- Phytochemicals
- A potential role for UV-B
- Conclusions

Photosynthetically active region (PAR)

Portion of the spectrum that enables photosynthesis in green plants

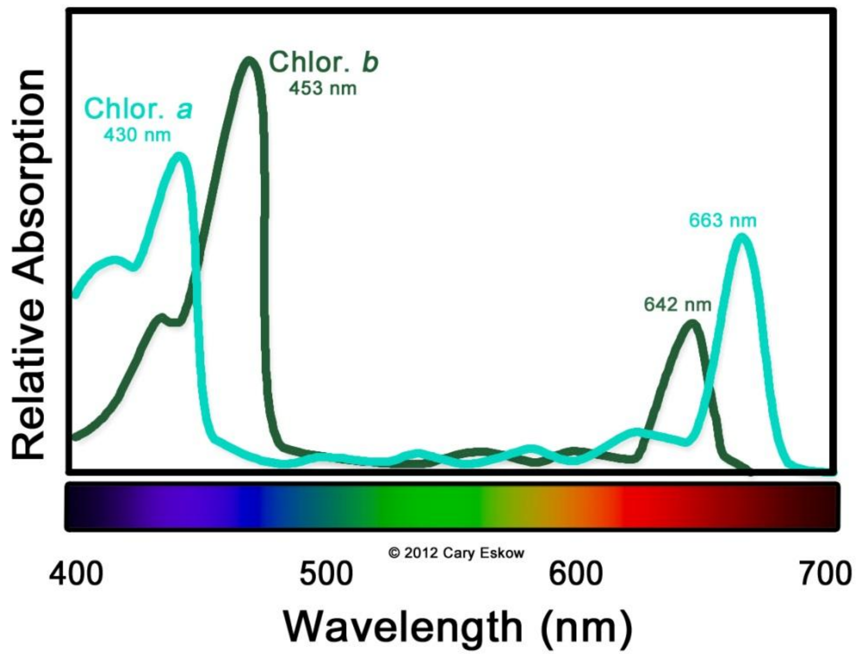
- Chlorophyll
  - Found in chloroplasts of green plants
  - Facilitates conversion of light into energy
  - Absorption peaks are in red and blue regions; green is *reflected*

- At a "macro level", light catalyzes CO2 and water, producing glucose and oxygen

$$6\ CO_2 + 6\ H_2O \xrightarrow{\text{chlorophyll in sunlight}} \underset{\text{(glucose)}}{C_6H_{12}O_6} + 6\ O_2$$

Photosynthetically active region (PAR)

- The two most common types found in green plants are chlorophyll *a* and *b*
  - LEDs closely matched to chlorophyll *a* are now available
  - Chlorophyll *a* absorption peaks are at 430 nm and 663 nm
  - Example, Osram “Oslon” with a peak wavelength at 660 nm



Photosynthetically active region (PAR)

- PAR-matched LEDs vs. high-pressure sodium lamps for photosynthesis
  - More energy efficient
  - Lifetime of *properly designed* LED systems can exceed 80K hours
  - Good coupling to chlorophyll maxima
  - Easy to control (modulate, dim, etc.)
  - Potential for hybrid/dynamic system using LEDs + daylight
  - Low heat, small size and weight
    - Can be placed directly above plant

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Photoperiodicity

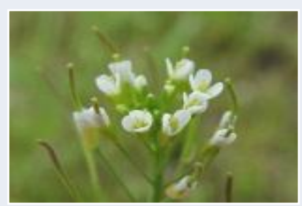
- Plants utilize light for *sensing*, in addition to photosynthesis
- One important characteristic that is sensed is light *duration* - used to predict and adapt to critical seasonal and environmental changes, or to be "opportunistic"
  - When short days are perceived, a woodland plant might be triggered to flower and seed before other plants are able to create a sun-blocking canopy of dense leaves
  - Other plants might synchronize their reproductive cycles to day length in order to coordinate internal processes with annual dry and rainy periods

- Plants can be categorized according to what photoperiodic stimulus results in their flowering

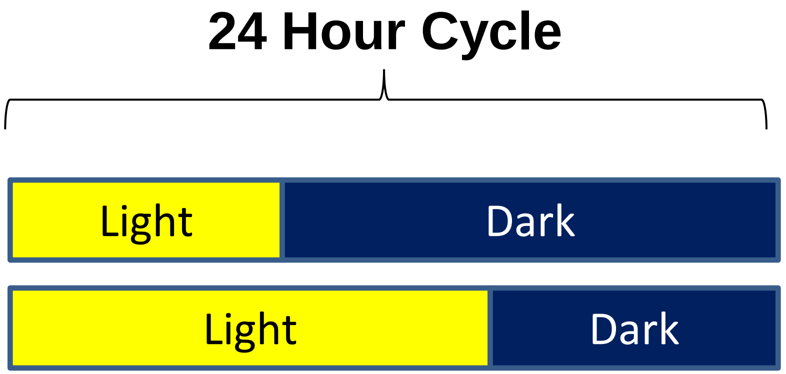
Photoperiodicity

- The three main categories are:
  - ***Short-day plants (SDP):*** Flower or flower more rapidly when the number of hours darkness exceeds a certain threshold
  - ***Long-day plants (LDP):*** Flower or flower more rapidly when the number of hours of darkness is less than a certain threshold
  - ***Daylength-neutral plants (DNP):*** Flower at the same time irrespective of the light/dark period
- Nature hides its secrets well… some plants require a sequence of short and long days to initiate flowering

Photoperiodicity: Examples

Short-Day Plants	Long-Day Plants	Day-Neutral Plants
Flower in late summer and autumn days get shorter, nights get longer	Flower in spring and early summer days get longer, nights get shorter	
 Rice	 Spinach	 Tomato
 Soybean	 Radish	 Cucumber
 Morning Glory	 Arabidopsis	 Rose

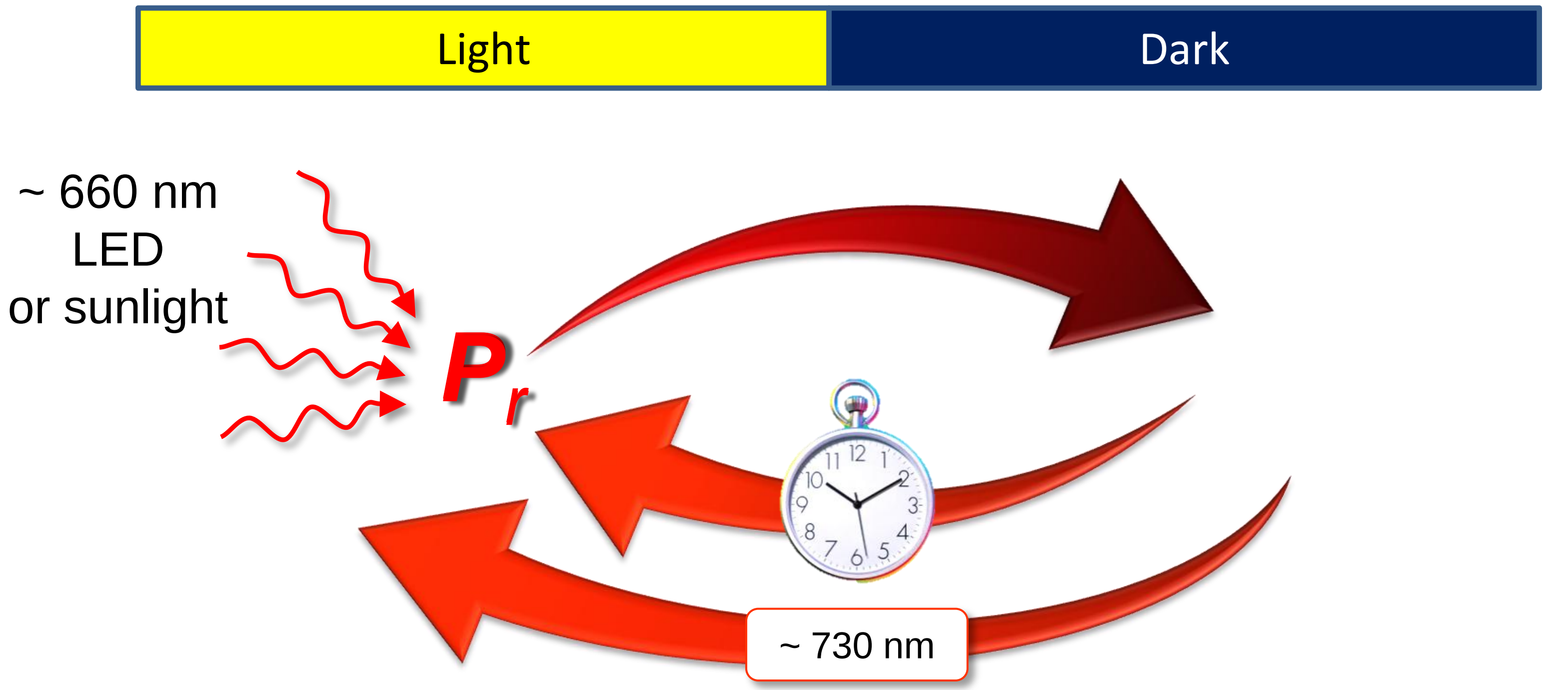
Photoperiodicity and photomorphogenesis



Short-Day Plant (SDP)	Long-Day Plant (LDP)
Flowering	Vegetative
Vegetative	Flowering

- A short flash of intense red light from an LED array during the dark will keep a short-day plant in the vegetative state, and initiate flowering in long-day plant
- Generally, only several minutes of red light are required
- Photomorphogenesis outside of flowering has not been extensively studied
- Many plants have yet to be characterized with regard to their photoperiodicity

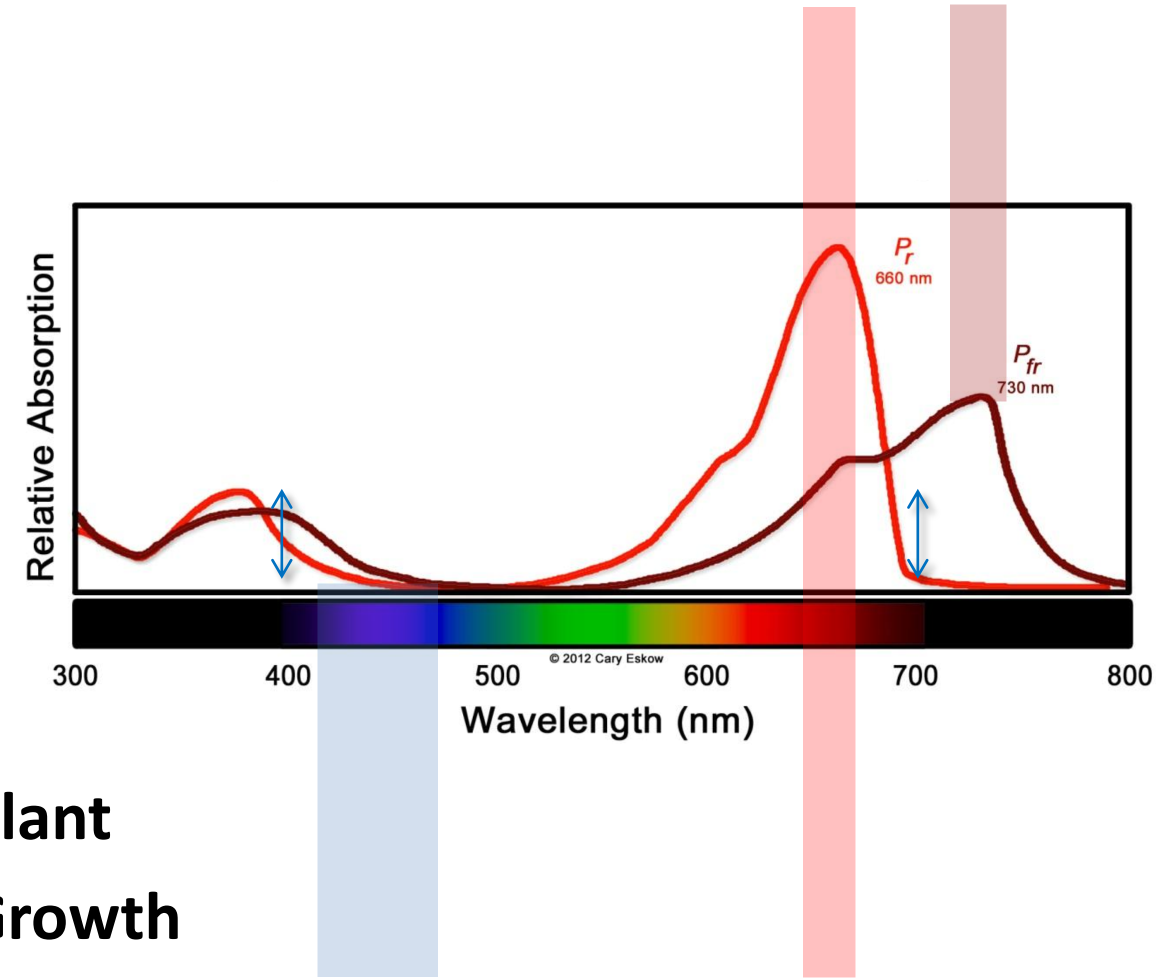
Photoperiodicity and photomorphogenesis



- Red light (~ 660 nm) converts the biologically inactive phytochrome P_r into its bio-active form $P_{fr\,;}$ LDPs will flower even during SDs, SDPs will stay vegetative during SDs
- Over time (in continuous darkness) P_{fr} reverts to P_r
- Interestingly, P_{fr} also reverts to P_r when exposed to far red (~ 730 nm) light – *the process is reversible*; LDPs will flower during SDs, SDPs will stay vegetative during LDs

Photoperiodicity and photomorphogenesis

Plant Control



Plant Growth

Important LED λ:

~ 660- 664 nm
- Photosynthesis
- Photomorphology
- Osram, Lumileds, others

~ 715 - 740 nm
- Photomorphology
- Shade Avoidance Syndrome
- LedEngin

~ 430 – 455 nm
- Photosynthesis
- Lumileds royal blue
- Osram blue L.D.
- Nichia blue L.D.

Not a complete list

Shade Avoidance Syndrome

Mediated, in large measure, by the ratio of red to far-red light

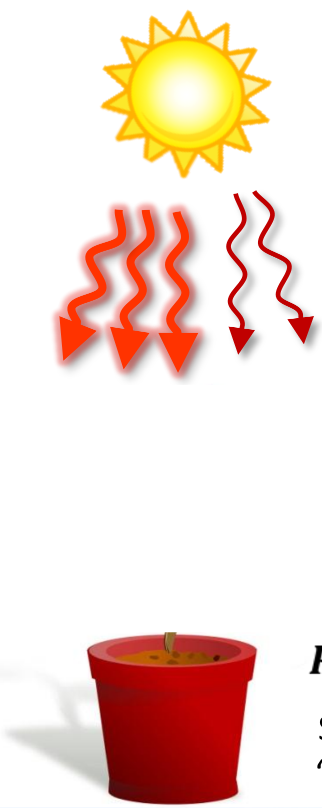
- When plants grow in *close proximity*, there is competition for light
  - An abundance of neighboring plants
  - A plant growing under a tall canopy of other leafy plants

- Evolved survival strategy:
  1. Is the shade caused by <u>other plants</u>? (not inanimate objects, clouds, etc.)
  2. If so, grow *differently*

Shade Avoidance Syndrome

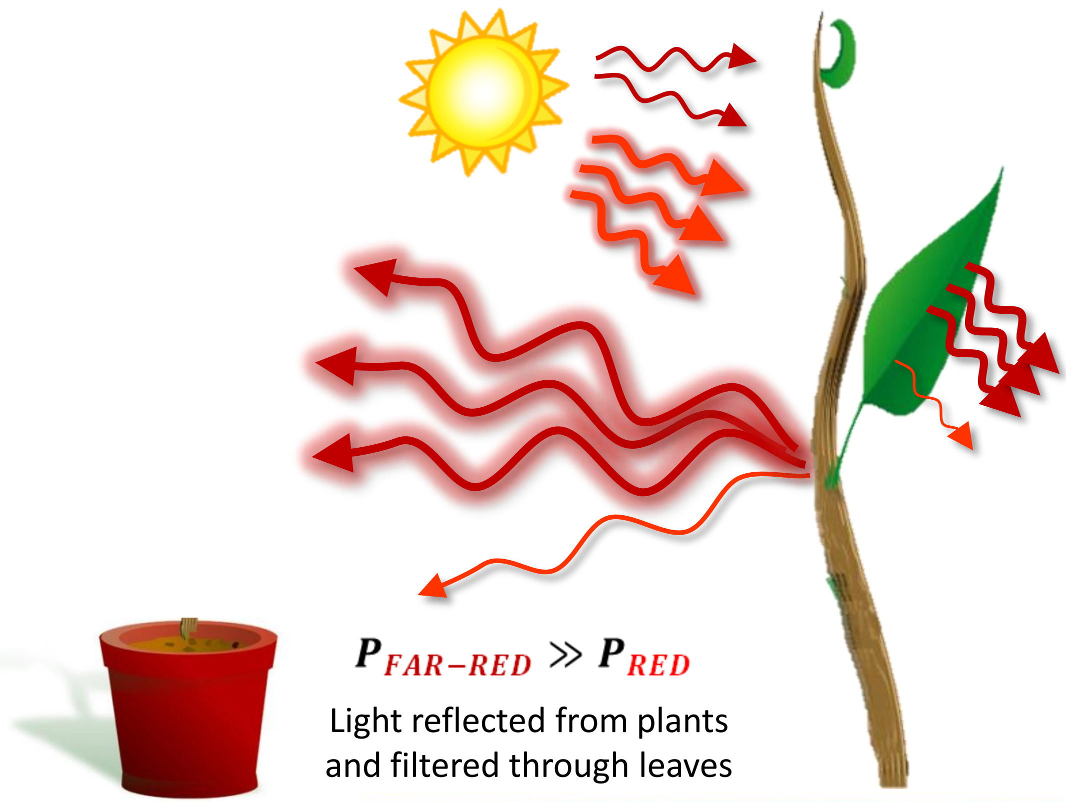
Mediated, in large measure, by the ratio of red to far-red light

- How can plants determine if the shade is from another plant?
  - By "sensing" the ratio of red to far-red $\frac{P_{Red}}{P_{Far-Red}} = \frac{\sim 660\ nm}{\sim 730\ nm}$



$P_{RED} \gg P_{FAR-RED}$

Sunlight, clouds, most "inorganic" reflections

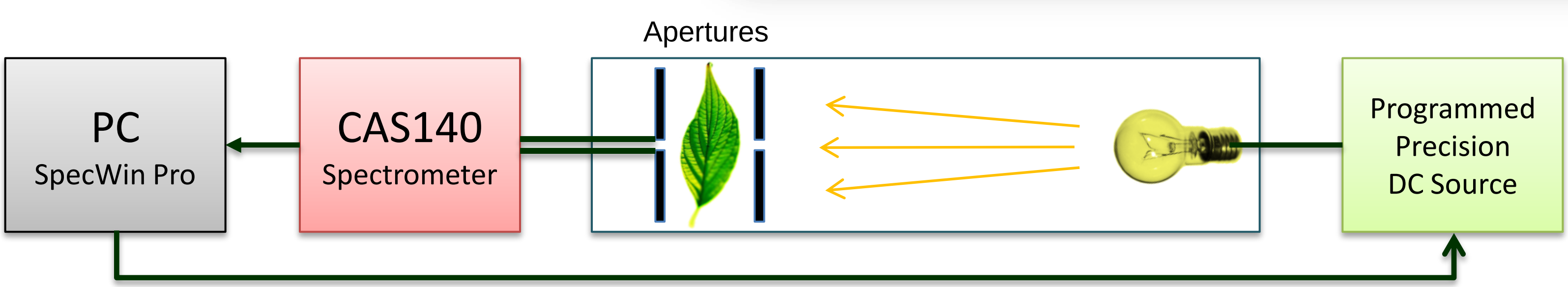


$P_{FAR-RED} \gg P_{RED}$

Light reflected from plants and filtered through leaves

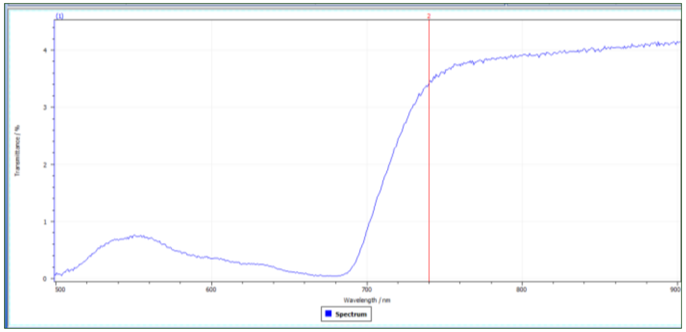
Leaf spectral analysis – Avnet LightLab

Goniometer

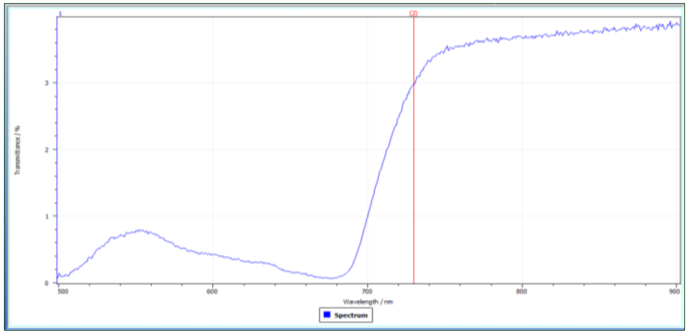


Leaf spectral analysis – Avnet LightLab

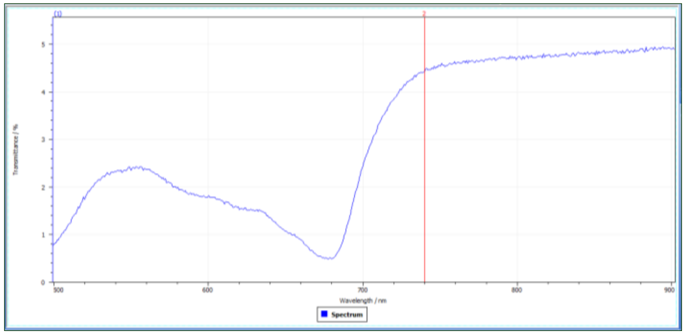
Colocasia



Fragaria × ananassa
(common strawberry)



Solanum
lycopersicum
(tomato)



Photoperiodicity and photomorphogenesis

Key Points

- *Photoperiodism* is a distinct process from *photosynthesis*
- Many plants can be induced to flower, or remain in their vegetative state, or perhaps undergo other internal processes simply by changing the length of light and dark exposure
  - Specific timing of certain wavelengths, and ratio of red to far-red, has a major impact on plant growth stages and growth characteristics
  - Plants use phytochromes to detect and respond to red and far-red wavelengths (red / far-red appear to be important photoperiodic cues)
- Where it is desirable to keep a short-day plant in its vegetative state, a short burst (in some cases, ~ 2-5 minutes) of far red LED light can be used to "pierce" the dark period – very inexpensive from an energy perspective
- Much is still unknown; most work has been focused on flowering state
- This is clearly an ideal application for LEDs

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Phytochemicals

May play an important role in human health

- It is generally accepted that there are health benefits related to the consumption of fruit and vegetable-rich diets
- There is evidence that some of these benefits may be related to the effects of flavonoids and phenolic compounds known as polyphenols
- These compounds appear to have many supplemental functions in a plant's various growth stages, including defense strategies and protecting chloroplasts from photodegradation by absorbing high-energy quanta while scavenging free radicals and reactive oxygen species
- There are active debates in the current literature regarding the bioavailability of polyphenols
- **Since we can use LEDs to grow plants efficiently (photosynthesis) and influence their characteristics (photoperiodism, photomorphogenesis), LEDs can have a direct impact on food *quantity* as well as *quality***

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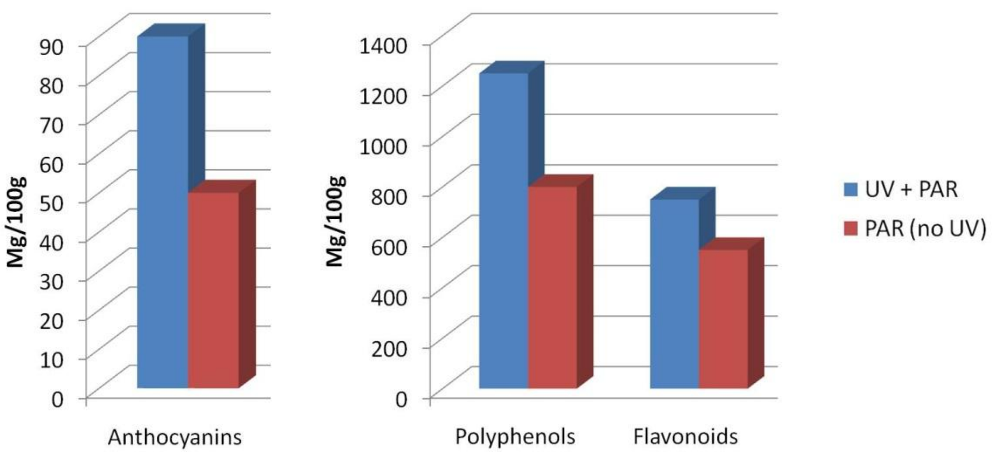
Increasing plant stress by design

to increase phytochemical production

- Environmental stresses are known to induce the accumulation of phenolic and flavonoids, in response to mechanical trauma, ultraviolet light, etc.
- An interesting strategy is to intentionally increase plant stresses to harvest those compounds – using UV-B light (a future role for UVLEDs)
- US Dept of Agriculture findings, presented at CLEO/IQEC 2009
  - "Results indicate that even low levels of UV-B region rapidly induce significant accumulation of polyphenolics in leaf lettuce and that LEDs can be attractive source for this purpose."



Increasing fungus stress by design

to increase vitamin D production

- Vitamin D_3 is produced when the skin is exposed to UV-B (270 - 300 nm), also available in some foods (fatty fish, mushrooms, eggs and meat)
  - Plays a pivotal role in many cellular processes as well as skeletal calcium balance
  - Some studies have linked Vitamin D deficiency to increased cardiovascular risks and elevated cancer rates
- A related form is vitamin D_2, known as ergocalciferol, produced from ergosterol in mushrooms
- Mushrooms exposed to flashes of UV-B *post-harvest*, dramatically increases effective D_2 levels
  - Concentration of D_2 in 84 g of white button mushrooms cultivated in the dark is ~ 0
  - Exposed to a single UV-B pulse, levels rose to 32 µg; with two pulses it rose to 56 µg, and with three pulses to 72 µg

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Conclusions

- Demand for higher crop yields and efficient land utilization are accelerating plant factory construction and other controlled growing environments
- The market for plant factory grow lights alone – not accounting for other grow light systems – was $740 M in 2011, projected to be $4 B in five years
- LEDs offer a unique, perhaps unparalleled, opportunity to directly influence plant morphology, growth cycles, and endogenous "natural" production of useful/healthy compounds, beyond the role of photosynthesis
- Even the value of ornamental crops (flowers) can be enhanced by synchronizing floral induction to high-demand events (e.g., Mother's Day)
- We are at the beginning, but IP will evolve and differentiate quickly

Thank you

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