Light-Emitting Diode Lights: The Future of Plant Lighting©

John F. Seelye and Andrew C. Mullan
The New Zealand Institute for Plant & Food Research Limited, Private Bag 11 600,
Palmerston North 4442
Email: john.seelye@plantandfood.co.nz

INTRODUCTION

Higher plants require light for growth. Sunlight, or solar radiation, arriving at the earth's surface is electromagnetic radiation energy given off by the sun, and filtered through the earth's atmosphere. It comprises visible light, as well as near infrared radiant heat and short wavelength ultraviolet (UV) radiation. The spectral characteristics of the sun coupled with selective absorption of different wavelengths in the atmosphere means there are unequal amounts of each wavelength reaching the earth's surface. Light is characterised by its quality (i.e., wavelength) and its intensity.

The human eye is sensitive to visible light (i.e., what we see) in the spectrum of wavelengths from 380 nm (blue light) to 760 nm (red light) but is most sensitive to light in the green and yellow regions, peaking at 555 nm (Fig. 1). Plants perceive light differently from humans, wherein they use both visible and nonvisible solar radiation. Plants use photoreceptors to sense changes in light intensity, quality

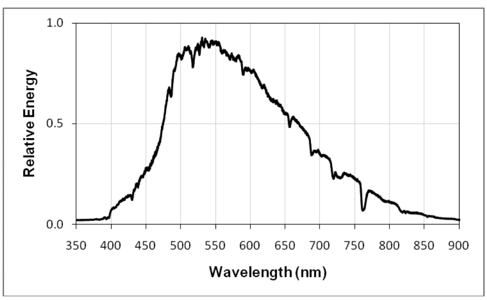

Figure 1. Spectral distribution of sunlight in the 350–900 nm range, which includes emissions in the nonvisble near infared region (>750 nm).

(wavelength), duration, and direction. They adapt their growth and development according to the light sensed. For instance, chlorophyll is a photoreceptor capturing the energy in light to convert carbon dioxide (CO_2) and water into carbohydrates through photosynthesis. Carbohydrates are the building blocks for the amino acids, proteins, fats, and vitamins required by living organisms. Carbohydrates with oxygen are necessary for plant and animal respiration, with CO_2 and water produced as by-products. Other photoreceptors control plant photomorphogenesis, shading resulting in etiolation or lengthening of internodes.

Understanding the spectral distribution characteristics of artificial light sources enables growers to match lamps to a desired plant response. To be commercially useful, plant lights need to be efficient converters of electrical energy to the wavelengths absorbed by the relevant plant photoreceptors. Traditional horticultural lighting produces a broad spectrum of light with some spectral enhancements in the regions required by plants for growth. This lighting has changed little over the past 20 years. However, new technologies involving combinations of light-emitting diodes (LED) lights, with defined spectral distributions, offer alternative and more efficient light sources for targeting individual, or multiple, photoreceptor-types. With the current rapid development of LED technology, it is possible they will become the major supplementary lighting source for plant production, replacing current broad-spectrum plant light sources.

MEASURING LIGHT

Solar radiation levels at the earth's surface can vary not only with season and time of day, but also with factors such as atmospheric water vapour content and CO_2 concentration. Meters such as the Licor LI-250A Light Meter (Li-Cor, Lincoln, Nebraska), can be used in conjunction with different sensors to measure total solar radiation or its components. Total global solar radiation is measured in units of kW/m^2 using a pyranometer and light brightness (i.e., intensity) as experienced by the human eye is measured with a photometric sensor, which detects the number of lumens falling on a square metre (expressed as lux).

The wavelengths of light that drive photosynthesis occur between 400 and 700 nm, which we call photosynthetically active radiation (PAR). The PAR comprises less than half of the total solar radiation (about 47%), so it is important to use the correct sensor to measure "light" intensities. Quantum sensors simulate the photosynthetic response of plants, expressing PAR in units of micromoles per second per square metre ($\mu mol \cdot m^{-2} \cdot s^{-1}$).

On a clear mid-summer day, PAR peaks in early afternoon at around 2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$. In the early morning, and evening, light intensity falls to the point where photosynthesis equals respiration (the CO_2 compensation point). The CO_2 compensation point varies among species. Knowledge of CO_2 compensation point is important for growers, as it marks the light intensity at which adding supplementary lighting would further enhance the rate of photosynthesis. For a commercial operation, a light intensity of at least 90 $\mu mol \cdot m^{-2} \cdot s^{-1}$ is generally required for significant photosynthetic activity, although it is also dependent on factors such as plant genotype, growing temperature, and water and nutritional status.

In addition to photosynthesis, plants use light to trigger other growth and development processes. Classic examples of this include plants responding to changing ratios in the amounts of red and far-red light they perceive, triggering flowering, vegetative growth, or even seed germination (i.e., photomorphogenetic response). Thus it can also be important to use a spectrometer to measure the full spectral distribution of light. The Ocean Optics UBS2000 Spectrometer (Ocean Optics, Dunedin, Florida) can continuously capture data, graphically presenting the distribution data on a personal computer. This makes it a valuable tool for comparing the spectral distribution of different artificial light sources for PAR.

THE ROLE OF LIGHT IN PLANT GROWTH AND DEVELOPMENT

Photosynthesis. Photosynthesis involves PAR being absorbed by chlorophyll and converted into chemical energy. There are two types of chlorophyll, a and b, each absorbing light in slightly different wavebands. Absorption is principally in the red and blue-violet spectral regions. Most green light is not absorbed, but reflected or transmitted, to be seen by our eyes as the green colour of leaves. Other plant pigments such as carotenoids, flavonoids, and xanthophylls are also found in the leaves, and depending on their concentrations and relative proportions give rise to yellow, orange, pink, red, and purple colours. Under conditions of adequate temperature and CO_2 concentration, photosynthesis increases with increasing light intensity (PAR) in a linear manner to the point where light saturation and factors such as tissue age and genotype limit further increases.

Photomorphogensis. Plants have evolved highly complex mechanisms to monitor their surroundings and adapt their growth and development to the prevailing environmental conditions. Light quality is sensed by different light receptors for specific wavelengths. In higher plants there are three groups of photoreceptors involved in photomorphogenesis: the red / far-red light-absorbing phytochromes, and the blue UV-A light-absorbing phototropins, and cryptochromes (Franklin and Whitelam, 2004).

The phytochromes with photo-reversing properties, exist as red (665 nm) and far-red (730 nm) absorbing forms. The red form converts to the far-red form following the absorption of red light and, conversely, following the absorption of far-red light, the far-red form converts to the red form. While leaves absorb most of the visible light, far-red light is transmitted or reflected. Plants use the ratio of red to far-red energy (R:FR) to sense shade, with higher proportions of far-red indicating shade, causing plants to activate shade avoidance measures. This includes removing an inhibitor of stem elongation, resulting in taller (etiolated) shoots with less branching and smaller leaves. Growth returns to normal once the shade conditions have been overcome, i.e., a lower proportion of far-red. Plants are able to differentiate between light on an overcast day and shade cast by other plant organs on the basis of R:FR ratios. Natural light, whether on a clear or cloudy day, has a relatively constant R:FR of about 1.1 : 1. Phytochromes also regulate chlorophyll and chloroplast development, leaf senescence, and leaf abscission. Phytochromes are also the principal energy receptors for photoperiodism. The signal for a plant to flower is often under photoperiodic control, whereby plants sense seasonal changes in daylength. Plants can be divided into short-day plants (e.g., strawberry, carnation, or chrysanthemum), long-day plants (e.g., lettuce or lily), or day-neutral plants (e.g., rose or tomato). By altering day length, either with blackout curtains, or supplementary photoperiodic lighting, flower initiation can be manipulated to promote out-of-season flowering.

Phototropins are blue light receptors that help to maximize photosynthetic activity by stimulating phototropism, stomatal opening, and chlorophyll synthesis. They are important for the early stages of seedling growth and establishment. Since they grow towards light, shoots are positively phototropic. This occurs when light alters cell auxin concentrations in cells on the side of shoots away from the light source, resulting in cell stretching, causing the shoot to curve towards the light source.

Cryptochromes absorb light in the blue to UV-A wavelengths. They work in conjunction with the phytochromes in the regulation of cell elongation and photoperiodic responses.

ARTIFICIAL LIGHT FOR PLANT GROWTH

Various sources of supplemental light have been used to enhance plant growth, usually by supplementing lower levels of natural light during the duller winter months or on overcast days. A major limiting factor is the efficiency of lights in converting electrical energy into light rather than heat. For example, an incandescent bulb radiates about 12% of the input wattage as light, mainly in the red spectral region, and 80% as radiant infrared heat; a typical fluorescent light radiates about 22% of the input wattage as light and 36% as infrared heat (Bickford and Dunn, 1972). In recent years, compact fluorescent lights (CFL) have become widely available. They are more energy efficient than standard fluorescent tubes, as they require lower wattages and generate less heat, but have similar spectral outputs, making them suitable for small-scale propagation applications, e.g., supplementary lighting at de-flasking of tissue culture plantlets.

High intensity discharge (HID) lamps, such as high pressure sodium (HPS) or metal halide (MH), convert 30% to 40% of the input electrical energy to light. The HPS lamps are, therefore, a popular source of supplementary greenhouse lighting, since they produce more PAR per watt of electrical energy. However, they are slightly biased towards the red end of the electromagnetic spectrum, which is more favourable for promotion of flowering. The heat they generate prevents use of them close to plants. In contrast, MH lamps have greater flexibility in their spectral output since their spectral properties can be manipulated through using different combinations of metal halides in their construction (Bickford and Dunn, 1972). Their ability to produce an abundance of blue light (Fig. 2) makes them more suitable for enhancing vegetative growth than HPS lamps. As with most lamps currently used in plant growth applications, reflectors are necessary to focus the emitted light towards the plants.

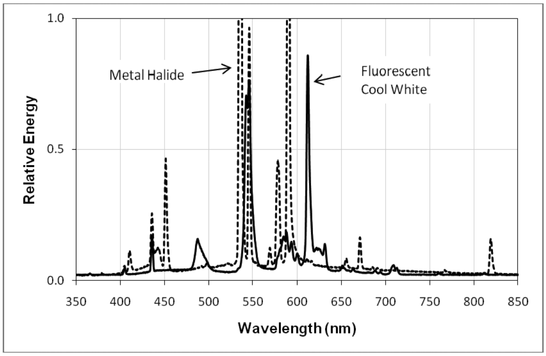

Figure 2. Metal halide lamps, a popular source of supplementary lighting in horticultural applications, emit radiation in the lower wavelength blue bands (400–470 nm) and a lesser amount in the red regions (620–700 nm) compared with fluorescent lamps (solid line). However, both produce a large portion of their energy in the region that has minimal roles in vegetative plant growth but to which humans are sensitive (around 550 nm). For direct comparison, the energy levels have been scaled to to show the relative energy from each light source.

Many lamps are deficient in far-red (700–800 nm), resulting in high R:FR (up to 7 : 1 for HPS) compared with sunlight, which has a ratio of 1.1 : 1 (Cummings et al., 2007). Under these lamps flowering would be delayed in long-day plants, and internode extension inhibited. An exception is incandescent lamps, which have a R:FR of 0.6 : 1. To achieve a R:FR close to natural light, MH lamps need to be used in combination with incandescent lamps.

LIGHT-EMITTING DIODES

Light-emitting diodes produce light by the movement of electrons in a solid-state semiconductor material. Since they do not warm up and "burn" like traditional light bulbs, they have a significantly longer life. Additionally they can be turned rapidly on and off for pulse lighting. The LEDs emit radiation in a relatively narrow wavelength band (Fig. 3), but combinations of LEDs do cover the PAR spectrum (van Leperen and Trouwborst, 2008) with over 75 different wavelengths from UV (210 nm) to near infrared (910 nm) now available (Stutte, 2009). Many are based on chemicals such as gallium, arsenic, and phosphor. As no semiconductor material emits pure white light, most white light-emitting LEDs are based on a blue light-emitting chip coated with phosphor, which causes yellow light to be emitted. This mixture of blue and yellow light is perceived as white light by the human eye, even though these "white" LEDs have spectral distribution peaks in both the blue and yellow regions (Figs. 3 and 4). White light can also be produced by combining the primary colours: red, green and blue (RGB) into a single LED.

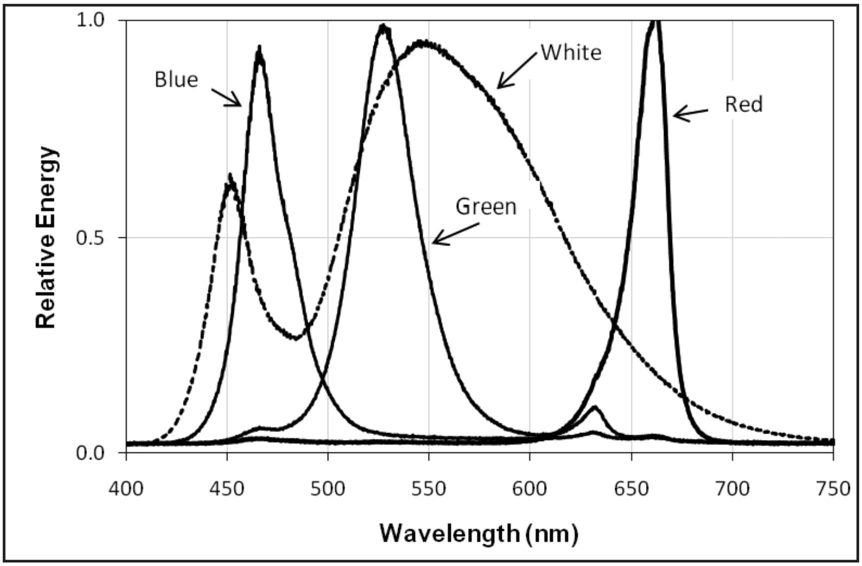

Figure 3. The spectral distributions of LEDs. Coloured LEDs (red, blue, and green) emit defined, relatively narrow, spectra of light energy. The LEDs perceived as white to the human eye are blue LEDs modified with phosphor to produce a wider spectrum peaking in the yellow wavelength band (550 nm). For direct comparison, the energy levels have been scaled to to show the relative distribution of each light source.

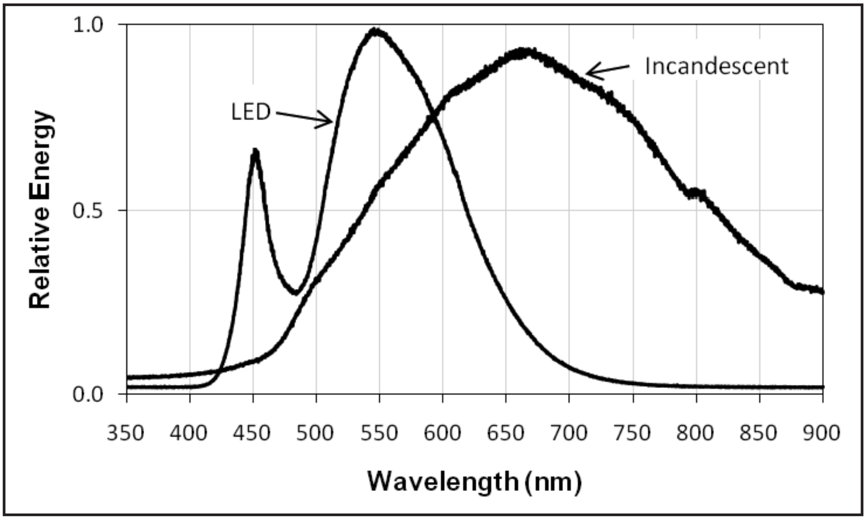

Figure 4. Spectral distributions for two white light sources. In contrast to the white LED, the incandescent lamp has a much wider spectrum, emitting a significant portion as non visible, infrared (>750 nm), radiation, which is experienced as heat. For direct comparison, the energy levels have been scaled to to show the relative distribution of each light source.

The LED technology is developing rapidly, with newer versions producing higher light intensities. This is now making them attractive as lighting sources in a wide range of nonhorticultural applications, including general street lighting, automotive signalling and television back-lighting. A consequence of this development and uptake of the technology is that production costs are steadily falling. Until recently the high cost of LED lighting restricted its use in horticulture primarily to research and controlled environment applications. Much of the early LED work with plants was associated with NASA's research into growing crops such as radish, spinach, and lettuce in space (Yorio et al., 2001). There is a rapidly developing scientific literature on applications for LEDs. For example, different ratios of red and blue LEDs can be used to manipulate lettuce seedling stem extension (Yanagi et al., 1996). Green LEDs have been used in the presence of red and blue LEDs to enhance the rate of photosynthesis (Kim et al., 2004). The addition of 1% blue or UV-A LED can reduce the presence and severity of tomato mosaic virus symptoms in peppers (Schuerger and Brown, 1997).

The small size of LEDs makes them amenable to being grouped together so that spectral outputs can be matched to the required plant response, thereby fully utilising the light energy. In addition, LEDs with different spectral outputs can be programmed to switch on to promote specific responses in a plant production system (e.g., photoperiodic response), without energy being wasted on nonproductive wavelengths. The more intense LEDs suitable for plant growth do require more power management, although voltages of individual LEDs are low (2–4 volts of direct current). An array of LEDs can be connected in series and/or parallel, to form a continuous electrical circuit, with the series voltage being the voltage drop of the individual LEDs multiplied by the number of LEDs in the series. Brightness is proportional to the current, which is typically in the 200 to 1000 mA range. Commercial lighting companies are now starting to fabricate complete multi-LED light units for the horticulture industry (for example, <http://www.led-grow-master.com> and <http://www.ledtronics.com/products>.

The LEDs produce little if any radiant heat. Although some of the electrical energy used is converted to heat energy, in contrast to lamps such as HPS lamps, the heat is nonradiant and can be readily dissipated using heat sinks and convective cooling systems. This allows the lights to be positioned close to plants, thus ensuring maximum efficiency of light interception by the plants.

The R:FR can be readily manipulated using combinations of light sources in conjunction with LEDs. For example, red LED light has been used to promote flower bud induction in short-day strawberry plants by altering the R:FR reaching the crown (Takeda and Newell, 2006). Far-red LEDs combined with incandescent lighting can produce deep canopy shade equivalent R:FR ratios without producing excessive radiant heat (Cummings et al., 2007).

In 2007, LED lighting was reported to be less efficient than HPS lamps, although it was noted that LED technology development was rapidly progressing, whereas HPS development was not (van Leperen and Trouwborst, 2008). Recent reviews on the progress of LEDs, as the technology moves to large-scale horticultural applications, have been published by Morrow (2008) and Yeh and Chung (2009).

LEDS AND TISSUE CULTURE

Fluorescent cool-white tubes have been a commonly used light source for tissue culture growth rooms, since they can provide a relatively uniform coverage of light in the visible spectrum (Fig. 2) on the shelves where plants are growing (two tubes 30 cm above a shelf typically provide around 30 to 40 $\mu mol \cdot m^{-2} \cdot s^{-1}$). In contrast to other growing systems, tissue culture plants grow heterotrophically, with their carbohydrate requirements satisfied by sugars in the nutrient media, thereby negating the need for photosynthesis and the required high PAR levels. In some countries, fluorescent lighting can account for 65% of the total electricity use within a tissue culture laboratory, making it the largest nonlabour cost in tissue culture plant production (Yeh and Chung, 2009). While LEDs are yet to be used routinely as a light source in commercial tissue culture laboratories, this is likely to change as the cost of LEDs continues to fall.

There is a range of examples illustrating the potential value of LEDs to the horticultural industry. Strawberry plantlets taken from culture can be grown under 70% red (660 nm) plus 30% blue (450 nm) LED lighting with a light intensity of 60 $\mu mols^{-1} \cdot m^{-2}$ using a rockwool system with a sugar-free medium (Nhut et al., 2003). Such plants are very healthy, with subsequent growth normal following transferral to soil. Fluorescent lights supplemented with red LEDs have been shown to increase chlorophyll and shoot length of in vitro potato plantlets (Miyashita et al., 1995). Applications such as these may provide a useful approach to aid plantlet acclimatisation and assist in reducing costs associated with plant losses at deflasking in vitro propagated plants.

CONCLUSION

Plant growth and development are complex processes, with light being essential for many of the associated physiological and morphological processes. Sunlight satisfies these needs but to maximize the growth of economically important indoor-grown crops, supplementary lighting can be beneficial. As a result of the low amount of energy actually converted to useful light, many conventional supplementary light sources are inefficient and therefore expensive to operate. LEDs offer efficient alternative light sources with defined spectral distributions for targeting specific plant photoreceptors for plant growth (photosynthesis), photomorphogenesis (morphology) or development (e.g., maturation). The rapid development and uptake of LED technology by many industries over the past decade means production costs are declining. As the light intensity of LEDs producing PAR improves with better technologies, LED lighting will become economically feasible for commercial plant production.

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