LEDs as a Replacement for Traditional Greenhouse Lighting; for Reduced CO_2 Emission, Improved Crop Yield, and Quality.

Keiri Swann
PhD student

- LEDs are reducing in cost, and increasing in efficiency rapidly with modules currently available at 4µmol/j.
- LEDs provide opportunities for vertical farming, inter-lighting and spectral control of crop morphology.

Personal statement

I find plant production with LED lights fascinating, and I think that we are only at the beginning of understanding how they can be used to control and improve morphology and crop production. Furthermore, system efficiency improvements in food production can only be a good thing. As our understanding is expanded and honed for every crop type the increased efficiency, quality and yield of LEDs lights as a horticultural lighting strategy will make them an obvious choice for growers.

Contents

Introduction

Food security is a pressing global issue, with unstable and continuing population growth through this century speculatively leading to populations of up to 10.9 billion by 2100 (Gerland et al. 2014). Glasshouse horticulture production is one of the highest yielding food production methods per unit area. Greenhouse lighting furthers this high productivity but is very energy intensive which increased CO_2 emissions. CO_2 emissions have resulted in global warming causing dramatic weather events destabilising agricultural practices around the world. Significant efforts need to be made to both source our energy more sustainably and use less of it. LED lighting is relatively new in horticulture and has the potential to reduce energy consumption in protective horticulture and bring about new options for more efficient and advanced plant production. The efficiency and spectral options of LED lights is rapidly advancing along with our knowledge of how to use them.

Here we explore the current state of greenhouse lighting and how the LEDs can be used to enhance crop production and efficiency.

Why use supplementary lighting?

Not using greenhouse lighting is the most obvious way of reducing CO_2 emissions in protected horticulture as they make up a large proportion of energy use (Brumfield 2007). However, there are many benefits to its use (Heuvelink et al. 2006). Light increases crop yield: 1% extra light equates to 1% extra yield, leading to higher yields per unit area. Over 2000ha of glasshouse in the Netherlands are lit with supplementary lighting, making up a significant part of the nation's energy use (Marcelis et al., 2006). Furthermore, there is up to 50% less natural light inside a greenhouse than outside due to infrastructure shading, light reflectance, shading materials and absorption, increasing the need for supplementary light (Faust et al. 2005; Hanan 2017).

The primary reasons for the use of supplementary lighting is to increase the photosynthetic rate and control plant morphology creating possibility for year round production, control of plant life stage and flowering, improved yield and crop quality when natural light levels are reduced (Craver and Lopez 2016; Heuvelink et al. 2006; Tian 2016). Year round production is beneficial for growers as it meets consumer demands in out of season months where prices are high and allows a continuous employment of workforce (Heuvelink et al. 2006). Photoperiod control lighting can be delivered at low fluence rates making it quite efficient, however, it does often require a high % of far-red, which is not a very energy efficient wavelength to produce (D. Singh et al. 2015). Supplementary lighting can also improve the growing environment by increasing temperature with the excess energy not converted to light (Toyoki Kozai and Zhang 2016). To make supplementary lighting more efficient the growing environment needs to be improved with CO2, humidity, and temperature.

Supplementary lighting

Supplemental lighting is moderate to high intensity lighting to enhance periods of low solar radiation (Lu and Mitchell 2016). Lighting started to be used in horticulture not long after the invention of electric lighting in the 19th century. Horticultural lighting is continuously evolving, utilising new lighting technologies and lamp types with varying efficiencies, positives, and negatives for plant production.

Types of supplementary lighting

Incandescent and Halogen

Incandescent bulbs were first patented in 1879, and function by heating a wire filament until it glows (Matulka and Wood 2013). This filament is encased in a glass tube containing an inert gas. Halogen bulbs are similar but contain halogen gas which prolongs the life span of the Tungsten wire. These bulbs have very low energy efficiency and are being phased out but are still used in some horticulture crops for night-break lighting due to their spectral output being predominantly red and far red (Landis, Pinto, and Kasten 2013; R. Singh and Bala 2020).

Fluorescent

Fluorescent bulbs work by passing an electrical current through a glass tube containing mercury vapour. The mercury vapour is excited by the electrical current and produces short wave ultraviolet light (Sağlam and Oral 2010). The UV light is absorbed by the phosphor coating on the inside of the glass tube, which then fluoresces producing the require light (Tian 2016). The mixture of phosphors can be altered for varied colours; however this is very limited. They have a more balanced multiple peak spectrum than incandescent lights and are dimmable (Cheng et al. 2010; Landis, Pinto, and Kasten 2013).

High intensity discharge (HID)

High intensity discharge lamps are types of electrical gas-discharge lamp mainly including metal halide, high-pressure sodium, low-pressure sodium and mercury-vapor lamps (Tian 2016). HID lamps produce light by striking an electrical arc across tungsten electrodes housed inside a transparent gas filled tube (Sağlam and Oral 2010). Commonly used in horticulture, HPS and metal halide lamps discussed here.

High pressure Sodium (HPS)

High pressure sodium (HPS) lights are the most used and most economical currently (Lu and Mitchell 2016). The light wavelengths produced are predominantly yellow and orange (565-700nm), with much less red, blue and far-red than other types of lighting (Landis, Pinto, and Kasten 2013). Only 5% blue compared to solar light with is 18% blue (Islam et al. 2012). They are more efficient than metal halide at converting energy to PAR and has a three times longer lifespan of roughly 10000-12000 hours (Dorais 2003; Lu and Mitchell 2016). About 30% of the electrical energy is converted to photosynthetically active radiation and the other 70% is lost as heat with efficiencies of 1.5 to 2.1µmol/j (Lu and Mitchell 2016; D. Singh et al. 2015; Yeh and

Chung 2009). The radiant thermal energy from HPS lights heats both the plants and the greenhouse reducing heating costs (Brault et al. 1987). The luminaires provide a very even light distribution; however, they do block some sunlight.

Metal halide

Metal halide lights produce a more balanced white light with proportionally more blue compared to Incandescent, florescent and high pressure sodium lights (Landis, Pinto, and Kasten 2013). They have a good colour rendering index and high efficiency (Tian 2016).

Light emitting diodes (LEDs)

Light emitting diodes are solid state semiconductor devices (Fujiwara 2016; Yano 2016). Photons emitted from the junction of a p and n type semiconductor (Fujiwara 2016). If the energy gap corresponds to a visible light wavelength then the emissions will be visible light (Nakamura 2015). Different diodes produce different monochromatic colours. The first red LED was invented in 1988 and the first high brightness blue was invented in 1994 (Morrow 2008). White light comes from blue LEDs with a phosphor coating (Pimputkar et al. 2009). Light output can be effected by temperature (Cho et al. 2010). Continuous heat removal necessary (Bourget 2008; Ye et al. 2013). Light can be continuous or pulsed. Lights are dimmable by controlling the forward current across the semiconductors or by turning the current on and off in 50-60hz pulses (Choi et al. 2015). LED failure is considered to be when it is at 70% of its initial light which occurs over a 50000hr lifetime (Lafont, Zeijl, and Zwaag 2012; Tungsram 2021). A higher forward current increases brightness but decreases lifespan. A uniform light distribution is ideal; however, LEDs are often brighter directly under the lamp, this varies with the lams distance from the bed (Bornwaßer and Tantau 2012). More direct light could be useful to irradiate just the plants rather than the spaces in between (Poulet et al. 2014). Over 50% of energy can be converted to light and this is constantly improving towards a theoretical maximum of up to 5.52µmol/j, with high red fixtures reaching 4 to 4.1 µmol/j currently (Kusuma, Pattison, and Bugbee 2020; Tungsram 2021).

LEDs compared to HPS

Table 1: A comparison of lightning characteristics and specifications between HPS and LEDs in horticulture.

Factor	LED	HPS	Reference
Efficiency	3.42-4.10 and improving to a maximum of 5.52	1.5-2.1	(Fisher and Runkle 2004; Kusuma, Pattison, and Bugbee 2020; P. V. Nelson 2012; D. Singh et al. 2015; Tungsram 2021; Yeh and Chung 2009)
Maintenance cost	Low	Bulbs dim and need replacing	(D. Singh et al. 2015; Tennessen, Singsaas, and Sharkey 1994; Yeh and Chung 2009)
Operation cost	Low	High- energy cost	(D. Singh et al. 2015; Yeh and Chung 2009)
Set up cost	High but reducing with demand	Low	(Morrow 2008; D. Singh et al. 2015; Yeh and Chung 2009)
Spectral output	Tuneable	Fixed, range (565-700nm)	(Islam et al. 2012; Landis, Pinto, and Kasten 2013; Tian 2016)
Dynamic control of intensity and spectrum	Yes	no	(Tungsram 2021)
Photosynthetic efficiency	High/ adjustable	Low	
Sole source lighting	Possible	Not used	(Tian 2016)
Lifespan	30,000–50,000 h	10000-12000	(Fisher and Runkle 2004; Lafont, Zeijl, and Zwaag 2012; P. V. Nelson 2012; D. Singh et al. 2015)
Long wavelength radiant heat	Minimal- can be close to plants- some heat conducted through frame	Very hot 450°C, have to be far from plants	(Fisher and Runkle 2004; Monostori et al. 2018; P. V. Nelson 2012; D. Singh et al. 2015)
possibility of use for multitiered farming or inter-lighting	Yes	No	(Monostori et al. 2018; D. Singh et al. 2015; Tennessen, Singsaas, and Sharkey 1994)
Even light diffusion	Poor, quite direct light	Very good	(Bornwaßer and Tantau 2012; Poulet et al. 2014)
Start up time	No start up time	Prolonged start up time	(Morrow 2008)
Direction of irradiance	Any	Downward	
Compatibility with digital control system	Good	Poor	(Yeh and Chung 2009)

Opportunities for LEDS in Horticulture

LEDs are a promising light source for the greenhouse industry looking forward (Morrow 2008). Their compact size, robust build, long lifespan, cool emitting temp, rapid turn on and off, controllable light intensity and spectrum output and containing no hazardous substances makes them very beneficial for greenhouse production (Fujiwara 2016; K. Li et al. 2014; Massa et al. 2008). LED lights can fulfil the roles of traditional horticulture lighting to extend days, increase yield and quality and effect morphology, through top lighting and night-break with options of sole source and inter-lighting with some key new benefits and opportunities:

1. The increased energy efficiency of LEDs allows for equal yields with lower energy consumption and carbon footprint. They are the most efficient light to produce blue, red and white wavelengths (J. A. Nelson and Bugbee 2014). They can be over three times the efficiency of HPS at 4µmol/j (Tungsram 2021).
2. The monochromatic nature of light from LEDs have allowed for research advancements in the effects of light wavelength on plant physiology (Fujiwara 2016; Massa et al. 2008). Researched since the 1980s for use in horticulture (Bula et al. 1991; Massa and Norrie 2015).
3. Spectrum control is the most unique benefit allowing for advanced control on plant morphology and physiology (Higuchi et al. 2012; Liao et al. 2014). LEDs are possible in almost all colours with 37 wavebands of light possible (Fujiwara, Eijima, and Yano 2013). LED lights can be more efficiently used by plants as there narrow wavebands of light can be used maximise photosynthetic efficiency for specific crops (Bourget 2008). Broad spectrums can be achieved by combining LEDs (Fujiwara and Yano 2011).
4. Lower radiant heat from LEDs allows the lights to be positioned closer to the plants giving higher intensities (Monostori et al. 2018; D. Singh et al. 2015; Tennessen, Singsaas, and Sharkey 1994), options for changing position and direction, inter-lighting and multitiered production (E. Goto 2012). Less thermal stress on plants. The lack of infrared radiation allows the control light and temperature separately(G. Zhang et al. 2015).
5. Light can be controlled to increase and fade mimicking natural daylight cycle with specific spectrums for dawn and dusk or cloudy skies (Fujiwara, Eijima, and Yano 2013). Dynamic control of photosynthesis is possible through altering led light intensity, CO_2 and temperature (Z. Li et al. 2012). Chlorophyll fluorescence can be used to inform control systems regarding LED output (Z. Li et al. 2012).
6. Last up to 10 times longer than traditional lighting forms with ongoing expected improvements (Tian 2016).
7. LEDs are also more easily integrated into digital control systems allowing for more complex light programs such as varying the light spectral composition and intensity throughout the plants life cycle (Yeh and Chung 2009).

Lighting strategies

Vertical farming

LED lights give the option for vertical farming and controlled environment agriculture due to the lower radiant heat allowing them to be positioned closer to the plants. With over half our populations living in cities, interest in urban agriculture is increasing. It has the potential to decrease the environmental impact of cities by reducing the amount of land/ pesticides/ resources to feed them as well as food transportation miles (Taylor Lovell 2010). Vertical farming allows for full control of process where production can happen in a limited area, with recycled water and nutrients, hygienically with no contamination risk, anywhere independent of environment, locally, sustainably and with guaranteed quantity and quality (Toyoki Kozai 2016; Toyoki Kozai, Fujiwara, and Runkle 2016). Furthermore, vertical farming reduces land pollution with pesticides, is safe from weather extremes, has less heat/ CO_2 losses, and produces dramatically higher yields per unit area (T. Kozai 2013; Tian 2016; Yeh and Chung 2009). However, the associated costs are 2-3 times higher, urban land price is higher and there is currently little knowledge on this form of crop production. Furthermore, there are many potential issues with complete lack of sunlight which may yet be unforeseen like effects on insect pollinators, disease, morphological disorders, or stress responses in the plant.

LED Inter-lighting

Inter-lighting provides light directly to the lower foliage in tall crops (Lu and Mitchell 2016), increasing efficiency of the radiation by lighting the interior of the crop stands where the unshaded upper leaves may be at full photosynthetic capacity (Akiyama and Kozai 2016; Lu and Mitchell 2016; Trouwborst et al. 2011; G. Zhang et al. 2015). The comparative coolness of LEDs makes this form of lighting possible with higher intensities closer to the plants (Massa et al. 2008). Dense crops benefit from inter-lighting as it prevents lower leaves from deteriorating in photosynthetic capacity and sensing prematurely, improves crop yield and quality (Hao et al. 2015; Lu et al. 2012; Massa et al. 2008; Moerkens et al. 2016; Tewolde et al. 2016). Combinations of overhead and underlighting have been shown to improve productivity in a variety of crops (Gunnlaugsson and Adalsteinsson 2006; Hao et al. 2015; Jokinen, Särkkä, and Näkkilä 2012; T. Li et al. 2012). Inter-lighting can also be used alone when there is sufficient sunlight to light the top of stands (Lu and Mitchell 2016). The spectrum has a bigger effect in inter-canopy lighting due to less background lighting (Craver and Lopez 2016).

LEDs in Propagation

Plant propagation ideally requires DLIs of at least 10-12 $molm^{-2}d^{-1}$ (Randall and Lopez 2014). Plants should be compact with lots of roots. Propagation material is often produced under light as this produces more starch and biomass in young plants (Faust et al. 2005). Light is also used in propagation for uniform consistent plant production, good quality and higher subsequent performance (Hernández and Kubota 2012). LEDs have been shown to be as good for propagation and give the option of producing more compact plants (Currey and Lopez 2013). The colour ratio can be used to control the vegetative growth to focus on the plantlets future yield and profitability. Also beneficial morphological traits can be emphasised like improving colour of lettuces (Garrett Owen and Lopez 2015). Coloration also increased with intensity of blue light (Craver and Lopez 2016).

Overhead lighting and crop finishing

Overhead lighting can be used to increase DLI, improve the growth, yield, and quality of finishing crops, and is the most used form of horticultural lighting. Overhead arrays do not utilise the benefits of LEDs being cool so can be placed closer to the crops but they work just as well as HPS (C. A. Mitchell et al. 2015). Furthermore, spectral control can be implemented to manipulate morphology, flowering and foliage colour which is very important for ornamentals (Garrett Owen and Lopez 2015; Q. Li and Kubota 2009). Top lighting is most efficient for tall crops (Massa et al. 2008). However, dense overhead arrays block solar radiation (Lu and Mitchell 2016).

Photoperiod lighting

Photoperiod lighting is very low intensity lighting used to regulate flowering and or vegetative growth (Okimura and Igarashi 1997; Erik S. Runkle et al. 1998). Only low light levels are needed so it has a low associate cost. However, a high far-red ratio is required which is not the most efficient light to produce (Kusuma, Pattison, and Bugbee 2020). Increased photoperiods can promote flowering in long day plants and inhibit it in short day plants.

Spectral control of morphology

Plants have evolved with the natural environment to utilise as wide a range of wavebands as sources of energy and information. To understand how we can utilise LED light wavelengths to control plant morphology it is important to understand how the light spectrum varies in the natural environment and how plants respond to it. If a plants natural response is desirable in the specific cultivar and life-stage, then it is likely to be beneficial when mimicked in a greenhouse. Plant photoreceptors absorbs photons of specific wavelengths and communicate that information to the plant bringing about morphological and physiological changes (Folta and Carvalho 2015; E. S. Runkle and Heins 2001). Responses have been noted as far out as ultraviolet-C (Magerøy et al. 2010) and near infra-red (Johnson et al. 1996). Monochromatic LED lights can be used to bring about desirable responses in plants. The extent to which this is possible in a variety of crops is yet to be fully researched.

Red/far-red

Red and far-red light is absorbed antagonistically by the phytochrome (Butler et al. 1959; Craver and Lopez 2016; Higuchi and Hisamatsu 2016). Far-red (700-800) makes up a higher proportion of natural light radiation in winter, the evenings and under shaded canopies (Chen et al. 2014; Higuchi and Hisamatsu 2016; Holmes and Smith 1975). Whereas red light (600-700nm) makes up a larger part of summer, daytime and direct sunlight (Mathews 2006). The phytochrome equilibrium regulates stem extension and flowering (Stutte 2009). Far-red induced shade response brings on earlier flowering ad petiole extension (Collins 1966; Philip Davis 2016; Franklin 2008; J. C. Sager et al. 1988; Lorrain et al. 2007; Monostori et al. 2018). Red light causes more compact plants, delayed flowering, deetiolated seedlings and mediates the effects of shade avoidance (Blázquez and Weigel 1999; Cao et al. 2016; Craver and Lopez 2016; Franklin et al. 2003; N. Goto, Kumagai, and Koornneef 1991; J. Li et al. 2011; Sharrock and Clack 2002; Whippo and Hangarter 2006). Plants are most sensitive to far-red at the end of the day light pulses can simulates growth in a low R:FR environment (Fankhauser and Casal 2004; Kasperbauer 1971). Far-red, aside from having potential beneficial morphological traits, is not the most efficient at driving photosynthesis. Red light is close to the absorption peak for chlorophyll, very efficient for biomass accumulation and most efficiently produced by LEDs (Massa et al. 2008). However, sole red light can be detrimental and cause excessive hypocotyl elongation (Goins et al. 1997; Hoenecke, Bula, and Tibbitts 1992) A small amount of blue with the red stops the detrimental effects (Goins et al. 1997; Hoenecke, Bula, and Tibbitts 1992).

Red blue ratio

Red light, followed by blue, are the most efficient for driving photosynthesis (Trouwborst et al. 2016). Neither red or blue light alone is sufficient for plant growth, some of the other is also required to mediate suboptimal morphological and aberrant genomic effects (Philip Davis 2016; Erik Runkle 2017; Hogewoning et al. 2010; Trouwborst et al. 2016). The red:blue ratio can be used to control plant morphology. Blue light can reduce plant hight. The ideal red:blue ratio has been shown to be 3:7 in tomatoes, 84:16 in brassica (Philip Davis 2016; He et al. 2015). Increasing blue light percentage at low light levels can manipulate leaf properties to mimic plants kept in high light intensities in field conditions (Hogewoning et al. 2010).

Blue

In the natural environment, blue light (400-500nm) makes up the largest proportion of natural light radiation in summer and in direct unlight. Blue light is absorbed by several different photoreceptors including, cryptochromes, phytotropins, phytochrome and Zeitlup family proteins (W. Y. Kim et al. 2007). Blue light is important in the regulation of stomatal opening, petiole extension, flowering, phototropism, secondary metabolite production, regulation of the circadian rhythm and chloroplast movement (Christie 2007; Giliberto et al. 2005; W. Y. Kim et al. 2007; Valverde et al. 2004; Yu et al. 2010).

Blue light Inhibits stem extension (Kigel and Cosgrove 1991; Lin et al. 1998; E. S. Runkle and Heins 2001). However monochromatic blue causes stem elongation (Van Ieperen, Savvides, and Fanourakis 2012). Both blue and red needed for compact plants (R. J. Mitchell et al. 2009). (Kinoshita et al. 2001; Taiz and Zeiger 2006a). Small amount of blue added to red increases stomatal opening and CO_2 uptake (Van Ieperen, Savvides, and Fanourakis 2012; Kinoshita et al. 2001). Blue light exposure produces darker leaves and increases secondary metabolites (Erik Runkle 2017). Blue light also has a species dependant effect on flowering (Giliberto et al. 2005). The quantity of blue light effects flowering time and the time taken for flowers to open reduces with blue light (Philip Davis 2016; Yoshida et al. 2016). Furthermore, blue light promotes vegetative growth (Phillip Davis 2015).

Green

Green light (490-570nm) is reflected by chlorophyll and is absorbed only in low levels by green plants, making its addition to supplementary lighting seam slightly erroneous (Terashima et al. 2009). However, it helps visibility for workers, can penetrate further into the canopy and has some morphological effects on the plants (Brodersen and Vogelmann 2010; Terashima et al. 2009). It can downregulate the effects of blue light in a similar antagonistic relationship as red and far-red (Taiz and Zeiger, 2006, 462). Green light has been shown to increase crop biomass accumulation when replacing some of the blue or red light in a mixture (H. H. Kim et al. 2004)

Light quality and secondary metabolites

Light stimulation enhances specific secondary metabolites, plant colour and flavour, health benefits like antioxidants, vitamins, sugars and pigments (Shimizu 2016). Many raw materials for making medicines and health benefits of plants, like antioxidant phenolic compounds, comprise plants secondary metabolites (Samuoliene et al. 2012). Different wavelengths effect different varieties differently (Samuoliene et al. 2012). Spectral improvements can either be added in propagation or to the adult plant (Johkan et al. 2010; K. Kim et al. 2013; Piao et al. 2013). Blue and UV light shows the biggest increase in secondary metabolites including, phenolic compounds, antioxidants, carotenoids, chicory acid, anthocyanins and the primary metabolite chlorophyll (Johkan et al. 2010; E.-Y. Kim et al. 2014; K. Kim et al. 2013; Q. Li and Kubota 2009; Ninu et al. 1999; Ouzounis et al. 2015; Samuoliene et al. 2012; Son and Oh 2013). However, higher ascorbic acid and anthocyanin concentrations were seen under red light in some species (Mizuno, Amaki, and Watanabe 2011). Also more antioxidants and a higher sugar content were seen with the addition of pulsing yellow light (Urbonavičiūtė et al. 2009; Žukauskas et al. 2011). Chlorophyll reduce under far-red (Johkan et al. 2010; Q. Li and Kubota 2009).

Supplementary lighting and fruit quality

There is a high demand for out of season food production, however, the high fruit quality standards for summer production remain (Lu and Mitchell 2016). Winter crops would ideally have equal sugar content, flavour, ascorbic acid content, lycopene, and oxygen radical absorbance capacity. Supplementary lighting can improve these fruit quality criteria making winter crops higher value and more acceptable to consumers (Lu and Mitchell 2016).

A lot of the taste comes from the amount of sugars present (Shimizu 2016). Increasing light intensity and duration increases the vitamin C and antioxidant content (Hanenberg, Janse, and Verkerke 2016; Verkerke, Labrie, and Dueck 2015). Tomatoes irradiated with red and blue ELD light increased the vitamin C content logarithmically with light exposure (Verkerke, Labrie, and Dueck 2015). Inter canopy LEDs increase sugar and ascorbic acid content in winter grown tomatoes compared to ambient lighting (Tewolde et al. 2016). Supplementary LED lighting also showed improvements in colour in cucumbers and green pepper (Alcock and Bertling 2013; Hao et al. 2015).

Efficiency

System efficiency

The amount of natural resources required for plant production decreases with the increased intensity of the system, replaced by increased infrastructure and energy use. In areas with scarce natural resources for plant production, like cities and deserts, intensive systems can be very effective. In any system the water, CO_2, heat, nutrients, and light use efficiencies are vital for reducing the environmental impact (Toyoki Kozai 2013). Looking at the growing system as a whole is important where waste energy from one element can be reused for another like heat from lighting reducing heating requirements.

Light efficiency

Light efficiency is very important for reducing energy consumption and is variable between types of lighting and brands. Light efficiency is the measurable output over input of a system µmol/joul, a higher number is more efficient, 1 watt is 1 j/second (Erik S. Runkle 2016). The growing system efficiency combines light efficiency and effective canopy photon capture, and is measurable by the energy input to plant biomass output (Ibaraki 2016; J. A. Nelson and Bugbee 2014). Increasing the percentage of light captured by plants and evenly distributing light on all leaves is important for increasing efficiency (Ibaraki 2016; Toyoki Kozai 2013; Murakami and Matsuda 2016). Using a mixture of overhead and inter-canopy lighting, decreasing the distance from the lamp to the plant, increasing planting density, improved canopy structure, and using reflectors behind the lamps and in the growing environment can increase capture (Bornwaßer and Tantau 2012; Ibaraki 2016; Toyoki Kozai 2013; Massa et al. 2008; J. A. Nelson and Bugbee 2014; Poulet et al. 2014). The timing and spectrum of the light can be modified to best fit plants morphology increasing efficiency (Ibaraki 2016). Where LEDs are positioned close to the plants there is a steep light gradient causing an intensity disparity between upper and lower leaves decreasing efficiency.

The efficiency of the plants converting light energy into chemical energy is also variable (Gitelson and Gamon 2015; Rosati 2003). This can be measured by assessing the PAR captured by the canopy compared to the increase in biomass. Different plant species and environmental conditions, like temperature, CO2 and availability of nutrients (Rosati 2003). It is hard to compare light use efficiencies between species as different studies definitions vary (Gitelson and Gamon 2015; McCallum et al. 2009).

Economics

Economics is the most important criteria for a new technology becoming widely used and indicates that it improves system efficiency (Toyoki Kozai 2016). For a system to be economically viable the all the cost input needs to be less than the product output (Toyoki Kozai 2013).

Winter grown crops need to compete with crops from warmer countries with lower capital and operational cost, making winter production economically challenging (J. A. Nelson and Bugbee 2014)**.** Lighting is the biggest expense in winter production. HPS lamps are mass produced and are comparatively cheap but have a high energy use. Furthermore, lots of waste long wave variation, however, this can be used to offset winter heating, although gas heating is cheaper than electrical. LEDs produce the same yield with lower running cost, increased longevity and higher efficiency (D. Singh et al. 2015; Yeh and Chung 2009). In 2014 LEDs and HPS had similar efficiency of about 1.7µmol/j, from there LED efficiencies have increased dramatically (Lu and Mitchell 2016). However, the initial capital cost of LEDs are much higher (J. A. Nelson and Bugbee 2014). LEDs will have to be run for many years before the energy savings from the increased efficiency cancel out the installation cost. Improved technology, demand and mass production is quickly pushing the price of LED lighting down. LEDs need replacing less often, reducing part and labour cost (H. Zhang, Burr, and Zhao 2017). LEDs have 38-47% less environmental impact than HPS (Lu and Mitchell 2016). Areas with high energy cost and a large demand for supplemental lighting favour LEDs (C. A. Mitchell et al. 2015).

Low light fast yielding crops like lettuce most likely to be economical under supplementary lighting; high light requiring tomatoes scored intermediate for profitability due to their productivity potential and heating offset of inter-lighting; Strawberries scored lowest in productivity potential and heating cost offset (Kubota et al. 2016).

Work environment and health effects

Working environment for labourers is often not well invested in with to few occupational regulations (Takao 2016). Monochromatic blue or red light changes the plants appearance. Colour is important when assessing fruit ripeness, which is hard to tell under monochromatic light, a broad spectrum needed. The plants colour is important to identify disease eg. Virus mosaic or over anthocyanins purple colour. It is however possible to identify diseases using particular spectrums of LEDs (Sankaran et al. 2010).

The circadian rhythm can be altered by bright blue light, like that in plant factories, putting workers at risk. Circadian rhythm regulates daily activities, 24hr oscillation in the brain. Blood pressure, body temperature, cognition, and sugar metabolism rises in the day and are lower at night (Tokura et al. 1994). Disruptions to circadian rhythm can cause disease like increased risk of diabetes mellitus and breast cancer in shift workers. Melatonin, secreted from pituitary gland, regulates many human cells (Ekmekcioglu 2006). Melatonin requires a robust circadian rhythm and is strongly inhibited by bright light. For comfortable sleep avoid evening exposure to bright light and have high light exposure in the mornings (Gradisar and Crowley 2013).

Conclusions

There are many ways to improve greenhouses system efficiencies, LED lighting is just one element of a larger effort to maximise plant growth while minimising energy use. Reducing shading in greenhouses and maximising the use of solar light should also be focused on as the most energy efficient form of production. LED technologies are advancing very quickly with new options for increased efficiency, vertical farming, and spectral control. This brings about new opportunities, which have not previously been possible with supplementary lighting, like control of colour and shape in ornamentals, and improved secondary metabolite production in medical crops. The economics of installing LED systems suffers from high installation costs, but as fitment prices drop and light efficiencies increase, should become less prohibitive in setting up new systems if not replacing currently installed ones. There are many potential areas for further research in LED horticultural production, including improving working environments, fine tuning crop specific spectral responses, creating complete light spectrum for sole source agriculture, exploring the effects of monochromatic lighting on pollinators, and using LEDs to further our knowledge of plant physiology.

References

Akiyama, Takuji, and Toyoki Kozai. 2016. “Light Environment in the Cultivation Space of Plant Factory with LEDs.” In *LED Lighting for Urban Agriculture*, Springer Singapore, 91–109.

Alcock, C. M., and I. Bertling. 2013. “Effect of Light and Fruit Maturity on Postharvest Colour Change in Green ‘Sondela’ Peppers (Capsicum Annuum L.).” In *Acta Horticulturae*, International Society for Horticultural Science, 171–78.

Blázquez, Miguel A., and Detlef Weigel. 1999. “Independent Regulation of Flowering by Phytochrome B and Gibberellins in Arabidopsis.” *Plant Physiology* 120(4): 1025–32.

Bornwaßer, T., and H. J. Tantau. 2012. “Evaluation of LED Lighting Systems in in Vitro Cultures.” *Acta Horticulturae* 956: 555–62.

Bourget, C. Michael. 2008. “An Introduction to Light-Emitting Diodes.” In *HortScience*, , 1944–46.

Brault, B, Chris Gueymard, R Boily, and Andre Gosselin. 1987. “High Pressure Sodium Lighting Effects on Greenhouse Heating Requirements.” *Am Soc Agri Eng* 89(4039).

Brodersen, Craig R., and Thomas C. Vogelmann. 2010. “Do Changes in Light Direction Affect Absorption Profiles in Leaves?” *Functional Plant Biology* 37(5): 403.

Brumfield, Robin. 2007. *Dealing with Rising Energy Costs* . www.biosafesystems.com (April 30, 2021).

Bula, R. J. et al. 1991. “Light-Emitting Diodes as a Radiation Source for Plants.” *HortScience* 26(2): 203–5.

Butler, W. L., K. H. Norris, H. W. Siegelman, and S. B. Hendricks. 1959. “Detection, Assay, and Preliminary Purification of the Pigment Controlling Photoresponcive Development of Plants.” *Proceedings of the National Academy of Sciences* 45(12): 1703–8.

Cao, Kai et al. 2016. “Effects of Red Light Night Break Treatment on Growth and Flowering of Tomato Plants.” *Frontiers in Plant Science* 7.

Chen, Fang et al. 2014. “Arabidopsis Phytochrome A Directly Targets Numerous Promoters for Individualized Modulation of Genes in a Wide Range of Pathways.” *The Plant Cell* 26(5): 1949–66.

Cheng, Chun An et al. 2010. “A Digitally Wireless Dimmable Lighting System for Two-Area Fluorescent Lamps.” In *IEEE Region 10 Annual International Conference, Proceedings/TENCON*, , 2173–78.

Cho, Jaehee et al. 2010. “Characteristics of Blue and Ultraviolet Light-Emitting Diodes with Current Density and Temperature.” *Electronic Materials Letters* 6(2): 51–53.

Choi, Joon ho et al. 2015. “Visible Light Communications Employing PPM and PWM Formats for Simultaneous Data Transmission and Dimming.” *Optical and Quantum Electronics* 47(3): 561–74.

Christie, John M. 2007. “Phototropin Blue-Light Receptors.” *Annual Review of Plant Biology* 58(1): 21–45.

Collins, W. B. 1966. “Floral Initiation in Strawberry and Some Effectsof Red and Far-Red Radiation as Components of Continuous White Light Light.” *Canadian Journal of Botany* 44(5): 663–68.

Craver, Joshua K., and Roberto G. Lopez. 2016. “Control of Morphology by Manipulating Light Quality and Daily Light Integral Using LEDs.” In *LED Lighting for Urban Agriculture*, Springer Singapore, 203–17.

Currey, Christopher J., and Roberto G. Lopez. 2013. “Cuttings of Impatiens, Pelargonium, and Petunia Propagated under Light-Emitting Diodes and High-Pressure Sodium Lamps Have Comparable Growth, Morphology, Gas Exchange, and Post-Transplant Performance.” *HortScience* 48(4): 428–34.

Davis, Philip. 2016. “Stockbridge Technology Center Plant Light Reponses.”

Davis, Phillip. 2015. “Lighting: The Principles.”

Dorais, Martine. 2003. “Use of Supplemental Lighting for Vegetable Crop Production: Light Intensity, Crop Response, Nutrition, Crop Management, Cultural Practices .” In *Canadian Greenhouse Conference* ,.

Ekmekcioglu, C. 2006. “Melatonin Receptors in Humans: Biological Role and Clinical Relevance.” *Biomedicine and Pharmacotherapy* 60(3): 97–108.

Erik Runkle. 2017. “Effects of Blue Light on Plants - Greenhouse Product News.” *Greenhouse production news*. https://gpnmag.com/article/effects-of-blue-light-on-plants/ (July 25, 2019).

Fankhauser, Christian, and Jorge J. Casal. 2004. “Phenotypic Characterization of a Photomorphogenic Mutant.” *The Plant Journal* 39(5): 747–60.

Faust, James E., Veronda Holcombe, Nihal C. Rajapakse, and Desmond R. Layne. 2005. “The Effect of Daily Light Integral on Bedding Plant Growth and Flowering.” *HortScience* 40(3): 645–49.

Fisher, Paul, and Erik Runkle. 2004. *Lighting up Profits : Understanding Greenhouse Lighting (Book, 2004) [WorldCat.Org]*. 1st ed. Willowby: Meister Media Worldwide.

Folta, Kevin M., and Sofia D. Carvalho. 2015. “Photoreceptors and Control of Horticultural Plant Traits.” *HortScience* 50(9): 1274–80.

Franklin, Keara A. et al. 2003. “Mutant Analyses Define Multiple Roles for Phytochrome C in Arabidopsis Photomorphogenesis.” *Plant Cell* 15(9): 1981–89.

Franklin, Keara A. 2008. “Shade Avoidance.” *New Phytologist* 179(4): 930–44.

Fujiwara, Kazuhiro. 2016. “Basics of LEDs for Plant Cultivation.” In *LED Lighting for Urban Agriculture*, Springer Singapore, 377–93.

Fujiwara, Kazuhiro, Kensuke Eijima, and Akira Yano. 2013. “Second-Generation LED-Artificial Sunlight Source System Available for Light Effects Research in Biological and Agricultural Sciences. LED Low-Light Irradiation Storage View Project Environment Control in Micropropagation View Project Second-Generation LED.” In *Luxpacifica2013*, , 140–45.

Fujiwara, Kazuhiro, and Akira Yano. 2011. “Controllable Spectrum Artificial Sunlight Source System Using LEDs with 32 Different Peak Wavelengths of 385-910 Nm.” *Bioelectromagnetics* 32(3): 243–52.

Garrett Owen, W., and Roberto G. Lopez. 2015. “End-of-Production Supplemental Lighting with Red and Blue Light-Emitting Diodes (LEDs) Influences Red Pigmentation of Four Lettuce Varieties.” *HortScience* 50(5): 676–84.

Gerland, Patrick et al. 2014. “World Population Stabilization Unlikely This Century.” *Science* 346(6206): 234–37.

Giliberto, Leonardo et al. 2005. “Manipulation of the Blue Light Photoreceptor Cryptochrome 2 in

Tomato Affects Vegetative Development, Flowering Time, and Fruit Antioxidant Content.” *Plant Physiology* 137(1): 199–208.

Gitelson, Anatoly A., and John A. Gamon. 2015. “The Need for a Common Basis for Defining Light-Use Efficiency: Implications for Productivity Estimation.” *Remote Sensing of Environment* 156: 196–201.

Goins, G.D., N.C. Yorio, M.M. Sanwo, and C.S. Brown. 1997. “Photomorphogenesis, Photosynthesis, and Seed Yield of Wheat Plants Grown under Red Light-Emitting Diodes (LEDs) with and without Supplemental Blue Lighting.” *Journal of Experimental Botany* 48(7): 1407–13.

Goto, E. 2012. “Plant Production in a Closed Plant Factory with Artificial Lighting.” *Acta Horticulturae* 956: 37–49.

Goto, Nobuharu, Tadashi Kumagai, and Maarten Koornneef. 1991. “Flowering Responses to Light-Breaks in Photomorphogenic Mutants of Arabidopsis Thaliana, a Long-Day Plant.” *Physiologia Plantarum* 83(2): 209–15.

Gradisar, Michael, and Stephanie J. Crowley. 2013. “Delayed Sleep Phase Disorder in Youth.” *Current Opinion in Psychiatry* 26(6): 580–85.

Gunnlaugsson, B., and S. Adalsteinsson. 2006. “Interlight and Plant Density in Year-Round Production of Tomato at Northern Latitudes.” In *Acta Horticulturae*, International Society for Horticultural Science, 71–75.

Hanan, Joe J. 2017. Greenhouses: Advanced Technology for Protected Horticulture *Greenhouses: Advanced Technology for Protected Horticulture*. CRC Press.

Hanenberg, M. A.A., J. Janse, and W. Verkerke. 2016. “LED Light to Improve Strawberry Flavour, Quality and Production.” In *Acta Horticulturae*, International Society for Horticultural Science, 207–12.

Hao, X., X. Guo, X. Chen, and S. Khosla. 2015. “Inter-Lighting in Mini-Cucumbers: Interactions with Overhead Lighting and Plant Density.” *Acta Horticulturae* 1107: 291–96.

He, Jie, Lin Qin, Yunman Liu, and Tsui Wei Choong. 2015. “Photosynthetic Capacities and Productivity of Indoor Hydroponically Grown *Brassica Alboglabra* Bailey under Different Light Sources.” *American Journal of Plant Sciences* 06(04): 554–63.

Hernández, R., and C. Kubota. 2012. “Tomato Seedling Growth and Morphological Responses to Supplemental LED Lighting Red:Blue Ratios under Varied Daily Solar Light Integrals.” *Acta Horticulturae* 956: 187–94.

Heuvelink, E. et al. 2006. “Horticultural Lighting in the Netherlands: New Developments.” In *Acta Horticulturae*, International Society for Horticultural Science, 25–33.

Higuchi, Yohei et al. 2012. “Day Light Quality Affects the Night-Break Response in the Short-Day Plant Chrysanthemum, Suggesting Differential Phytochrome-Mediated Regulation of Flowering.” *Journal of Plant Physiology* 169(18): 1789–96.

Higuchi, Yohei, and Tamotsu Hisamatsu. 2016. “Light Acts as a Signal for Regulation of Growth and Development.” In *LED Lighting for Urban Agriclture*, eds. Toyoki Kozai, Kazuhiro Fujiwara, and Eric S. Runkle. Singapore: Springer, 57–73.

Hoenecke, M. E., R. J. Bula, and T. W. Tibbitts. 1992. “Importance of ‘blue’ Photon Levels for Lettuce Seedlings Grown under Red-Light-Emitting Diodes.” *HortScience : a publication of the American*

Society for Horticultural Science 27(5): 427–30.

Hogewoning, S. W. et al. 2010. “Blue Light Dose-Responses of Leaf Photosynthesis, Morphology, and Chemical Composition of Cucumis Sativus Grown under Different Combinations of Red and Blue Light.” *Journal of Experimental Botany* 61(11): 3107–17.

Holmes, M. G., and H. Smith. 1975. “The Function of Phytochrome in Plants Growing in the Natural Environment.” *Nature* 254(5500): 512–14.

Ibaraki, Yasuomi. 2016. “Lighting Efficiency in Plant Production under Artificial Lighting and Plant Growth Modeling for Evaluating the Lighting Efficiency.” In *LED Lighting for Urban Agriculture*, Springer Singapore, 151–61.

Van Ieperen, W., A. Savvides, and D. Fanourakis. 2012. “Red and Blue Light Effects during Growth on Hydraulic and Stomatal Conductance in Leaves of Young Cucumber Plants.” *Acta Horticulturae* 956: 223–30.

Islam, M. Ashraful et al. 2012. “Artificial Light from Light Emitting Diodes (LEDs) with a High Portion of Blue Light Results in Shorter Poinsettias Compared to High Pressure Sodium (HPS) Lamps.” *Scientia Horticulturae* 147: 136–43.

J. C. Sager, W. O. Smith, J. L. Edwards, and K. L. Cyr. 1988. “Photosynthetic Efficiency and Phytochrome Photoequilibria Determination Using Spectral Data.” *Transactions of the ASAE* 31(6): 1882–89.

Johkan, Masahumi et al. 2010. “Blue Light-Emitting Diode Light Irradiation of Seedlings Improves Seedling Quality and Growth after Transplanting in Red Leaf Lettuce.” *HortScience* 45(12): 1809–14.

Johnson, Corinne F. et al. 1996. “Infrared Light-Emitting Diode Radiation Causes Gravitropic and Morphological Effects in Dark-Grown Oat Seedlings.” *Photochemistry and Photobiology* 63(2): 238–42.

Jokinen, K., L. E. Särkkä, and J. Näkkilä. 2012. “Improving Sweet Pepper Productivity by LED Interlighting.” *Acta Horticulturae* 956: 59–66.

Kasperbauer, M. J. 1971. “Spectral Distribution of Light in a Tobacco Canopy and Effects of End-of-Day Light Quality on Growth and Development.” *Plant Physiology* 47(6): 775–78.

Kigel, Jaime, and Daniel J. Cosgrove. 1991. “Photoinhibition of Stem Elongation by Blue and Red Light: Effects on Hydraulic and Cell Wall Properties.” *Plant Physiology* 95(4): 1049–56. https://plantphysiol.org (April 23, 2021).

Kim, Eun-Young et al. 2014. “Growth and Antioxidant Phenolic Compounds in Cherry Tomato Seedlings Grown under Monochromatic Light-Emitting Diodes Introduction.” *Hort. Environ. Biotechnol* 55(6): 506–13.

Kim, Hyeon Hye, Gregory D. Goins, Raymond M. Wheeler, and John C. Sager. 2004. “Green-Light Supplementation for Enhanced Lettuce Growth under Red-and Blue-Light-Emitting Diodes.” *HortScience* 39(7): 1617–22.

Kim, KangMin et al. 2013. “The Effect of Blue-Light-Emitting Diodes on Antioxidant Properties and Resistance to Botrytis Cinerea in Tomato.” *Journal of plant pathology and microbiology* 4(9).

Kim, Woe Yeon et al. 2007. “ZEITLUPE Is a Circadian Photoreceptor Stabilized by GIGANTEA in Blue

Light." *Nature* 449(7160): 356–60.

Kinoshita, Toshinori et al. 2001. "Phot1 and Phot2 Mediate Blue Light Regulation of Stomatal Opening." *Nature* 414(6864): 656–60.

Kozai, T. 2013. "Sustainable Plant Factory: Closed Plant Production Systems with Artificial Light for High Resource Use Efficiencies and Quality Produce." *Acta Horticulturae* 1004: 27–40.

Kozai, Toyoki. 2013. "Resource Use Efficiency of Closed Plant Production System with Artificial Light: Concept, Estimation and Application to Plant Factory." *Proceedings of the Japan Academy Series B: Physical and Biological Sciences* 89(10): 447–61.

Kozai, T. 2016. "Why LED Lighting for Urban Agriculture?" In *LED Lighting for Urban Agriclture*, eds. Toyoki Kozai and Kazuhiro Fujiwara. Singapore: Springer, 3–18.

Kozai, Toyoki, Kazuhiro Fujiwara, and Eric S Runkle. 2016. *LED Ligthing for Urban Agriculture*. Singapore: Springer, Singapore.

Kozai, Toyoki, and Geng Zhang. 2016. "Some Aspects of the Light Environment." In *LED Lighting for Urban Agriculture*, Springer Singapore, 49–55.

Kubota, C. et al. 2016. "Does Supplemental Lighting Make Sense for My Crop?-Empirical Evaluations." *Acta Horticulturae* 1134: 403–11.

Kusuma, Paul, P. Morgan Pattison, and Bruce Bugbee. 2020. "From Physics to Fixtures to Food: Current and Potential LED Efficacy." *Horticultural research* 7(56).

Lafont, Ugo, Henk Van Zeijl, and Sybrand Van Der Zwaag. 2012. "Increasing the Reliability of Solid State Lighting Systems via Self-Healing Approaches: A Review." In *Microelectronics Reliability*, Pergamon, 71–89.

Landis, Thomas D., Jeremiah R. Pinto, and R Kasten. 2013. *Light Emitting Diodes (LED): Applications in Forest and Native Plant Nurseries*.

Li, Jigang, Gang Li, Haiyang Wang, and Xing Wang Deng. 2011. "Phytochrome Signaling Mechanisms." *The Arabidopsis Book* 9: e0148.

Li, Kun, Qi Chang Yang, Yu Xin Tong, and Ruifeng Cheng. 2014. "Using Movable Light-Emitting Diodes for Electricity Savings in a Plant Factory Growing Lettuce." *HortTechnology* 24(5): 546–53.

Li, Qian, and Chieri Kubota. 2009. "Effects of Supplemental Light Quality on Growth and Phytochemicals of Baby Leaf Lettuce." *Environmental and Experimental Botany* 67(1): 59–64.

Li, T., E. Heuvelink, T.A. Dueck, and L.F.M. Marcelis. 2012. "Understanding How Diffuse Light Increases Yield in Tomato." : 98. https://research.wur.nl/en/publications/understanding-how-diffuse-light-increases-yield-in-tomato (April 25, 2021).

Li, Z. et al. 2012. "In Situ Monitoring System for Chlorophyll Fluorescence Parameters of Tomato at Greenhouse in Northern China." *Acta Horticulturae* 956: 583–89.

Liao, Yi et al. 2014. "Night Break Effect of LED Light with Different Wavelengths on Floral Bud Differentiation of Chrysanthemum Morifolium Ramat ^|^lsquo;Jimba^|^rsquo; and Iwa No Hakusen." *Environmental Control in Biology* 52(1): 45–50.

Lin, Chentao et al. 1998. "Enhancement of Blue-Light Sensitivity of Arabidopsis Seedlings by a Blue Light

Receptor Cryptochrome 2." *Proceedings of the National Academy of Sciences of the United States of America* 95(5): 2686–90.

Lorrain, Séverine et al. 2007. "Phytochrome-Mediated Inhibition of Shade Avoidance Involves Degradation of Growth-Promoting BHLH Transcription Factors." *The Plant Journal* 53(2): 312–23.

Lu, Na et al. 2012. "Effects of Supplemental Lighting with Light Emitting Diodes (LEDs) on Tomato Yield and Quality of Single Truss Tomato Plants Grown at High Planting Density." *Environmental Control in Biology* 50(1): 63–74.

Lu, Na, and Cary A. Mitchell. 2016. "Supplemental Lighting for Greenhouse-Grown Fruiting Vegetables." In *LED Lighting for Urban Agriculture*, Springer Singapore, 219–32. https://link.springer.com/chapter/10.1007/978-981-10-1848-0_16 (April 24, 2021).

Magerøy, Melissa Hamner, Erin H. Kowalik, Kevin M. Folta, and James Shinkle. 2010. "Evidence of Physiological Phototropin1 (Phot1) Action in Response to UV-C Illumination." *Plant Signaling & Behavior* 5(10): 1204–10.

Massa, Gioia D., Hyeon Hye Kim, Raymond M. Wheeler, and Cary A. Mitchell. 2008. "Plant Productivity in Response to LED Lighting." In *HortScience*, , 1951–56.

Massa, Gioia D., and Jeff Norrie. 2015. "LEDs Electrifying Horticultural Science: Proceedings from the 2014 Colloquium and Workshop." *HortScience* 50(9): 1272–1273.

Mathews, Sarah. 2006. "Phytochrome-Mediated Development in Land Plants: Red Light Sensing Evolves to Meet the Challenges of Changing Light Environments." *Molecular Ecology* 15(12): 3483–3503.

Matulka, Rebecca, and Daniel Wood. 2013. "The History of the Light Bulb | Department of Energy." https://www.energy.gov/articles/history-light-bulb (April 28, 2021).

McCallum, Ian et al. 2009. "Satellite-Based Terrestrial Production Efficiency Modeling." *Carbon Balance and Management* 4(1): 8.

Mitchell, Cary A. et al. 2015. "Light-Emitting Diodes in Horticulture." *Horticultural Reviews* 43: 1–87.

Mitchell, Randall J., Rebecca E. Irwin, Rebecca J. Flanagan, and Jeffrey D. Karron. 2009. "Ecology and Evolution of Plant–Pollinator Interactions." *Annals of Botany* 103(9): 1355–63. https://academic.oup.com/aob/article-lookup/doi/10.1093/aob/mcp122 (January 30, 2018).

Mizuno, T., W. Amaki, and H. Watanabe. 2011. "Effects of Monochromatic Light Irradiation by LED on the Growth and Anthocyanin Contents in Leaves of Cabbage Seedlings." In *Acta Horticulturae*, International Society for Horticultural Science, 179–84.

Moerkens, R., W. Vanlommel, R. Vanderbruggen, and T. Van Delm. 2016. "The Added Value of LED Assimilation Light in Combination with High Pressure Sodium Lamps in Protected Tomato Crops in Belgium." *Acta Horticulturae* 1134: 119–24.

Monostori, István et al. 2018. "LED Lighting – Modification of Growth, Metabolism, Yield and Flour Composition in Wheat by Spectral Quality and Intensity." *Frontiers in Plant Science* 9.

Morrow, Robert C. 2008. "LED Lighting in Horticulture." In *HortScience*, , 1947–50.

Murakami, Keach, and Ryo Matsuda. 2016. "Optical and Physiological Properties of a Leaf." In *LED Lighting for Urban Agriculture*, , 113–23.

Nakamura, Shuji. 2015. “Nobel Lecture: Background Story of the Invention of Efficient Blue InGaN Light Emitting Diodes.” *Reviews of Modern Physics* 87(4): 1139.

Nelson, Jacob A., and Bruce Bugbee. 2014. “Economic Analysis of Greenhouse Lighting: Light Emitting Diodes vs. High Intensity Discharge Fixtures.” *PLoS ONE* 9(6): e99010.

Nelson, Paul V. 2012. *Greenhouse Operation and Management, 7th Edition | Pearson*. 7th ed. Upper Saddle River: Pearson Prentice Hall.

Ninu, Luciano et al. 1999. “Cryptochrome 1 Controls Tomato Development in Response to Blue Light.” *The Plant Journal* 18(5): 551–56. http://doi.wiley.com/10.1046/j.1365-313X.1999.00466.x (April 27, 2021).

Okimura, M., and I. Igarashi. 1997. “Effects of Photoperiod and Temperature on Flowering in Everbearing Strawberry Seedlings.” In *Acta Horticulturae*, , 605–8.

Ouzounis, Theoharis et al. 2015. “Predawn and High Intensity Application of Supplemental Blue Light Decreases the Quantum Yield of PSII and Enhances the Amount of Phenolic Acids, Flavonoids, and Pigments in Lactuca Sativa.” *Frontiers in Plant Science* 6(FEB).

Piao, Xiang-Min et al. 2013. “Variation in Antioxidant Activity and Polyphenol Content in Tomato Stems and Leaves.” *Plant Breeding and Biotechnology* 1(4): 366–73.

Pimputkar, Siddha, James S. Speck, Steven P. Denbaars, and Shuji Nakamura. 2009. “Prospects for LED Lighting.” *Nature Photonics* 3(4): 180–82.

Poulet, L. et al. 2014. “Significant Reduction in Energy for Plant-Growth Lighting in Space Using Targeted LED Lighting and Spectral Manipulation.” *Life Sciences in Space Research* 2: 43–53.

Randall, Wesley C., and Roberto G. Lopez. 2014. “Comparison of Supplemental Lighting from High-Pressure Sodium Lamps and Light-Emitting Diodes during Bedding Plant Seedling Production.” *Hortscience* 49(5): 589–95.

Rosati, A. 2003. “Estimating Photosynthetic Radiation Use Efficiency Using Incident Light and Photosynthesis of Individual Leaves.” *Annals of Botany* 91(7): 869–77.

Runkle, E. S., and R. D. Heins. 2001. “Specific Functions of Red, Far Red, and Blue Light in Flowering and Stem Extension of Long-Day Plants.” *Journal of the American Society for Horticultural Science* 126(3): 275–82.

Runkle, Erik S. 2016. “Recent Developments in Plant Lighting.” In *LED Lighting for Urban Agriculture*, , 233–36.

Runkle, Erik S., Royal D. Heins, Arthur C. Cameron, and William H. Carlson. 1998. “Flowering of Herbaceous Perennials under Various Night Interruption and Cyclic Lighting Treatments.” *HortScience* 33(4): 672–77.

Sağlam, Şafak, and Bülent Oral. 2010. *Modern Lighting Sources and Controls for Energy Efficient Lighting and a Smart Control Algorithm Application*.

Samuoliene, Giedre, Ramunas Sirtautas, Aušra Brazaityte, and Pavelas Duchovskis. 2012. “LED Lighting and Seasonality Effects Antioxidant Properties of Baby Leaf Lettuce.” *Food Chemistry* 134(3): 1494–99.

Sankaran, Sindhuja, Ashish Mishra, Reza Ehsani, and Cristina Davis. 2010. “A Review of Advanced Techniques for Detecting Plant Diseases.” *Computers and Electronics in Agriculture* 72(1): 1–13.

Sharrock, Robert A., and Ted Clack. 2002. “Patterns of Expression and Normalized Levels of the Five Arabidopsis Phytochromes.” *Plant Physiology* 130(1): 442–56.

Shimizu, Hiroshi. 2016. “Effect of Light Quality on Secondary Metabolite Production in Leafy Greens and Seedlings.” In *LED Lighting for Urban Agriculture*, , 239–60.

Singh, Devesh, Chandrajit Basu, Merve Meinhardt-Wollweber, and Bernhard Roth. 2015. “LEDs for Energy Efficient Greenhouse Lighting.” *Renewable and Sustainable Energy Reviews* 49: 139–47.

Singh, Ranjit, and Madhu Bala. 2020. “Effects of Different Sources of Light as Night Break on Growth Characteristics of Korean Chrysanthemum (Chrysanthemum Morifolium Ramat.) Genotypes.” *Bangladesh Journal of Botany* 49(4): 967–74.

Son, Ki-Ho, and Myung-Min Oh. 2013. “Leaf Shape, Growth, and Antioxidant Phenolic Compounds of Two Lettuce Cultivars Grown under Various Combinations of Blue and Red Light-Emitting Diodes.” *HortScience* 48(8).

Stutte, Gary W. 2009. “Light-Emitting Diodes for Manipulating the Phytochrome Apparatus.” *HortScience* 44(2): 231–34.

Taiz, Lincoln, and Eduardo Zeiger. 2006a. “Blue Light Responces: Stomatal Movements and Morphogenisis.” In *Plant Physiology*, eds. Lincoln Zaiz and Eduardo Zeiger. Sunderland: Sinauer Associates, 445–66.

———. 2006b. *Plant Physiology*. Fourth. Sunderland: Sinauer Associates.

Takao, Motoharu. 2016. “Health Effects of Occupational Exposure to LED Light: A Special Reference to Plant Cultivation Works in Plant Factories.” In *LED Lighting for Urban Agriculture*, , 429–43.

Taylor Lovell, Sarah. 2010. “Multifunctional Urban Agriculture for Sustainable Land Use Planning in the United States.” *Sustainability* 2: 2499–2522.

Tennessen, Daniel J., Eric L. Singsaas, and Thomas D. Sharkey. 1994. “Light-Emitting Diodes as a Light Source for Photosynthesis Research.” *Photosynthesis Research* 39(1): 85–92.

Terashima, Ichiro et al. 2009. “Green Light Drives Leaf Photosynthesis More Efficiently than Red Light in Strong White Light: Revisiting the Enigmatic Question of Why Leaves Are Green.” *Plant and Cell Physiology* 50(4): 684–97.

Tewolde, Fasil T. et al. 2016. “Nighttime Supplemental LED Inter-Lighting Improves Growth and Yield of Single-Truss Tomatoes by Enhancing Photosynthesis in Both Winter and Summer.” *Frontiers in Plant Science* 7(APR2016): 448.

Tian, Feng. 2016. “Study and Optimization of Lighting Systems for Plant Growth in a Controlled Environment.” Université Paul Sabatier, Toulouse.

Tokura, H., M. Yutani, T. Morita, and M. Murakami. 1994. “Effects of Bright and Dim Light Intensities during Daytime upon Circadian Rhythm of Core Temperature in Man.” In *Temperature Regulation*, , 285–89.

Trouwborst, Govert et al. 2011. “The Effect of Intracanopy Lighting on Cucumber Fruit Yield-Model

Analysis." *Scientia Horticulturae* 129(2): 273–78.

Trouwborst, G. Hogewoning, S. W. VanKooten, O. Harbinson, J. VanIeperen, Wim. 2016. "Plasticity of Photosynthesis after the 'red Light Syndrome' in Cucumber." *Environmental and Experimental Botany* 121: 75–82.

Tungsram. 2021. *Tungsram Flexigrow Toplight Datasheet*.

Urbonavičiūtė, A. et al. 2009. "Effect of Flashing Amber Light on the Nutritional Quality of Green Sprouts." *Agronomy Research* 7(2): I761–767.

Valverde, Federico et al. 2004. "Photoreceptor Regulation of CONSTANS Protein in Photoperiodic Flowering." *Science* 303(5660): 1003–6.

Verkerke, W., C. Labrie, and T. Dueck. 2015. "The Effect of Light Intensity and Duration on Vitamin C Concentration in Tomato Fruits." *Acta Horticulturae* 1106: 49–53.

Whippo, Craig W., and Roger P. Hangarter. 2006. "Phototropism: Bending towards Enlightenment." *Plant Cell* 18(5): 1110–19. www.plantcell.org (October 29, 2020).

Yano, Akira. 2016. "Configuration, Function, and Operation of LED Lighting Systems." In *LED Lighting for Urban Agriculture*, Springer Singapore, 403–15.

Ye, H. et al. 2013. "Two-Phase Cooling of Light Emitting Diode for Higher Light Output and Increased Efficiency." *Applied Thermal Engineering* 52(2): 353–59.

Yeh, Naichia, and Jen Ping Chung. 2009. "High-Brightness LEDs-Energy Efficient Lighting Sources and Their Potential in Indoor Plant Cultivation." *Renewable and Sustainable Energy Reviews* 13(8): 2175–80.

Yoshida, Hideo et al. 2016. "Effects of Varying Light Quality from Single-Peak Blue and Red Light-Emitting Diodes during Nursery Period on Flowering,Photosynthesis,Growth,and Fruit Yield of Everbearing Strawberry." *Plant Biotechnology* 33(4): 267–76.

Yu, Xuhong, Hongtao Liu, John Klejnot, and Chentao Lin. 2010. "The Cryptochrome Blue Light Receptors." *The Arabidopsis Book* 8: 135.

Zhang, Geng et al. 2015. "Supplemental Upward Lighting from Underneath to Obtain Higher Marketable Lettuce (Lactuca Sativa) Leaf Fresh Weight by Retarding Senescence of Outer Leaves." *Frontiers in Plant Science* 6: 1110.

Zhang, Hao, John Burr, and Fu Zhao. 2017. "A Comparative Life Cycle Assessment (LCA) of Lighting Technologies for Greenhouse Crop Production." *Journal of Cleaner Production* 140: 705–13.

Žukauskas, A. et al. 2011. "Effect of Supplementary Pre-Harvest LED Lighting on the Antioxidant Properties of Lettuce Cultivars." In *Acta Horticulturae*, International Society for Horticultural Science, 87–90.