Light-emitting diode technology status and directions: Opportunities for horticultural lighting

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Light-emitting diode technology status and directions: opportunities for horticultural lighting

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Abstract

Light-emitting diode (LED) technology has advanced rapidly over the last decade, primarily driven by display and general illumination applications ("solid-state lighting (SSL) for humans"). These advancements have made LED lighting technically and economically advantageous not only for these applications, but also, as an indirect benefit, for adjacent applications such as horticultural lighting ("SSL for plants"). Moreover, LED technology has much room for continued improvement. In the near-term, these improvements will continue to be driven by SSL for humans (with indirect benefit to SSL for plants), the most important of which can be anticipated to be: expanded chromaticity range and control; higher efficiency at higher current densities; improvements in reliability; intelligent control of chromaticity and intensity; and decreased cost of light. In the long-term, additional improvements may be driven directly by SSL for plants, the most important of which can be anticipated to be: even further expanded chromaticity range and control; and control over the light intensity distribution in space and time. One can even anticipate that plants and artificial lighting (as well as other aspects of a plant's environment) will ultimately co-evolve, with plants evolving to thrive in artificial lighting environments, and artificial lighting environments evolving to best serve plants.

Keywords: LEDs, solid-state lighting, plant biology and environment co-evolution, chromaticity, light distribution, intelligent control

INTRODUCTION

We are in the midst of a revolution in lighting. LEDs are displacing conventional incandescent, fluorescent, and high-intensity-discharge (HID) lamps in almost every lighting application – in residences, stores and offices, in streets and parking lots, and even in giant outdoor stadiums. The primary advantage of LEDs over conventional lamps is significantly higher energy efficiency, but important secondary advantages are lower cost of ownership, longer lifetime, smaller form factor, and greater control over directionality, intensity (e.g., dimmability and instant-on), and chromaticity (spectrum). Moreover, LED technology has room for significant continued improvement. Some of these improvements will be within the dominant current paradigm in which SSL generally emulates the form factors and functionality of conventional lamps that have been with us for decades or even a century, just with much higher efficiency. But, as illustrated in Figure 1, some will soon break out of the existing lighting paradigm and instead enable lighting products and delivery systems that are much better and much more optimized for humans.

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	SSL for Humans	SSL for Plants
Current LED technologies, backward compatible with lighting architectures optimized for traditional lighting technologies	**Now**	**Near-term future**
New LED technologies, enabling new lighting architectures optimized for the application	**Near-term future**	**Long-term future**

Figure 1. Possible evolution of LED technologies: from the current generation, designed for humans but constrained by backward compatibility with lighting architectures optimized for traditional (non-LED) lighting technologies; to newer generations, designed independently for humans and plants, and not constrained by backward compatibility.

LED technology will not only alter how artificial light is used and experienced in our day-to-day lives (SSL for humans), it will also enable artificial light to improve productivity in new and emerging applications, including, as illustrated in Figure 1, horticulture (SSL for plants) (Yeh and Chung, 2009; Singh et al., 2015). Moreover, the same types of improvements can be imagined. Some improvements will be within the dominant current paradigm in which SSL simply replaces, with similar functionality and form factor, lamps currently used for horticulture. But some improvements will break out of the existing paradigm, using LED technology as an opportunity to reconsider the entire lighting system. LEDs offer an almost infinite range of color options, including UV and infrared sources, a range of brightness and distribution options, reduced heat generation and improved thermal handling, full dimmability and instant on/off, and more robust and longer lived systems. Indeed, it is difficult to predict the opportunities that will be unleashed when one starts with "a blank sheet of paper" in designing systems using SSL for plants. This is especially true as our scientific understanding of the kind of artificial light that can maximize productivity and value from plants is in its infancy.

The remainder of this paper is organized into two sections. In the first section, we discuss the present and near-term-future status of LED lighting – a status which is being driven by SSL for humans, but which has significant side-benefit to SSL for plants. In the second section, we discuss the opportunities for long-term-future advancement of LED lighting were it to be increasingly driven by SSL for plants. Both discussions are from the point of view of LED technologists rather than plant biologists, hence cover in much more detail LED technology than plant biology.

THE PRESENT AND NEAR-TERM FUTURE: ADVANCEMENT DRIVEN BY SSL FOR HUMANS

In this section, we discuss the current status of LED lighting technology – ranges of color, light output, form factor options, etc. We also discuss ongoing LED research and technology directions that will likely improve the technology state of the art and that will provide more options for researchers using light as a tool and for product developers creating optimized lighting systems.

As mentioned above, the current status and research directions in LED lighting technology are driven largely by SSL for humans. However, there is significant cross-over benefit to SSL for plants, and we will point these out as appropriate. Also as mentioned above, current LED products for general illumination (SSL for humans) look and act very much like the products they are replacing. They fit into the same base, fixture, or hole in the ceiling, and they generally provide similar light distribution and light quality. The benefits with this approach are rapid consumer acceptance, quick retrofit installation, and hence rapid adoption of energy saving technology. The drawbacks of this approach are that the

LED technology is shoe-horned into non-optimized retro-form factors, and lighting performance parameters are defined by the pre-existing lighting system/layout. For horticultural applications (SSL for plants), the situation is similar. LED-based lighting products for plants may have a differently tailored spectrum than those for humans, but they are generally still one-for-one luminaire replacements of the HID products they are meant to replace (Nelson and Bugbee, 2014), with similar light output levels and light distribution patterns. Generally speaking, for both applications – SSL for humans *and* plants – there is thus an opportunity to start with a blank sheet of paper and re-engineer the entire light delivery and usage system in such a way as to maximize benefit and minimize cost well beyond what can currently be purchased off the shelf.

Chromaticity range and control

Current LED technology offers an excellent palette of color options using either direct emitters (where LEDs themselves emit light of the desired wavelength) or phosphor conversion (where phosphors downconvert light from the LEDs into light of the desired wavelength). Using direct emitters is the most desirable, so as to avoid phosphor conversion losses in the system as well as to enable more resolved spectral control of the light output (the spectral width of light emission from LEDs is generally much narrower than that from phosphors). But the color options for direct emitters do not yet span (with high efficiency) the entire wavelength spectrum of interest either to humans or to plants. Thus, LED technology is continuing to develop and be refined through ongoing research and development.

Perhaps the most obvious gap for direct emitters (at least for SSL for humans, though less so for SSL for plants) is the so-called "green gap", the color range within which direct emitters suffer from low efficiency. To help close this gap, recent research is exploring the tuning of the specific LED structures within the epitaxial process used to grow the LED crystalline structures (Hashimoto et al., 2013). This is a promising development since typical industry epitaxial growth processes (metalorganic chemical vapor deposition, or MOCVD) can still be employed, and the results applied more broadly to a range of colors – green, amber, and, possibly, red – that are based on InGaN semiconductor alloys. Another approach for tackling the green efficiency gap is LED structures on non-basal crystal growth planes of InGaN to reduce or remove detrimental polarization fields in the LED (Sharma et al., 2005). Still another is the use of techniques to relax the strain of InGaN layers to improve material quality and critical thickness/composition limitations (Zhang and Tansu, 2011). Note, though, that these approaches hold theoretical promise but have thus far shown limited progress in terms of practical efficiency advancements.

Absent progress in high efficiency direct emitters in the green (and extending to the amber), phosphor conversion is used. Indeed, phosphor performance is itself improving, providing additional color and system options at improved efficiency and more targeted, narrower emission spectra. Typical LED packages used in general illumination have a blue LED chip that is coated with a phosphor blend. The blue light from the LED chip excites the phosphor and a portion also leaks through. The phosphor emission combined with the leaked blue light creates white light and can be tuned across a range of correlated color temperatures (CCTs) and color rendering indexes (CRIs). New phosphors are emerging that may be more efficient, more stable, and have narrower emission spectra resulting in improved luminous efficacy (Pust et al., 2014; Murphy et al., 2105). Quantum dots, which are semiconductor nano-crystaline down converters, are also emerging as a viable option (Shirasaki et al., 2012). Quantum dots can be synthesized to emit spectrally narrow light at specific wavelengths (i.e., tunable). They have demonstrated good efficiency and stability but, so far, can only be used in remote phosphor configurations (not directly on the LED chip) where their temperature can be better controlled. Quantum dot down-converters are being used with LED LCD televisions and tablet displays for improved color gamut and may provide additional color options and higher resolution color control for lighting systems.

Higher efficiency at higher current density

Current LED technology, particularly for blue emitters, is also quite efficient. However, it is most efficient at relatively low current densities. At higher current densities, internal quantum efficiency is reduced, a phenomenon known as current (or efficiency) droop. Current droop fundamentally limits how hard an LED can be driven and thus how much light can be generated from a given area of LED material. In other words, it increases the cost per photon. The cause of droop has been experimentally identified as non-radiative Auger recombination which is a function of charge carrier density within the LED active region (Shen et al., 2007; Iveland et al., 2014).

An important area of research and development is thus finding ways to eliminate or mitigate current droop. Doing so would enable higher brightness at the LED source, which would in turn enable tighter beam distributions in spotlight type products, and also could change cost performance trade-offs that currently favor the use of more, lower power LEDs in lighting systems. Such lower power LEDs typically use lower cost packaging materials and are run at lower current density to minimize droop and increase efficiency. The downside of this approach is that many more LED chips or packages need to be employed for a given light output, and this reduces effective source brightness and increases cost. Removing or mitigating droop will enable more options in terms of brightness and LED layouts within the luminaire and should enable system cost reductions as fewer components within the luminaire are necessary.

Reliability

Research into LED lighting system reliability is also moving forward. While there is still no single metric for LED lighting system reliability, it is typically broken down into three aspects: lumen maintenance, catastrophic failure, and color stability.

Lumen maintenance is often used as a proxy for LED lighting system reliability. It describes the expected long-term degradation of the light output, though usually only the output degradation of the LED package and not the entire lighting system. LED lumen maintenance is fairly well understood and estimated and is typically expressed as a function of LED junction temperature. There is a standard test protocol (IES LM-80) for measurement and projection of LED package lumen maintenance which is provided by LED manufacturers. However, within the luminaire there may be additional optical elements such as lenses and reflectors that also degrade over time, accelerating the lumen depreciation of the LED lighting system, particularly in hot, moist environments such as greenhouses.

Catastrophic failure in LED lighting systems is typically a function of solder or electronic component failure within the luminaire power supply (Lall et al., 2014). Often, under-rated electrolytic capacitors fail within the power supply well before the projected lumen maintenance lifetime of the system. Horticultural lighting systems may be able to use simpler power supplies with fewer at-risk components since the same level of flicker reduction may not be necessary for horticultural consumers of light (although workers under these lighting conditions might appreciate flicker-free lighting).

Color stability refers to a tendency for the color of LED lighting to drift outside the range of suitability for the application, and thus for the product to be considered "failed". Different lighting applications require different levels of color maintenance and consistency, but research is enabling an improved understanding of color drift mechanisms and will hopefully result in predictive methods for color shift. In phosphor-converted approaches typical color shifts are a result of degradation of reflectance within the package, thus reducing phosphor conversion and increasing the ratio of blue to phosphor-downconverted light output. Delamination of phosphors can result in a yellow shift, while chemical changes within the phosphor material and/or silicone binder can result in a green shift (Tuttle Presentation, Department of Energy, 2015). Different LED package types and different calibers of LED products will suffer at different rates from these color shift mechanisms. For multi-channel direct emitter systems, color shifts are a result of uneven degradation of the different LED chip semiconductor materials as well as possible degradation of feedback and sensor systems that are employed to maintain light and color levels. Advancements in understanding and predicting full system reliability will allow for systems that are designed to meet the specific economic and performance requirements of the application. This can be particularly important for applications that require a large up-front cost and long-term consistent performance. Note, though, that humans are likely much more sensitive to subtle color shifts than plants are.

Intelligent control of chromaticity and intensity

While research is expanding the range of colors, brightness, reliability, and performance levels of LED lighting, an especially exciting area of development is in intelligent control and feedback of LED lighting systems. As a semiconductor technology, LEDs are fundamentally much more compatible with digital control than conventional lighting technologies. LED output can be dimmed from 0-100%, and LEDs are instant on/off, requiring no restrike time. Combining this controllability with new LED color options provides the ability to control colors and light output levels over long or short periods of time to mimic or optimize growth environments.

Not only are these features important for optimized commercial greenhouse growth operations, but they can also be used to research fundamental interactions between lighting and plants at a level not previously possible. Indeed, we might point out here that different kinds of light that affect human health and performance can be non-trivial to unravel from other factors. With plants, however, there is the possibility of doing massive numbers of experiments in much more controlled environments, and thus to unravel much more readily how different kinds of light affect plant health and performance. In other words, LED lighting is not only interesting for horticultural applications in the present, but it also represents a new, higher resolution research tool for better understanding of the underlying interactions between light and plants, and thus to enable even more interesting horticultural applications in the future.

Decreased levelized cost of light

A final, very important area of intense interest for SSL for humans, one that will also be of intense interest for SSL for plants, is cost. Note, though, that SSL for humans and SSL for plants require different metrics for light output. For humans, who do not have much variation (from human to human) in the wavelength region over which they are visually sensitive, the standard metric of light output is lumens: the convolution of optical power (in Watts) and the standard human visual response (in lumens Watt^{-1}) over the entire wavelength spectrum. For plants, with a much wider variation in the wavelength regions over which they are photo sensitive, not only across plants but across the life cycle of plants, the standard metric of the usefulness of optical power is photosynthetic photon flux (PPF) expressed as µmol photons s^{-1} within ranges of wavelengths specific to particular photochemical pathways. Because the photo sensitive wavelength ranges of humans and plants (and even across plants) are different, interconversion between the two units can be problematic.

Here, because we are particularly interested in the cost of light, and because a major component of the cost of light is the electricity used to create the light, we use a common unit, Watts, to measure both the electricity used as well as the light created. Thus, for SSL for humans we use lumens, which includes both the efficiency with which light is created and the match of the light to the human visual response, while for SSL for humans and plants we use the common unit of optical Watts. Fortunately, it is easy to go back and forth between these two units by multiplying or dividing by a so-called luminous efficacy of radiation (LER), a factor which measures the convolution of light assumed created at 100% efficiency with the human visual response. For our purpose here, we use a luminous efficacy of radiation of 331 lm W^{-1}, the current state-of-the-art for phosphor converted LED lighting for humans at a correlated color temperature (CCT) of 3,000 K and a color rendering index (CRI) of 80.

Progress in cost in terms of both of these units (the axes on the left panels use lumens, the axes on the right panels use Watts) is summarized in Figure 2 – both over this past decade, and anticipated progress in the coming decade. The data and projections are taken from the 2015 US Department of Energy Solid-State Lighting Research and Development Plan, and are for the currently best developed Edison-style incandescent replacement lamp emitting both warm (in green) and cool (in blue) white light. Note that the projections for luminous efficacy (bottom panel 2c) go out to 2025, while those for purchase cost (middle panel 2b) and inferred for levelized costs (top panel 2a) only go out to 2020.

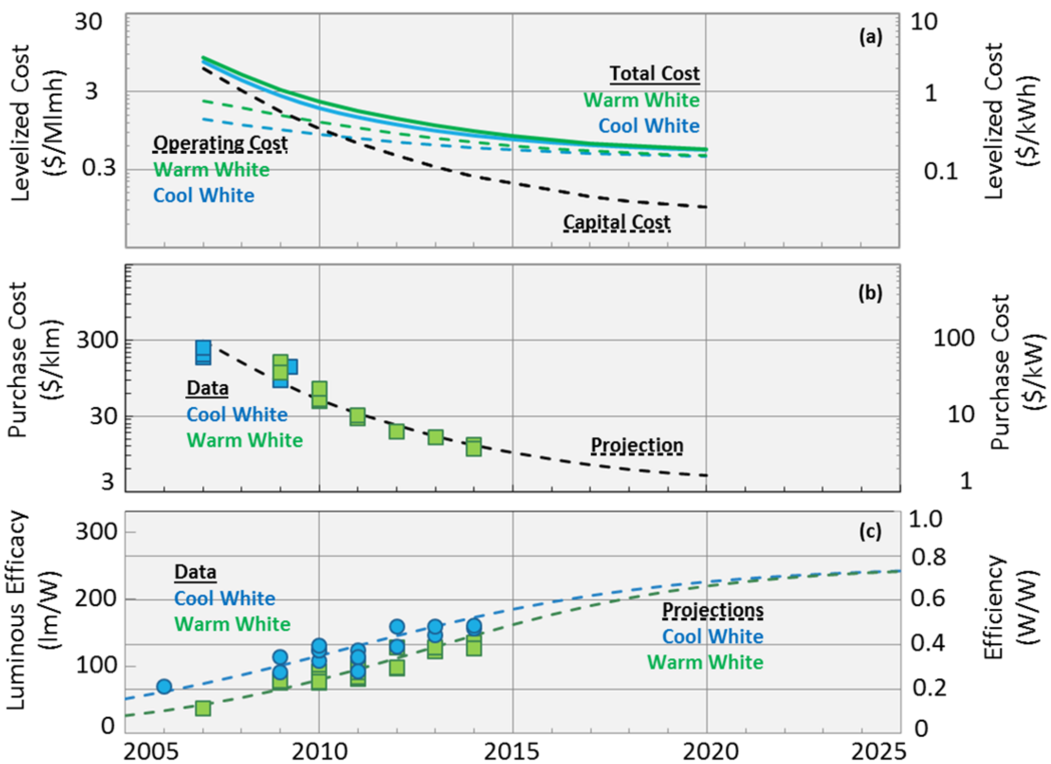

Figure 2. History and projections of SSL for humans: (a) levelized costs (total, capital and operating), (b) lamp cost, and (c) efficiency. Data and projections taken from the US Department of Energy (2015). Levelized costs were calculated from capital (purchase) and operating costs using a 50,000-h lifetime. Left and right axes units were scaled using a 2015 state-of-the-art luminous efficacy of radiation of 331 lm W^{-1}. Similar projections can be anticipated for horticultural lighting (SSL for plants).

The bottom panel 2c shows both the luminous efficacy (lm W^{-1}) and the efficiency (W W^{-1}) of white light LED packages over time. These luminous efficacies and efficiencies are crucial, because they determine the "operating" cost of the LED lamp: the cost of the electricity (in \$ kWh^{-1}) that powers the LED divided by either the luminous efficacy with which the LED produces light within the human visual response, or by the raw efficiency with which the LED produces light. A steady increase in luminous efficacy over time can be seen, from 10-30 lm W^{-1} in 2002 to 140-180 lm W^{-1} in 2014, and in source efficiency over time, from 4-9 to 40-55%. Moreover, one can reasonably project by 2020 luminous efficacies on the order of 220 lm W^{-1} and efficiencies on the order of 70%.

The middle panel 2b shows the purchase cost of the white light LED lamps over time, both in \$ klm^{-1} (cost of the lamp per kilolumen of light that the lamp can produce within the human visual response) and in \$ W^{-1} (cost of the lamp per Watt of light that the lamp can produce). These purchase costs are crucial, because they determine the "capital" cost of the

LED lamp: the purchase cost divided by (amortized over) the lifetime of the LED lamp in hours. One sees a steady decrease in purchase cost, from 300 \$ klm^{-1} or 100 \$ W^{-1} in 2007, to 12.5 \$ klm^{-1} or 4 \$ W^{-1} in 2014. Moreover, one can reasonably project by 2020 purchase costs on the order of 5 \$ klm^{-1} or 1.6 \$ W^{-1}.

The top panel 2a shows the inferred "levelized" operating (in dashed colored lines) and "levelized" capital (in the dashed black line) costs of white light LEDs over time. Note that for the capital cost of white light LEDs we have used a relatively long (50,000 h) life, both because these are possible with current technology as well as because SSL for plants is likely to be a relatively intense use for which the full SSL lifetime would be "used". In the early years (pre 2009), the dominant cost was the capital cost, because purchase costs were so high. In recent years (post 2009), the dominant cost has become the operating cost, because purchase costs have become so low. Note that the sum of the levelized capital and operating costs is the levelized total cost of light. This is the most important cost to the industrial consumer of light, and these are shown as the solid colored lines in the panel. Progress has been remarkable: from about 8 \$ $klmh^{-1}$ or 2.5 \$ kWh^{-1} in 2007 to 0.9 \$ $klmh^{-1}$ or 0.3 \$ kWh^{-1} in 2014. Moreover, one can reasonably project by 2020 levelized costs on the order of 0.5 \$ $klmh^{-1}$ or 0.2 \$ kWh^{-1}. Because of the efficiency with which white LED lamps produces light, and the low cost of those lamps, these levelized costs are approaching the cost of the electricity itself, which we have assumed in these calculations to be 0.1 \$ kWh^{-1}.

Note, though, that these costs only apply to light produced within the human visual response, as they are for white LED lamps whose progress has been driven by the market for SSL for humans. Nevertheless, as discussed below, the wavelength range over which LEDs can in principle produce light efficiently extends beyond the wavelength range within which the human eye is sensitive; and, with sufficient motivation, one can imagine similar levelized costs for the wider wavelength range useful for SSL for plants.

THE LONG-TERM FUTURE: OPPORTUNITY FOR ADVANCEMENT DRIVEN BY SSL FOR PLANTS

As discussed above, SSL will continue to evolve largely driven by the needs of the huge market for displays and general illumination for human beings. Because many of the needs of horticultural lighting are similar to those of lighting for human beings (high efficiency, low cost, reliability, digital control, filling out the visible spectrum), horticultural lighting can to some extent piggy-back off of this ongoing evolution of SSL. As the market for horticultural lighting increases in size, however, SSL will begin a separate evolution driven by the different needs of horticultural lighting.

Chromaticity

A first area where SSL might evolve somewhat differently is chromaticity. As discussed above, plants have a much wider range of photo-active molecules and a wider range of wavelength ranges within which efficient SSL would be desirable than are present in the human visual system. This provides incentive for innovation into SSL in those other wavelength ranges.

There are a wide number of photo-sensitive molecules that play important direct and indirect roles in how plants currently make use of light – both sunlight and, increasingly, artificial light. The absorption spectra of these molecules are generally broad, but with peaks in particular wavelength ranges. Examples of spectra from known-important classes of photo-sensitive molecules in plants are given in the top six panels of Figure 3.

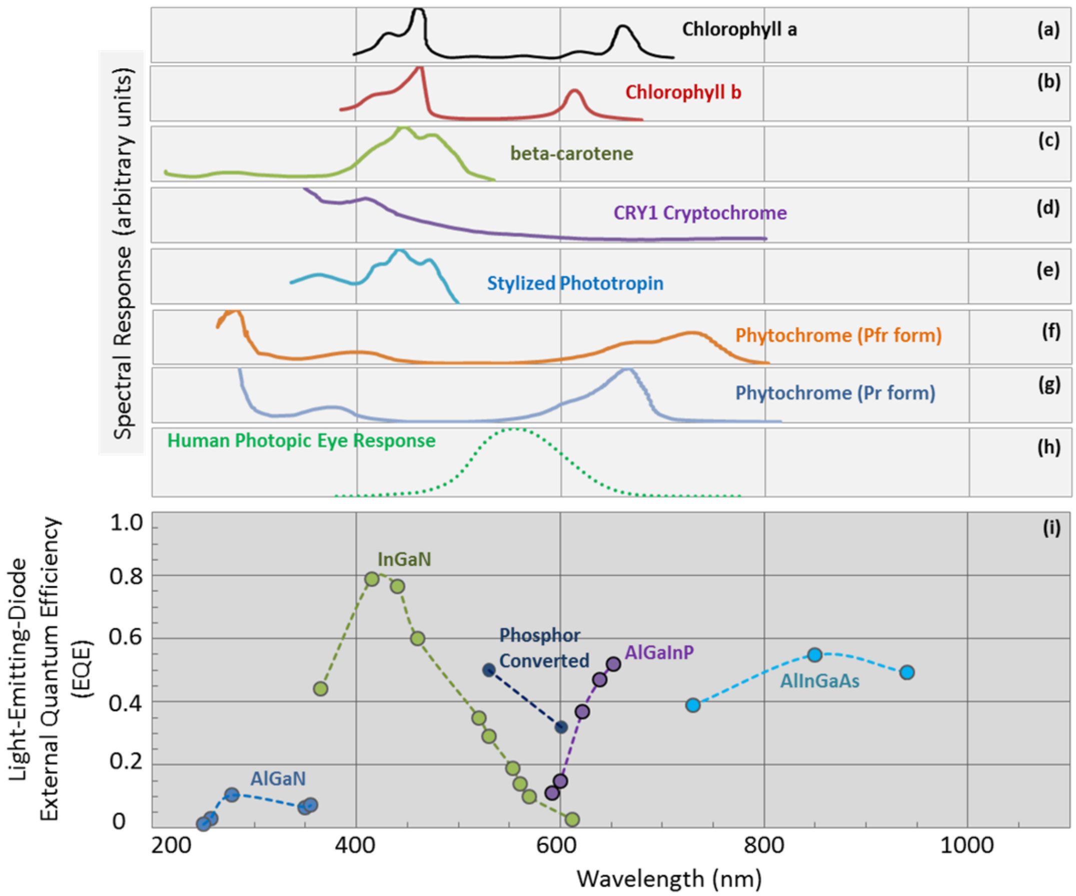

Figure 3. (a-g) Representative horticultural action spectra of various known-important classes of photo-sensitive molecules in plants: (a,b) Chlorophyll a and b (Atwell et al., 1999); (c) Beta-carotene (Evens, 2015); (d) CRY1 Cryptochrome (Ahmad et al., 2002); (e) Stylized Phototropin (Briggs and Christie, 2002); (f, g) phytochrome Pfr and Pr forms (Fankhauser, 2001); (h) Human Photopic eye response (DiLaura et al., 2011); (i) Current state-of-the-art LED external quantum efficiencies at various wavelengths and in various semiconductor materials families, with dotted lines to guide the eye): AlGaN data from Pernot et al. (2010), Hirayama et al. (2010), Nakashima et al. (2014), Shatalov et al. (2012), Passow et al. (2013); InGaN data from Hurni et al. (2015), Hwang et al. (2014), Hashimoto et al. (2013), Hashimoto et al. (2014), Lumileds (2015), Osram (2015), Narukawa et al. (2010), Morita et al. (2004); AlGaInP data from Krames (pers. commun.); AlInGaAs data from Osram (2015); Phosphor Converted data from Schiavon et al. (2013), Lumileds (2015).

Figure 3a and b show the absorption spectra of chlorophylls a and b, the two molecules responsible for most photosynthesis in plants. Figure 3c shows the absorption spectrum of beta-carotene, an example of a carotenoid, molecules which are active both in photosynthesis as well as in photo-protective processes that are necessary at very high light intensities. Figure 3d shows stylized action spectrum for phototropins, molecules which mediate phototropism, the tendency of plants to re-orient in response to light. Figure 3e shows the absorption spectrum of CRY1, an example of a cryptochrome, molecules which help regulate the Circadian rhythm of plants, as well as help mediate phototropism. Figure 3f and g show the absorption spectra of Pr and Pfr, two interconvertible states of phytochrome molecules which effectively enable the sensing of light direction. The human eye response is provided in Figure 3h, highlighting the difference in "action spectra" for humans and plants.

Importantly, because these molecules absorb light in different wavelength ranges, it is in principle possible to selectively excite them and therefore to some extent to selectively activate their function through choice of light excitation wavelength. Moreover, with LEDs, it is also in principle possible to produce artificial light over the entire wavelength range over which these known-important classes of photo-sensitive molecules absorb light. We note, though, that this is currently not possible. There are gaps in the wavelength ranges over which LEDs currently produce light efficiently. These are illustrated in Figure 3i, the bottom panel of Figure 3, in which is plotted the external quantum efficiency (EQE) of state-of-the-art LEDs. EQE represents the probability that an injected electron will produce an emitted photon that exits the LEDs and is detected (or utilized).

LEDs are currently quite efficient in the blue (400-480 nm), deep red (640-680 nm), and near-IR (700-1000 nm) wavelength ranges. Blue LEDs, based on the InGaN materials family, are extremely efficient due to fundamental physical factors, but also probably in large part because they are the basis for white LEDs and thus much more effort has been invested in making them efficient. Deep red and near-IR LEDs, based respectively on the AlGaInP and AlGaInAs materials families, are relatively efficient in large part because of the coincidence that their atomic crystal lattices match well to available high quality GaAs substrates on which they can be readily fabricated. Moreover, LEDs in all of these ranges have room for further improvement: there is no fundamental reason why they cannot achieve near 100% efficiency.

LEDs in two other wavelength ranges, UV (250-400 nm) and green-yellow-red (480-640 nm) are less efficient. In the UV regime, the lack of a low-cost, high-quality substrate (AlN) and difficulty in realizing transparent p-type material represent severe challenges that limit performance. In the green-to-red, increasing strain of InGaN-on-GaN and miscibility issues between InN and GaN make realizing high quality active regions extremely challenging. In addition, the Wurtzite (In,Ga)N materials system produces built-in electric fields in LED layer structures which frustrate charge-carrier injection and distribution. These issues combine to result in a severe reduction in (In,Ga)N EQE as emission wavelength is increased from violet/blue to deep green, yellow and red. For (Al,Ga)InP, efficiency reduces in the other direction (red to geen) as increasing AlInP mole fraction increases carrier scattering to indirect bandgap valleys as well as reduces potentials for charge carrier confinement, reducing EQE overall in addition to degrading over-temperature performance. The consequence of the resulting "green" (extending to amber) gap is the use of wavelength down-conversion (with phosphors) to produce more efficient green and amber emitters.

However, it is also worth noting that reduced performance in these particular wavelength regimes is in part because their markets have been much smaller than the general lighting market, and hence much less effort has been invested in making them efficient. Investment in novel device structures and new (or augmented) compound semiconductor material systems could result in breakthrough efficiencies, similar to what is observed today for InGaN blue/violet or GaInAs infrared. Indoor farming, if taken to a planetary-scale extreme, would certainly be a market of sufficient size to drive increased investment where necessary. Also, the potential emergence of direct-view micro-LED displays, as an alternative to backlit LCD panels for mobile applications, will drive improvements in at least the green and red which could further benefit horticulture lighting.

Intensity distribution in space and time

A second area where SSL might evolve somewhat differently is in the absolute intensity and intensity distribution of light in space and time. In terms of absolute intensity, light levels equivalent to that of the bright outdoor sun (~30,000 lux) are unnecessarily high for the human visual system, so lighting architectures for humans are typically designed to produce ~60× lower light intensities (~500 lux). Plants, however, evolved to utilize bright outdoor sun many hours per day, and hence may benefit from lighting architectures capable of delivering much higher light intensities. In fact, a key characterstic of SSL is its ability to offer a wide range of flux density levels that can deliver the right amount of light for the specific application.

In terms of intensity distribution in space, because of its logarithmic sensitivity dependence, the human eye is relatively insensitive to small (20-30%) 2D spatial variations in light intensity over a field of view. But in many situations, plant growth is linear in light intensity and hence can be sensitive to such variations. Depending on the desired harvest uniformity, lighting architectures may need to deliver light with greater 2D spatial uniformity than current lighting architectures do. Moreover, because shadows in most indoor scenes are tolerated and compensated for relatively well by the human visual system, even greater 3D spatial non-uniformity in lighting delivery is tolerated in lighting for humans. Plants, in contrast, are complex three-dimensional objects. Architectures which enable illumination of such objects with 3D spatial uniformity could lead to significant increases in plant productivity. Such architectures could make use of the flexibility with which LED lights can be configured. LED lights can be edge-fed into light guides or sheets which can then distribute the light extremely uniformly over large areas, either above canopy or even intra-canopy. Alternatively, spotlight type products making use of the small form factor of LEDs can enable brighter and tighter beams where needed.

In terms of intensity distribution in time, because of the ease with which LEDs can be intelligently controlled, tailored light distributions in space can be augmented by tailored light distributions in time. This could enable not only optimizing plants' daily Circadian rhythm but also their seedling-juvenile-mature-senescence life cycle, through optimizing the different light levels beneficial for plant growth at different stages of that cycle.

Co-evolution of plant biology and environment

Beyond the evolution of SSL for properties which would be more optimal for existing plants, one can also envision a long-term scenario in which plants *also* evolve, through selection/breeding or bio engineering, to make optimal use of SSL (as opposed to sunlight). For example, plants have by necessity evolved to incorporate self-protection mechanisms: against variations in light intensity, chemical environment, temperature, etc. Too-high light intensities trigger defense mechanisms necessary to prevent that light energy from inducing damage via the generation of high levels of reactive oxygen species (Murchie and Niyogi, 2011). If such too-high light intensities are eliminated through engineered artificial lighting, the need for such energy-costly defense mechanisms might be reduced or even eliminated, and the overall efficiency of photosynthesis increased.

Many other long-term scenarios can be imagined, in which plant biology and plant environment (of which lighting is an essential component) *co-evolve*. In other words, if we are liberated from the use of sunlight, and use instead nearly infinitely customizable SSL, can we engineer different kinds of plants that can best utilize SSL? And, as plants are re-engineered, SSL will in turn have different requirements (including optimal wavelengths), and can themselves be re-re-engineered. One can imagine, as illustrated in Figure 4, a virtuous spiral of co-engineering or co-evolution which ultimately leads to significant increases in the overall efficiency and decreases in the overall cost of food harvested via artificial lighting (Murchie et al., 2009). This may be extremely valuable in a future in which human population, standards of living, and food needs continue to grow (Martellozzo et al., 2014; Despommier, 2010).

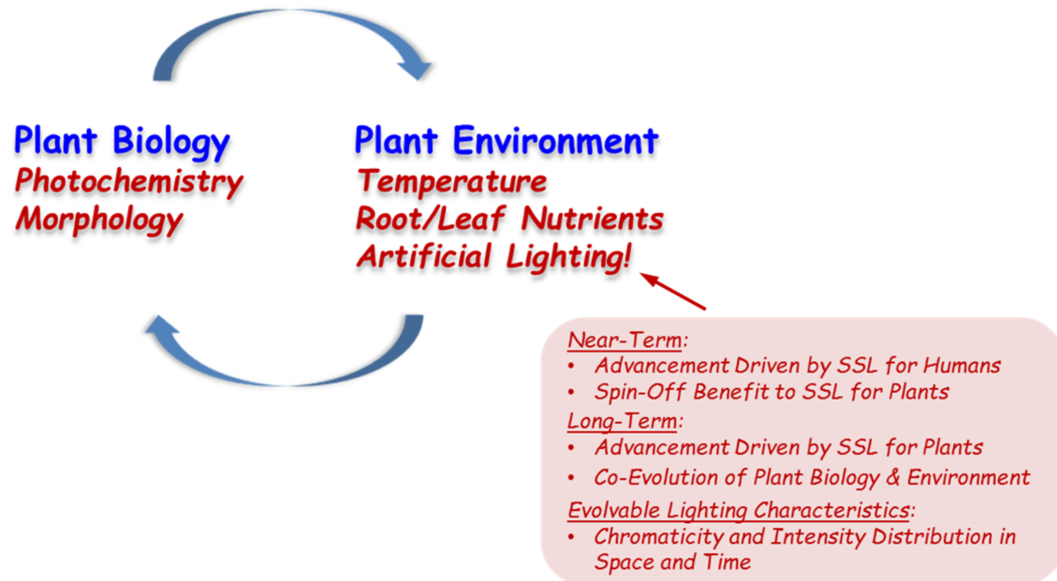

Figure 4. Schematic of how plant biology (including photochemistry and morphology) and plant environment (including temperature, root/leaf nutrients and artificial lighting) might co-evolve. Artificial lighting, in turn, will evolve in response to the needs of both SSL for humans and SSL for plants.

CONCLUSIONS

In the short run, LED technology for humans continues to improve, with huge headroom. Advancements continue to made in the underlying LED package, luminaire, and system, including: current droop, green gap; phosphors and quantum dots; packaging; light distribution control; and active control of intensity and color over time. These advancements will provide new opportunities to optimize lighting systems for specific applications. We are also gaining an improved understanding of manufacturing, system requirements, and system reliability which enables more effective, lower cost lighting systems.

In the long run, LED technology for humans will advance beyond constraints which apply to systems optimized for earlier technologies. Moreover, LED technology will increasingly be optimized not just for humans but also for plants. Developments in lighting technology will be symbiotic with developments in plant physiology and the total green-house growth environment. And LED technology will offer important research tools for improving our scientific understanding of optimal green-house plant growth.

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