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Jump to page
1 2 3 4

Plant photosynthetic growth and photomorphogenesis under LED light

In this month's Nursery Paper Industry Development Officer David Reid shines a light on LED use in production nurseries.

Plant photosynthetic growth and photomorphogenesis under LED light

Light is undeniably one of the most influential, complex and particularly challenging factors to control in plant development.

To meet the demands of peak sales a majority of production will occur in late winter to early spring, however natural light levels or the photosynthetic daily light integral (DLI) is understandably low at this time of year. Fortunately, the level required to produce quality material can be supplemented with additional lighting. The use of artificial light is technology worth exploration in Australian nurseries, in order to increase production and quality. This is supported by recent studies suggesting that growers can benefit from supplementary lighting such as light emitting diodes (LEDs), high-pressure sodium lights (HPS) and numerous other alternatives.

DLI or the Daily Light Integral is the number of light particles or photons received during one day in the photosynthetically active radiation (PAR) region of 400-700nm, over an area of 1 square metre. The DLI has a significant effect on growth habit, flower number, shoot growth, root development and stem thickness and as a rule, quality usually increases as DLI increases. In addition to the DLI, plants also react to quality, intensity, duration and the direction of light. DLI is measured in mol/m^2/day. The DLI needed to grow high-quality plants should hover around a 10-12mol/m^2/day target. Shade crops are generally exceptions with African violets and Phalaenopsis orchids preferring a DLI of 4-6 mol/m^2/day.

LEDs in particular, whilst still a relatively new technology, have the potential to offer greater efficiencies, longer lifetimes and wavelength specificity, over conventional lighting sources. They are also appropriate for different horticultural sectors, such as tissue culture, cut flower, plug and tube production and other protected cropping situations. Tissue culture in particular has seen the largest uptake of LEDs.

LEDs should be investigated, as current research has found they can give growers greater control over various anatomical, morphological and physiological characteristics. Greater uniformity, reduced production time, healthier rooted cuttings, increased control over rhizogenesis, axillary shoot formation, shoot elongation, leaf anatomy, colour variability and somatic embryo induction are just some characteristics found to be governed by specific wavelengths. It is this ability to select a specific wavelength for a targeted plant response that illustrates LEDs potential application in horticulture's future.

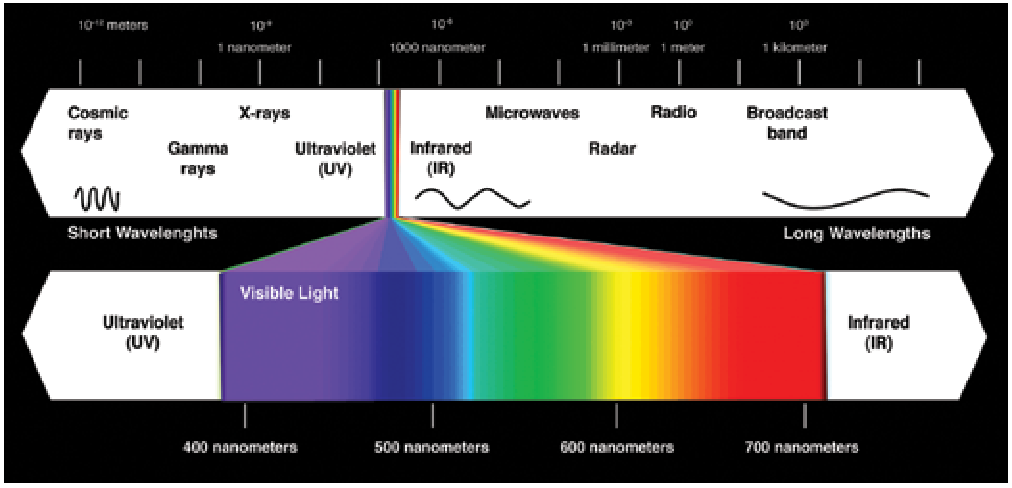
Plants and the electromagnetic spectrum

The effect of light on plant responses is illustrated in many aspects of their growth and development. Light energy initiates photosynthesis, when chlorophyll and carotenoid pigments absorb specific light wavelengths, utilising CO^2 and H^{2}O, and then converting it to chemical energy for metabolism and growth. Gene expression manipulation in plants is initiated by light intensity and quality, which in turn prompts a cascade of particular photoreceptors which control varied plant responses.

People see the visible part of the electromagnetic spectrum as white light; however plant photoreceptors are excited by specific colours (wavelengths) in the spectrum (See fig 1). Phytochromes for example are sensitive to the ratio of red and far-red-absorbing light and act as an environ¬mental sensor to measure day length and control several aspects of seedling phenology, such as seed germination and bud set.. The part of the electromagnetic spectrum that is considered to enable the highest photosynthetic rates is the PAR between 400-700nm (nanometers) and is generally considered to be found in two bands; red and blue wavelengths.

Plants respond to visible light by two general mechanisms that are keyed to specific wavelengths: photosynthesis that has a higher-energy requirement and photomor¬phogenesis that has a lower-

Fig 1. **Electromagnetic Spectrum**



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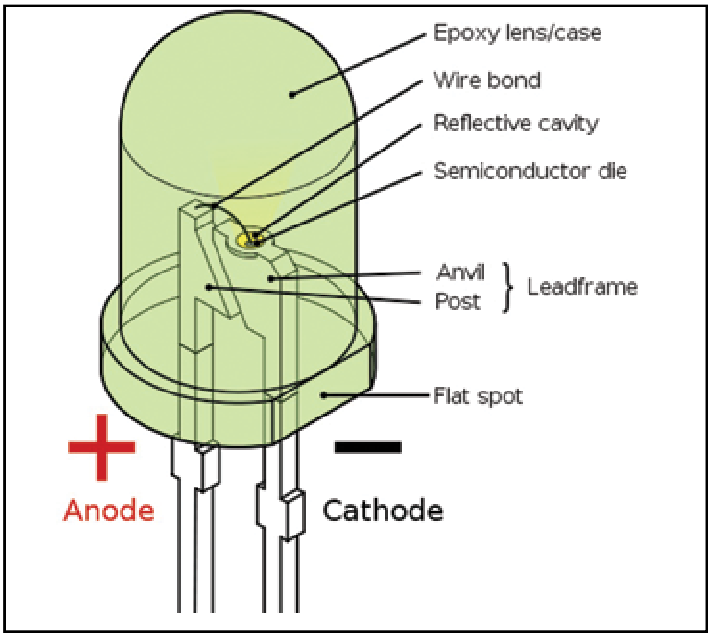
Jump to page
1 2 3 4

Fig 2. **LED schematic**



energy requirement. Plants using wavelengths outside of PAR are generally undergoing photomorphogenesis, which is light regulated changes in development, biochemistry, morphology and cell structure and function e.g.: far-red light is critical for the flowering of many plants.

Photosynthetic growth rates are able to increase with supplementary lighting within the 400-70nm range, but only up to a particular point and this can also vary between species. You will find that shade-loving plants reach their maximum photosynthetic rate significantly earlier than shade intolerant plants.

LED lights

The only way to increase the DLI in a protected cropping situation is to use supplemental lighting. Light sources such as, high-pressure sodium (HPS), metal-halide, incandescent and fluorescent lamps have been available for use in plant production for decades, however, these lights will only increase photosynthetic rates to a point. Traditional lighting systems are inefficient in delivery as they contain unnecessary wavelengths located outside the PAR spectrum.

LEDs are a solid-state device that is more closely related to a computer chip than a light bulb (see Fig 2). During an LEDs operation, electricity will pass through a junction made of a particular semi-conductor material found in the device, with the semiconductor materials' properties determining the lights' wavelength (or colour). LEDs can have peak emission wavelengths from UV-C (~250 nm) to infrared (~1000 nm) and it is the first light source to have the capability of spectral control, allowing wavelengths to be matched to plant photoreceptors.

The units themselves are approx 0.2-.05mm in size, can be set up in linear arrays or standard fixtures and are protected in a casing (see Fig 3). Compared to conventional light sources, LED lighting systems have several unique advantages.

- Long operating lifetimes, - LEDs last up to 2-3 times longer than fluorescent and 50 times longer than a typical incandescent lamp. A key difference to traditional lighting alternatives is that LEDs do not burn out, although intensity will reduce over time. It is recommended that once they reduce to 70% of original strength they should be replaced, with typical lifetimes ranging from 25,000 to 100,000 hours.

- Wavelength specificity - As LEDs can produce light in such specific wavelengths, they will generate only the most useful wavelengths (colours) in the visible spectrum for each targeted species and can even be combined to create 'white light'.

- Minimal heat radiance - As LEDs generate a minimal level of radiant heat they can be positioned deep within the canopy to reach leaves that would ordinarily be sheltered, without burning (See Fig 4).

- Energy efficient - Energy efficiency is usually calculated as useful output divided by energy input. When compared to a traditional supplementary lighting, LEDs exceed any competitors and continue to increase their efficiency with every new generation. LED efficiency, in general, is projected to increase considerably, for example it is predicted, that the photosynthetic efficacy of red LEDs will be double HPS lamps by the year 2020 (Pinho et al. 2012).

- Versatile - Small LED size allows flexible design of the lighting unit and as they are solid-state devices, LEDs are easily integrated into digital control systems (Morrow, 2008). This facilitates complex lighting programs that control for intensity or spectral composition over the course of photoperiod or during plant developmental stages (Yeh & Chung, 2009).

- Safer to use in a nursery -. There is no fragile glass cover to break, no extreme temperatures and they contain no hazardous materials, such as mercury.

Disadvantages

- A potential disadvantage to using LEDs as a light source is the relative financial viability when compared to traditional lighting methods, although there is an argument for cost neutrality when you consider the electricity savings. However with advancement in LED technology and growth in demand, the cost of LEDs will decrease.

- LEDs are limited in the light coverage they can provide; the light intensity will rapidly decrease as the distance to the plants increases and placing the lights lower to compensate may interfere with irrigation. Before switching to LEDs, be sure that light coverage is adequate and confirmed with a light meter at crop level.

- When used as a sole source for photosynthetic, photomorphogenic and/or photoperiod lighting, LEDs must be chosen and installed carefully to obtain desired plant responses. Developing the ideal mix of LED light wavelengths can be difficult and success may only be achieved after extensive trials.

Despite these obstacles, with improvements being made all the time with regards to efficiencies and decreasing costs, growers should be aware of future developments with this technology.

Jump to page
1 2 3 4

Plant reactions to LED lighting

Light reaching plant surfaces can evoke different photomorphogenetic and photosynthetic responses and can vary amongst different plant species. These responses are of practical importance to production technologies, since LEDs wavelengths can be tailored, enabling growers to control plant growth, development and nutritional quality.

- Photosynthetic rates - HPS and metal halide lamps, have been used in protected environments to supplement natural light however, due to the significant energy required to power a growth house full of lamps, supplementary lighting can be impractical. With the advent of LEDs a change can now be considered. As not all wavelengths are equally effective for pho¬tosynthesis, artificial lighting should be high in the PAR wavelengths bands; blue (460 nm) and red (680 nm) wavelengths.

- Increasing photoperiod - When day length becomes shorter, photoperiodic lighting might be more appropriate than photosynthetic lighting. A variety of different lighting arrangements have been effective in keeping plants actively growing when natural day length is limited. Light levels only need to be low in order for daylight extension, with most artificial lighting methods generating enough light to be effective because they all emit light in the red wavelength. Research trials have determined photoperiodic lighting intensity should be at least "8 μmol/s/m2 and should be increased to 16 μmol/s/m2 when the crop has a greater light requirement" (Landis, et.al. 2013).

Increasing the germination rate or the growth rate of a plant and potentially increasing crop turns, is not the only characteristic of a plant that affects salability. In addition to photosynthetic rate, flowering, leaf and flower colour, habit, shape, taste, smell and root development all help to improve plant quality.

Red wavelength effects (640- 690nm)

Red light is generally the base component in the lighting spectrum and has proven sufficient to be the sole lighting source for normal plant growth and photosynthesis. Low intensity LEDs emitting red wavelengths are as useful as traditional supplementary lighting will use less energy and last longer

- Biomass yield increased on particular vegetable crops when the wavelength of red LED emitted light increased from 660 to 690 nm (Goins et. al., 2001)

- 660 nm LED light, applied as sole light source in the controlled environment, stimulated anthocyanin accumulation in red leaf cabbages and 640 nm LEDs resulted in enhanced lutein and glucosinolate sinigrin accumulation (Mizuno et al. 2011)

- Germination in three species of Pinus was positively affected by application of red wavelengths (Merkle et al. 2005)

- The elongation of stem and internode length of Chrysanthemum (Kim et al. 2004) and grape (Puspa et al. 2008) were greatest under red LED light.

- 658 nm red light in combination with cool white fluorescent lamps resulted in 6% higher phenolics concentration in baby leaf lettuce (Li & Kubota, 2009).

Combination red & blue

Plant photoreceptors are most efficient in the blue and red area of the spectrum, and combinations of red and blue LED lights have been proven to have the greatest impact on plant growth compared to a monochromatic system.

- Increase fresh and dry weights of Lilium (Lian et al. 2002), banana (Duong et al. 2003), strawberry (Nhut et al. 2003) and Chrysanthemum plantlets (Kim et al. 2004c).

- Promote shoot organogenesis in Anthurium, by exposure to higher percentages of red than blue illumination, however, the number of shoots was more when exposed to higher percentages of blue than red LEDs (Budiarto, 2010).

- End of production lighting with red and blue LEDs increases purple pigmentation of red leaf lettuce and Pennisetum 'Rubrum' (Randall & Lopez, 2014)

There is no clear relationship between red and blue light ratios when manipulating plant growth and photomorphogenesis, with some studies showing growth to be higher under 10 % blue LEDs, with others increasing under 30% blue LEDs in a blue and red combination (Nhut & Nam, 2010).

Green light (505- 535 nm)

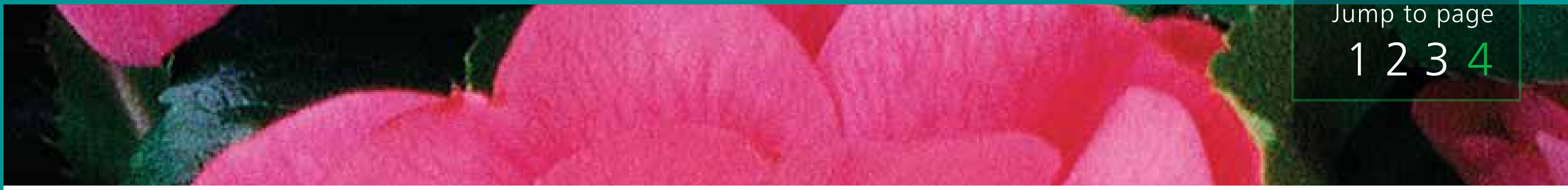
- Enhances vegetative biomass accumulation and affects chlorophyll and carotenoid synthesis, improving leaf colour.

- Promotes lettuce growth (Kim et al. 2004)

- Affects nutritional quality of different baby leaf lettuce varieties (Samuolien et al. 2012, Li & Kubota 2009).

***Fig 3.* LED interlighting Source: Phillips Australia**

Jump to page
1 2 3 4



Blue light - (450- 470 nm)

Blue light is critical to morphological development, par¬ticularly with regard to shoot strength and branching and is particularly favourable for growth, especially in leafy greens.

- Important for phototropism and chlorophyll formation (Blaauw & Blaauw-Jansen, 1970; cited in Massa, 2008)
- Promtes stomatal opening and inhibits stem and leaf cell elongation (Schwartz & Zeiger, 1984; cited in Massa, 2008);
- Inhibits seedling growth on emergence from a growing media (Thomas & Dickinson, 1979).
- Controls factors such as circadian rhythms and de-etiolation in plants (Devlin et al., 2007).
- Increases stem length in marigold (Heo et al. (2002)
- Inhibits Chrysanthemum in vitro culture plantlet extension and increases dry matter content and photosynthetic pigments (Kurilcik et al. 2008).
- Stimulates antioxidant status in green vegetables, increasing polyphenol (Johkan et al. 2010), vitamin C (Li et al. 2012), carotenoid (Lefsrud et al. 2008, Li and Kubota 2009) and anthocyanin contents (Stutte et al. 2009)
- Increases photosynthetic capacity and plant biomass in tomato, cucumber plants and pepper (Samuoliene et al. 2012c).
- Decreases elongation growth) and leaf area expansion in tomato and cucumber transplants (Nanya et al. 2012.

Far red light (720, 740nm)

- Results in tomato hypocotyl elongation (Brown et al. 1995, Kubota et al. 2012);
- Stimulates flowering of long-day plants (Deitzer et al., 1979, Downs, 1956; cited in Massa, 2008)
- Promotes internode elongation (Morgan & Smith, 1979; cited in Massa, 2008).
- Can be necessary for normal photomorphogenetic processes in plants (Kubota et al. 2012).

Pest & disease management

Another potential trend in LED usage is the possibility to reduce disease, pest and pathogen loads in particular crops (Massa et al. 2008). The thought of managing pest and disease with reduced chemicals is an attractive one, however, the initial studies point to it being cultivar or species specific.

- Massa (2008) showed that certain wavelengths could be used to minimise or even eliminate fungal proliferation. This study also suggested that LEDs could interfere with insects attempting to navigate to host species and reproduce. This was proven by (Vanninen et al. 2012) who showed that wavelength effects on insect phototactic behavior interfered with the ability of pests to successfully locate host plants
- The changes that some wavelengths could have on primary or secondary plant metabolites (defence mechanisms) could interrupt disease development and interactions with pests (Vänninen et al. 2012).
- Cucumber plants, grown under red LED light were more resistant to powdery mildew. (Shuerger & Brown, 1997).
- Blue-light on some species limited the efficacy of gray mold (*Botrytis cinerea*), most likely closely associated with the increase of antioxidant capacity as well as the development of compact morphology (Kook et al. 2013).

At present the majority of studies with LED lighting were performed in controlled environment growth chambers, where the primary environmental parameters can be controlled independently of external influences. This does not necessarily indicate that the same results will occur in a protected cropping situation (Pinho et al. 2007).

Conclusion

Research into LED lighting for supplementary or as the sole light source has been advancing for decades, however there are still many unanswered questions. What particular wavelength is required for what species; will a crop do better with a combination or a monochromatic approach; is there a critical time in a plants growth to apply supplementary lighting? The answers to these questions could be as numerous as there are plant species.

Furthermore, the interactions between light and plant photosynthesis and photomorphogenesis are complex and still being slowly unraveled at a molecular level, however, with the ability to focus on individual or combination of wavelengths, the attention that LEDs attract is warranted. The accumulation of evidence showing their ability to enhance desired features in plants' appearance, productivity or other responses will see a greater uptake of LED technology, but only after extensive successful (and unsuccessful) trials.

Thank you to Matt Mansfield @ Mansfields Propagation Nursery and Tony Bundock @ Powerplants for images and advice.

***Fig 4.* LEDs maximising space with multilayering Source: Phillips Australia**

Compiled and edited by Chris O'Connor NGIA Technical and Policy Officer; banner photography by Anthony Tesselaar.

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