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Light-Emitting Diodes in Horticulture

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ABSTRACT

Light-emitting diodes (LEDs) have great potential to revolutionize lighting technology for the commercial horticulture industry. Unique LED properties of selectable, narrow-spectrum emissions, long life spans, cool photon-emitting surfaces, and rapidly improving energy use efficiency encourage novel lighting architectures and applications with promising profitability potential. In greenhouses, such unique properties can be leveraged for precise control of flowering and product quality for the floriculture industry, for energy-efficient propagation of ornamental and vegetable transplants, and for supplemental lighting of high-wire greenhouse vegetable crops for all-year production. In a sole-source lighting mode, LEDs can also be used for transplant production, as well as for production of rapid-turning vegetable and small fruit crops. Evidence is accumulating that nutritional and health attributes of horticultural products may be enhanced by specific wavelength combinations of narrow-spectrum light from LEDs. During periods of seasonally limited solar light, LEDs have potential to enhance daily light integral in greenhouses by providing supplemental photosynthetic radiation, particularly of red and blue light. The cool photon-emitting surfaces of LEDs permit their novel placement relative to crop foliar canopies, including close-canopy overhead lighting as well as within-canopy lighting, which greatly reduces electrical energy requirements while maintaining adequate incident photon fluxes. Because of the small size of individual LEDs and narrow beam angles from LED arrays, light distribution can be highly targeted and waste of light from LEDs minimized compared with other light sources traditionally used for horticulture. Prescriptions of spectral blends (e.g., red:far-red and red:blue ratios) can be developed for LEDs to accomplish specific photomorphogenic goals for seedling development, flowering, and possibly yield and produce quality. LED light quality may also be useful to control pest insects and to avoid physiological disorders otherwise caused by low-intensity or narrow-spectrum lighting. Complex factors such as rapidly improving LED luminous efficacy, favorable mass-manufacturing costs, local costs of electrical energy, and capital investment will interact to determine for which applications and when LEDs become the dominant lighting technology in horticulture.

KEYWORDS: energy savings; greenhouse; intracanopy; light quality; night interruption; photomorphogenesis; photoperiod; propagation; sole-source lighting; solid-state lighting; supplemental lighting

ABBREVIATIONS

ABRS	Advanced Biological Research System
AC	Alternating current
ASHS	American Society for Horticultural Science
B	Blue
BF	Blue fluorescent
CEWG	Controlled Environments Working Group
DC	Direct current
DE	Day extension
DIF	Day temperature – night temperature
DLC	Dynamic lighting control
DLI	Daily light integral
DOE	Department of Energy
DPPH	2,2-Diphenyl-1-picrylhydrazyl
EOD	End of day
ESD	Electrostatic discharge
FL	Fluorescent
FR	Far-red
G	Green
HID	High-intensity discharge
HPS	High-pressure sodium
HR	Hyper-red
IC	Integrated circuit

ICL	Intracanopy lighting
INC	Incandescent
ISS	International Space Station
kWh	Kilowatt hour
LD	Long day
LDP	Long-day plant
LED	Light-emitting diode
lm	Lumen
MH	Metal halide
NASA	National Aeronautics and Space Administration
NBL	Narrowband lighting
NCERA-101	North-Central Extension and Research Activity-101
NI	Night interruption
OH	Overhead
PAR	Photosynthetically active radiation
PBB	Polybrominated biphenyl
PBDE	Polybrominated diphenyl ether
P_{FR}	Far-red-absorbing form of phytochrome
PPF	Photosynthetic photon flux
P_R	Red-absorbing form of phytochrome
PS	Photosynthesis
PWM	Pulse-width modulation
QI	Quality index
R	Red
RDM	Root dry mass
RWB	Red + white + blue
SD	Short day
SDP	Short-day plant
SL	Supplemental lighting
SPAD	Relative chlorophyll content
SSBRP	Space Station Biological Research Program
UV	Ultraviolet
VOC	Volatile organic compound
W	Watt
WF	White fluorescent

I. INTRODUCTION

Horticultural lighting long has borrowed technology from the lighting industry that was not originally designed or intended for plant growth and development. As a consequence, horticulturists and plant physiologists learned to "make do" with the range of lamps that were available for supplemental or sole-source lighting of horticultural crops. Incandescent lamps became the standard for photoperiod control in greenhouses (Downs et al. 1958). Fluorescent (FL) ± incandescent (INC) lamps were widely used to achieve "normal" plant growth and development in growth chambers (Biran and Kofranek 1976; Bickford 1979), and when high-intensity discharge (HID) lamps came along, they quickly became the standard for supplemental lighting (SL) in greenhouses and for sole-source lighting in phytotrons and some growth chambers (Warrington et al. 1978; Tibbitts et al. 1983). All of these light sources do the job, but also have serious limitations. At the time they were adopted, there were no good alternatives. Incandescent lamps are highly wasteful of energy, are very short-lived (Bickford and Dunn 1972), and are rapidly disappearing from the marketplace. Fluorescent lamps have limited photon output and a short effective life span (Sager and McFarlane 1997). High-intensity discharge lamps require high voltage, emit intense radiant heat (McCree 1984), and require wide spatial separation from plants and/or thermal barriers. Light-emitting diodes (LEDs) were first tested with plants more than 20 years ago (Bula et al. 1991; Barta et al. 1992), and a revolution in lighting technology for horticulture has been underway ever since. This chapter compiled by a multi-institutional team of researchers investigating the feasibility of adopting LED technology for commercial specialty crop production (Mitchell et al. 2012) summarizes the state of knowledge regarding LED technology for horticulture and plant responses to various spectral combinations of LED lighting as of 2015.

II. PROPERTIES OF LEDs

A. What Are LEDs?

An LED is a light source that, unlike traditional lamps, does not use a filament or gas discharge. Illumination is produced solely by movement of electrons in a semiconductor material (Held 2009). Electrons cross a semiconductor junction and recombine with electron holes, releasing energy as photons (electroluminescence) in a narrow waveband. The color of a specific LED is determined by the energy gap of the semiconductor used, which is based on the semiconductor chemical composition.

LEDs are available in a variety of wavebands ranging from the ultraviolet (UV)-C (about 250 nm) to the near-infrared range (about 1,000 nm), with half-peak bandwidths generally ranging from 25 to 50 nm. Broad-spectrum white LEDs are also available—these create white light by using a blue (400–500 nm) LED combined with a phosphor coating. LEDs can also be used to create white light by mixing appropriate amounts of light from individual red (600–700 nm), green (500–600 nm), and blue LEDs.

Unlike traditional lamps, LEDs do not radiate heat directly in the light beam. However, a significant amount of heat is still produced and this heat must be conducted out of the device to prevent premature failure. Modern, high-power LEDs have a thermal pad directly connected to the light-emitting (and heat-generating) substrate. This pad moves heat from the junction to the solder point, through the circuit board, and to the heat sink by conduction, and then from the heat sink to the environment by convection and radiation.

B. LEDs as a Horticultural Lighting System

Solid-state lighting using narrow-waveband LEDs represents a fundamentally different technology from the broad-spectrum gaseous discharge-type lamps currently used in horticulture (Sager and McFarlane 1997). The semiconductor nature of LEDs makes them potentially one of the most significant advances in horticultural lighting since the development of HID lamps (Morrow 2008). The specific advantages of LEDs include capability to control spectral output and light intensity and to provide high or low light levels. Because LEDs can be rapidly turned on and off, and easily incorporated into electronic circuits, they can respond to complex control protocols. LEDs also provide the potential for reducing lighting operational costs through their long operating life and ability to operate directly adjacent to plant tissues due to their low radiant heat output (thereby reducing power use). Light-emitting diodes lack glass envelopes and toxic materials such as mercury, have low touch temperatures, and generally are operated at low direct current (DC) voltages, making them safer than current lamp types. Other benefits include their thin cross section, rugged construction, and flexibility for assembly into lighting systems with specialized configurations. Their use of DC would be an advantage in a setting using DC power generated from alternative power systems such as batteries or solar panels.

Disadvantages of LEDs compared with existing lamp types include currently high hardware costs. Since LEDs operate most effectively using DC, implementation requires conversion of standard alternating current (AC) to DC (using AC-to-DC power converters).

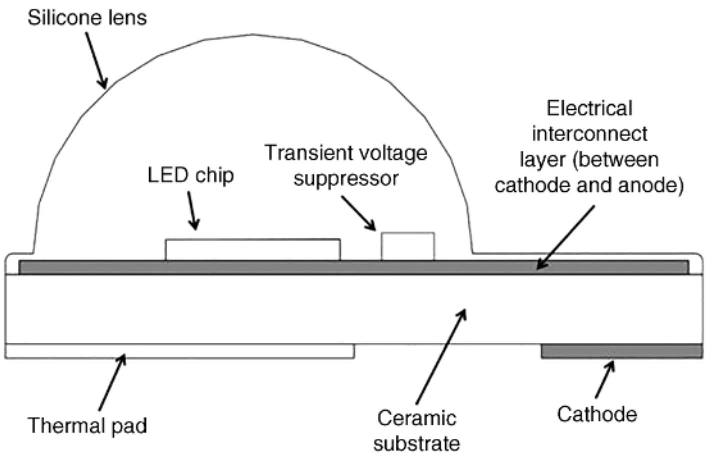

Fig. 1.1. Cross section of example LED package, about 2 mm × 3 mm in size. This package is designed to be soldered to a circuit board. The ceramic substrate provides a means to remove heat from the LED chip through the thermal pad to the circuit board. The transient voltage suppressor protects against electrostatic discharge and the silicone lens shapes light and shields the chip.

C. LED Packaging

Light-emitting diode lighting systems are generally used as groupings of many individual LED devices, each device being approximately 2 mm × 3 mm in size. The device includes the actual LED semiconductor chip, a lens, and components to provide mechanical support and transfer of heat away from the chip. Components are included to allow integration of the LED into an electronic circuit (Fig. 1.1).

D. Wavebands of Interest

Several wavebands of interest to horticulturists are available in LEDs (Olle and Virsile 2013). Commonly available red wavebands include 627 and 660 nm, whose spectra are close to the maximum chlorophyll absorption peak. Red light of 660 nm also matches a phytochrome absorption peak, as does 735 nm. Ultraviolet and blue wavebands, including 365, 400, 450, and 470 nm, are absorbed by cryptochrome pigments, which also impact plant development and physiological functions. Green wavebands (i.e., 540 nm) may have some utility due to improved foliar penetration increasing canopy photosynthesis. Other colors are used for specialized functions such as providing excitation for visualization of fluorescing proteins. In addition, several phosphors are available that can be used with blue LEDs to provide broader spectrum light in a variety of colors (Mills 2004), which is the primary technique used to produce white LEDs.

E. Performance Trends and Outlook

Light-emitting diode technology (both for research and for general area lighting in homes and businesses) has improved significantly in terms of physical shapes and designs, number of color wavebands available, reduced power use per unit light output, higher light output per unit power input, and reduced cost per unit light output (Morkoc and Mohammad 1995; Norlux Corporation 2004; Philips Lumileds Lighting Company 2004, 2005, 2006, 2007, 2008a, 2011, 2012/2013). The technical development of LEDs is said to follow Haitz's law, named after Dr. Roland Haitz, who states that every decade the cost per unit of useful light emitted for a given waveband of light falls by a factor of 10 and the amount of light generated per LED package increases by a factor of 20 (Haitz et al. 1999; Haitz and Tsao 2011). LED lighting applications may ultimately be limited by market forces (e.g., achievable light levels are already in excess of what is needed to meet large commercial market requirements).

F. Misconceptions About LED Lighting

With the great interest in LED lighting systems, a number of misconceptions about their capabilities have become commonplace. One of the primary misconceptions is about LED inherent luminous efficacy. It is widely discussed how much more efficient LEDs are than currently used lamp types. Interestingly, this has been a common statement for many years, even when LED efficiency was actually substantially less than current sources (whose efficiency has also improved over the last several years), and it is only recently that some LED devices (e.g., blue LEDs) are approaching or exceeding the best of the fluorescent and high-intensity discharge lamps (Nelson and Bugbee 2014). Although LEDs are projected to exceed all other current lighting technologies in the next few years (DOE 2013a), it should be emphasized that the potential for large improvements in power efficiency in horticultural settings is not so much related to the LED semiconductor die composition per se, but to the fact that their solid-state nature and physical characteristics allow implementation of unique configurations and operating protocols that can bring about large efficiency gains (Fig. 1.2).

Efficiency of a specific LED package (a single LED with mount) is related to factors such as semiconductor composition and doping, and mounting package configuration (DOE 2014). Efficacy of an LED package differs for each color, with blue LEDs being most efficient, while other

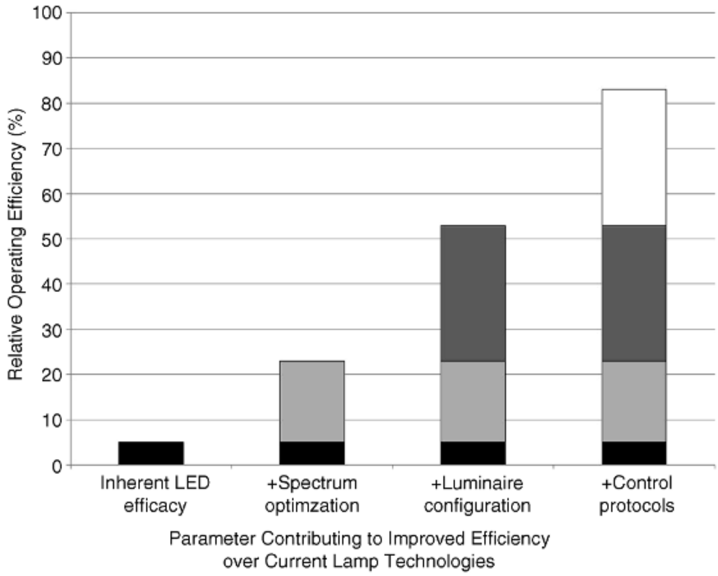

Fig. 1.2. Stacking different LED attributes illustrates the potential for developing LED horticultural lighting systems with very high operational efficiency (numbers are approximate and shown as additive for illustrative purposes). Refer to the text for detailed explanation for basis of graph.

colors, such as green, have room for improvement. Increases in photosynthetic efficiency by matching wavelengths to chlorophyll absorption peaks have been shown in some plant testing (Stutte et al. 2009). Luminaire configuration relates to reflector design, lenses, how the LEDs are arranged, and how the luminaire is positioned (operating in close proximity to plants can significantly reduce light loss because it is falling on walls and walkways rather than on plant tissue) (Morrow 2008; Nelson and Bugbee 2014). Control protocols can also be used to optimize energy consumption. For example, control protocols have been developed that detect the locations of plant tissue and only provide light to those locations (Massa et al. 2005b; Morrow and Bourget 2009).

Another common perception is that LED systems have an extensive operating life. While manufacturer's literature provides a conservative figure, often around 50,000 h of operation (DOE 2006), the actual life of the devices is dependent on a number of parameters when used in a real system. The output and operating life of an LED can be adversely impacted by high LED junction temperatures, poor current regulation, manufacturing quality (e.g., soldering quality), component quality, excessive shock and vibration (though LEDs are more resistant to shock

Table 1.1. Cooling mechanism for different lamp types.

Source	Efficacy (lm W^{-1})	Heat loss (%)		
		Radiation	Convection	Conduction
Incandescent	15	90	5	5
Fluorescent	90	40	40	20
HID	100	90	5	5

Source: http://www.ledtransformations.com/Lightfair_5-28-08.pdf (accessed September 3, 2014).

and vibration damage than traditional lamp types), and the operating environment (humidity, cleanliness, etc.). Also, different color devices may degrade differently, and phosphors used with some LEDs may degrade faster than the LED die itself.

An LED lighting system is composed of a number of other electronic components (such as capacitors) that may have a shorter inherent life span than the LEDs themselves. Other components such as power supplies (which are complex devices with many electronic components), fans, connectors, and temperature or light sensors may also impact operating life; therefore, the effective operating life of an LED lighting system is based on interaction between an array of operating conditions and individual hardware characteristics. Based on experience, it is likely that LED devices themselves are not usually the life-limiting component in an integrated LED lighting system.

One other major misconception is that "LEDs don't generate heat." Light-emitting diodes certainly do generate heat, just in a different fashion from currently used lamps. While INC and HID lamps lose heat primarily as radiant heat, and FL lamps through radiation and convection, LEDs lose heat primarily through conduction (Table 1.1). Because LEDs produce very little radiant heat, they will not significantly heat plant tissue and can thus be operated in close proximity to the plant surface, allowing target photon fluxes to be achieved using much less operating power compared with traditional lighting devices. Nevertheless, LED systems need to be designed with effective conduction/convection-based cooling systems.

III. DESIGN CONSIDERATIONS

A. General Design Requirements

A total system approach to LED lighting design is necessary; this includes the type and arrangement of LED devices used, mechanical packaging, thermal management, power and control electronics, and optical considerations. Light-emitting diode systems should take advantage of LED solid-state features including rapid on/off capabilities, easy dimming, low radiant heat output, ruggedness, long life, and small size allowing for easy integration into a wide variety of shapes, designs, and forms.

B. Thermal Management

To operate an LED system at high light outputs, heat generated at the backplane must be effectively managed to ensure long life and high performance, especially with high-power LEDs (≥1 W). Cooling mechanisms of LED systems all use direct conduction from the LED to the LED mounting surface, and then to a heat sink, which then dissipates the heat by mechanisms such as natural convection, forced convection (using fans), or liquid cooling.

C. Control

The light output of an LED is proportional to the amount of electrical current flowing through it. Therefore, LEDs should be operated in a current-controlled manner; that is, the driver circuit is actively controlling current flow through the LED rather than the voltage across it. This allows very precise control over the range of LED light intensity. Two common methods of control include linear and pulse-width modulation (PWM). Linear dimming simply reduces the DC current flowing through the LED: as the current is lowered, the LED gets dimmer. However, some LEDs exhibit a wavelength shift of up to 10 nm as the current changes, so a different strategy is often used (Gu et al. 2006). In PWM dimming, the LEDs are pulsed at a constant frequency (typically a few hundred hertz). When the LED is on, it is always at the same current level. To dim the LED, the percentage of time that the pulse is "on" (duty cycle) is reduced, thereby reducing the total photon output. The human eye cannot discern the rapid pulses, so it appears that the LED is dimming.

1. Warm-Up and Restrike Times. LEDs can switch on and off instantaneously, essentially having no warm-up and restrike times. This provides a high degree of flexibility in control of a lighting system, allowing rapid, precise changes in light levels. Conversely, gas-discharge lamps like FL lamps require about 3 min to reach at least 80% of full light output (warm-up time), and HID sources require 3–7 min to reach full brightness and several minutes to cool down before they can be switched on again.

2. "Smart" Control Systems. Control systems can range from simple manual adjustments of intensity to complex computerized controls. Light-emitting diodes are ideal for use with sensor feedback. For example, it is easy to integrate ambient light sensors to control LEDs for supplemental daily light integral (DLI) control systems that measure the amount of light received by a crop and then make up any deficit in lighting by applying SL at a precise level and duration (Seginer et al. 2006; Torres and Lopez 2010). Another example is the use of LEDs to enable an adaptive control system to prevent the unproductive practice of providing lighting over areas where there are no plants. Traditional electric overhead lighting illuminates significant "empty space" both above the crop height and between plants before the crop canopy fills in. To increase productivity per unit area or per volume of crop space, some approaches have changed plant spacing over time. This approach requires either extensive automation or labor, and the opposite approach, of changing the position of lights rather than that of plants (Wheeler et al. 1992), previously has been difficult to do with hot, bright HID lamps. Coupling precision LED lighting arrays with plant detection techniques (e.g., reflectance or imaging) can eliminate loss of light by illuminating space occupied only by photosynthetic tissue (Morrow and Bourget 2009). This strategy has the potential to increase energy use efficiency significantly. Intelligent controls can also compensate for reduced LED output as they age, and automatically compensate for failed LEDs or driver circuitry. Future developments in solid-state lighting will enable other new techniques to improve overall plant production efficiency, or improve marketable properties.

D. LED Lighting Systems

There are essentially three physical LED configurations used for horticultural applications, each with variations. These configurations can be applied either as sole-source lighting or as supplemental or photoperiodic lighting.

1. Intracanopy Lighting. Intracanopy lighting (ICL) consists of a linear LED luminaire that is placed within a plant canopy either as a sole source of light or as a source of light supplementing solar or overhead electric lighting in a greenhouse or similar protected agriculture, controlled-environment setting. Planophile crop stands, within which leaves present themselves perpendicular to overhead light, eventually close off their inner canopy to light resulting in mutual shading of lower leaves by those above, which in turn leads to net carbon loss via respiration, premature leaf drop, and often flower bud and fruit abortion within the canopy. Intracanopy lighting can provide light distribution throughout the canopy of a crop, allowing a much greater percentage of available leaf surface to be utilized for photosynthesis. This should increase biomass output per unit of input energy (Massa et al. 2006). Light-emitting diodes provide an opportunity for horticulturalists to utilize ICL protocols because of their low radiant heat output, ease of cooling, small volume, and high light output capabilities.

Intracanopy lighting can be implemented in either vertical or horizontal configurations. Clear benefits of one configuration over the other have not yet been determined. Vertical orientation results in a reduced chance of entanglement with plant tissue and facilitates the use of adaptable lighting approaches (i.e., providing light only where it is needed). Horizontal orientation avoids interference with watering systems and may require less hardware. The total linear length of lighting required is thought to be similar between the two configurations. Applications of vertical and horizontal ICL are included in Section VI.E.3.

2. Overhead Point Source. Overhead point source lighting consists of a light fixture with a tight grouping of LED devices that provides light output in a cone pattern meant to cover a broad growing area. This configuration most closely matches HID lamps in form and can be used as sole-source lighting, SL, or for photoperiod lighting. When using LEDs, overhead point source lighting is effective for photoperiodic lighting, but for applications requiring higher light output it fails to take advantage of the unique properties of LEDs (e.g., low radiant heat output) and can result in significant light loss due to scattering. In addition, it can be difficult to remove heat efficiently from a dense grouping of LEDs, reducing device efficiency and operating life.

3. Overhead Distributed Source. This is essentially the opposite of a point source. In this configuration, the LEDs are distributed over a broad area and provide very diffuse irradiance. This configuration can be applied as the sole lighting source in growth chambers and growth rooms, or as SL in a greenhouse setting. Diffuse overhead systems better utilize the inherent advantages of LEDs than do point sources. For example, their low radiant heat output allows them to be operated in close proximity to plants while retaining a uniform light level across the growing area. A point source moved close to the plant tissue would not provide uniform lighting. A broad array of LEDs also facilitates the use of precision lighting techniques, where various segments of the array can be set to different colors and turned on or off independently.

E. Strategies for Maximizing Life and Maintaining Output

For LEDs, as with other lamp types, careful design, manufacturing, and operation are required to maximize lamp life and to minimize decline of light output. A factor critical to maximizing lamp life and light output is keeping the temperature of the LEDs per se as low as possible (Keeping 2011). To accomplish this, it is necessary to use heat sinks attached to the back of the LEDs (Comerford 2011). The heat sinks can be cooled passively through natural air convection, by forced convection, or by using other cooling fluids such as chilled water (conduction). Passive cooling techniques tend to be insufficient except at very low light levels. Liquid-cooled systems can be unwieldy and expensive to maintain, but are highly effective and provide a mechanism to capture heat from the lamps for other uses. Forced convection is currently the most common cooling technique used, although fans add to the cost of the light fixture. An integrated temperature sensor can be used to monitor the temperature of an LED luminaire and cut off power if the temperature becomes too high, preventing damage to the LEDs and other electronics in case the cooling system fails. Another technique that can be used to maintain lower operating temperatures is adding more LEDs to a luminaire than are required to meet light output goals, and then operate these devices at a lower power. This reduces thermal degradation of the devices, improving electrical efficiency and extending life span. The primary disadvantage is the additional component cost. For SL fixtures in greenhouse applications, the use of surfaces that reflect solar (heat) irradiance can also help reduce LED operating temperatures.

Light-emitting diode luminaire design is critical. The fixture should provide protection from physical abrasion or impact and from moisture (including condensation), which can cause corrosion. It is also important to design the fixtures with good circuit protection to prevent propagation of electronic failures as LEDs are at higher risk than traditional lamps for damage from electrostatic discharge (ESD) and electrical transients caused by power supply problems (Publitek 2013). In addition, temperature cycling and vibration need to be accounted for, as both can damage wire bonds. Light fixture components should be made accessible as LED systems are relatively straightforward to repair, which offers the potential to greatly extend operating life without LED fixture replacement.

As discussed earlier, LEDs themselves may not be the life-limiting component in an LED lighting system, where components such as connectors, integrated circuit (IC) chips, op-amps, voltage regulators, driver chips, resistors, and capacitors may also be life limiting. Electronic components are generally quite reliable when circuitry is properly designed (proper grounding paths, circuit protection, etc.). Connectors, however, can be consistent failure points, if they are exposed to harsh environments, such as might be encountered in a greenhouse. Cabling is another weak point, as any external cables are susceptible to harsh environments, along with pulling, grabbing, and physical damage. Components of the cooling systems may also have a more limited lifetime than the LEDs, particularly fans, although cooling pumps and valves (used in fluid-cooled systems) may also fail before electronic components do. Most of these items are parts of the active cooling systems needed to keep LEDs within their proper operating temperature range, but should be easily replaceable.

IV. HISTORICAL OVERVIEW OF LED USE IN HORTICULTURE

Testing of LEDs for plant growth applications in the United States was concomitant with the development of the first terrestrial LED arrays in the late 1980s and space-based arrays in the early 1990s. An overview of this early development history is discussed by Morrow (2008). The first work with LEDs for plant lighting used red LED (peak wavelength 660 nm) arrays to produce a light intensity adequate for plant growth. These arrays were made of individually lensed devices often referred to as discrete LEDs. Over time, as new LED chip technologies became available, LED modules were developed using high-density chip-on-board or "surface-mount" designs. Early surface-mount LED modules, often referred to as light engines, might contain hundreds of low-to-moderate-output LED chips in a variety of colors (Emmerich et al. 2004). This technology was too expensive for large-scale use, but ideal for specialty or research applications that required high light output with several independently controllable spectral bands. In the late 1990s, high-output LEDs that could be manufactured in an automated process (Philips Lumileds Lighting Company 2008b) were developed, making the fabrication of solid-state lighting arrays of more than several square meters in area feasible.

The physical and operational flexibility of solid-state lighting has enabled the development of many alternative lighting configurations,

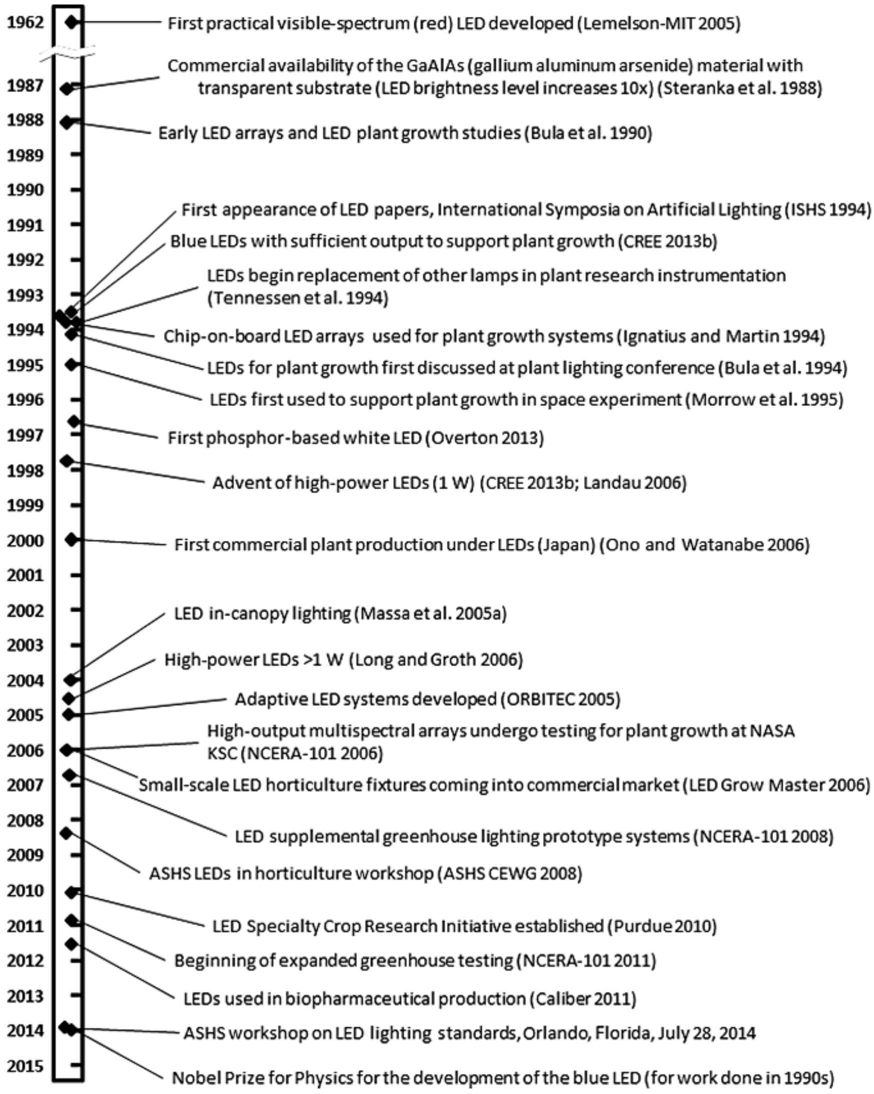

Fig. 1.3. Timeline of developments impacting the use of LED lighting for horticultural applications.

such as ICL (Massa et al. 2005a,b, 2006), and new control protocols such as adaptive or "smart" lighting (Morrow and Bourget 2009). A timeline of some developmental milestones critical in the development of LED-based horticultural lighting systems is shown in Fig. 1.3.

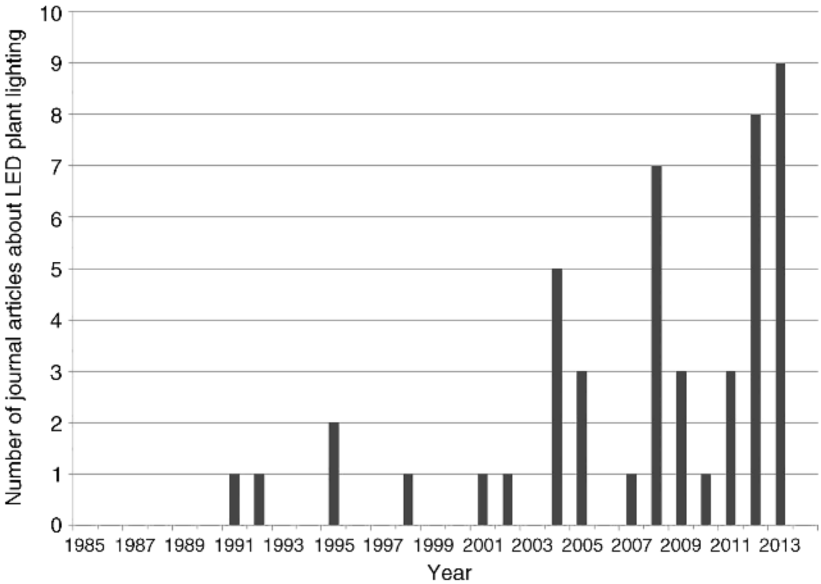

Fig. 1.4. Frequency of LED plant lighting-related journal articles between 1985 and 2013. Journals examined include *HortScience*, *HortTechnology*, *Journal of the American Society of Horticultural Science*, *Chronica Horticulturae*, and *Scientia Horticulturae*.

Massa et al. (2008) provide a comprehensive historical overview of work related to growing plants under LEDs from the early 1990s through the mid-2000s. A review of five scientific horticulture journals showed that a sharp increase in the number of LED plant growth research papers occurred during and after that mid-2000s time frame (Fig. 1.4). Much recently published work is cited in other sections of this chapter.

V. SUMMARY OF PLANT EXPERIMENTS IN SPACE WITH LEDs

The space program was the primary driver behind the development of the first LED plant lighting developments in the United States. Light-emitting diode systems were first used in microgravity spaceflight experiments in 1994 to support the growth of dwarf wheat (*Triticum aestivum*) and rapid-cycling *Brassica* in the Astroculture plant growth chamber (Astroculture 4 experiment; Morrow et al. 1995). They were also used in subsequent Astroculture and Advanced Astroculture experiments (Zhou 2005). Light-emitting diode prototype plant growth lighting hardware was developed and tested for the Plant Research Unit (Emmerich et al. 2004) that was to be part of the Space Station Biological Research Program (SSBRP) prior to that program's termination by NASA in 2005/2006. Another plant growth system called the Advanced Biological Research System (ABRS) was placed on the International Space Station (ISS) in 2009. The ABRS used LEDs for photosynthetic lighting and also for fluorescent protein imaging (Levine et al. 2009). As of 2014, the Vegetable Production System (Veggie), on board the ISS, and the Plant Habitat, being developed for ISS by Kennedy Space Center and ORBITEC, both utilize complex LED-based plant lighting systems (Massa et al. 2014; Morrow 2014). Terrestrial LED research in support of space research has been summarized in the general LEDs-in-horticulture history discussion.

VI. HORTICULTURAL APPLICATIONS OF LEDs

A. Providing Photosynthetic Light for Young Ornamental Plants

1. Introduction. Ornamental plants are commonly propagated either sexually from seeds or asexually from unrooted cuttings, or by micropropagation. Seedlings growing in plug trays are commonly propagated in greenhouses, though potential exists for production of plugs in more controlled environments similar to the "plant factories" used for vegetable transplant production. Production of rooted cuttings as liners typically occurs in a greenhouse, whereas tissue culture production is primarily performed in sole-source-lighted environments. High-intensity discharge lamps or LEDs may provide photosynthetic light as a supplement to sunlight in a greenhouse or as a sole source of light in a controlled environment for propagation of ornamental young plants. Here we review literature associated with the use of supplemental or sole-source lighting for sexual and asexual propagation of ornamental young plants in both greenhouse and more controlled environments.

2. Supplemental Lighting. Ornamental young plants typically are propagated from late winter to early spring in northern latitudes for spring sales. During this period, solar DLIs are at seasonally low levels (Korczynski et al. 2002). Light transmission into a greenhouse may also be reduced by 40–70% due to glazing materials, changing angles of solar incidence, cleanliness, infrastructure (i.e., lights, shade curtains, etc.), and hanging baskets (Hanan 1998; Lopez and Runkle 2008), further lowering DLI at canopy level.

Daily light integral affects growth and quality of seedlings, as well as subsequent development (Pramuk and Runkle 2005; Oh et al. 2010; Torres and Lopez 2011; Randall 2014). A high-quality seedling is one that is compact, fully rooted with a large stem caliper and high root dry mass (RDM). Compact seedlings with a large stem caliper and RDM are less likely to be damaged during shipping and transplant (Pramuk and Runkle 2005). Pramuk and Runkle (2005) reported that shoot dry mass per internode of celosia (*Celosia argentea* var. *plumosa*), bedding impatiens (*Impatiens walleriana*), salvia (*Salvia splendens*), marigold (*Tagetes patula*), and pansy (*Viola* × *wittrockiana*) grown under DLIs ranging from 4.1 to 14.2 $mol\,m^{-2}\,day^{-1}$ increased by 47% (bedding impatiens) to 68% (pansy) as the DLI increased by 10.1 $mol\,m^{-2}\,day^{-1}$. Similarly, Torres and Lopez (2011) reported that increasing DLI from 0.75 to 25.2 $mol\,m^{-2}\,day^{-1}$ during seed propagation of tecoma (*Tecoma stans*) enhanced biomass accumulation of roots and shoots by 2,388%.

Cuttings also respond favorably to increasing DLI during propagation (Lopez and Runkle 2008; Currey et al. 2012). Lopez and Runkle (2008) reported that after 16 days in propagation, root mass of petunia (*Petunia* × *hybrida*) and New Guinea impatiens (*Impatiens hawkeri*) increased linearly as DLI increased from 1.2 to 8.4 $mol\,m^{-2}\,day^{-1}$ and from 1.3 to 10.7 $mol\,m^{-2}\,day^{-1}$, respectively. In addition, Currey et al. (2012) reported that increasing DLI during root development of argyranthemum (*Argyranthemum frutescens*), diascia (*Diascia barberae*), lantana (*Lantana camara*), nemesia (*Nemesia fruticans*), osteospermum (*Osteospermum ecklonis*), scaevola (*Scaevola hybrid*), bacopa (*Sutera cordata*), and verbena (*Verbena* × *hybrida*) cuttings in propagation from 1.2 to 12.3 $mol\,m^{-2}\,day^{-1}$ increased root and shoot mass by 156–1,137% and 110–384%, respectively.

In a greenhouse environment, the only way to appreciably increase DLI is to provide SL. Currently, HPS lamps are the most frequently employed source of supplemental photosynthetic light for use inside greenhouses. However, LEDs are an emerging technology with application as supplemental sources of photosynthetic light in greenhouses (Plate 1.1a). The main selection criteria for SL are investment capital for the fixture, energy cost to power the light source, and spectral composition and irradiance capability of the SL source. Other potential opportunities as well as challenges associated with the use of overhead LED lighting are similar to those outlined in Sections II.C III. D.2 and III.D.3.

Seed Propagation. Little research has been published comparing HPS and LED SL for plug production in greenhouses. Randall and Lopez (2014)

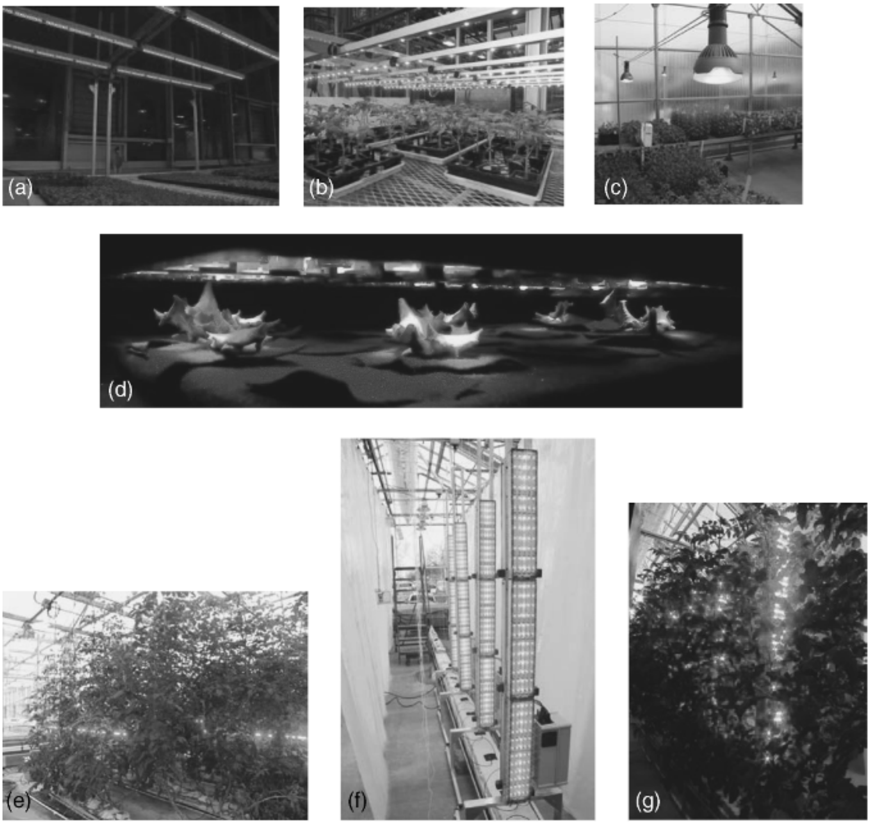

Plate 1.1. LED lighting. (a) Stimulation of bedding plant seedling growth in a greenhouse by day length extension under red + blue LEDs. (b) Overhead, widely spaced bars of alternating red + blue LEDs for supplemental lighting of transplants that block minimal solar radiation as the sun tracks across the greenhouse throughout the day. (c) Philips red + white + far-red lamps being used to stimulate flowering of ornamental annuals at Altman Plants (Vista, CA). (d) Targeted close-canopy lighting of hydroponic leaf lettuce. (e) A row of Philips interlights providing supplemental lighting to the mid foliar canopy of a high-wire tomato crop. (f) A row of ORBITEC intracanopy lighting towers with all vertical zones of red + blue LEDs energized. (g) A row of LED towers providing intracanopy light to a stand of high-wire tomatoes. (See color version of this figure in the color plates section.)

placed seedlings of snapdragon (*Antirrhinum majus*), wax begonia (*Begonia* × *semperflorens*), vinca (*Catharanthus roseus*), celosia, bedding impatiens, geranium, petunia, salvia, marigold, and pansy under a 16 h photoperiod of ambient solar light plus SL of 100 μmol m^{-2} s^{-1} from either

HPS lamps or LED arrays with varying red:blue (R:B) photon flux ratios (100:0, 85:15, or 70:30). Height of vinca, celosia, bedding impatiens, petunia, marigold, salvia, and pansy was 31%, 29%, 31%, 55%, 20%, 9%, and 35% shorter, respectively, for seedlings grown under 85:15 R:B LEDs compared with those grown under HPS lamps. Snapdragon, vinca, bedding impatiens, geranium, petunia, and marigold grown under 85:15 and 70:30 R:B LEDs were generally more compact with a larger stem diameter and higher relative chlorophyll content than plants grown under HPS lamps. The root dry mass of these species was statistically similar to that produced under HPS lamps. However, shoot dry mass of bedding impatiens and petunia was lower when seedlings were grown under LEDs containing blue light. The quality index (QI = total dry mass × (root:shoot dry mass ratio + stem diameter/stem length)), a quantitative measurement of quality, was similar to that found under HPS lamps or higher for snapdragon, vinca, bedding impatiens, geranium, petunia, salvia, marigold, and pansy grown under LEDs. Subsequent time to flower of celosia, bedding impatiens, salvia, and marigold was generally slower for plants grown under LEDs compared with HPS lamps. However, time to flower for snapdragon, catharanthus, petunia, and pansy was not significantly different for plants grown under supplemental lighting from HPS or LEDs. These results indicate that seedling quality for the majority of species tested under SL from LEDs providing both red and blue light was similar to or higher than that for seedlings grown under HPS lamps.

Vegetative Propagation. Currey and Lopez (2013) placed cuttings of New Guinea impatiens, geranium (*Pelargonium* × *hortorum*), and petunia under 70 $\mu mol\, m^{-2}\, s^{-1}$ delivered from HPS lamps or LED arrays with varying R:B photon flux ratios (100:0, 85:15, or 70:30) for 16 h day^{-1} after a week of callusing under low light (~5 $mol\, m^{-2}\, day^{-1}$). After 14 days under these SL treatments, there were no significant differences in gas-exchange parameters (photosynthesis, conductance, and transpiration) among New Guinea impatiens and geranium cuttings grown under different SL sources. However, compared with cuttings propagated under HPS lamps, stem length of petunia cuttings grown under 100:0 R:B LEDs was 11% shorter, whereas leaf dry mass, root dry mass, root–mass ratio (root dry mass/total plant mass), and root:shoot ratio of cuttings grown under 70:30 R:B LEDs were 15%, 36%, 17%, and 24% higher, respectively. The supplemental light source used during propagation had minimal impact on plants following transplant. Currey and Lopez (2013) concluded that LEDs are suitable replacements for HPS lamps as SL sources during cutting propagation.

Conclusions. There appears to be potential for LED lighting as an alternative SL source for propagating seeds and cuttings of ornamental young plants. Selecting SL sources for greenhouse production of young ornamental plants must take into consideration the desired impact of SL: minimal investment cost, reduced energy consumption, efficiency as a source of photosynthetic light, and/or for photomorphogenic lighting. As is the case for propagation using sole-source lighting, the selection of spectrum for an LED array depends on the plant species as well as the goals of the propagator.

3. Sole-Source Lighting. Propagation in enclosed/controlled environments lacking sunlight requires that light be provided as sole-source lighting. Seedling/plug production and tissue culture *in vitro* propagation of ornamental plants have been shown to be affected differently by various kinds of sole-source lighting. Sole-source lighting for tissue culture has been evaluated, primarily with low-wattage FL lights varying in spectral composition (Lian et al. 2002; Kim et al. 2004; Jao et al. 2005; Nhut et al. 2005; Wongnok et al. 2008; Gu et al. 2012; Wu and Lin 2012). However, there is a paucity of information reporting seedlings (plugs) grown in controlled environments for their entire production cycle.

One of the main challenges associated with providing sole-source lighting is selection of wavelengths that are effective for the desired response. The germination of seed, regeneration, development, and elongation of shoots, adventitious root growth, and explant growth are all aims of seedling plug production and *in vitro* propagation. However, the effectiveness and efficiency of different light spectra vary across these different processes and species as highlighted in the following sections.

Seed Propagation. A few studies have been performed using LEDs with varying light qualities as a sole light source during propagation of ornamental seedlings in enclosed environments (Wollaeger and Runkle 2013; Randall 2014; Wollaeger and Runkle 2014). Seedlings of bedding impatiens, petunia, and marigold were grown under six LED treatments providing a photosynthetic photon flux (PPF) of 160 $\mu mol\ m^{-2}\ s^{-1}$ for 18 h day^{-1} (Wollaeger and Runkle 2014). The treatments consisted of blue (B_{10}; 10% light from blue LEDs; 446 nm) and green (G_{10}; 516 nm) light, with the remaining percentage consisting of O_{20}:R_{30}:HR_{30}, O_0:R_{80}:HR_0, O_0:R_{60}:HR_{20}, O_0:R_{40}:HR_{40}, O_0:R_{20}:HR_{60}, or O_0:R_0:HR_{80}, where O refers to orange (596 nm), R refers to red (634 nm), and HR refers to hyper-red (664 nm). Lighting treatments had no consistent effects on leaf area, height, or shoot fresh weight across the three species. For example, height of marigold seedlings was 13% shorter under O_0:R_{40}:HR_{40} than under O_0:R_{80}:HR_0, and height of bedding impatiens was similar under all treatments. However, differences were observed when seedlings were grown under light intensities of 125 or 250 μmol m^{-2} s^{-1} consisting of B_{10} and G_{10} light and R_0:HR_{80}, R_{40}:HR_{40}, or R_{80}:HR_0. For example, chlorophyll concentration was greatest for bedding impatiens and petunia under the R_0:HR_{80} low light intensity treatment and for salvia under the R_{40}:HR_{40} low light intensity treatment. In addition, shoot dry weight of petunia and salvia was 62% and 30% higher under the high-intensity R_{40}:HR_{40} than under the low-intensity R_{40}:HR_{40} treatment, respectively.

In a separate study, LEDs or cool-white FL (CWF) lamps providing a PPF of 160 μmol m^{-2} s^{-1} for 18 h day^{-1} were evaluated for bedding impatiens, petunia, and salvia (Wollaeger and Runkle 2013). The LED treatments consisted of blue, green, and two red peaks that emitted the following percentages: B_{100} (100% light from blue LEDs), $B_{50}+G_{50}$, $B_{50}+R_{50}$, $B_{25}+G_{25}+R_{50}$, and R_{100}. They determined that leaf area of all species was 47–130% higher for those seedlings grown under R_{100}. Height of bedding impatiens and salvia was also greatest under R_{100}. However, height of bedding impatiens and salvia seedlings grown under ≥25% blue light was 47–53% and 41–57% shorter, respectively, than for seedlings grown under R_{100}.

Randall (2014) placed seedlings of vinca, bedding impatiens, geranium, petunia, and marigold under sole-source LED lighting providing a PPF of 185 μmol m^{-2} s^{-1} from either R_{87}:B_{13} or R_{70}:B_{30} for 16 h day^{-1}. These seedlings were compared with those grown in a greenhouse under ambient solar light or ambient solar light plus SL providing a PPF of 70 μmol m^{-2} s^{-1} from HPS lamps, plasma lamps (PLs), or LED arrays providing R_{87}:B_{13} for 16 h day^{-1}. Generally, quality was best for seedlings grown under indoor sole-source lighting than in the greenhouse. For example, height of geranium, petunia, and marigold was reduced by 21% and 26%, 75% and 79%, and 18% and 16% for seedlings grown under sole-source LEDs providing a R:B ratio of R_{87}:B_{13} and R_{70}:B_{30}, respectively, compared with supplemental greenhouse lighting from HPS lamps. In addition, relative chlorophyll content of vinca was 25% or 16% higher under sole-source LEDs providing R_{70}:B_{30} compared with seedlings under ambient solar light or HPS lamps, respectively, and relative chlorophyll content of impatiens was 10–47% greater under the sole-source LEDs providing R_{70}:B_{30} compared with ambient solar light, HPS lamps, sole-source or supplemental LEDs providing R_{87}:B_{13}, or PL.

Collectively, these studies indicate that high-quality seedlings that are compact (i.e., have shorter stems and less biomass accumulation and leaf area) and have high chlorophyll concentrations can be produced in controlled environments under sole-source LED lighting that includes at least 13% blue light. In addition, orange, red, and hyper-red light have similar effects on seedling growth when 10% blue and 10% green light are provided.

Vegetative Propagation. The majority of research with sole-source LED lighting for vegetative propagation has been performed during *in vitro* propagation or tissue culture of ornamental plants (Lian et al. 2002; Kim et al. 2004; Jao et al. 2005; Nhut et al. 2005; Gu et al. 2012; Wu and Lin 2012). Applications of LEDs as a sole light source in tissue culture propagation primarily focus on propagule regeneration and propagule growth and development.

Gu et al. (2012) evaluated the rooting and growth of adventitious shoots *in vitro* of anthurium (*Anthurium andraeanum*) grown under 40 μmol m^{-2} s^{-1} provided by FL light, or red (658 nm), blue 460 nm), yellow (585 nm), or red + blue LEDs (1:1 photon flux ratio). The number, length, and dry mass of roots were highest for shoots grown under FL or red + blue light, whereas growth and development was generally diminished for shoots grown under different monochromatic LED light, and poorest for shoots grown under yellow light. The researchers attributed poor rooting and growth of shoots to small leaves formed under monochromatic light. Leaf size increased by 2.8–3.3 cm^2 for plants grown under R + B light compared with plants grown under monochromatic light.

For example, *in vitro* plantlets of calla lily (*Zantedeschia jucunda*) 'Black Magic' were grown under 80 $\pm$ 5 μmol m^{-2} s^{-1} provided by LEDs with a R:B photon flux ratio of 100:0 or 60:40 to determine the effectiveness of LEDs as a sole light source during propagation (Jao et al. 2005). Growth and development of calla lily plantlets under 100% red light was considered satisfactory for commercial production. However, the chlorophyll content, total dry mass, and root-to-shoot dry mass ratio were highest, and plant height was shortest, for plantlets grown under red plus blue light. Tuber diameter of plantlets ranged from 3.9 to 4.5 cm across light sources, with no significant differences among treatments. Therefore, sole-source LED lighting can generate acceptable-sized propagules of calla lilies.

Lian et al. (2002) compared light sources for lily (*Lilium*) bulblet regeneration and subsequent growth. In one experiment, 5 mm^2-scale explants were placed in darkness or under 70 μmol m^{-2} s^{-1} for 16 h day^{-1} from FL light, or red (660 nm), blue (450 mm), or red + blue (1:1 photon flux ratio) LEDs. The number of bulblet explants regenerated from *Lilium* scales was 14–19% more for explants cultured under WF light compared with explants cultured under the same PPF from red, blue, or red + blue light from LEDs; however, there were no differences in number of bulblets produced per regenerating scale among explants cultured under blue, red + blue, or WF light. In a subsequent experiment, bulblets were placed under the same five treatments. Growth and development of bulblets, including bulb diameter, root number, and bulblet and root dry mass, was highest for bulblets grown under red + blue or WF light.

Shoot explants of chrysanthemum (*Chrysanthemum* × *morifolium*) 'Cheonsu' were placed in culture under 50 ± 5 μmol m^{-2} s^{-1} provided by blue (440 nm), red (650 nm), 1:1 red + blue, 1:1 blue + far-red (720 nm), or 1:1 red + far-red LEDs, or FL lamps (Kim et al. 2004). Fresh weight, dry weight, and leaf mass of chrysanthemum plantlets were highest under WF or red + blue LED lighting, whereas plantlets grown under blue + far-red LED light had the poorest growth, with more than a 50% reduction for each trait compared with plantlets under FL lighting. Plantlets under red or red + far-red light were tallest (4.7–5.0 cm), whereas those under blue + far-red light were shortest (1.4 cm). The reduction in height was due to blue light inhibition of internode elongation, since the number of nodes for plantlets was similar across lighting treatments. Net photosynthesis of plantlets was highest (4.5 μmol m^{-2} s^{-1}) under red + blue LED lighting and lowest (0.5 μmol m^{-2} s^{-1}) under blue + far-red LEDs. Furthermore, the number of stomata per unit leaf area was lowest for plantlets under blue + red LED light (56.4 mm^{-2}), but stomatal size was largest (32.9 μm diameter × 44.7 μm long). Stomatal density for plantlets under blue + far-red LED light was the highest (98.7 mm^{-2}), but stomatal size was the smallest (24.3 μm diameter × 31.7 μm long). Overall, the use of blue + red LED lighting was a more suitable alternative to WF light than was B + FR LED light for *in vitro* propagation. Nhut et al. (2005) evaluated the use of LEDs during *in vitro* propagation on development and subsequent growth of peace lily (*Spathiphyllum*) in a greenhouse. Plantlets were grown under 45 μmol m^{-2} s^{-1} of light provided by FL lamps or LEDs with R:B ratios of 100:0, 90:10, 80:20, or 70:30. There were few significant differences in growth among *in vitro* shoots of calla lilies receiving these light sources. The relative chlorophyll content (SPAD value) increased by 33% as blue light increased from 0 to 30%. Plant height was more compact for shoots under all LED treatments compared with that of shoots under FL lighting. After explants had been grown in a common greenhouse environment for 60 days after transplant, shoots that had been propagated under LEDs providing 70:30 R:B light had lower root and shoot fresh mass than those grown under the other LED treatments or FL light. Alternatively, shoots propagated under LEDs providing 100:0, 90:10, or 80:20 R:B had similar or more shoot and root dry weight and leaf number than plantlets grown under FL lights. The use of blue light during *in vitro* propagations is beneficial, although there likely are species-specific thresholds, above which blue light inhibits *in vitro* and subsequent growth.

The use of specific wavelengths during *in vitro* propagation of king protea (*Protea cynaroides*) was evaluated for potential to alleviate the recalcitrant rooting nature of that ornamental species (Wu and Lin 2012). Shoot explants were cultured under 50 μmol m^{-2} s^{-1} of light provided by cool-WF lamps, red or blue alone, or 1:1 R:B LED light. Nearly 7 weeks after the onset of culture, rooting percentage was 66.7% for plantlets grown under red light only compared with 6.7% for FL versus 13.3% for blue alone or 1:1 R:B. The researchers also found the lowest levels of phenolic compounds, including 3,4-dihydroxybenzoic, gallic, caffeic, and ferulic acids, in plantlets cultured under red light only, likely increasing the adventitious rooting of plantlets. This raises the potential to utilize specific spectra during tissue culture to diminish, or enhance, phytochemicals of interest.

Conclusions for Sole-Source Lighting of Ornamental Propagules. The use of LEDs for sole-source lighting in controlled environments has promise for use in sexual and asexual propagation of ornamental plants. One of the primary challenges will be identifying which spectral compositions will achieve the aims of controlled-environment plant propagation. The inclusion of blue light generally seems to complement effects of red light. However, the proportion of blue light to include in LED lighting will be determined by the goals of propagators, as well as by economics. Wollaeger (2013) states that while increasing the proportion of blue light may reduce stem extension and result in more compact plants, this comes at a cost of reduced biomass accumulation and leaf expansion. This point highlights the need for propagators to carefully select the amount of red, blue, and other wavelengths to include in sole-source LED light intended for propagation. Blue light requires more energy per photon, so the decision of how much blue light to use can also be related to economics. However, blue LEDs are improving in luminous efficacy, reducing the energy-input-to-photon-output ratio, faster than other LEDs. In addition to the role of specific wavelengths used for sole-source lighting, the impact of sole-source light spectra on subsequent growth and development in the greenhouse and landscape has yet to be determined. Research in this area may help improve the selection process of spectra for use in sole-source lighting in growth chambers, striking a balance between plant growth during propagation and subsequent forcing and landscape performance.

B. Photoperiodic Lighting with LEDs

1. Historical Background. The length of light and dark periods each day regulates flowering of a broad range of plants, including many economically important agronomic and ornamental crops (Erwin and Warner 2002; Runkle and Heins 2003; Mattson and Erwin 2005). A photoperiodic response is determined primarily by the duration of the dark period, also known as the critical night length (Thomas and Vince-Prue 1997). Plants are commonly classified into response groups based on how the critical night length influences flowering. Short-day (SD) plants (SDPs) flower most rapidly when uninterrupted dark periods are longer than some species-specific critical night length, whereas flowering of long-day (LD) plants (LDPs) is most rapid when dark periods are shorter than some critical duration. Within each category, the flowering response can be further classified into either a qualitative or quantitative response, meaning that the photoperiod is required for or accelerates flowering, respectively. For example, a quantitative LDP will flower under SDs, but will flower earlier under LDs.

Plants perceive light before sunrise and after sunset, so the length of the "natural" photoperiod is approximately 30–40 min longer than from sunrise to sunset, depending on latitude, time of year, and cloud cover (Faust and Heins 1995; Runkle 2002). When day length is naturally short, low-intensity (photoperiodic) lighting is used by commercial crop producers to inhibit flowering of SDPs or promote flowering of LDPs. This manipulation of photoperiod can lower production costs by reducing production time and improving the overall quality of the crop (Runkle and Heins 2006). When the ambient photoperiod is short, LDs can be created by operating lamps beginning at the end of the day until the desired photoperiod is completed, which is known as day-extension (DE) lighting, or during the middle of the night, which is known as night-interruption (NI) lighting. During a long night, 4 h of NI lighting is recommended for the most complete and rapid flowering of LDPs, although shorter durations are effective for some crops (Runkle et al. 1998).

Photoperiodic lighting is typically provided continuously during the otherwise dark period, although intermittent, or cyclic, lighting is sometimes as effective. Cyclic lighting can reduce energy consumption by reducing the amount of time lamps operate or the number of lamps needed to light a crop. Cycling INC lamps on for 6 min every half hour, during a 4 h NI, was as effective as a continuous NI for some crops, but not for others (Runkle et al. 1998; Blanchard and Runkle 2010). This technique is well suited to LEDs, since unlike many conventional lamp types, their lifetime is not negatively influenced by on/off cycles. Cyclic lighting can also be delivered successfully by HPS lamps that remain on, but their reflectors rotate to caste a moving beam of light below (Blanchard and Runkle 2010). For example, the rotating reflector of a 600 W HPS lamp can light a relatively large area (e.g., 140 m^2) at regular intervals (e.g., once per minute) (Blanchard and Runkle 2010). Another technique to deliver LD lighting is placing lamps on irrigation booms programmed to run (with lights on and water off) during the night. There is limited research-based information on this technique, but some commercial growers have developed their own successful strategies, generally delivering ≥15,000 $\mu mol\, m^{-2}$ each night and ensuring that plants are lighted at least once every 20–30 min over a 4 h period (M. Blanchard and E. Runkle, unpublished). For example, delivery of 1 $\mu mol\, m^{-2}\, s^{-1}$ for 4 h equals 14,400 $\mu mol\, m^{-2}$ of NI lighting, which is broadly effective in providing an LD response.

Plants perceive the light environment through multiple classes of photoreceptors, including red and far-red light-absorbing phytochromes, UV-A (320–400 nm) and blue light-absorbing cryptochromes, and blue light-absorbing phototropins. Phytochromes are the primary photoreceptors that regulate flowering of photoperiodic crops, although at least in some species, such as in the Brassicaceae, phytochromes and cryptochromes interact and overlap in function (Cashmore et al. 1999). Green light was reported to influence flowering of some plants only in a few studies (Hamamoto et al. 2003; Hamamoto and Yamazaki 2009), although its mode of action has not been determined.

2. Red and Far-Red Light. Red/far-red photoreversibility refers to phytochrome-mediated responses that can be reversed to regulate seed germination, the shade-avoidance response, and flowering. For example, if red light triggers a response by converting phytochromes into their biologically active form, the far-red-absorbing form (P_{FR}), immediate exposure to far-red light can, in some instances, counteract the response by reversing P_{FR} back to the inactive, red-absorbing form (P_R). There are multiple phytochrome proteins in angiosperms, which have been named *PHYA*, *PHYB*, *PHYC*, *PHYD*, and *PHYE* (Sharrock and Quail 1989; Clack et al. 1994). Each phytochrome has two forms, P_{FR} and P_R, and can exist in plant cells as homodimers and heterodimers (Sharrock and Clack 2004). The proportion of P_{FR} and P_R depends on the red-to-far-red (R:FR) light ratio, which creates a phytochrome photoequilibrium (P_{FR}/P_{R+FR}) that mediates extension growth and flowering responses in plants (Sager et al. 1988). Although both P_R and P_{FR} absorb photons from <300 nm to approximately 800 nm, their spectral absorption curves differ

(Sage 1992). For example, the peak absorption wavelengths of extracted oat phytochromes are 665 nm for P_R and 725 nm for P_{FR} (Butler et al. 1964). Therefore, the conversion of P_R to P_{FR} is promoted most effectively by red light (Butler et al. 1964; Sager et al. 1988).

Different mechanisms and pathways of flowering may exist in SDPs and LDPs in response to the R:FR. Studying the use of LEDs that emit red and/or far-red light can increase the understanding of how red and far-red light in photoperiodic lighting regulate flowering without other, potentially confounding spectra. Night-interruption lighting with a moderate-to-high R:FR effectively inhibits flowering of SDPs, which are typically dark-dominant plants (Vince 1969; Runkle and Heins 2006). For example, a 4 h LED NI with an R:FR of 0.66 or higher inhibited flowering of chrysanthemum, whereas a 4 h LED NI with an R:FR of 0.28 or lower was not perceived as an LD (Craig and Runkle 2013). Similarly, flowering of the SDP perilla (*Perilla ocymoides*) was strongly suppressed under a 10 h SD with a 10 min NI provided by red LEDs compared with no NI or a 10 min NI provided by far-red LEDs (Choi 2003). Interestingly, two cultivars of chrysanthemum responded differently to NI lighting delivered by red LEDs with peak wavelengths of 630 or 660 nm; they prevented flowering of 'Jimba' but had no effect on 'Iwa No Hakusen' (Liao et al. 2014). In the same study, far-red LEDs delayed flowering of 'Iwa No Hakusen' but had no effect on 'Jimba', whereas red + far-red LEDs effectively delayed flowering of both cultivars. In Japanese pear (*Pyrus pyrifolia*), delivery of far-red light during an otherwise 16 h night induced early termination of vegetative growth and promoted flowering compared with an 8 h short day with or without red light during the night (Ito et al. 2014).

The efficacy of NI lighting also depends on its intensity. For example, flowering of chrysanthemum was completely inhibited when the red light intensity, delivered as a DE, was above 1.4 $\mu mol\ m^{-2}\ s^{-1}$ (Hong et al. 2013). Similarly, as the light intensity of an effective 4 h NI (e.g., from red or white LEDs) increased, flowering time of chrysanthemum 'Huang-Hsiu-Feng' and 'Lung-Feng-Tzu' increased (Ho et al. 2012). Therefore, red or white LEDs and FL lamps can create LDs that delay flowering of SDPs (Padhye and Runkle 2011). Several studies also show that far-red light alone is generally not effective as an NI (Craig and Runkle 2012; Liao et al. 2014; Meng 2014).

Some LDPs flower most rapidly when DE or NI lighting contains both red and far-red light. For example, an LED NI with an R:FR of 0.66 or 1.07 most effectively promoted flowering of petunia and snapdragon (Craig and Runkle 2012), which confirms previous studies performed with broad-spectrum conventional lamps (Thomas and Vince-Prue 1997).

For example, replacement of conventional INC lamps with far-red-deficient FL lamps can delay flowering of these and additional LD crops (Lane et al. 1965; Runkle et al. 2012). Similarly, lack of far-red light in white LEDs delayed flowering of petunia, but not other long-day crops apparently less sensitive to far-red light, such as rudbeckia (*Rudbeckia hirta*) (Meng 2014).

In some ornamental production scenarios in the United States, a wide range of crops are grown in the same greenhouse environment. Therefore, an effective photoperiodic lighting strategy must regulate flowering of all photoperiodic species simultaneously (Plate 1.1c). A 7 h DE (to create a 16 h LD) and a 4 h NI were equally effective at promoting flowering of LDPs (Craig 2012). An NI provided by blue, red, or far-red LEDs did not stimulate complete, rapid flowering of a variety of LDPs (Hamamoto et al. 2003; Craig and Runkle 2012, 2013; Meng 2014). Therefore, a combination of different spectral wavebands (specifically, red and far-red light) is essentially required to manipulate flowering of a wide range of photoperiodic crops.

3. Blue Light. The effects of blue light on flowering responses mediated by cryptochromes and potentially phytochromes are variable and less understood. Delivering an NI with blue light can inhibit flowering of some SDPs and promote flowering of some LDPs, but have no effect on others. Flowering of the SDP perilla was strongly inhibited by a 3 h NI provided by blue LEDs at a PPF of 8–10 $\mu mol\, m^{-2}\, s^{-1}$ during natural SDs (Hamamoto et al. 2003). In addition, flowering of chrysanthemum was strongly inhibited by a 4 h NI provided by blue LEDs at a PPF of 20 $\mu mol\, m^{-2}\, s^{-1}$ when a 12 h main photoperiod was provided by blue LEDs at a PPF of 100 $\mu mol\, m^{-2}\, s^{-1}$ (Higuchi et al. 2012). An NI with blue or red light was effective at delaying flowering of the SDP rice, but an NI with far-red light was not (Ishikawa et al. 2009). Delivering blue light as DE or NI lighting may result in different reproductive responses in some species; blue LEDs delayed flowering of the SDP okra (*Abelmoschus esculentus*) when delivered as DE lighting but did not when delivered as NI lighting (Hamamoto and Yamazaki 2009). The LDP lisianthus (*Eustoma grandiflorum*) flowered earlier under a 5 h NI provided by blue LEDs at a PPF of 5 $\mu mol\, m^{-2}\, s^{-1}$ compared with under ambient SDs (11–12.5 h) without an NI (Yamada et al. 2011).

However, blue light in photoperiodic lighting was ineffective at controlling flowering of other crops. A 4 h NI provided by blue LEDs at a PPF of 3.3 $\mu mol\, m^{-2}\, s^{-1}$ was not perceived as an LD by the LDPs petunia, rudbeckia, and tickseed (*Coreopsis verticillata*) (Craig 2012). Similarly, a 4 h NI provided by blue LEDs at a PPF of 0.8 or 3.3 $\mu mol\, m^{-2}\, s^{-1}$ was not perceived as an LD by chrysanthemum (Ho et al. 2012). Even at a higher PPF of 7 μmol m^{-2} s^{-1}, a 4 h DE provided by blue LEDs failed to inhibit flowering of chrysanthemum (Jeong et al. 2012).

Mixing blue and red LEDs can accelerate flowering of some LDPs. Although a 4 h NI provided by blue, red, or far-red LEDs at a PPF of 4 μmol m^{-2} s^{-1} promoted flowering of the LDP cyclamen (*Cyclamen persicum*) compared with the 9 h SD, the NI from a mixture of blue and red LEDs was most effective (Shin et al. 2010). Moreover, although a 4 h NI provided by blue LEDs alone or a mixture of blue and far-red LEDs was not perceived as an LD by rudbeckia, marigold, or chrysanthemum, a mixture of blue and red LEDs promoted flowering of most LDPs tested (Meng 2014). This suggests that in some instances blue light can at least partially substitute for far-red light when added to red light to regulate flowering of LDPs. Additional flowering research on the interactions between blue, red, and far-red light is merited.

4. Green Light. Early studies on a limited number of plants indicated that green light was a relatively ineffective LD signal (Thomas and Vince-Prue 1997). However, green light was reported to be effective at regulating flowering of some noncruciferous SDPs and LDPs. A 2 h NI provided by green LEDs at a PPF of 8–10 μmol m^{-2} s^{-1} was as effective as that provided by yellow or red LEDs at inhibiting flowering of cosmos (*Cosmos bipinnatus*) and perilla and promoting flowering of spinach (*Spinacia oleracea*) grown during an SD season (Hamamoto et al. 2003). A 4 h NI provided by green LEDs delayed flowering of the SDP okra grown under an 8 h SD more effectively than that provided by blue LEDs but less effectively than that provided by red LEDs (Hamamoto and Yamazaki 2009). Following a 12 h photoperiod provided by FL lamps, a 4 h DE provided by green LEDs at a PPF of 70 μmol m^{-2} s^{-1} was as effective as that provided by red or white LEDs at inhibiting flowering of chrysanthemum (Jeong et al. 2012). Appearance of visible inflorescences of chrysanthemum grown under natural SDs followed by a 1 h NI provided by green FL lamps was delayed by 17 days compared with those grown without an NI or with an NI provided by UV-A or blue FL lamps. Furthermore, a 15 min NI provided by orange LEDs (596 nm) was more effective at inhibiting flowering than green (530 nm) or red (639 or 660 nm) LEDs at the same intensity (Sumitomo et al. 2012).

5. Growth Response Parameters. In many ornamental crop production situations, a grower's goal is to produce plants that are uniform with respect to stage of development (e.g., all vegetative or all reproductive) and morphology (e.g., of a desirable shape and height). Common metrics used to judge horticultural crops when marketed are flowering percentage, flower or inflorescence number, and plant height. A crop can have reduced value if standards set by the buyer, such as 90% of plants in flower, are not met. Therefore, commercial growers must consider how the spectral distribution of photoperiodic lighting influences flowering and morphological characteristics.

A far-red-rich (i.e., low R:FR) environment triggers the shade-avoidance response that typically includes changes in plant morphology and physiology (Cerdán and Chory 2003). Manipulating the R:FR in photoperiodic lighting can elicit extension responses without exogenous application of plant hormones. For example, chrysanthemum plants grown under a 9 h natural SD with a subsequent 30 min DE provided by red and far-red LEDs were taller when the R:FR was $\leq$0.7 than at 2.4 (Lund et al. 2007). However, when the functions of irradiance and the R:FR were investigated, irradiance did not influence plant height at an R:FR of 0.4, whereas at an R:FR of 2.4, plants were taller if far-red light, rather than red light, was maintained at 1 $\mu mol\ m^{-2}\ s^{-1}$ (Lund et al. 2007). In a study with the LDP lisianthus, internode length on the main stem was shorter under an NI with an R:FR of 5 or 10 than under an NI with an R:FR of 0.5, 1, 2, or 3 (Yamada et al. 2011). Results from studies using LEDs are in accordance with earlier work using spectral filters, which indicated that stem extension was promoted as the R:FR (or P_{FR}/P_{R+FR}) decreased (Runkle and Heins 2001). Therefore, the use of LEDs in photoperiodic lighting at low intensities is a feasible way to control morphogenesis of some crops while consuming little energy. For example, a 30 min DE provided by red LEDs at 5 $\mu mol\ m^{-2}\ s^{-1}$ suppressed stem elongation of poinsettia (*Euphorbia pulcherrima*) grown under a 10 h SD (Islam et al. 2012).

Low-intensity blue light can also inhibit stem elongation for desired compact plant growth. For example, internode elongation of chrysanthemum was suppressed by 60% under a 4 h NI provided by blue LEDs compared with FL lamps (Shimizu et al. 2005). However, blue light promoted stem elongation of chrysanthemum (Jeong et al. 2014), eggplant (*Solanum melongena*) (Hirai et al. 2005), and marigold (Heo et al. 2002). Therefore, the effects of blue light on stem elongation are not consistent and can be influenced by light intensity, other wavebands of light, and possibly additional environmental factors.

6. Comparison of LEDs with Traditional Light Sources. In 2013, a coordinated trial was conducted at six locations, including five commercial greenhouses, to evaluate how red/white/far-red (R + W + FR) LEDs and various conventional lamps regulated flowering of day

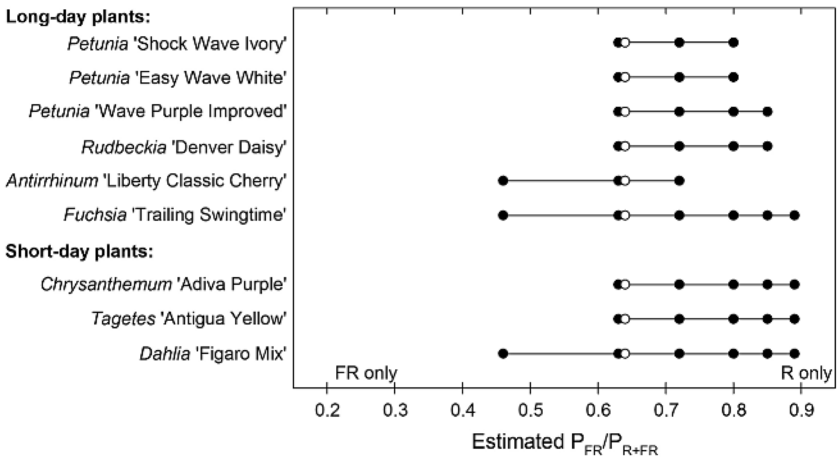

Fig. 1.5. Summary of the efficacy of 4 h night-interruption lighting treatments that promoted flowering of long-day plants and inhibited flowering of short-day plants (Craig 2012). LEDs (solid symbols) or incandescent lamps (open symbols) emitted different ratios of red (R, 600–700 nm) and far-red (FR, 700–800 nm) light. The phytochrome photo-equilibria (P_{FR}/P_{R+FR}) values were estimated using the spectral distributions of the treatments and the model described by Sager et al. (1988). A lamp was considered effective for each species if flowering percentage was ≥90% for long-day plants and if time to flower was statistically similar to plants that flowered most rapidly (for long-day plants) or most slowly (for short-day plants).

length-sensitive ornamental crops. Flowering time and stem extension parameters of most bedding plants tested were similar under a 4 h NI provided by the R + W + FR LED lamps and INC or HPS lamps, showing that LEDs are a viable, energy-efficient replacement for traditional lamp types (Meng 2014). Previous studies indicated that red and far-red LEDs with an intermediate R:FR of 0.66 ($P_{FR}/P_{R+FR} = 0.63$) or 1.07 ($P_{FR}/P_{R+FR} = 0.72$) promoted flowering of LDPs as effectively as INC lamps with an R:FR of 0.59 ($P_{FR}/P_{R+FR} = 0.64$) (Fig. 1.5; Craig 2012). The R + W + FR LEDs emitted an R:FR of 0.62 ($P_{FR}/P_{R+FR} = 0.65$), so their efficacy was not surprising. Another study compared the efficacy of NI lighting from INC lamps or LEDs that emitted red + white with or without far-red on flowering of long-day plants. When the photosynthetic DLI was low (6 mol m^{-2} day^{-1}), flowering of two cultivars of petunia occurred earlier under R + W + FR LEDs or INC lamps than R + W LEDs (Kohyama et al. 2014). However, flowering was similar under the NI treatments when the DLI was higher (>11 mol m^{-2} day^{-1}), which suggests that the flowering response to far-red light in NI lighting apparently diminishes as the DLI increases.

C. Propagation of Vegetable Transplants Under LED Lighting

1. Introduction and Brief History. High-quality transplant material is critical for successful vegetable production. The level of technology used in such operations depends on the target market, climatic region, and often the cost of labor. In the United States, most vegetable seedlings grown for field production are started in rather simple greenhouses to minimize cost (pennies per seedling), whereas greenhouses used for the production of grafted seedlings typically are equipped with more advanced environmental control systems (including SL) due to the higher value of grafted seedlings (Lewis et al. 2014).

The main objective of SL used for vegetable transplant production in greenhouses is to enhance seedling growth and development by increasing DLI. Target PPF levels delivered at the top of the canopy by the SL system applied in commercial practices vary from as low as 55 μmol m^{-2} s^{-1} (calculated from 4,500 lx; L. Benne, pers. commun.) to as high as 180 μmol m^{-2} s^{-1} (calculated from 15,000 lx; Peet and Welles 2005) using HPS lamps.

The recent introduction of LED lighting for seedling production aims to improve seedling growth and morphology, as well as reduce operational costs. Some commercial operations in Asia use "closed" systems (i.e., completely shielded from solar radiation and with a mechanical climate control system) for producing high-quality seedlings under electric lighting (Kozai 2013a). Use of lamps in such systems is intensive, and the reduction of electrical cost without reducing product quality is of highest priority for these facilities.

The transplant quality of vegetable seedlings generally is determined by visual inspection (e.g., compactness, vigor, and color) to evaluate the potential for growth and establishment following transplant. Vigorous vegetable transplants typically have well-developed leaves and roots with short internode length and thick stems. In addition to these properties, especially for tomato (*Solanum lycopersicum*), flower development status is a crucial attribute of transplant quality, as first flower clusters often develop during the propagation period (i.e., two-leaf stage for tomato). The morphological characteristics desired for scion and rootstock seedlings to be used for grafting are often different from those of nongrafted transplants. For example, rootstock seedlings need to be more "leggy" than "stocky" (i.e., long hypocotyls) to enhance grafting success and to ensure that the height of the graft union is well above the soil line (Chia and Kubota 2010). As monochromatic light sources, LEDs of selected peak wavelength can be used to induce desired responses at selected growth stages of propagation as discussed in the following sections.

2. Improving Transplant Morphology with LED Lighting

Sole-Source Lighting. Morphology of vegetable seedlings was improved when grown under specific combinations of LEDs as sole-source lighting (Brown et al. 1995; Kim et al. 2005; Massa et al. 2008; Hogewoning et al. 2010; Liu et al. 2011a; Nanya et al. 2012; van Ieperen et al. 2012). For example, pepper seedling stems were longer for plants grown under red LEDs (660 nm) or a combination of red and far-red (735 nm) LEDs compared with plants grown under a combination of red LEDs with a blue FL lamp or metal halide (MH) lamps at a PPF of 300 μmol m^{-2} s^{-1} for 12 h day^{-1} (Brown et al. 1995). Liu et al. (2011a) evaluated tomato seedling responses to different light colors such as red (650 nm), blue (450 nm), green (520 nm), yellow (590 nm), or combinations of R:B or R:B:G providing a PPF of 320 μmol m^{-2} s^{-1} for 12 h day^{-1} and concluded that a combination of red + blue wavelengths produced stronger, shorter tomato seedlings, whereas seedlings grown under red LEDs alone had the longest hypocotyls. Savvides et al. (2012) and van Ieperen et al. (2012) found that petiole length of cucumber (*Cucumis sativus*) seedlings was shortest under R:B light with a 7:3 photon flux ratio (640 and 400 nm for red and blue, respectively), followed by red light alone and blue light alone under 100 μmol m^{-2} s^{-1} for 16 h day^{-1}. Nanya et al. (2012) reported shorter stem length for tomato using a 1:1 R:B photon flux ratio, compared with a 9:1 or 7:3 R:B photon flux ratio (660 and 450 nm for red and blue, respectively) using a PPF of 150 μmol m^{-2} s^{-1} for 16 h day^{-1}.

Supplemental Lighting. Studies using LEDs as a SL source have been conducted, reporting the impact of LED light quality on vegetable seedling morphology (Plate 1.1b). In greenhouse environments, due to varying levels of concomitant solar radiation, interactions are expected between the effect of supplemental LED light quality and DLI provided by solar radiation. Hernández and Kubota (2012, 2014a,b) examined different photon flux ratios of supplemental red (661 nm) plus blue (455 nm) LED lighting (3.6 mol m^{-2} day^{-1}) for tomato and cucumber seedlings under varied solar DLIs. For both species, there was no significant difference in seedling morphology among different R:B photon flux ratios of supplemental LED lighting under high solar DLI (16–24 mol m^{-2} day^{-1}). However, under low solar DLI (5.2–8.7 mol m^{-2} day^{-1}), a lower R:B photon flux ratio decreased leaf area expansion for cucumber, but no significant differences were observed for tomato. These studies suggest that 100% red LEDs can be used for SL and that addition of blue LEDs is not beneficial under 5–24 mol m^{-2} day^{-1}

of solar DLI. Gómez and Mitchell (2015) quantified morphological responses of six tomato cultivars to different R:B treatments from LEDs (100:0, 95:5, and 80:20; 627 and 450 nm for the red and blue LEDs, respectively) or HPS (emitting 38% and 13% broadband red and blue light, respectively), SL (5.1 mol m^{-2} day^{-1}) across changing solar DLIs (0.4–19.1 mol m^{-2} day^{-1}). They found that for all cultivars evaluated, hypocotyl diameter and leaf area increased with the addition of blue light in SL. Further studies are needed to identify species-specific morphological and developmental responses of vegetable transplants to LED lighting and how such SL interacts with seasonally and/or regionally different levels of solar DLI.

End-of-Day Light Quality Application. Red or far-red end-of-day (EOD) lighting is known to affect stem elongation through the well-studied phytochrome response (Kasperbauer and Peaslee 1973; Decoteau et al. 1988; Blom et al. 1995). Due to the low light intensity requirement, EOD lighting using red and/or far-red LEDs may be an economically feasible, nonchemical means to control plant morphology in which EOD red or far-red light treatments may reduce or enhance stem or hypocotyl elongation rate, respectively. While some electric lighting contains a significant amount of far-red light (e.g., INC lamps), far-red light (735 nm) from LEDs could be used to maximize the response when stem elongation of vegetable seedlings is desired. Studies conducted using tomato (Chia and Kubota 2010) and squash (*Cucurbita maxima* × *Cucurbita moschata*) rootstock (Yang et al. 2012) seedlings indicated two key characteristics that maximized hypocotyl length: (1) a species-specific EOD far-red light response curve (typically a saturation curve), and (2) a daily minimum dose (photon flux multiplied by duration applied each day) of EOD far-red lighting. The authors concluded that (1) a daily minimum far-red dose of 4 mmol m^{-2} day^{-1} was sufficient to enhance hypocotyl length for tomato and squash rootstocks, and (2) the photon flux and duration of far-red light can be flexible as long as the minimum required dose is achieved. Based on these findings, Yang et al. (2012) pioneered the idea of installing far-red LEDs on a bar moving horizontally above the plant canopy to apply EOD far-red light to transplants growing in propagation greenhouses.

3. Improving Transplant Photosynthesis and Growth. When LEDs were used for sole-source lighting, Fan et al. (2013a) examined varied levels of PPF (50–550 μmol m^{-2} s^{-1} for 12 h day^{-1}) using red (658 nm) and blue (460 nm) LEDs (photon flux ratio 1:1) and found that a PPF of 300 μmol m^{-2} s^{-1} (DLI = 13 mol m^{-2} day^{-1}) was most suitable for growing young tomato seedlings, because further increases in PPF did not generate substantial gains in plant growth and transplant quality. For light quality requirements, as reviewed in Section VI.B.2, several studies (e.g., Brown et al. 1995) indicated the necessity to add blue light to otherwise monochromatic red LED lighting (660 nm). For example, pepper seedlings grown under monochromatic red LEDs had significantly lower plant dry mass compared with that under a combination of red LEDs and blue FL light (99:1 R:B photon flux ratio) under a PPF of 300 $\mu mol\,m^{-2}\,s^{-1}$ for 12 h day^{-1} (Brown et al. 1995). One exception was reported by Liu et al. (2011a), who found that the dry mass of cherry tomato seedlings was higher for plants grown under monochromatic blue LEDs (450 nm) compared with that under a combination of red (650 nm), blue, and green LEDs (520 nm) or monochromatic red LEDs using a PPF of 320 $\mu mol\,m^{-2}\,s^{-1}$ for 12 h day^{-1}. Conflicting results have been reported regarding the optimum amount of blue light (often reported as the R:B photon flux ratio) needed to promote vegetable seedling growth. Nanya et al. (2012) showed that tomato seedlings (17 days after seeding) had greater dry mass with a 9:1 R:B photon flux ratio compared with a 7:3 or 1:1 R:B photon flux ratio (660 and 450 nm for red and blue light, respectively) (150 $\mu mol\,m^{-2}\,s^{-1}$ for 12 h day^{-1}), indicating that a larger amount of blue light is not beneficial for tomato seedling growth; this was attributed to the lower photosynthetic quantum efficiency of blue light compared with that of red light (McCree 1972). In contrast, Hogewoning et al. (2010) found a higher net photosynthetic rate for cucumber seedlings grown under lower R:B photon flux ratios (with increasing percentages of blue light up to 50%; 638 nm red and 450 nm blue light) at a PPF of 100 $\mu mol\,m^{-2}\,s^{-1}$ for 16 h day^{-1}; this was attributed to lower leaf conductance to CO_2 diffusion and damage to photosystem II under 100% red light. Increasing the amount of blue light increased the stomatal conductance and thus the leaf intercellular CO_2 concentration.

When used for SL, the impact of light quality (e.g., monochromatic red LEDs versus a combination of red and blue LEDs) seemed to be minimum, especially when background solar irradiance provides sufficient PPF. For example, research was conducted on tomato (Hernández and Kubota 2012, 2014b) and cucumber (Hernández and Kubota 2014a,b) seedlings grown under different photon flux ratios of supplemental blue (450 nm) and red (661 nm) LEDs under varied solar DLI conditions (5–24 $mol\,m^{-2}\,day^{-1}$) using a supplemental PPF of 56 $\mu mol\,m^{-2}\,s^{-1}$ for 18 h day^{-1}. Tomato seedlings did not exhibit significant differences in growth between the different R:B photon flux ratios provided by the supplemental LED lighting. However, cucumber seedlings exhibited a significant decrease in the number of leaves and in dry mass, but an increase of chlorophyll content with decreasing R:B photon flux ratios (i.e., an increasing amount of blue photon flux) under low solar DLI conditions (5.2 mol m^{-2} day^{-1}). However, there seems to be a threshold background solar DLI or a relative level of supplemental DLI that requires additional blue photon flux through SL.

4. Considerations in Evaluating Electric Lighting for Greenhouses. Studies introducing LED technology in horticulture often involve comparisons with conventional lighting technology such as HID lamps or FL lamps (e.g., Gislerød et al. 2012; Currey and Lopez 2013; Gómez et al. 2013; Hernández and Kubota 2014b; Randall and Lopez 2014). Morphological differences in vegetable transplants were observed when grown under LEDs compared with conventional HPS SL in greenhouses. Gislerød et al. (2012) reported reduced leaf expansion and stem extension for tomato, cucumber, and lettuce seedlings grown under red (630 nm) and blue (465 nm) LEDs compared with HPS SL. Hernández and Kubota (2014b) compared growth of tomato and cucumber seedlings under supplemental red LEDs (632 nm) or HPS lamps. Tomato seedlings exhibited no significant differences in shoot dry mass between the light quality treatments, whereas cucumber seedlings had greater shoot dry mass when grown under HPS lamps than under red LEDs. Species-specific responses to light quality were also observed for mature plants. For example, the addition of intracanopy blue light supplementing overhead HPS light had a positive effect on development and photosynthetic pigment accumulation in cucumber plants, but not for tomato or pepper plants (Ménard et al. 2006; Samuoliene et al. 2012a).

In addition to plant response, comparison of costs, especially for electric energy use, between different lighting technologies is critical information for introducing LEDs to commercial horticultural operations. However, differences in optical design make it difficult to directly compare capital and operating costs of LED lamps with those of conventional HID lamps (e.g., HPS) used for small growing areas in a typical academic research setting. Scientists and engineers must consider such differences when comparing different lighting technologies and installation schemes, and should apply calculated corrections to extrapolate from experimental results to commercial-scale settings. Such lighting comparisons can be performed using computer simulations. For example, Pinho et al. (2013) used a computational approach to compare energy use of supplemental LED and HPS lamps in a greenhouse. The direct measurements obtained from a 1 m^2 lettuce stand showed that 400 W HPS fixtures consumed 68% (429 kWh) more energy than

LED lamps (256 kWh). However, recognizing the challenges of direct comparison for such a small experimental growing area, Pinho et al. (2013) used computer simulation to select the optimum mounting pattern (height and input electric power density) to provide the same target PPF (150 μmol m^{-2} s^{-1}) with a target uniformity (i.e., >70% minimum/average PPF ratio) for both lamp types to irradiate a relatively large area (800 m^2 cultivation area inside a 1,000 m^2 greenhouse). Results indicated that a similar input electric power density (139–142 W m^{-2}) was required using either 400 W HPS lamps or red/blue LED lamps, but the calculated PPF uniformity was higher (92.8% versus 72.7%) using red/blue LEDs versus HPS lamps.

5. LEDs for Sole-Source Lighting of Vegetable Transplants

Closed Seedling Production Systems. Light-emitting diode arrays have been used commercially for sole-source lighting in indoor systems for vegetable seedling (transplant) production or for grow-out production of compact vegetable crops such as lettuce and herbs. These indoor production systems, commonly known as closed production systems, vertical production systems, or plant factories, often employ multilayer shelving units in order to maximize space use efficiency. Typically, each layer is equipped with lighting, irrigation, and air circulation systems. A typical distance between lamps mounted on the bottom surface of an upper shelf and the top of the irrigation system below is 30–40 cm (Kozai 2013b), with varied depths and lengths of shelves. The concept of closed transplant production systems was developed in Japan in the 1990s (Ohyama and Kozai 1998; Kozai et al. 2000), and today many commercial nurseries use the environmental control aspect of this technology to assure the quality of seedlings (Kozai 2007). Until recently, most commercial systems have utilized WF lamps due to their availability, relatively small fixture size, and a reasonable fixture price (especially when purchased in bulk). However, along with the advancement of LED technology for plant applications, nurseries are interested in replacing current FL lamps with LED lamps, and some have begun to use LED lamps as their sole lighting source for seedling production. Earlier studies with LEDs for plant growth by Bula et al. (1991) revealed that the growth response of young lettuce under red LEDs (660 nm) supplemented with blue light was comparable to that under the conventional combination of WF and INC lamps using a PPF of 325 μmol m^{-2} s^{-1} for 16 h day^{-1}. Kato et al. (2011) compared tomato seedling growth under white LED lamps and WF lamps providing 97–103 μmol m^{-2} s^{-1} and concluded that there was little difference in seedling response between white LEDs and WF lamps. Wollaeger and Runkle (2014) compared tomato seedling growth and morphology under different blue, green, and red LED ratios (446, 516, and 634/664 nm, respectively) of 100R, 50R:50G, 50R:25G:25B, 50R:50G, 50R:50B, or 100B, or WF lamps using a PPF of 160 μmol m^{-2} s^{-1} for 18 h day^{-1}. Their results showed that all LED treatments except 100% red LEDs reduced shoot fresh weight and leaf area compared with those under WF lamps. Under 100% red LEDs, tomato plants exhibited greater shoot fresh and dry weight than those under WF lamps, but a higher incidence of intumescences was also observed under the 100% red LEDs. Cope and Bugbee (2013) grew radish (*Raphanus sativus*), soybean (*Glycine max*), and wheat in growth chambers under three types of white LEDs (warm, neutral, or cool, with 11%, 19%, or 28% blue light, respectively) comparing two PPFs (200 and 500 μmol m^{-2} s^{-1}) for 16 h day^{-1}. They sought to determine whether certain growth or developmental parameters are better predicted by either absolute (μmol m^{-2} s^{-1}) or relative (percentage of total PPF) blue light within a closed production system. From their findings, it is clear that blue light responses are species dependent, and that total intensity of light and relative distribution of light quality interact to determine plant morphology. Similarly, Cope et al. (2014) evaluated the interactive effects of blue light and PPF on growth and development of lettuce, radish, and pepper. Plants were grown under monochromatic (red, blue, red + blue, or red + green + blue) or broad-spectrum white LED arrays providing different fractions of blue light (from 0.3% to 92% under monochromatic LEDs or from 11% to 28% under broad-spectrum white LEDs). Their study confirmed that blue light responses are species specific and depend on light quality and PPF. Cope et al. (2014) also suggested that the photobiological sensitivity of pepper changes with plant age. More information is needed regarding species- and development-specific responses to LEDs in general and to blue LEDs in particular.

Graft Healing with LED Lighting. Another important lighting system deployed by commercial nurseries is used for the healing process of recently grafted plants, which typically lasts 5–7 days and requires lighting to maintain a minimum photosynthetic rate. White FL lamps have been the standard light source to provide a PPF of 30–100 μmol m^{-2} s^{-1} at the top of the canopy inside a healing chamber equipped with multilayered shelving units. However, the healing process also requires high relative humidity, which can be problematic when using FL tubes. Therefore, nursery operators are interested in switching from FL lamps to waterproof LED fixtures. Jang et al. (2013) examined LED lamps (100%

red, 100% blue, or 71% red + 29% blue; 639 and 469 nm for red and blue, respectively) and standard WF lamps for the healing of grafted pepper (*Capsicum annum*) seedlings. Under 100% red LED light, grafted pepper seedlings became epinastic (abaxial leaf curling). The addition of blue to the red light can eliminate this problem, as described for other plant species grown under LED lamps (Massa et al. 2008). Moreover, under 100% blue light, grafted seedlings have been noted to elongate (Jang et al. 2013). Vu et al. (2014) evaluated the influence of irradiation with LED lamps (blue, red, and far-red; 450, 660, and 730 nm, respectively) and WF lamps during the healing period on the graft-take ratio and quality of tomato seedlings. Plants had a better graft-take ratio and plant quality under the red LED or WF treatment than for blue or far-red LEDs. Growth of tomato seedlings under red LEDs was similar to that under WF lamps after grafting.

D. LED Applications for Indoor Crop Production

1. Full-Coverage Sole-Source Lighting. Because LED arrays typically are used with low power density per unit growth area (kW m^{-2}), offer a diversity of narrow-waveband availability, and can deliver high light intensities with low heat radiation to crops, LEDs are strong candidates for sole-source photosynthetic lighting in indoor plant production scenarios. Goins et al. (1997) compared photomorphogenesis, photosynthesis, and seed yield of wheat plants produced in a growth chamber using 350 $\mu mol\ m^{-2}\ s^{-1}$ from daylight FL (white) lamps, red LEDs (660 nm), or a combination of red LEDs + either 1% or 10% blue light provided by blue fluorescent (BF) lamps. They reported that plants grown under red LEDs alone produced fewer shoots and less seed yield compared with plants grown under white light. However, wheat grown under red LEDs + 10% BF light had comparable shoot dry matter accumulation and seed yield relative to wheat plants grown under white light. They also observed that wheat plants completed their life cycle under red LEDs alone, but larger plants were obtained with higher yields under red LEDs supplemented with blue light. Ménard et al. (2006) conducted a growth chamber study comparing yield and development of tomato and cucumber grown under different DLIs using HPS (510 $\mu mol\ m^{-2}\ s^{-1}$) or HPS + blue LEDs (455 nm). They evaluated different PPFs of blue light from LEDs (6.7, 7.5, or 16 $\mu mol\ m^{-2}\ s^{-1}$) and concluded that adding 6.7 $\mu mol\ m^{-2}\ s^{-1}$ of blue light for 20 h or 16 $\mu mol\ m^{-2}\ s^{-1}$ of blue light for 12 h promoted fruit yield of cucumber but had no significant effect on tomato yield. Ménard et al. (2006) also reported a reduction in internode elongation with the addition of blue for both vegetable species. A study by Kobayashi et al. (2013) compared growth of hydroponically grown miniature lettuce in a growth room under 59 μmol m^{-2} s^{-1} from sole-source blue LEDs (peak wavelength not defined), red LEDs (peak wavelength not defined), or FL lamps. The authors reported that shoot dry weight was similar among treatments and concluded that LEDs could serve as an alternative lighting source for indoor miniature lettuce production. Chin and Chong (2012) evaluated red (620 and 645 nm) and blue (440 and 460 nm) LEDs as sole-source lighting for indoor lettuce production. They compared lettuce grown in a growth room with LEDs (no PPF defined) versus that grown in a greenhouse under no SL and found that sole-source lighting with LEDs induced faster growth rates compared with greenhouse-grown lettuce.

Heo et al. (2012) compared lettuce ('Ttuksum' and 'Jaju') grown under FL lamps with that under blue (450 nm), red (660 nm), or red + blue (1:1) LEDs (90 ± 10 μmol m^{-2} s^{-1}) for 10 days. They found that either red or blue LEDs resulted in increased fresh and dry weights compared with FL-grown controls. Interestingly, the two varieties performed differently in that red light stimulated fresh and dry mass production in 'Ttuksum', whereas blue light was more effective for 'Jaju'. Lin et al. (2013) grew 'Capitata' lettuce under a 16 h photoperiod of 210 μmol m^{-2} s^{-1} using FL lamps, red + blue (454 and 660 nm) LEDs, or red + white + blue (RWB, 400–700 nm) LEDs. Shoot and root fresh weights were significantly higher for plants grown under the RWB LEDs than the red + blue LEDs or the FL lamps. Park et al. (2012) also used RWB LEDs to grow 'Seonhong Jeokchukmyeon' lettuce under 140 μmol m^{-2} s^{-1} of FL light, white LEDs, or RWB LEDs (8:1:1). In addition, they compared responses to different CO_2 concentrations (350, 700, and 1,000 μmol mol^{-1}) and found that 1,000 μmol mol^{-1} of CO_2 coupled with the RWB LEDs gave the largest increase in vegetative growth. Li and Kubota (2009) grew 'Red Cross' baby leaf lettuce in growth chambers using FL lamps as the primary light source to achieve a total PPF of 300 μmol m^{-2} s^{-1}. Photon flux added by LEDs for UV-A, blue, green, red, and far-red (373, 476, 526, 658, and 734 nm, respectively) was 18, 130, 130, 130, and 160 μmol m^{-2} s^{-1}, respectively. Added far-red light was found to significantly increase fresh and dry weight of lettuce plants due to the larger leaf area of the plants, which increased light interception. This conclusion was previously reached by Stutte et al. (2009) in a similar study using sole-source LED lighting to grow 'Outredgeous' lettuce.

Fan et al. (2013a) used red, yellow, green, blue, or red + blue LEDs (658, 590, 520, and 460 nm, respectively) and compared their effects on

Chinese cabbage (*Brassica campestris*) grown under dysprosium lamps at a PPF of 150 μmol m^{-2} s^{-1}. The combination of red + blue LED light had the greatest impact on dry and fresh mass accumulation with an almost twofold difference in fresh mass compared with plants grown under dysprosium lamps. Samuoliene et al. (2013a) grew Kohlrabi 'Delicacy Purple' mustard (*Brassica juncea* 'Red Lion'), red pak choi (*Brassica rapa* 'Rubi F1'), and tatsoi (*Brassica narinosa*) microgreens within growth chambers using LEDs (455, 638, 665, and 731 nm). They compared five different PPFs (545, 440, 330, 220, and 110 μmol m^{-2} s^{-1}) with a 16 h photoperiod and found that 330–440 μmol m^{-2} s^{-1} produced the highest quality microgreens in terms of leaf area and nutritional properties.

Sabzalian et al. (2014) grew three *Mentha* species (*M. piperita*, *M. spicata*, and *M. longifolia*), lentil (*Lens culinaris* Medic), and basil (*Ocimum basilicum*) within an incubator equipped with red (650 and 665 nm), blue (460 and 476 nm), red + blue (70% and 30%, respectively), or white (broad spectrum from 380 to 760 nm) LEDs. For all species grown, Sabzalian et al. (2014) compared indoor production using 500 μmol m^{-2} s^{-1} of sole-source lighting with greenhouse production lacking SL as well as with field production. They found that for *M. longifolia*, indoor production with red + blue LEDs yielded more fresh weight compared with field production. Also, they reported that indoor production led to faster growth rates of lentil and basil compared with greenhouse production. The study showed that sole-source lighting with LEDs could improve yield and accelerate production of different plant species relative to field or greenhouse production.

2. Targeted Close-Canopy Lighting. The fact that waste heat is rejected remotely from the photon-emitting surfaces of LEDs allows LED arrays to be placed close to crop surfaces. Their relative coolness suggests that LEDs may be a suitable alternative for sole-source lighting in commercial vertical farming (VF) scenarios where plants are grown in multitiered, high-density growing systems, as suggested by Yeh and Chung (2009), Watanabe (2011), Liu (2012), and Kozai (2013b). Moreover, because LEDs and their arrays can be designed to cast narrow beams of light, targeted lighting can be applied by selectively switching on LEDs positioned directly above individual plants as the crop grows (Plate 1.1d). Poulet et al. (2014) reported that targeted, close-canopy lighting of lettuce using red and blue LEDs (630 and 455 nm, respectively) reduced energy consumption per unit dry mass by 50% or 32% compared with total coverage sole-source lighting using either red + blue or broad-spectrum white LEDs, respectively.

E. LED Applications for Greenhouse Vegetable Crop Production

Plants that develop indoors typically are exposed to a limited light spectrum that depends on the electric lamp type used. In contrast, greenhouse-grown plants receive a broad spectrum of light from solar radiation in addition to that provided by any SL source. Thus, if LEDs are used to supplement sunlight, additional blue light may not be necessary because sunlight's broad light spectrum contains significant amounts of blue light at midday, which may be sufficient for normal plant growth and development. Then again, it is difficult to determine photomorphogenic and physiological effects of SL on greenhouse crops because a distinction cannot easily be made between light sources. Because SL typically constitutes only a fraction of total irradiance received by plants during light-limited seasons, photomorphogenic and physiological disorders that have been reported for plants grown under narrowband lighting in growth chambers (Morrow and Tibbitts 1988; Morrow 2008; Hogewoning 2010) are potentially less likely to occur in greenhouse production using narrowband SL.

1. Current Standard. It is well established that yield and quality of greenhouse vegetables can be increased by using SL in light-limited environments (Rodriguez and Lambeth 1975; Tibbitts et al. 1983; McAvoy and Janes 1984; Dorais et al. 1991). Overhead HID lamps are the preferred type of greenhouse SL because their high-intensity capability allows them to deliver adequate supplemental PAR. However, HID lamps, which include mercury vapor, MH, and HPS lamps, have a relatively high life cycle cost (cost of buying, installing, operating, and maintaining a lamp during its lifetime) and a significant environmental impact compared with other lamps that do not contain mercury or other hazardous materials.

High-pressure sodium lamps have been considered the most suitable light source for large-scale SL in greenhouses. Furthermore, HPS lamps are up to 30% efficient in terms of converting electricity into useful light, and the remaining "waste" thermal energy can be used to increase ambient greenhouse and plant temperature and offset winter heating costs (Tiwari 2003). Brault et al. (1989) estimated that, in temperate climates, the heat emitted from HPS lamps can provide between 25% and 41% of the heating requirement for a greenhouse operation. Thus, heat generation is sometimes considered a useful by-product of HPS lamps. Also, HPS lamps typically require reflectors to direct the light from the bulbs onto crops, thereby providing satisfactory light distribution and efficiency, but as a result blocking some sunlight from reaching the crop. In addition, their significant thermal output often requires a considerable separation distance between plants and lamps to avoid tissue scorching, which contributes to a higher lamp power requirement to provide adequate PPF at increasing distances (Cathey and Campbell 1977).

Like most available light sources, HPS lamps were originally designed for human use. These lamps emit an orange (590–620 nm)-biased, low-blue spectrum that does not correspond with the absorption peaks of chlorophyll pigments. Nonetheless, any wavelength of light within the PAR spectrum contributes to photosynthesis and crop productivity (McCree 1972). Thus, with their high-intensity capabilities, HPS lamps have been widely adopted for greenhouse SL and currently are the most economically viable mass-produced light source available to provide adequate PAR irradiance for plant growth.

Markham (1969) conducted one of the first greenhouse experiments with HPS SL and reported that a number of different plant species could be grown under these lamps. Further greenhouse research by Meijer (1971) reported more fresh and dry mass accumulation by tomato and cucumber seedlings grown under HPS compared with MH lamps. Austin and Edrich (1974) compared mercury halide versus HPS lamps for growing cereals in glasshouses during winter. They observed increased tillering and concluded that HPS lamps were more suitable than MH for growing plants to seed. Elgin and McMurtrey (1977) reported similar results when comparing flowering and seed production of greenhouse-grown alfalfa using HPS, MH, mercury vapor, INC, or no SL, and concluded that HPS was most effective for increasing seed yields. Later, McAvoy and Janes (1984) reported an increase in greenhouse tomato production when plants were grown under HPS lamps compared with unsupplemented controls, especially during winter months. Clark and Devine (1984) reported enhanced plant growth of ‘Altex’ rapeseed (*Brassica napus*), ‘Neepawa’ spring wheat, ‘Kay’ orchard grass (*Dactylis glomerata*), Canada thistle (*Cirsium arvense*), ‘Gaertn.’ Tartary buckwheat (*Fagopyrum tataricum*), and ‘Buttercrunch’ lettuce when using HPS lamps compared with MH and FL lamps in a greenhouse experiment. Over the years, HPS lamps have served as an adequate light source for greenhouse SL. However, recent interest has focused on alternative SL sources that can reduce production costs by decreasing electrical energy consumption while maintaining crop yield and quality.

2. Sole-Source Lighting Pretreatments. Studies have evaluated the aftereffects (carryover effects) of sole-source LED lighting on growth, development, and yield of indoor-grown transplants subsequently grown in greenhouses. Brazaitytė et al. (2009b) evaluated aftereffects of various wavelength combinations of LEDs on the subsequent growth of tomato. They compared HPS lamps versus five LED lamps with blue, yellow, and red LEDs (447, 638, and 731 nm, respectively), which provided different light intensities ranging from 178 to 220 μmol m^{-2} s^{-1}. Each lamp was additionally supplemented with LEDs of different peak wavelengths that included at least one of the following: 380, 520, 595, 622, 660, or 669 nm. Initial lighting effects on subsequent plant growth and development lasted 4 weeks after sole-source LED lighting treatments had ceased, after which effects from the different lighting treatments were no longer noticeable. No treatment effect was observed for time of harvest. However, a decrease in total yield was reported for plants grown under the LED lamps supplemented with 595 + 669 nm. A similar study evaluated the aftereffects of different LED treatments on cucumber growth and yield (Brazaitytė et al. 2009a). Results indicated that even though no differences in fruit yield occurred, adding green or orange light from LEDs (520 or 622 nm, respectively) accelerated plant maturity and thus could potentially reduce overall energy consumption for greenhouse cucumber production. Samuoliene et al. (2010) evaluated the aftereffects of sole-source LED lighting on strawberries (*Fragaria* × *ananassa*) subsequently grown in a greenhouse. They reported improved carbohydrate accumulation and overall better plant growth when a combination of red and blue LEDs (640 and 455 nm, respectively) was used during early crop establishment. Johkan et al. (2010) grew red leaf lettuce in a growth chamber using different combinations of light spectra to provide a total PPF of 100 μmol m^{-2} s^{-1}. The treatments evaluated were white FL lamps, and red (660 nm), blue (468 nm), or 1:1 red (655 nm) + blue (467 nm) LEDs. After 1 week of treatment, all plants were transplanted into a greenhouse supplemented with FL lamps and grown for 28 days. They evaluated the aftereffects of light quality on subsequent growth and yield and reported that, at harvest, leaf area and shoot fresh mass were highest for lettuce plants initially treated with blue alone or red + blue LEDs.

3. Supplemental Lighting. Limited scientific literature exists on the use of LEDs as SL sources for greenhouse operations. However, with ongoing improvements in light output levels, expanded wavelength availability and control, higher energy efficiencies, and relatively low operating temperatures, efforts have been made to test different LED technologies for growing greenhouse crops.

Hogewoning et al. (2007) were the first to describe the use of LEDs for greenhouse tomato production. Their concern with introducing LED SL in greenhouses was related to the capacity of daylight-adapted leaves to reacclimate their photosynthetic apparatus to narrowband lighting (NBL). They tested the reacclimation capability of leaves to NBL by illuminating 70-day-old leaves positioned low in the canopy of a high-wire tomato crop with 70 μmol m^{-2} s^{-1} provided by arrays of a single LED type with peak wavelengths of 470 nm (blue), 537 nm (green), or 642 nm (red). They reported that the maximum photosynthetic capacity of lower, older leaves increased over time after being irradiated with NBL, suggesting that leaves can reacclimate their photosynthetic capacity to higher light intensities delivered by supplemental NBL. In addition, in order to distinguish effects of leaf age and light intensity on photosynthesis, they compared the maximum photosynthetic capacity of tomato leaves at different developmental stages. For this purpose, plants were grown horizontally (accomplished by constantly binding the growing tip to a horizontal wooden frame) to avoid shading of older leaves by newer leaves and thus ensuring equal light distribution throughout the canopy. The findings of Hogewoning et al. (2007) indicated that older tomato leaves never exposed to shading kept a photosynthetic capacity similar to that of younger leaves, suggesting that losses of photosynthetic capacity commonly observed for lower, older leaves of high-wire crops are not attributable to leaf age, but rather to mutual shading within the plant canopy. They suggested that maintaining a higher light level within the canopy would be an effective way to keep lower leaves, otherwise in a shaded position, productive. No effects on fruit yield were mentioned for that study.

Interlighting and Intracanopy Lighting. Traditionally, greenhouse crop production has relied on the use of overhead lamps for SL. However, overhead lighting tends to favor upper leaf layers by maximizing light interception incident at the top of the foliar canopy. This results in unequal light distribution where the middle and lower leaf canopies are shaded and thus PAR limited. In addition, foliar canopy architecture differs among species and should be considered as an important factor for greenhouse SL. With low-growing rosette crops such as lettuce and cabbage, overhead lighting seems to be appropriate for delivering adequate PAR to plants positioned underneath the lamps. However, mutual shading occurs for planophile crops, where upper leaf layers shade the lower leaf canopy and overhead photons are excluded from the inner canopy, thereby inducing premature senescence and leaf abscission (Frantz et al. 2000).

Some of the first attempts to evaluate LEDs as SL sources for greenhouse vegetable production focused on their relative coolness (i.e., low radiant heat output), which allows for greater flexibility in lamp placement and resulting light distribution. This is especially beneficial for high-wire cropping systems (i.e., tomato, cucumber, sweet pepper, and eggplant), where plants are trained vertically along support wires, thereby creating conditions conducive to shading of middle and lower leaves by upper leaves, and potentially row-to-row shading, depending on lamp mounting pattern, row direction, and ever-changing solar angle. Intracanopy lighting and interlighting both refer to the strategy of lighting along the side or within the foliar canopy, and could help prevent mutual shading within high-wire-crop foliar canopies. For this chapter, the terms "ICL" and "interlighting" are used interchangeably.

Both vertical ICL (Plate 1.1e and f) and horizontal interlighting (Plate 1.1g) help increase the efficiency of irradiation by allowing direct light into the inner canopy of crop stands. It has been reported that ICL in a sole-source lighting mode can delay leaf senescence for cowpea (*Vigna unguiculata*) (Frantz et al. 2000; Massa et al. 2005a,b) and soybean (Stasiak et al. 1998) by maintaining irradiance in the understory of the foliar canopy. Other studies have shown that partial interlighting (hybrid = overhead + ICL) can increase fruit yield (size, weight, and number), increase percentage of first-class fruit, and extend the postharvest shelf life of produce (Hovi et al. 2004; Gunnlaugsson and Adalsteinsson 2006; Hovi-Pekkanen et al. 2006; Hovi-Pekkanen and Tahvonen 2008; Pettersen et al. 2010). Moreover, research has shown that hybrid lighting can increase crop photosynthesis in high-wire greenhouse production of tomatoes (Trouwborst et al. 2010), cucumber (Pettersen et al. 2010), and field-grown soybean (Johnston et al. 1969). However, all of these studies were conducted using FL, microwave-powered, or HPS lamps.

To our knowledge, Trouwborst et al. (2010) were the first to measure the effects of partial LED interlighting on yield of a high-wire greenhouse-grown cucumber crop. In addition, they quantified light interception and photosynthetic capabilities of different vertical leaf levels within the crop. The experiment was conducted for 13 weeks during a winter production cycle using either a combination of LED interlighting + overhead (OH)-HPS or OH-HPS only to provide an average PPF of 221 $\mu mol\, m^{-2}\, s^{-1}$. For the hybrid treatment, they used LED arrays that provided 80% red (667 nm) + 20% blue (465 nm) light and 400 W HPS lamps. The LED and HPS portions of the hybrid treatment contributed to a PPF of 139 and 82 $\mu mol\, m^{-2}\, s^{-1}$, respectively. For the OH-HPS treatment, 600 W HPS lamps were used. Trouwborst et al. (2010) reported that hybrid SL improved photosynthetic properties in lower leaf layers and increased dry mass allocation to leaves. However, fruit production was not increased using LEDs + OH-HPS relative to OH-HPS only. The authors attributed their results to overall limiting light intensities in the experimental greenhouse and reduced light interception resulting from leaf curling caused by the LEDs. Dueck et al. (2012) compared the effects of different SL systems on growth and production of greenhouse-grown tomatoes in the Netherlands. They provided 170 $\mu mol\, m^{-2}\, s^{-1}$ from OH-HPS lamps, OH-LED arrays, or hybrid lighting with OH-HPS + OH-LEDs or OH-HPS + LED interlighting. The LED lighting was composed of 12% blue (450 nm) and 88% red (660 nm) light. They concluded that a combination of OH-HPS + LED interlighting is the most promising alternative for their climate, when taking into consideration production parameters and energy costs (lighting + heating) of using the different systems. Another experiment compared hybrid lighting using red (660 nm), blue (460 nm), or white (broad spectrum from 400 to 700 nm) LED interlighting + OH-HPS versus OH-HPS lamps (400 W) for the production of greenhouse mini-cucumber (Hao et al. 2012). The LED interlighting treatments provided an additional PPF of 14.5 $\mu mol\, m^{-2}\, s^{-1}$ to that received by plants under the OH-HPS treatment (145 $\mu mol\, m^{-2}\, s^{-1}$). The study revealed that all hybrid SL treatments improved fruit visual quality (based on a color rating scale and fruit curvature ratings) compared with the OH-HPS treatment. However, fruit yield increased with LED interlighting only during early stages of production. It gradually decreased in effectiveness toward the mid and late stages of production, becoming even less effective than the OH-HPS treatment. Jokinen et al. (2012) reported an increase of 16% in total marketable yield of sweet pepper using LED interlighting (light spectrum not reported) compared with plants grown with no SL and concluded that their results were due to an increase in fruit number and earlier fruit maturity induced by LED interlighting. The recorded PPF levels inside the canopy showed less than 10 $\mu mol\, m^{-2}\, s^{-1}$ measured close to leaves with no SL and up to 300 $\mu mol\, m^{-2}\, s^{-1}$ close to leaves with the LED interlighting treatment.

Research by Lu et al. (2012) compared effects of interlighting on yield and quality of greenhouse tomatoes grown at high planting densities using a single-truss tomato production system. They provided PPFs ranging from 70 to 143 $\mu mol\, m^{-2}\, s^{-1}$ at a distance of 5 cm from lamps using white (broad spectrum from 400 to 700 nm), red (660 nm), or blue (442 nm) LEDs. Results indicated that white and red LEDs increased fruit fresh mass by 12% and 14%, respectively, compared with plants grown under no SL. However, plants receiving blue LEDs showed no increase in fruit fresh mass. After calculating the effects of light quality on fruit fresh mass per unit of photons emitted, the authors concluded that white

LEDs were the most efficient promoting fruit fresh mass gain. They suggested that this was due to higher light penetration into the foliar canopy by green wavelengths emitted by the white LEDs.

Gómez et al. (2013) compared yield and energy use for the production of two tomato cultivars grown with either ICL-LEDs (95% red (627 nm peak) plus 5% blue (450 nm)) or OH-HPS (1,000 W) lamps providing 9 mol m^{-2} day^{-1} of SL. The authors reported significantly lower energy requirements from SL when using ICL-LEDs compared with OH-HPS lamps (129 versus 31 kWh day^{-1}, respectively) while maintaining comparable fruit yield. Furthermore, a study by Gómez and Mitchell (2014) reported 75% or 55% energy savings from SL when using ICL-LEDs compared with OH-HPS lamps during a winter-to-summer or a summer-to-winter production cycle. No differences in fruit yield were measured between treatments for their study.

Deram et al. (2014) compared three light levels (135, 115, or 100 μmol m^{-2} s^{-1}) and three red (661 nm)-to-blue (449 nm) ratios (5:1, 10:1, or 19:1) of LED interlighting for high-wire greenhouse tomato production. The light intensities were measured using a spectroradiometer and a spherical quantum sensor (for comparison). The LED interlighting arrays were placed no more than 10 cm below the top of the plant canopy, and lamp height was adjusted depending on crop growth. In addition, Deram et al. (2014) compared several LED treatments (different light intensities from interlighting, OH lighting with red light only, bottom lighting with red light only, or hybrid lighting with LED interlighting + OH-HPS (1:1)) versus OH-HPS lighting. The study showed that vegetative biomass production was greatest when a 19:1 R:B ratio was used, with increasing total irradiance resulting in greater growth. However, fruit yield was enhanced only when using 135 μmol m^{-2} s^{-1} at the 5:1 R:B ratio. Results also showed that marketable fruit production was highest when plants were grown under hybrid lighting with LED interlighting + OH-HPS (1:1).

Overhead SL. Martineau et al. (2012) compared OH-HPS (wattage not reported) versus OH-LED lamps (with 400, 450, 640, and 735 nm + cool white (no spectrum defined) LEDs) as SL sources for greenhouse lettuce production. They reported similar yield for both treatments even though plants grown under the OH-LEDs received about half of the average irradiance from SL that plants under the OH-HPS lamps received (35.8 versus 71.3 mol m^{-2}, respectively, over 4 weeks). Energy savings of 34% were reported for the OH-LED SL treatment compared with OH-HPS. Later, Gajc-Wolska et al. (2013) compared several harvest and physiological parameters for greenhouse-grown tomatoes using 100 μmol m^{-2} s^{-1}

of supplemental PPF from OH LEDs (640, 660, and 450 nm) or OH-HPS (400 W) lamps versus no SL and reported that although both SL treatments improved production relative to unsupplemented controls, OH-HPS increased marketable yield and fruit number compared with OH-LEDs. Moreover, they found that most physiological responses were similar between plants grown under OH-LEDs or without SL. Hidaka et al. (2013) compared growth and yield for ‘Fukuoka S6’ strawberry production grown under blue + green LEDs (450 and 550 nm, respectively) versus FL lamps and found that LED SL increased average fruit weight, number of fruits, and marketable yield compared with FL lamps. However, the authors reported that plants grown under LEDs received up to four times the PPF that plants grown under fluorescents lamps received. Therefore, their results were attributed to the higher light intensities that LED SL delivered at plant height (up to 1,200 μmol m^{-2} s^{-1} at plant height) compared with FL SL. Another comparison of OH-HPS lamps versus OH-LED lighting investigated the effects of dynamic lighting control (DLC) on energy consumption and yield of lettuce plants grown in a greenhouse (Pinho et al. 2013). The LED-DLC treatment consisted of warm-white (broad spectrum from 400 to 700 nm) LED lamps that automatically compensated for variations of daylight intensity below a defined threshold PPF at plant canopy level. The authors used an on–off switching algorithm in order to maintain a constant PPF of 150 μmol m^{-2} s^{-1} during the lighting period when the available solar PPF was below that value. As a reference, two additional lighting treatments were used: OH-HPS (400 W) and OH-LED (broad spectrum from 400 to 700 nm) lamps. The latter were controlled using a conventional on–off regime based on outside solar irradiances. The use of LED-DLC reduced energy consumption by 20% and 52% compared with the OH-LED and OH-HPS treatments, respectively. However, plants grown under both LED treatments performed similarly in terms of average fresh mass accumulated per electrical energy unit consumed. Results indicated that further optimization of the DLC regimes is needed in order to reduce energy consumption without affecting plant yield.

4. Current Status and Challenges. As indicated by studies evaluating effects of narrow-spectrum lighting on plant growth and development, as well as testing of LED technologies for greenhouse operations, LEDs seem to be a promising SL technology for greenhouse crop production. Nonetheless, significant opportunities remain to optimize spectral quality effects on plant growth and development. Considerable genetic variability across species (and sometimes cultivars) exists for plant responses to different R:B ratios, as well as to other wavelengths that may alter productivity and yield of greenhouse vegetables. In addition, studies of targeted lighting, changing spectral composition throughout crop life cycles, and photomorphogenic optimization of leaf–light interactions are areas for further inquiry to fully leverage the benefits of LEDs as SL sources.

With ongoing, anticipated energy efficiency improvements, as well as ever-improving light distribution architectures, LEDs could become the dominant future SL technology for greenhouse crop production, eventually replacing OH-HPS and hybrid lighting technologies. Nevertheless, extensive field trials are needed to establish economically viable "best practices" for how to use LED lighting in greenhouse production and in this way help encourage its widespread adoption for horticultural enterprises.

F. The Potential of LEDs to Enhance Produce Quality

With the promise of LEDs for application in commercial horticulture, plant scientists have another powerful set of experimental tools to better understand the role of various components of white light, and possibly to better manipulate plant responses for more desired and healthful outcomes. These metabolic shifts are mediated through a complex suite of photoreceptors that plants have evolved to better cope with changes in their surroundings. As the structure and function of these photoreceptors continue to be elucidated, scientists are better able to leverage plant responses by manipulating the light environment in order to benefit consumers. One of the many areas of interest is using narrow-waveband LEDs to influence the preharvest or postharvest quality of produce.

A growing body of literature supports the conspicuous role that light plays affecting produce quality (e.g., secondary metabolites such as polyphenolics and glucosinolates) for many species, among which are commercially valuable crops such as strawberry, tomato, salad greens, and microgreens.

1. Strawberry. Watson et al. (2002) studied the effect of plant shading on strawberry flavor compounds. In addition to monitoring common mono/disaccharides and citric acid, they also measured the presence of 13 volatile organic compounds that have been correlated with perception of strawberry flavor. Shading significantly altered the ratios of sugars and acids present in fruits as well as several volatile organic compounds (VOCs), generally decreasing the concentrations of these compounds. Whether altered sugar/acid ratios and decreased VOC concentrations had an effect on human perception was not tested in that study. If light recipes to optimize strawberry flavor can be developed, LEDs could be strategically placed above the canopy to enhance strawberry quality by enhancing specific wavebands available to leaves and/or fruits.

In another study, Choi et al. (2013) used sole-source LED lighting (200 μmol m^{-2} s^{-1}) to grow strawberries in growth chambers. In addition to increased yield under mixed red (634 and 661 nm) plus blue (448 nm) LEDs compared with red or blue alone, they found that different combinations of narrow-waveband light elicited a host of quality attribute responses such as increased fructose and anthocyanin content from mixed-wavelength LED treatments, or increased antioxidant levels from blue or red LEDs alone similar to results from Heo et al. (2012). Blue LEDs alone hastened fruit ripening, whereas red or mixed LED wavebands boosted overall production. These findings showcase the potential for growers to capitalize on the narrow-waveband capabilities of LEDs to reduce time to harvest, increase yield, or optimize the flavor and/or healthfulness of their crops.

2. Salad and Microgreens. Stutte et al. (2009) used LEDs to compare plant responses and quality attributes under different wavelengths of light (730, 640, 530, or 440 nm) at 300 μmol m^{-2} s^{-1} with those under blue-biased FL lamps. Different combinations of red and other wavelength LEDs were used as sole-source lighting for 'Outredgeous' lettuce. Under blue LEDs, lettuce exhibited a purple-leafed phenotype consistent with the dogma that blue light enhances the biosynthesis of phenolic compounds through cryptochrome- or phototropin-mediated signaling pathways. These findings are strongly supported by Johkan et al. (2010) and Son and Oh (2013). When Zhang and Folta (2011) exposed *Arabidopsis thaliana* plants to blue, green, or a mix of blue and green sole-source LED lighting after having grown the plants under white FL light for 1 month, they confirmed that blue light increases the accumulation of anthocyanins in leaves. Zhang and Folta (2011) found that the addition of green light negated anthocyanin accumulation, even in the presence of a similar intensity of blue light.

Li and Kubota (2009) performed a similar experiment with baby leaf lettuce, but used FL lamps as the primary light source (300 μmol m^{-2} s^{-1}) and supplemented with UV-A, blue, green, red, or far-red light from LEDs (18, 130, 130, 130, or 160 μmol m^{-2} s^{-1}, respectively). Phenolics increased significantly with supplemental red light, whereas xanthophylls, β-carotene, and chlorophyll were increased by blue and, to a lesser degree, by UV-A. Far-red light was found to decrease anthocyanins, carotenoids, and chlorophyll concentration in leaves. For both the

Li and Kubota (2009) and the Stutte et al. (2009) studies, far-red light significantly increased leaf elongation, dry mass, and the amount of leaf area available for photosynthesis compared with red light alone.

Lefsrud et al. (2008) used sole-source LED lighting (1.4 $\mu mol\, m^{-2}\, s^{-1}$ at 730 nm, 226 $\mu mol\, m^{-2}\, s^{-1}$ at 640 nm, 5.7 $\mu mol\, m^{-2}\, s^{-1}$ at 525 nm, 10 $\mu mol\, m^{-2}\, s^{-1}$ at 440 nm, or 2.9 $\mu mol\, m^{-2}\, s^{-1}$ at 400 nm) after starting plants under a combination of INC and FL lamps at 275 $\mu mol\, m^{-2}\, s^{-1}$ to modify levels of sinigrin, a cancer-preventing glucosinolate, as well as lutein, β-carotene, and chlorophyll a/b in kale (*Brassica oleracea*). Sinigrin and lutein were reported highest under red LEDs, whereas β-carotene accumulation was highest under blue LEDs.

Kopsell and Sams (2013) cultivated broccoli microgreens under a mix of red (627 nm) plus blue (470 nm) LEDs with a PPF of 350 $\mu mol\, m^{-2}\, s^{-1}$. The plants were then transferred to a blue-only growing environment (41 $\mu mol\, m^{-2}\, s^{-1}$) or remained in the original red/blue environment. Microgreens transferred to the blue-only environment had significantly higher levels of β-carotene, glucosinolates, and a host of micronutrients essential for human metabolic activity.

Chinese cabbage was grown under 150 $\mu mol\, m^{-2}\, s^{-1}$ of light produced by either red, blue, green, yellow, or red plus blue (6:1) LEDs and compared with responses to dysprosium lamps by Fan et al. (2013b). They found that the combination of red and blue LEDs not only increased fresh and dry mass, but also enhanced the concentration of soluble proteins and photosynthetic pigments. These findings further strengthen the idea that light recipes could be developed to enhance the quality attributes of produce while enhancing yield.

A study by Samuoliene et al. (2012c,d) involved microgreens of amaranth (*Amaranthus cruentus* 'Red Army'), 'Sweet Genovese' basil, 'Red Russian' kale, broccoli, 'Red Lion' mustard, orach (*Atriplex hortensis*), borage (*Borago officinalis*), beet (*Beta vulgaris* 'Bulls Blood'), parsley (*Petroselinum crispum*), and pea (*Pisum sativum*, 'Meteor') with HPS SL (300 $\mu mol\, m^{-2}\, s^{-1}$ for 16 h day^{-1}) in a greenhouse. Adding light from red LEDs (638 nm, 170 $\mu mol\, m^{-2}\, s^{-1}$) near the finishing stage of the microgreens enhanced phenolic concentrations in all species, except amaranth. As for anthocyanins and ascorbic acid, responses varied depending on the species tested. Such responses illustrate the metabolic variation present in species that evolved in different environments and the need to optimize lighting regimes on a species-by-species basis. Samuoliene et al. (2013a) also found that a PPF between 340 and 440 $\mu mol\, m^{-2}\, s^{-1}$ from LED arrays (455, 638, 665, and 731 nm) provided an acceptable balance between plant growth and nutritional quality.

Tarakanov et al. (2012) cultivated Indian mustard, lettuce, basil, coleus (*Plectranthus scutellarioides*), and marigold in growth chambers outfitted with LEDs (460, 635, and 660 nm) at a total PPF of 170 µmol $m^{-2} s^{-1}$ using different combinations of LED wavelengths (e.g., 25% 460 nm + 25% 635 nm + 50% 660 nm). Plants grown under these conditions were compared with greenhouse-grown plants supplemented with 170 µmol $m^{-2} s^{-1}$ for 16 h day^{-1} using HPS lamps. The effects of different lighting regimes varied substantially for chlorophyll a/b, carotenoids, and anthocyanin content, echoing the need to develop lighting protocols on a species-specific basis to attain desired attributes. Perhaps more consequential was the large variation in growth parameters observed between light treatments, making it apparent that a balance between yield and phytochemical composition must be maintained.

Mizuno et al. (2011) grew two cultivars of cabbage seedlings ('Kinshun' and 'Red Rookie') under FL lamps (150 µmol $m^{-2} s^{-1}$) until two true leaves unfolded. At that stage, plants were placed under LEDs of either 470, 500, 525, or 660 nm in addition to 50 µmol $m^{-2} s^{-1}$ of PAR from a FL light source. The two cabbage cultivars reacted differently to the lighting treatments. 'Red Rookie', a red-leafed cabbage variety, showed increased anthocyanin content under the red (660 nm) treatment. 'Kinshun', a green-leafed variety, developed similar anthocyanin levels under all light treatments, but had increased chlorophyll content in the blue (470 nm) and blue-green (500 nm) treatments.

Samuoliene et al. (2013b) conducted three studies using romaine lettuce 'Thumper' that further capitalized on narrow-waveband LED light. The first study was conducted in growth chambers providing lettuce plants with a blend of 638, 445, 660, and 735 nm light from LEDs. Groups of plants were then supplemented with UV-A (380 nm), green (510 nm), yellow (595 nm), or orange (622 nm) light at a PPF of 175 µmol $m^{-2} s^{-1}$. Phenolic compounds were increased by supplementation with UV-A or orange light, whereas UV-A light increased α-carotene, and green light enhanced both anthocyanins and α-carotene. It should be noted that control plants (those receiving only 638, 445, 660, and 735 nm light from LEDs) had the highest levels of tocopherol and ascorbic acid. The second study was conducted in a greenhouse using HPS lamps (90 µmol $m^{-2} s^{-1}$ for 16 h day^{-1}) as a primary source of SL with the addition of either blue (455 or 470 nm) or green (505 or 530 nm) LEDs at 30 µmol $m^{-2} s^{-1}$. That lighting strategy was not effective due to the fact that, while certain metabolites may have increased, it did not necessarily counterbalance the decrease in others. The last study also took place in a greenhouse setting using 90 µmol $m^{-2} s^{-1}$ for 16 h day^{-1} of SL derived from HPS lamps. Three days prior to harvest, plants were provided with 210 μmol m^{-2} s^{-1} of sole-source 638 nm light from LEDs. This treatment did not significantly modify phytochemical profiles with the exception of increasing tocopherol content. Zukauskas et al. (2011) performed a similar experiment by growing three lettuce cultivars ('Lolo Bianda', 'Grand Rapids', and 'Lolo Rosa') in a greenhouse with 130 μmol m^{-2} s^{-1} for 12 h day^{-1} of SL from HPS lamps. Three days before harvest, LED arrays provided 170 μmol m^{-2} s^{-1} of red (638 nm) light to the plants. The cultivars 'Grand Rapids' and 'Lolo Bianda' exhibited large increases in α-carotene and phenolic compounds under the red LED treatment. Both of these cultivars are green-leaf-type lettuce that naturally have lower antioxidant properties compared with red-leaf-type lettuce (e.g., 'Lolo Rosa').

Mattson and Harwood (2012) grew arugula (*Eruca sativa* 'Astro') aeroponically and utilized LEDs for sole-source lighting (460 and 620 nm at a ratio of 8:92). Treatment 1 illuminated plants with continuous 150 μmol m^{-2} s^{-1} from days 3 to 18 (end of cropping cycle). Treatment 2 began with 225 μmol m^{-2} s^{-1} and decreased to 75 μmol m^{-2} s^{-1} by day 18. Treatment 3 increased from 75 to 275 μmol m^{-2} s^{-1}. Treatment 4 increased from 75 to 325 μmol m^{-2} s^{-1}. These treatments were compared with a control group that used HPS lamps emitting a continuous 113 μmol m^{-2} s^{-1}. It was found that only treatment 1 had a flavonoid content higher than control, likely induced by the higher amount of light that the LED treatment plants received during the cropping cycle.

Lin et al. (2013) grew lettuce in growth chambers under a combination of red (660 nm) and blue (454 nm) LEDs, red, blue, and white (RBW) LEDs, or FL lamps (control), all at 210 μmol m^{-2} s^{-1}. They found soluble sugar to be significantly higher in plants grown under RBW, whereas nitrate content was significantly lower, which parallels results of Zhou et al. (2013). Chlorophylls, soluble proteins, and carotenoids remained statistically similar in all three light treatments. In regard to chlorophyll and carotenoids, these results differ from Chen et al. (2014), who found the highest chlorophyll and carotenoid contents in 'Green Oak Leaf' lettuce grown under a combination of FL lights + red LEDs or FL lights + blue LEDs. In the Chen et al. (2014) study, however, the plants were grown with 133 μmol m^{-2} s^{-1} as opposed to 210 μmol m^{-2} s^{-1} in the Lin et al. (2013) study, further illustrating the complex interaction between spectral quality, light intensity, and cultivar.

Samuoliene et al. (2012d) grew baby leaf lettuce 'Multired 4', 'Multigreen 3', and 'Multiblond 2' in a greenhouse with HPS lights providing 170 μmol m^{-2} s^{-1} of SL (16 h day^{-1}). In addition, groups of plants were supplemented with blue (455/470 nm) or red (605/635 nm) LEDs. The results of that study were complex due to possible interactions among varieties, light quality, and time of year. However, the authors stated that trends for vitamin C and tocopherols were as follows: 535 > 505 > 455 > 470 nm; phenolics: 505 > 535 = 470 > 455 nm; 2,2-diphenyl-1-picryl-hydrazyl (DPPH) free-radical scavenging capacity: 535 = 470 > 505 > 455 nm; and anthocyanins: 505 > 455 > 470 > 535 nm. This study is consistent with the findings of Samuoliene et al. (2012b).

Park et al. (2012) grew 'Seonhong Jeokchukmyeon' lettuce in growth chambers with 140 $\mu mol\ m^{-2}\ s^{-1}$ of light sourced from FL lamps, white LEDs, or an 8:1:1 mixture of RBW LEDs (wavelengths for each color not specified). In addition, CO_2 levels inside the chambers were 350, 700, or 1,000 $\mu mol\ mol^{-1}$, allowing comparison of plant responses to CO_2 conditions as well as light. They found that the highest growth was achieved with the RBW array at 1,000 $\mu mol\ mol^{-1}$ CO_2, but the highest anthocyanin content came from plants grown under the FL fixtures at 1,000 $\mu mol\ mol^{-1}$ CO_2, indicating the need for optimizing conditions for the highest possible growth and nutraceutical content.

Perilla frutescens was cultivated by Park et al. (2013) under cool-white FL lamps, white LEDs, or a mixture of RBW LEDs with an 8:1:1 ratio at 140 $\mu mol\ m^{-2}\ s^{-1}$. In addition, several temperature treatments including +8, +4, and 0°C DIF were used. Plants grown under the LED arrays with a +8°C DIF had the highest accumulation of anthocyanins. However, this trend was not continued in the +4°C DIF. The results of this study indicate a complex interplay between light quality and growing environment temperature.

3. Tomato. Gautier et al. (2005) made innovative use of transparent plastics, allowing only specific wavelengths of light to be incident on fruit clusters. Measurements of fruit quality such as titratable acidity were affected very little by different wavelengths of light. Lycopene and β-carotene increased with exposure to blue light, implicating the involvement of cryptochrome and/or phototropin, whereas vitamin C and sugar content increased with infrared light exposure, possibly due to a slight increase in temperature. Thomas and Jen (1975) found that red light stimulated carotenoid levels in ripening tomatoes compared with dark controls. Moreover, tomatoes exposed to a brief amount of far-red light had a decrease in overall carotenoid level compared with dark-control fruits. That study implied that the active state of phytochrome is involved with carotenoid accumulation, and that interpretation is supported by the findings of Alba et al. (2000) and Toledo-Ortiz et al. (2010).

Kowalcyzk et al. (2012) compared physicochemical and sensory attributes of tomato F_1 hybrids 'Komeet' and 'Starbuck' grown with

HPS or LED supplementation in greenhouses to control plants (no SL) during the autumn–winter transition in northern Europe. Both HPS and LED SL provided 100 μmol m^{-2} s^{-1} when solar radiation was less than 175 μmol m^{-2} s^{-1}; lamps were turned off when solar radiation was above 225 μmol m^{-2} s^{-1}. They found that 'Komeet' fruits produced under HPS and LED fixtures had 39% and 18% increase in total sugars, respectively. Fruits from plants that received SL had lower levels of nitrates, but phosphorous levels were not statistically different among the three treatments. A 20-person sensory panel revealed differences in the quality of fruits, namely, that fruits from supplemented plants were juicier, sweeter, and had an overall better quality. However, the methods used in that study represent just one way to utilize LEDs for high-wire tomato production (e.g., LEDs were used to irradiate the upper portion of the plant canopy as opposed to Gómez et al. (2013), who irradiated the entire canopy). Further testing is needed on fruit quality of tomatoes grown with HPS and LED supplemental lights that are utilized in commercial production settings.

Pek et al. (2011) related fruit surface temperature to solar exposure of tomato fruits. This group found an association between higher fruit surface temperatures and reduced lycopene content, which concurs with findings of Dumas et al. (2003). Due to the lower operating temperature of LED light-emitting surfaces, appropriate levels of fruit irradiation may be possible without the negative consequences of higher fruit surface temperatures.

4. Postharvest. Aside from using LEDs to grow and modify plants, there is burgeoning interest in modifying produce during postharvest shipment and/or storage with select wavelengths of light. Among the different irradiances of UV-B (280–320 nm) that were compared, Liu et al. (2011b) demonstrated increased antioxidant capacity, phenolics, and flavonoid contents in tomato fruits using 20 or 40 kJ m^{-2} of UV-B radiation during postharvest storage. Castagna et al. (2013) increased both ascorbic acid (vitamin C) and carotenoids in tomatoes by irradiating fruits with UV-B for 1 h day^{-1}. In another study, Liu et al. (2009) increased lycopene content in tomato fruits with short exposures to UV-C (100–280 nm) or red light. It should be noted that the above experiments used UV-emitting fixtures that are space consuming and had a wide, less specific waveband compared with LEDs. There is a need to develop more efficient and economically affordable UV LEDs in order to pass potential benefits of UV irradiation of produce on to consumers. Ultraviolet LEDs could be installed in postharvest storage rooms or even in home refrigerators and could positively benefit consumers. Naturally, any UV-emitting source for the purpose of enhancing produce quality would have to be utilized in a manner that is safe for humans.

Colquhoun et al. (2013) used LEDs (455, 668, and 755 nm at 50 $\mu mol\,m^{-2}\,s^{-1}$) to effectively modulate the concentration of volatile compounds in 'Mitchell Diploid' petunias, 'Strawberry Festival' strawberries, blueberries (*Vaccinium corymbosum* 'Scintilla'), and 'M82' tomatoes. Concentration of VOCs varied depending on species and the wavelength of light used, implicating complex biochemical regulation. From a postharvest perspective, storage conditions could be supplemented by specific wavelengths of radiation to enhance and/or extend produce quality, thereby improving consumer acceptance of high-value horticultural products.

5. Summary. Potential for use of LEDs in horticulture, with the specific application of enhancing or maintaining fruit and produce quality, is supported by a steadily growing stream of research literature. For a compilation of the role of light quality on the growth and development as well as quality attributes of horticultural and agronomic crops, see Carvalho and Folta (2014). The role of light is known both anecdotally and experimentally to play a key role in produce quality. With LEDs, scientists are better equipped to isolate the effects of specific wavelengths of light on quality responses. In many ways, this is helping to form bridges between the applied and basic scientific communities—fostering multidisciplinary collaboration. As LED technology continues to improve, consumers will benefit from ongoing advances being made in photobiology with respect to specialty crop quality attributes.

VII. LED LIGHTING AND PLANT HEALTH

A. Physiological Disorders

Plants can be susceptible to physiological disorders related to their light environment. The most common of these disorders are those related to abnormal photoperiod effects, high irradiance damage, and undesirable responses related to spectral quality (Morrow and Wheeler 1997). LEDs can cause light-related disorders just as traditional lamps can. However, the basic attributes of LED lighting (narrow waveband, high light output, and low radiant heat generation) are different enough from those of HID lighting that they may exacerbate known light-related problems or result in previously unobserved or rare responses. One physiological plant disorder linked to light quality is known as intumescence injury (sometimes referred to as edema), which can occur on a wide variety of plant species grown in protected growing environments (Lang and Tibbitts 1983; Morrow and Tibbitts 1988), adversely impacting growth and productivity, sometimes to the point of plant death. The lack of UV light appears to trigger this response, causing abnormal development when UV light is absent from the light spectrum through absorption by greenhouse glazing materials or lamp barrier materials. Lamp barriers are generally used with FL and HID lamps to separate lamp heat from the growing volume and to absorb long-wave radiation that can heat plants. This disorder also responds to the red-to-far-red light balance, being promoted by red light and inhibited by far-red light. Thus, a standard LED plant lighting system that has no UV wavebands and a high percentage of red light may create a lighting environment conducive to the development of intumescence injury in susceptible plant varieties. This disorder has been observed in some LED-related research already, examples of which are presented by Massa et al. (2008). As the technology of UV LEDs (with a maximum wavelength of approximately 350 nm) improves and becomes more cost effective, they can be integrated into lighting systems used for growing plant varieties that are prone to intumescence injury (a particular problem for solanaceous species). The capability of LEDs to provide high light intensities has also led to instances of tissue damage when operated in close proximity to plants, resulting in photobleached spots corresponding to individual LEDs in the array or the leaf tissue forming a concave shape in interveinal spaces on the side of the leaf facing the LEDs (Morrow 2008). The cause of this response may be due to uneven growth of leaves due to isolated highlight areas on the leaf surface. As LED-based horticultural lighting is implemented on a larger scale, it is likely that other undesirable light-related plant responses will be identified, and this will undoubtedly lead to further refinement and modification of LED lighting system configurations and controls.

B. Insect Pests

Altering light environments in which plants are produced may be able to reduce insect predation through interference with insect visual perception systems. Small-scale choice tests with green peach aphids (*Myzus persicae*), western flower thrips (*Frankliniella occidentalis*), and whiteflies (*Bemisia tabaci*) established that, when given a choice, green peach aphids and whiteflies prefer targets (colored paper, leaves, or whole plants) illuminated by a mixture of green and yellow light over targets illuminated by a mixture of red and blue light. Western flower thrips had an opposite response. Larger scale tests suggest that a strategy of red/blue light for crop plants used in conjunction with plants maintained under green/yellow light acting as trap plants may be an effective tool in integrated pest management systems (R.C. Morrow, pers. commun.). Plant growth is not adversely impacted by the use of a mixture of red and blue light as observed during plant testing under LED lighting by many researchers.

VIII. LEDs AND LIGHT POLLUTION

To achieve light levels sufficient in magnitude to sustain acceptable rates of productivity regardless of climate or season, or to provide lighting in a sufficiently consistent manner to regulate crop development (e.g., timing of flowering for ornamentals), it is necessary to use SL in the form of electric lamps. Currently, the primary sources of greenhouse SL are HID lamps, primarily HPS or MH lamps (or a combination of the two). Both types of lighting produce high heat loads (typically less than 30% of the supplied electricity is converted to useful light; the rest is converted to heat), and the lamps need to be placed a minimum distance above the crop canopy to prevent heat damage to the plants. Due to inadequate reflector designs and reflections off of interior greenhouse structures and the plant canopy, a significant amount of light can be redirected to the outside environment. This so-called light pollution from greenhouses using SL disrupts enjoyment of the night sky, and has been implicated in behavioral and migratory dysfunction in insects, birds, mammals, zooplankton, and in human health due to the impact on sleeping patterns (Schmidt 2004). It also represents a waste of electrical and light energy intended to support plant growth and development. Several western European countries with high population densities and extensive greenhouse production areas are at the forefront of this issue that is most pronounced during nighttime periods with overcast skies. In some cases, regulations have been enacted that require greenhouses to be outfitted with opaque screens that minimize or eliminate the escape of light to the outside environment. Nevertheless, the SL that escapes from Dutch greenhouses has been compared with the light emissions from a city of 500,000 people (Narisada and Schreuder 2004). Solid-state lighting technology (e.g., LEDs) has several characteristics that may significantly reduce light pollution while providing SL to greenhouse crops in an energy-efficient manner.

A. Control of Spectral Output

Light spectra can be customized for specific crops and production protocols by using LEDs with output in the desired waveband (primarily red and some blue). Use of specific wavelengths minimizes the total light needed for optimal plant growth, thereby reducing the amount of light that scatters to the outside of the greenhouse. Red light is harder to perceive by humans and may not have as large a visual impact on the night sky.

B. High Light Intensity

Light-emitting diodes can provide high light levels if desired, and can be operated adjacent to plant tissue since they produce very little radiant heat. The lights can be lowered to within inches of the plant canopy or be placed within and between rows, further minimizing the amount of light scatter.

C. High-Resolution Control

With an advanced control system, LEDs can provide high-resolution zonal control to ensure that only areas containing plants are illuminated.

IX. LED LIGHT DISTRIBUTION ISSUES

As for other electric lighting systems, the distribution of LED-generated light will impact intensity and uniformity at the plant canopy level. Uniformity of lighting is preferred for most applications, and high intensities are often needed for assimilation lighting in SL applications (Li and Kubota 2009; Olle and Virsile 2013). Due to the inverse square law (i.e., light intensity decreases by the square of incremental distance between a point source and the receiving surface), it is preferable to position the light source closer to the receiving surface in order to reach a high intensity at the target surface and also to increase the light utilization efficiency (the ratio of number of photons reaching the target surface to the number of photons emitted). However, placing light sources in close proximity to the plant canopy can cause challenges. For example, the light source creates shadow patterns that block sunlight from reaching the plant canopy inside the greenhouse, and heat radiated from the light sources can cause plant stress. In addition, plant canopies are three-dimensional structures that change their shape (e.g., position and size of individual leaves) and orientation (e.g., as a result of water stress or the direction of incoming light) over time as plants grow and develop. As a result, delivering light with high uniformity, high intensity, and high utilization efficiency is particularly challenging for horticultural applications.

The use of LEDs provides more opportunities for novel configurations and placement of light sources in controlled-environment plant production facilities than do traditional light sources. While in the past light sources were typically installed in a horizontal plane and mounted some distance above the canopy, LED lamps can be installed in multiple locations, including within the plant canopy, and the generated heat energy can be mostly dissipated by convection, not radiation (Dueck et al. 2012; Mitchell 2012). In that case, light sensors installed at the top of the plant canopy (ICCEG 2004) are no longer appropriate, and other means are needed to characterize the light environment. In fact, canopy light environments may have to be evaluated as so-called light fields to capture their three-dimensional features (or four-dimensional features when changes in time are considered). Such multidimensional representations may require novel evaluation methods.

Computational approaches (e.g., de Visser et al. 2012, 2014) can be used to determine the light environment in plant production facilities, but they require a mathematical representation of the plant canopy, detailed knowledge of lamp and solar radiation characteristics, and sufficient computing power to evaluate light distribution and uniformity. Ibaraki et al. (2012) used digital images to evaluate the light environment in greenhouses. Conversely, lighting design strategies (e.g., genetic algorithms used by Ferentinos and Albright (2005) and Delepoulle et al. (2009) or commercial lighting design software programs such as those used by Both et al. (2002)) can be used to determine the type, number, and placement of light sources before such designs are implemented in plant production facilities. But so far, few of these design strategies included three-dimensional light distribution characteristics (they typically only perform planar calculations).

For plant growth facilities with (often overhead) electric lamps for sole-source lighting, additional light distribution issues need to be considered, including the reflectance of wall, floor, or shelf surfaces as well as geometry of the growing space (especially the distance between the lamps and the plant canopy; Ohyama and Kozai 1998). The use of highly reflective surface materials can increase the amount of light received at the target surface and thus improve the light utilization efficiency. Plant canopies typically reflect little PAR (Jones (2014) reports a reflectance of approximately 0.05), further impacting the light distribution in plant growth facilities with sole-source lighting. Poulet et al. (2014) compared a novel targeted LED lighting system with a conventional total coverage LED system for lettuce growth. The targeted LED system minimized the amount of photons wasted on the empty spaces between young seedlings. However, they found that lettuce plants grown under the total coverage red plus blue LED lighting system accumulated more biomass than under the targeted red plus blue LED system, presumably due to the increased light utilization by the plants as a result of increased light reflections within the growing volume. Therefore, while targeted lighting systems can reduce the overall energy consumption (and thus increase the energy conversion efficiency), more research is needed to determine the resulting light environment and compare the light utilization efficiency with that of conventional (total coverage) lighting systems and incorporate issues such as surface reflectance and plant spacing.

X. LED ENVIRONMENTAL AND HEALTH ISSUES

A. Disposal

Light-emitting diode disposal is less complex than the disposal of HID lamps that contain sodium, metal halides, and mercury. Disposal of LEDs is similar to disposal or recycling of other electronic circuit boards. Most LEDs and other lighting board components fabricated using standard processes are RoHS (Reduction of Hazardous Substances) compliant (RoHS 2003), which restricts the use of six hazardous materials: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBBs), and polybrominated diphenyl ether (PBDE). End-of-life disposal of LEDs is summarized in a Department of Energy (DOE) fact sheet (DOE 2013b) that provides a list of more detailed references.

B. Optical Safety for LEDs

Based on international standards as of 2013, light sources that emit white light and are used for general lighting applications (including LEDs) are not considered hazardous to the retina of healthy adults. However, horticultural applications often use much higher light levels than general-use lighting. The primary photobiological hazard felt to be applicable to LEDs is the blue light hazard (CREE 2013a), a spectral region critical to many horticultural applications. The DOE provides fact sheets that summarize current standards for photobiological safety

(DOE 2013c). Consensus at this point is that LEDs pose the same vision hazards as other lamps, and the same precautions should be used as for any intense lighting source, such as not looking at the light source directly and wearing eye protection (e.g., light filtering or blocking eyewear). Such risks can also be minimized in luminaire design by using engineering controls (e.g., light-blocking screens or filters). However, the optical safety of LEDs in a horticultural setting must be considered on a case-by-case basis. Some situations may require particular attention, including infants in close proximity (infants do not have aversion reflexes), persons suffering from lupus or eye disease, applications where very high light levels are being used, and when UV (<400 nm) LEDs are in use.

XI. ADOPTION OF LED TECHNOLOGY BY HORTICULTURAL INDUSTRIES

When it comes to predicting technology diffusion rate, a few independent factors appear to be significant. One commonly accepted framework involves use of five theorized factors (Rogers 2003). These include perceived benefit, perceived risk, fit with current practice, complexity in use, and trialability. The most compelling of these factors may be perceived benefit. The savings in energy by LEDs is fairly compelling as growers attempt to control input factor costs. However, the benefit of energy savings comes at higher upfront cost, enhancing economic risk. Risk is mitigated by evidence-based research and accumulated industry experience. Effectively, it is difficult to displace years of proven practice. This challenge is compounded when we add economic risk to a change in current practice such as intracanopy versus overhead lighting, for example.

These factors of adoption are supported by research in the agricultural sector where distinction is made between embodied technologies, such as hybrid corn, which show rapid adoption where there is little need for change of practice, equipment modification, or learning versus technologies that may be coupled with other practices or integration of information (Tenkorang and Lowenberg-DeBoer 2008). A parallel for aiding our understanding may be to look at the adoption of precision agriculture practices such as remote sensing, grid soil sampling, and yield monitoring. Evidence suggests that characteristics such as farm size correlates positively with adoption due to ability to bear risk (Roberts et al. 2004; Walton et al. 2010). However, when looking at combinations of technologies, evidence also suggests that the planning horizon of the decision maker depends on the person's age and whether they are owners versus leasers of land, the analog being owner versus employee. Additional factors include the use of consultants and availability of credible evidence (Watcharaanantapong et al. 2014).

A. Economics

Claims of energy savings come at a significant upfront cost as LED fixtures currently represent a large multiple compared with HID fixtures. Not all applications and growing situations are equivalent in terms of suitability for conversion to LEDs at current efficiency levels and price. Financial modeling suggests that economic justification favors high energy prices and high use. Economic benefit is idiosyncratic to design, asset prices, input factors, and operational parameters.

Nelson and Bugbee (2014) studied the economics and the relationship to light pattern and use in design. Many HID fixtures are designed to spread light over a large area. However, LEDs in current design or through the use of optics can focus light where it is most useful. In their analysis, if photons coming out of the fixture are considered at all angles from 180° downward), the capital cost of the most efficient 400 W LED fixtures tested in their analysis was five to seven times more per photon than for 1,000 W, double-ended, electronic ballast HPS fixtures. The high capital cost of LEDs makes the 5-year cost per mole of photons more than twice that of double-ended HPS fixtures. This is because LED and double-ended HPS have nearly the same photon efficiencies of 1.66–1.70 μmol J^{-1}, yet LED fixtures currently cost much more. In contrast, they also measured the efficiency of HPS with a standard mogul base to be only 1.02 μmol J^{-1}.

Importantly, when highly focused radiation is considered useful, such as from an LED array focused on a bench between aisles (±34° off axis mounted 2 m above canopy), some LED fixtures have a lower cost per photon than the best HPS fixtures. This is because the photons are focused on plant leaves versus also lighting aisles in that scenario.

Such findings point to two critical aspects of LEDs in horticulture. First, that there can be problems of measurement equivalence between lighting systems. LEDs, by nature, tend to have a significant decline in light intensity off-axis. HPS, in contrast, typically is equipped with luminaires that spread a high-power light beam in ways that achieve greater lighting uniformity across an absorbing surface. If a user specifies a given irradiance below lamps mounted above a bench surface, for an HPS versus an LED system mounted well above the bench top, widely spaced, lower power LED arrays will have less uniformity of irradiance across the bench surface (i.e., high photon density in the center, with lower densities near the perimeter).

Second, language has been cropping up about "*x*-factors" for users of LEDs where more biomass is produced. The science suggests that this differential is nothing more than LEDs putting the right wavelengths of light where it is most beneficial. That is, the center axis of an LED light beam generates high PPF even though the average light beam coverage per unit area is significantly lower. In their empirical test, Nelson and Bugbee (2014) reported one LED fixture to have a PPF of 1,400 μmol $m^{-2}\,s^{-1}$ on axis and a PPF of only 400 μmol $m^{-2}\,s^{-1}$ 34° off axis when hung 2 m above the measurement plane.

Singh et al. (2014), assuming energy costs of \$0.10 kWh^{-1} and a daily 14 h photoperiod, demonstrated that, by year 7, cumulative costs of HPS would exceed LED costs. It should be noted that findings such as these are subject to a wide range of assumptions that need to be considered for normative implications. This method of calculation is more commonly known as "payback period," which is the period of time needed to recoup the investment (or when saving equal differences in initial capital outlay).

This leads to embracing appropriate methodology for financial analysis. For decades, financial textbooks have lamented the shortcomings of using payback period. In fact, payback periods ignore the time value of money, capital costs, adjustments for project risk, and cash flows beyond the cutoff period. More appropriate methods to evaluate projects with long-term impact are discounted cash flow models, namely, net present value (NPV) or internal rate of return (IRR). These methods take into account total cash flows for the life of the project and discount them to present-day value. The use of these methods easily incorporates items that may vary by firm such as cost of capital (interest rate) or have a large impact on operating cash flows such as depreciation. This is especially important where cash flows extend for long periods of time. Some LED systems are rated at 90% output for 25,000 h and warranted for much longer. Firm-specific use of lighting can dramatically affect the timing of benefits that, in combination with cost of capital, will affect the time-adjusted value of the benefits. In addition, depreciation cash flows for these systems in the United States are currently 7 years and significantly longer in many other countries, and may be linear or nonlinear. Thus, while payback period is mentioned by many companies and used for simplicity, it does not incorporate the idiosyncratic differences between firms, uses, or regions.

Weston and Brigham (1981) argued that payback period is a rational approach for severely capital-constrained firms. For example, if a project does not pay back quickly, cash-constrained firms could reach financial distress. In a broad survey of 392 chief financial officers, Graham and Harvey (2001) reported that, while the use of payback period is still popular behind the use of NPV and IRR, they conclude it is due to lack of sophistication. They found its use more prevalent by older, longer tenured chief executive officers without MBAs and in private firms lacking the auditing rigor of public firms. They also found no evidence that the use of payback period correlates with leverage, credit ratings, or dividend policy.

Economies of scale or economies of learning in LED fixture manufacturing may bring down prices and make LEDs a more viable economic alternative regardless of greenhouse configuration. However, economies of scale and learning depend on technologies and processes being new; in this case, a new application of existing technology. To the extent that these components have already been standardized, asset-specific investments in production have already been made, and volume production has already been achieved. Expectations of future economies of scale may not materialize, since economies of scale have diminishing returns. We then look to the amount of value added, unique parts, or production processes that are unique to these applications. Such things will be subject to volume-based economies of scale or production-based economies of learning.

B. Evolution of Design and Industry

When new technologies appear, there typically are early adopters willing to experiment or willing to use a product that is not well refined or that has technological uncertainty. Because such users generally are seen as unique, the input they provide about products often is discounted by the broader consumer base. These early majority adopters are often seeking more evidence or iterations of the product that will be more relevant to their own use and experience. This transition from early adopters to early majority is known as "crossing the chasm" (Moore 2006). Products either fail despite having early success or adapt to fit the needs of a larger audience after achieving some initial success and market feedback. There is no reason that LED light fixtures would be immune to the same market phenomena, especially with added technological uncertainty. While there are some commercial installations of LEDs, use has not deeply penetrated the mainstream consumer base at the time of this writing.

To date, it would appear from web sites, trade shows, and trade publications of many LED suppliers that that the discussion is around substitution of HID light fixtures with LEDs in order to save energy. While this is compelling due the cost of energy, the main issue is that LEDs and HIDs are imperfect substitutes for each other. In addition to PAR, HID systems provide radiant heat to leaves, more uniform light distribution over larger areas, and at relatively low capital cost. LED systems can provide focused, point source light, can be placed close to crops due to low radiant heat emissions, can be used in multitiered growing systems, and allow for a tailored color spectrum. While each of these traits can be a strength, it can also be a weakness. For example, even if higher DLI increases desired biomass, increasing DLI with HIDs may not be desirable due to excess heat load. If lighting a large greenhouse propagation area, SL from LEDs may be a challenge where uniformity of supplemental lighting is required, or a high density of LED arrays to achieve that uniformity may block more solar than they provide supplemental. What we are observing in the industry is an evolving structure where the natural properties of each technology are different; thus, the challenge is to find the right natural application. This is no different than something like the discovery of nylon. Nylon was thought to be a miracle fiber and a replacement for silk. However, only over time can we look back and see that both of these materials have equilibrium of use in concert with all other natural and man-made fibers available. Silk was not replaced, but is used selectively when the natural benefits of the material have highest value.

Traditional designs for greenhouse facilities that accommodate supplemental lighting have been relatively general purpose and flexible. These greenhouse assets consist of a modular frame for glass and HID lights that can be reconfigured depending on need. Naturally, decisions are made with respect to the crop type grown and the level of supplemental lighting necessary (e.g., wattage for target DLI or row/bench spacing). This reflects the dynamic nature of the industry where different products are grown depending on market-driven requirements. It also reflects the flexibility necessary for many growers. A flexible facility allows growers to configure greenhouses depending on what products have sufficient demand at the time and where they feel they can best compete. This type of facility is not locked into raised beds or aisle width. In fact, the modular nature of most greenhouse designs demonstrates that, over time, the lighting needs of growers will change.

Flexibility comes at a cost, but for many the benefit of preserving flexibility outweighs the benefit of specialization. LEDs allow users to focus light where it is most beneficial, to place them closer to the plant, and to deliver photons without significant heat. As such, the design of a facility with LEDs may be more specific to how the facility is going to be used. One simple example is width between aisles. If the argument to be made for LED lighting is that photons are not wasted in the aisles and are therefore more economically efficient, then growers need to assess the cost of these photons versus the cost of giving up some flexibility. If they design around a specific aisle width and focused LEDs, the lighting may need to change if they change what is grown or reconfigure the space. This is not to say that LEDs are inflexible. It is a matter of degrees in terms of relative flexibility and asset specialization.

Rather than thinking of LEDs as substitutes for HIDs, perhaps they are complements. Some growers may be constrained with space in a controlled environment. The natural properties of LEDs may be conducive to growth applications in a closely stacked, multitiered geometry, something that is not practical for HID systems. Growers of high-DLI crops may be able to take advantage of intracanopy use of LEDs in combination with traditional lighting if heat load limits HID use. Over time, we should see standards of practice emerge as growers learn the natural benefits of each technology and as technology changes.

Consideration needs to be given to the real source of a firm's competitive advantage. Competitive advantage lies in a company's resources and capabilities (Wernerfelt 1984). Assets that are publicly available and readily transferable are generally not sources of sustainable competitive advantage. Lighting in a more efficient form, if available to competition with similar operations, will not lead to a firm's sustainable competitive advantage. However, if the competition is not in kind, such as field-grown tomato shipped long distance versus greenhouse grown with supplemental lighting, changing the cost structure of the greenhouse-grown tomato can result in increased market share or profitability.

What may be a more sustainable advantage is what the firm does with that asset and what new capabilities the firm can develop. Unique combinations or deployment of resources may also lead to competitive advantage. Firms may find that yield can be significantly improved with intracanopy LEDs and CO_2 enrichment. Plant morphology may be affected by different spectra of light with potential for a more attractive or robust plant. Repellance of pests from the plant may also be affected by the wavelength of SL under different spectra. To the extent that such innovations in lighting can be proprietary, they can lead to competitive advantage. If not proprietary, then the advantage may be temporary, but still sufficient to justify investment. Just like explosion of the Internet did not change the nature of business but acted as a facilitator in some areas, it is likely that commercial horticulture still is in the process of finding appropriate uses for LED technology.

XII. THE FUTURE OF PLANT APPLICATIONS FOR LEDs

A. Improvements in Technology

Future improvements in LED lighting will include new LED "chemistries," resulting in availability of new wavebands, more electrically efficient devices, higher output devices of horticultural interest (UV, far-red, etc.), along with development of new hybrid devices, much like the use of phosphors in combination with LEDs, and improvements in LED mounting and packaging that improves output and functionality.

Future improvements will also certainly occur in the area of optics, with the development of more efficient chip mounting and improved optics such as reflectors, collimators, and lenses that provide better light mixing and distribution. The importance of effective heat removal from LEDs will continue to drive improvements in the area of more thermally efficient, lower volume, and lower mass heat sinks, along with improved cooling techniques.

One of the largest LED system cost drivers currently is fabrication costs. As physical configurations become optimized for specific horticultural applications, production volume will increase, bringing hardware costs down. Decreases in LED chip manufacturing costs are also anticipated.

B. Improved Use of Light to Achieve Specific Horticultural Goals

As LED technology advances, one of the primary benefits that will occur will include value-added outcomes involving the use of LEDs as a tool to improve the quality and economics of horticultural specialty crops. Examples where spectral control could be used to reduce production costs or increase specialty crop value include enhanced flavor attributes of vegetables and small fruits, enhanced nutritional quality, manipulation of plant morphology and crop timing, reduced pest and/or disease pressure, phased light quality to increase plant yield, improved ornamental quality, and increased postharvest shelf life. Horticultural LED users likely will continue to develop hardware configurations and control protocols to take advantage of the unique characteristics of LEDs to provide more comprehensive control of the plant environment and allow manipulation of plant form and function in ways not easily done with previous lighting technologies.

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