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LEDs for Extraterrestrial Agriculture:

Tradeoffs between Color Perception and Photon Efficacy

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TECHNICAL MEMORANDUM

LEDs for Extraterrestrial Agriculture: Tradeoffs between Color Perception and Photon Efficacy

1. Abstract

Growing food on extraterrestrial surfaces requires the development of efficient lighting technologies to provide photons for photosynthesis. Here we discuss the development and demonstration of LED panels with a high color fidelity index that can achieve a photon efficacy of 3.6 µmol of photons per joule of input electrical energy. As of June 2021, this is higher than commercial LED fixtures on Earth. This high efficacy makes LED technology a preferred option to solar fiber optics for extraterrestrial applications. Increasing the fraction of red LEDs and photons increases the efficacy but decreases the perception of color.

2. Introduction

For most of human history fires, candles and oil lamps provided light for human vision in the dark. Then, over 200 years ago, advances in electric technology began to revolutionize lighting. The first practical electric light was the carbon arc lamp, which was commercialized decades before the well-known incandescent light bulb[1]. Arc lamps conduct electricity through the air, ionizing the gaseous particles in the process. These ionized atoms can transfer electrons as they collide. When an ionized gaseous atom accepts an electron, the electron “relaxes” to a lower energy level, releasing a photon in the process. Carbon arc lamps were phased out in favor of Thomas Edison’s safer and more reliable incandescent light bulb. Incandescent bulbs use electricity to heat a filament until it glows (following Planck’s law), providing light in a similar manner to the Sun. The incandescent bulb dominated for much of the 20th century, but towards the mid to end of the century fluorescent lamps, a type of gaseous discharge lamp, began to dominate due to its higher efficiency. Gaseous discharge lamps operate in the same manner as carbon arc lamps, but they ionize a specific, contained gas rather than just ionizing air. Fluorescent lamps, which ionize mercury gas, are so named because they use a material called a phosphor that absorbs ultra-violet (UV) photons and re-emits them in the visible region - a process called fluorescence. Fluorescent lamps have low internal gas pressures. Increasing the pressure within gaseous discharge lamps results in high intensity discharge (HID) lamps, such as high-pressure sodium (HPS) and metal halide lamps, which became popular in the latter half of the 20th century and are still widely used (e.g., for street lights). These HID lamps are even more efficient than fluorescent lamps and typically have high power ratings (e.g., 400, 600, and 1000 W). Within the last two decades, fluorescent lamps and even some HID lamps have been phased out in favor of much higher efficiency light-emitting diodes (LEDs), a solid-state-lighting-technology. Like gaseous discharge lamps, LEDs also emit photons through the relaxation of excited electrons, but LEDs conduct charge through a solid material rather than a gas and operate at low voltage instead of high voltage. Each technology replaced its predecessor due to the newer technology’s higher efficiency (Figure 1; Narukawa et al., 2010).

[1] The invention of incandescent light bulb predated carbon arc lamps by four years, but these early incandescent bulbs were too short-lived to have practical application.

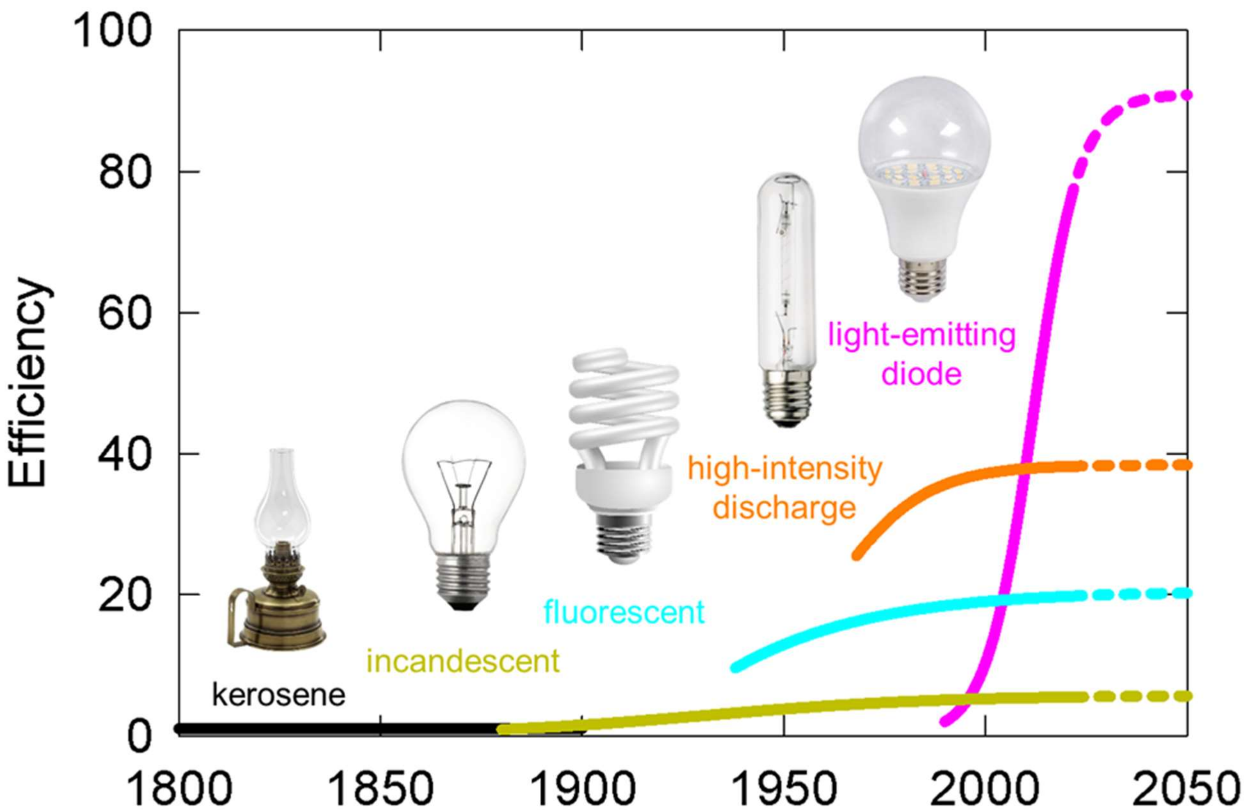

Figure 1. Historical increase in efficiency of lighting technologies. Efficiency here describes the visible photon (400 to 700 nm) energy output divided by the electrical energy input. Dashed lines indicate the projected increase in technologies for the next 30 years. LED efficiency in this graph represents efficiency of a combination of red and blue LEDs at about 350 mA per mm^2. Under lower drive currents, the efficiency of these LEDs can approach 90%.

Electric lighting for use in plant growth environments closely followed developments in human lighting (Wheeler, 2008). Early plant photobiology research utilized both carbon arc and incandescent lamps to provide sole-source lighting in indoor environments (Sage, 1992), but carbon arcs were generally not favored due to their high maintenance requirement and hazardous operation. In these early days of plant photobiology, studies investigated the effects of different colors on crop growth by using colored filters and prisms (Sage, 1992). With the development of fluorescent lamps, many growth chambers in the latter half of the 20th century were fitted with fluorescent and incandescent lights (Downs, 1977). Fluorescent lamps could be designed with specific phosphors that re-emitted the absorbed photons at specific wavelengths, thus fluorescent lamps could output a green or red dominant (for example) spectrum. This further allowed the investigation of the effect of specific wavelength photons on plant growth[2].

[2] Regarding spectral effects on plant growth, it is interesting to consider the physics related to unique spectral output from specific types of lamps. In gaseous discharge lamps and LEDs, as electrons 'relax' the wavelength of the emitted photon depends on the energy difference between the excited and relaxed states. The spectral photon distribution from gaseous discharge lamps depends on the emission spectrum of the specific gas, which is determined by the discrete potential energy states of the excited electron. Under low pressure, the atoms are dispersed and in a relatively uniform energy state, limiting the emission spectrum to fewer and fewer wavelengths, but at higher pressures, the atoms are packed in higher density, decreasing the uniformity of energy states, and therefore the energy difference between the exited and relaxed states becomes increasingly broad (collision broadening), as does the spectral photon distribution. LEDs can be designed to carefully control the energy bandgap between the excited and relaxed states of the electrons, limiting the photons to narrow bandwidths (in a relatively Gaussian distribution). The spectral photon distribution of incandescent lamps, on the other hand, is determined by their temperature and Planck's law. In terms of converting electrical energy to electromagnetic radiation, incandescent lamps are very efficient, but most of the radiation is infrared. Halogen lamps are a type of incandescent lamp that can reach higher temperatures than traditional incandescent lamps, shifting the

But, as with human lighting, these older technologies are being phased out for LEDs. Broad spectrum white LEDs contain a phosphor (like fluorescent lamps) that absorb blue photons and re-emit longer wavelength photons, but LEDs can also be designed to output narrow spectrum photons across the visible spectrum (and beyond). The much higher efficiency of LEDs compared to other technologies make indoor farming possible.

These considerations of lighting efficiency for crop growth in a closed environment has been a primary focus for NASA for the past 35 years. This is because the technology used to provide photons for crop growth in deep-space is a mission critical consideration, especially when the launch mass of associated power and cooling requirements are considered (Drysdale et al., 2008; Anderson et al., 2018). Because an increase in efficiency decreases both the power and cooling requirements for a crop growth system, it is vital to optimize the lighting system (Hardy et al., 2020).

NASA realized the potential of LEDs in crop growth environments as far back as 1988 (Morrow, 2008; Ignatius et al., 1991), before the development of reliable (and Nobel-Prize winning; Tsao et al., 2015) blue LEDs (Nakamura et al., 1994). At the time, only red LEDs with a peak at about 660 nm that were 5 to 10% efficient were available. However, abnormal growth under sole source red light became quickly apparent, and researchers found that adding a small amount of blue photons from fluorescent lights or (inefficient) blue LEDs removed these abnormal growth defects (Yorio et al., 1998). The development of higher efficiency blue LEDs began to replace the fluorescent blue light in these environments, but in the early days of testing these were prone to issues like static discharge overdriving and burning out the blue LEDs. Through NASA funding, the companies Quantum Devices and Percival developed CERES plant growth chambers that used modules of red and blue LEDs, but these were not a commercial success primarily due to the low efficiency and high price of LEDs at the time. Since then, the past two decades have seen rapid advancements in LED technology, driven primarily by the human lighting market. Currently, on the International Space Station (ISS) the Vegetable Production System (Veggie), a plant growth unit, contains a combination of blue (455 nm), green (530 nm) and red (630 nm) LEDs (Khodadad et al., 2020), while the Advanced Plant Habitat (APH) contains blue (455 nm), green (530 nm), red (630 nm), far-red (735 nm) and white (4100 K) LEDs (Monje et al., 2020). The green LEDs were added to the Veggie to aid human vision of the plants, although at the time the Veggie was developed, phosphor-converted (PC) white LEDs (blue LEDs with a phosphor) were not as abundant as they are today. Currently, PC white LEDs are a much better method of providing broad spectrum white light than green LEDs (Kusuma et al., 2021).

Now that LED technology is approaching its theoretical maximum in light source efficiency (Kusuma et al., 2020), NASA can once again develop cutting-edge lighting systems for crop growth in deep-space. Because LED technology allows for the selection of specific wavelengths in the growth spectrum, it is important to consider both how plants perceive different color in order to maximize growth, and how wavelength of the photons affect the overall energy balance of the system. Photons with wavelengths between 400 and 700 nm have high enough energy to drive photosynthesis - with an extension out to 750 nm if provided in combination with 400 to 700 nm photons (Zhen and Bugbee, 2020). In this range, blue LEDs with a peak at about 450 nm and red LEDs with a peak at about 660 nm are promising. Both of these LEDs (blue and red) have relatively similar efficiencies (Kusuma et al., 2021), but due to the lower energy of red photons, the red LEDs input 32% less energy for the same quantity of photons. Additionally, red photons drive photosynthesis with about 25% higher quantum efficiency than blue photons (McCree, 1971). For both reasons LEDs at 660 nm would comprise a large fraction of the overall lighting fixture for deep-space crop production, but other wavelengths (especially some blue photons) are necessary for normal plant growth and development.

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spectrum to shorter (blue) wavelengths. The high temperature required to produce this higher flux of shorter wavelength (higher energy) blue photons in a halogen bulb evaporates the tungsten in the filament. This would shorten the life of a normal incandescent lamp, but the halogen bulb contains an inert noble gas mixed with a small portion of a halogen (iodine or bromine), which sets up a reversible reaction cycle wherein the evaporated tungsten is deposited back onto the filament (halogen cycle).

In addition to designing lighting fixtures to address both the needs of the plants and the system efficiency, considerations ought to be made regarding the human-plant interactions. Plants have been suggested as a countermeasure for stressful and psychological difficulties associated with the isolated, confined, and extreme conditions of long-duration space missions (Bates et al., 2010; Vessel and Russo, 2015; Odeh and Guy, 2017). Humans appear to prefer natural (as opposed to urban/built) environments and studies have suggested potential benefits of both active and passive interactions with plants – although benefits of passive interactions appear to be limited to stress reduction and increased pain-tolerance (Bringslimark et al., 2009). When considering both passive and active interaction with plants for psychological benefits, it is useful to consider the color rendering under different light sources. Broad-spectrum white light sources generally have a high color fidelity, which means that plants will appear true to color under this light source. Color fidelity is commonly expressed by the color rendering index CRI Ra (CIE 13.1-1995) or fidelity index Rf (ANSI/IES TM-30-18). LED combinations that are typically of horticultural lighting (with high fractions of red photons and sometimes the absence of green photons) can induce poor visualization of plants. For example, we compare the visualization of plants in the Veggie (with no broad-spectrum white LEDs) to plants in the APH (Figure 2). Visualization (high Ra and Rf) of plants is important for diagnosis of plant disorders by the human eye, but it could also be important for the human-plant interactions where astronauts may not perceive plants under a low Ra and Rf as nature, and may thus not receive psychological benefits from plants under these light sources.

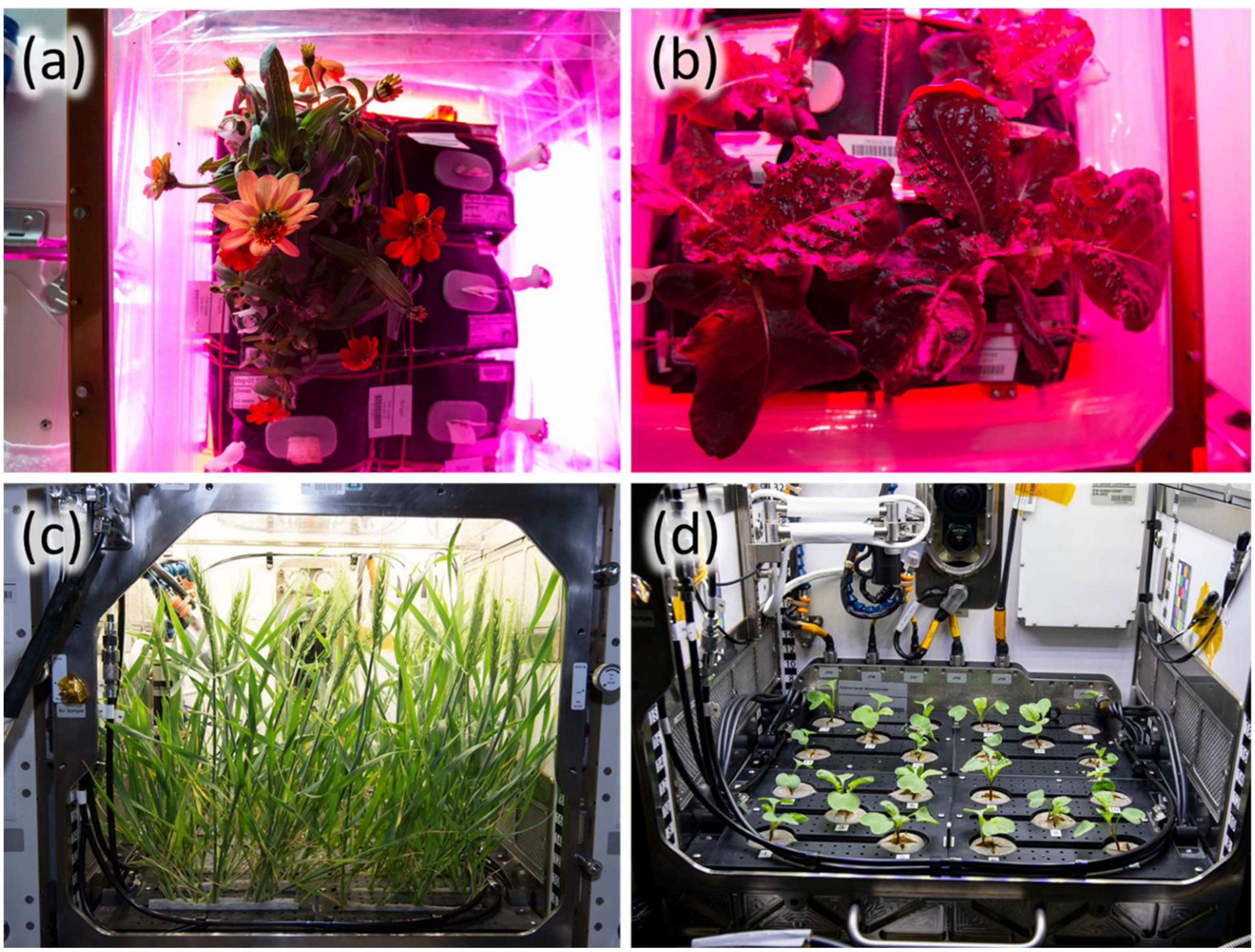

Figure 2. Photos of plants growing aboard the International Space Station (ISS). Differences in visualization with and without white LEDs are apparent underneath the Veggie (a, b) compared to the Advanced Plant Habitat (c, d). (a) Zinnia, (b) lettuce, (c) wheat, (d) radish. Credit: NASA

In a previous publication, we suggested the design of a high efficiency LED fixture that contained PC white LEDs with a high fraction of red LEDs (Kusuma et al., 2020). In collaboration with the company Lumileds, we have developed high performance LED panels that meets this description. Here we report the results of a high efficiency lighting fixture for crop production in deep-space.

3. Design of the LED Panel

Each LED panel contains one hundred PC white LEDs and one hundred 660 nm red LEDs, with each type on a separate circuit. The 660 nm red LEDs are arranged in five parallel strings, and the PC white LEDs are arranged on 10 parallel strings (Figure 3). Two different types of white LEDs were selected for this demonstration: warm white (4000 K) and cool white (6500 K). These two types of LEDs were not combined on a single panel. The mass of a panel is 420 g with dimensions of 30×30×0.16 cm. This panel has not been optimized for mass and was instead designed for durability. One simple way to reduce the mass of the system would be to decrease the thickness of the panel by half (to 0.8 mm) providing a total mass of approximately 210 g per panel.

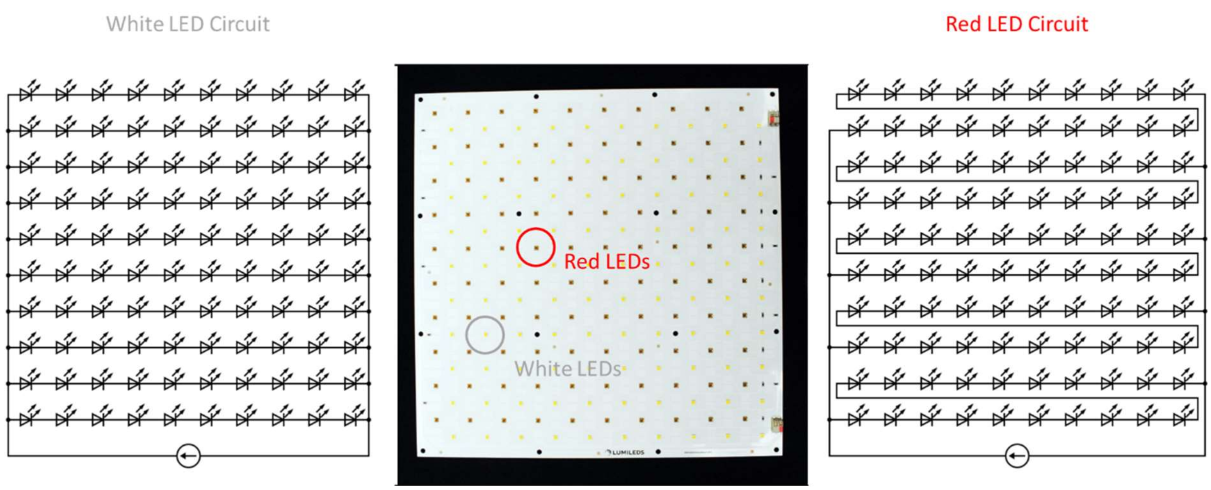

Figure 3. Board layout of the LED panel. The white LED circuit and the red LED circuit are shown to the left and right of the photo, respectively. There are 10 white LEDs on each parallel string and 20 red LEDs on each parallel string.

4. Performance of the LED Panel

The photon output of the LED panels was measured in an integrating sphere. The panels were tested at a range of input currents, with the lowest current at 220 mA and the highest at 3500 mA (Table 1). Forward voltage (V_f) at these input currents was also measured. Input power was calculated by multiplying the drive current by V_f. The forward voltage (V_f) of the red LEDs increases 20-fold between single LED packages and the whole panel, while V_f for the white LEDs only increases 10 fold. These differences, along with differences in drive current between individual LEDs and the whole panel, are due to the layout of white and red LEDs on the panel (10 parallel strings with 10 white LEDs or 5 parallel strings with 20 red LEDs).

Table 1. Characteristics of the three types of LEDs used in these panels. Values are provided for the individual LEDs and for the whole panel. Although efficiency and efficacy are only listed in the single LED section, these values apply to both the single packages and the whole panels.

	Red	Phosphor-converted white	
	660 nm	4000 K	6500 K
	Single LED packages		
maximum drive current	1000 mA	480 mA	480 mA
nominal drive current	175 mA	65 mA	65 mA
V_f *	1.89	2.73	2.73
Efficiency (W per W) *	78	63	66
Efficacy (µmol per J) *	4.26	2.90	2.93
	Characteristics for the whole panel		
maximum drive current	5000 mA	4800 mA	4800 mA
nominal drive current	875 mA	650 mA	650 mA
V_f *	37.7	27.3	27.3
Photosynthetic photon flux (µmol per s) *	141	51	52

* These values are for the nominal drive current

4.1 Efficiency/Efficacy

Increasing the drive current through the LEDs increases the photon output, but also decreases the efficiency. This decrease in efficiency is called current droop and is shown in Figure 4a for the three types of LEDs used in these panels. Efficiency is calculated as the power flux divided by the electrical power input, multiplied by 100. This method of calculating efficiency for the white LEDs leads to an inevitable decrease in efficiency caused by Stokes shift, meaning that white LEDs can never reach 100% efficiency.

Current droop can also be expressed as the decrease in photon efficacy (Figure 4b). It is apparent that the 4000 K and 6500 K LEDs produces very similar efficacies under the same operating conditions. Figure 4b also shows the efficacy of the panel assuming the white and red LEDs are operated at the same drive current – only one line is used due to the similarity between the 4000 K and 6500 K LEDs. It is critical to note that because the white and red LEDs are on separate circuits, they are operated independently, and the current does not have to be equal for both types of LEDs. Thus, the efficacy of the whole panel can potentially be between the highest performance of the red LEDs and the lowest performance of the white LEDs.

Although the efficacy decreases as the drive current increases, the output also increases (Figure 5). The photosynthetic photon flux described in Figure 5 is for one 0.09 m^2 panel, but the LEDs could be arranged over a wider or smaller area to decrease or increase the photosynthetic photon flux ***density*** (µmol $\boldsymbol{m^{-2}}$ s^{-1}), without a change in the photon flux (µmol s^{-1}) or power input.

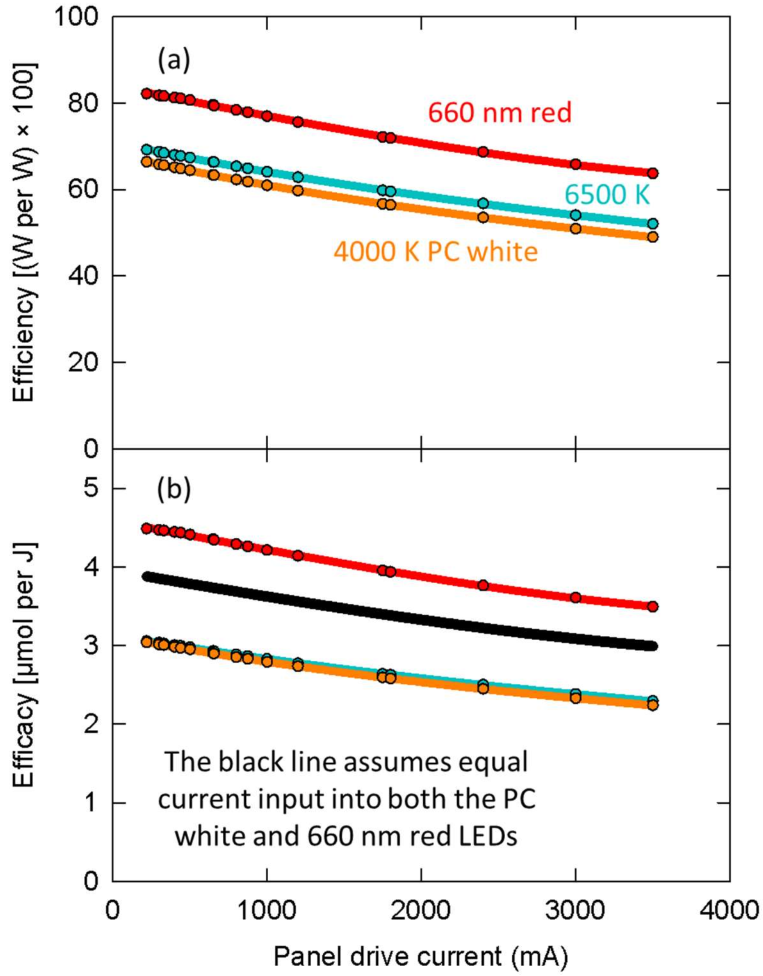

Figure 4. Current droop of the three types of LEDs used in these panels. (a) efficiency. (b) efficacy. Panel (b) also shows the average efficacy assuming the white and red LEDs are both operated at a 1:1 rate.

Under the lowest tested drive current (resulting in an input power of about 13.4 W) the photosynthetic photon flux (400 to 700 nm) is about 51.9 µmol per s, and the photosynthetic photon efficacy is 3.87 µmol per J for both types of panels (with either 4000 K or 6500 K PC white LEDs). Extending photosynthetic photons to include photons to 750 nm, the extended photosynthetic photon efficacy is 3.88 µmol per J for the panel with 6500 K LEDs and 3.91 µmol per J for the panel with 4000 K LEDs. Under nominal drive current through both types of LEDs, the photosynthetic photon flux is 192 µmol per s and the power consumption is 50.7 W, resulting in a photosynthetic photon efficacy of 3.79 µmol per J (Table 1). Additionally, under nominal conditions, 11 panels would cover a one square meter area and output 2100 µmol per s.

4.2 Additional Losses

In addition to current droop, LED fixtures experience decreases in output from three other losses: thermal droop, power supply inefficiency and optical losses.

It is difficult to determine the thermal droop that these LEDs would experience in a practical setting because it depends on the thermal management. Under the lower input power, the panels are more efficient and produce little heat. Running only the red LEDs at panel-level input

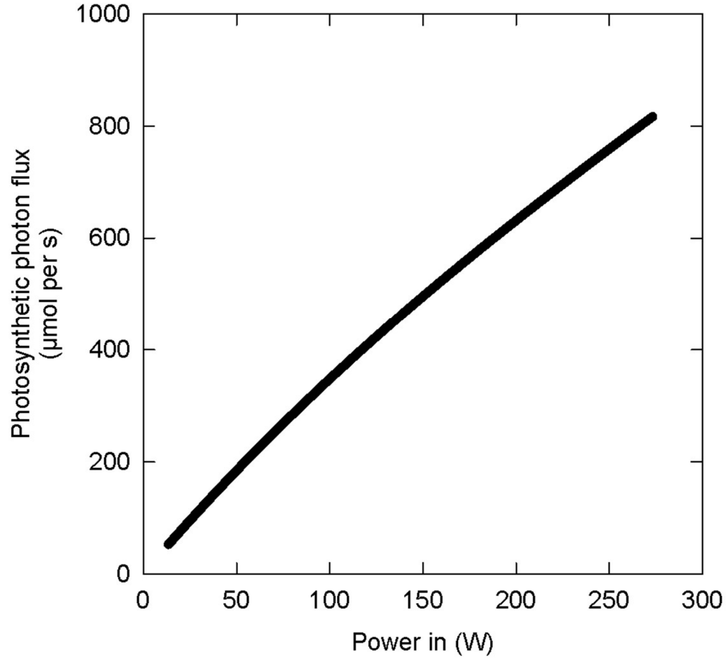

Figure 5. Photosynthetic photon flux as a function of input power for a single panel. This figure assumes that the white and red LEDs are both driven at the same current. The output of the two different types of panels (with 4000 K or 6500 K PC white LEDs) is approximately the same.

current of 500 mA with good air circulation resulted in a 4 ˚C increase in the panel temperature above ambient temperature. At higher input power, the operating temperature of LEDs within a fixture is often 40 to 80 ˚C above ambient temperature. This may result in a 5 to 10% decrease in photon output. Operating both the white and red LEDs at 1 A input at panel-level resulted in a panel temperature of about 20 ˚C above ambient temperature. Poor air circulation would result in reduced heat dissipation from the LED panel leading to a higher degree of self-heating. When these panels are operated at the lowest power input, we assume a low amount of self-heating resulting in a 2% decrease in output (which is likely a high estimate).

LED power supplies regulate current and voltage into the LEDs. These electronic devices are typically between 80 to 95% efficient. The LED power supplies used in our application are 95% efficient.

Optical losses, caused by the absorbance of low angle photons, are expected to approach 0%. Protection for the LEDs, especially when used in higher humidity environments, may reduce the output by 5 to 10%, but this reduction is often significantly lower. There is no additional protection in these LEDs (Figure 3), and thus the optical loss associated with incorporating the LEDs into the fixture could potentially result in a 1% loss, but since the LEDs were already incorporated into the fixture during the measurements in the integrating sphere, these losses have already been accounted for.

The resulting overall efficacy of the fixture under the lowest tested current (220 mA) would be:

$$3.87\ \frac{\mu\mathrm{mol}}{\mathrm{J}} \times 0.98 \times 0.95 \times 1.0 = 3.60\ \frac{\mu\mathrm{mol}}{\mathrm{J}} \tag{1}$$

This value is about 10% higher than any other white + red LED fixture that has been measured by the DesignLights Consortium (DLC). This is a rapidly advancing market and improvements are expected to continue for the next few years. The highest efficacy reported by the DLC is 3.69 µmol per J for a fixture with 4% blue and 96% red spectral output.

4.3 Spectrum and Color Rendering/Fidelity

The spectrum changed slightly with an increase in the drive current. This is caused by the different efficiencies of the red and white LEDs under different operating conditions. The ratios of different wavelengths along with the correlated color temperature (CCT), the Delta u,v (Duv), the CIE CRI Ra, and the TM-30-18 Rf are presented in Table 2.

Higher CCT values indicate a cooler (bluer) color of white light, while lower values indicate warmer (redder) color. A neutral white color facilitates color discrimination as spectral power is well distributed over the visible wavelength range; extremely low CCTs (less than 2000 K) generally have insufficient short-wavelength content to properly render blue colors, while very high CCTs (greater than 20,000 K) may not properly render deep red colors. CCT is often described alongside Duv, which is the distance to the black body locus/curve, and values closer to zero are preferable. Positive Duv values indicate a yellow/green color and negative values indicate magenta/pink color.

Ra and Rf are color rendering/fidelity metrics describing how natural colors appear to the human eye under these light sources. For both metrics, 100 is the maximum value. Operating the white LEDs at a higher input power than the red LEDs will increase Ra and Rf, but decrease the efficiency.

Regarding spectral effects on plant growth, the low fraction of blue will induce stem elongation and leaf expansion in many species, potentially increasing yields (Snowden et al., 2016; Kusuma et al., 2021). As discussed in the introduction, it is important to have some fraction of blue photons, as plants grown in the absence of blue have reduced yields (Yorio et al., 1998). One potential concern with the use of high red fixtures at high intensity is that this spectrum has been observed to lead to lower chlorophyll concentrations and increased photo-damage to plants (Zhen et al, 2021). These considerations, in addition to associated decreases in yield must be further studied.

To further demonstrate the importance of these color fidelity metrics, Figure 6 shows wheat plants growing under a 3:1, 1:1, and 1:3 ratio of the white (4000 and 6500 K) to red LEDs,

Table 2. Spectral output of the LEDs under the lowest and highest currents applied to the LED panels. The blue, green and red fluxes are expressed as a percent of the photosynthetic photon flux (PPF). Four metrics associated with human vision (CCT, Duv, Ra and Rf) are also provided. A higher Ra and Rf are preferable for human vision.

	6500K+Red		4000K+Red	
	220 mA	3500 mA	220 mA	3500 mA
%BLUE (400 to 500 nm)	10	9	6	5
%GREEN (500 to 600 nm)	17	16	17	16
%RED (600 to 700 nm)	73	75	77	79
PPF (400 to 700 nm)	52	818	52	816
Correlated color temperature (CCT)	2498	2361	2083	1980
Delta u,v (Duv)	-0.036	-0.039	-0.022	-0.024
CIE CRI Ra (Ra)	52	50	68	65
TM30 Rf (Rf)	65	60	71	65

based on input current. Higher fractions of red photons result in lower values of Ra and Rf, which can be seen to result in less green leaf color.

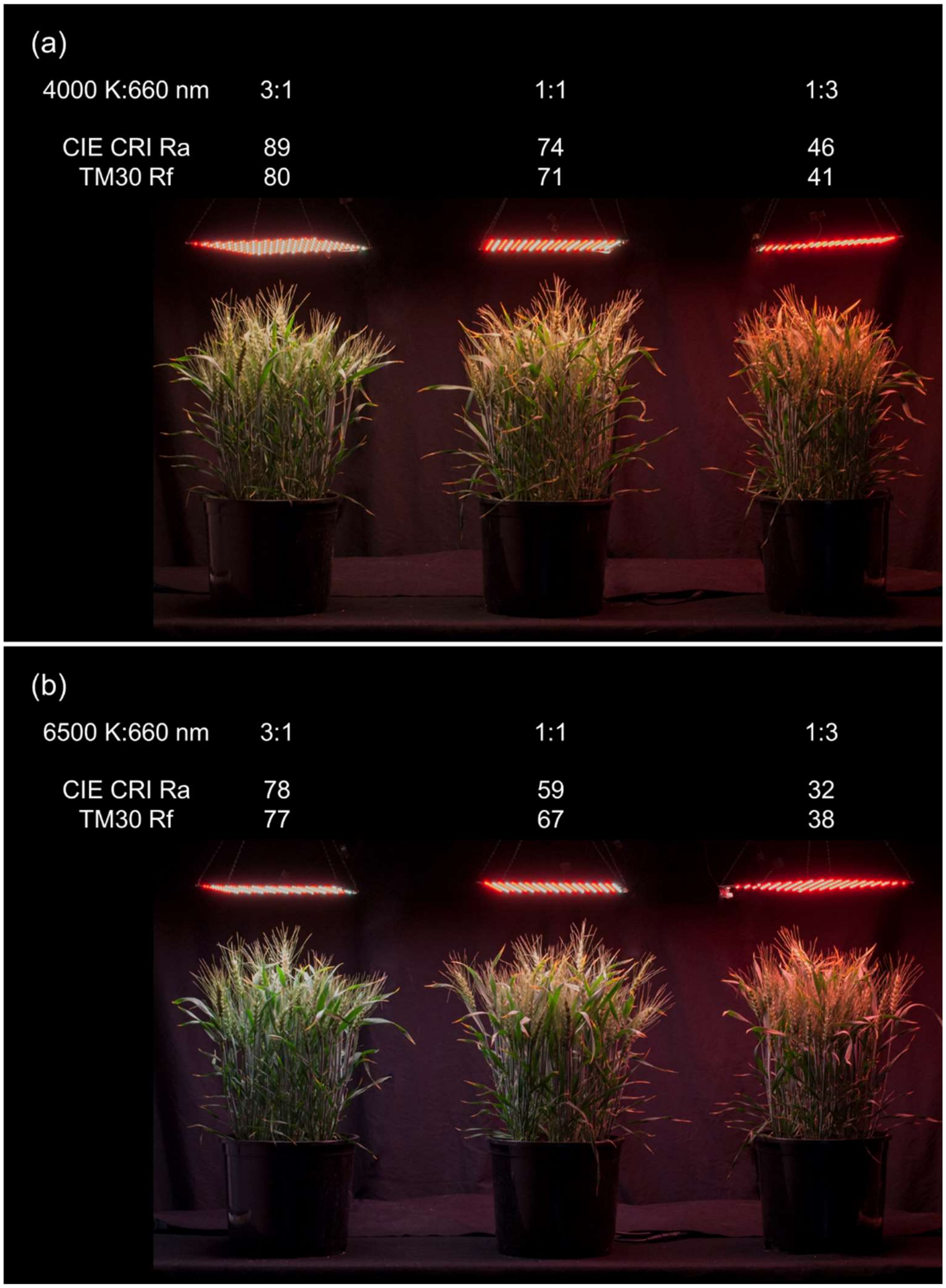

Figure 6. Visual quality of wheat growing under three white:red ratios based on input drive current – 3:1, 1:1 and 1:3. Total panel drive current was 2 A. Calculated CIE color rendering index (CRI Ra) and TM-30-18 color fidelity index (Rf) are provided for each light source. (a) has 4000 K white LEDs and (b) has 6500 K white LEDs.

Studies have investigated how active and passive interactions with plants can potentially benefit astronaut mental health following either 1) the Psycho-evolutionary Theory of stress reduction proposed by Ulrich et al. (1991), which proposes that benefits are unconscious and associated with familiar and safe spaces; or 2) the Attention Restoration Theory proposed by Kaplan and Kaplan (1989), which proposes that easy fascination with nature allows for the restoration of attention capacity. Both concepts are reviewed in Bates et al. (2010), Vessel and Russo (2015), and Odeh and Guy (2017). Studies associated with either theory have not specifically reported on the importance of plant color fidelity. It has been suggested that plants in cold/technical/artificial environments will not have the same restorative benefits as nature, because they would not be seen as a part of nature (Bringslimark et al., 2009), but this remains to be investigated. It seems likely that poor visualization of plants under higher red (and therefore higher efficacy) fractions would exacerbate this issue.

We compare Ra and Rf of the white + red panels operated under increasing fractions of red photons to other commonly used horticultural lighting fixtures. Blue + red fixtures, which can be potentially highly efficient (depending on the ratio of blue to red LEDs and the operating conditions), lack green photons, making the color fidelity under these light sources exceedingly poor (Figure 7). The white + red LED fixture shown in Figure 7 has a spectral output similar to the white + red panels demonstrated here when operated at a lower fraction of red photons, and thus the Ra and Rf values are similar. Finally, 1000 W double-ended HPS (DE-HPS) lamps are a common horticultural lamp that are used both in greenhouses and sole-source environments. Not only are 1000 W DE-HPS higher efficiency than their mogul base and lower wattage counterparts, but they also have higher values of Ra and Rf. But, these values for DE-HPS are still potentially half the efficiency and Ra and Rf compared to LED lamps.

Figure 7. Visual quality of wheat growing under a blue + red combination of LEDs (left), a white + red combination of LEDs (middle), and a double-ended high-pressure sodium lamp (DE-HPS; right). Calculated CIE color rendering index (CRI Ra) and TM-30-18 color fidelity index (Rf) are provided for each light source. The photon intensity under the light sources was uniform.

There is good evidence for the benefits of human-plant interactions, but many aspects remain unclear and unknown. Although we have shown differences in Ra and Rf under different light sources, the importance of this is not well known. Separate from psychological questions surrounding the color fidelity, higher Ra and Rf are important both for human and machine vision, especially in the identification of plant physiological disorders, nutritional imbalances, and pest abundance.

4.4 Testing at Utah State University

We show the operation of both types of LEDs in our canopy gas exchange system in Figure 8. We show the measured spectra in these chambers in Figure 9.

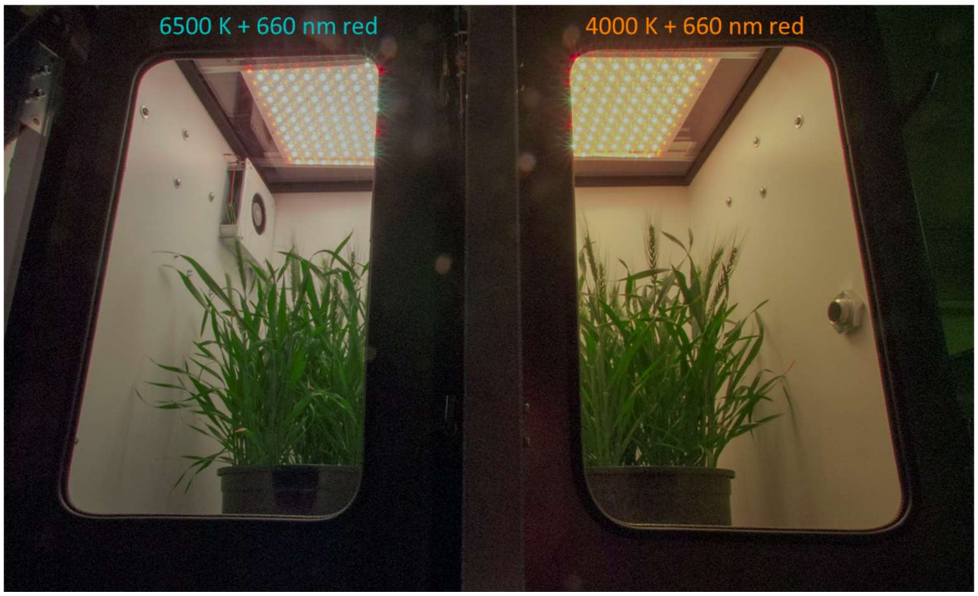

Figure 8. Both LEDs in a canopy gas exchange system. The 6500 K LED panel is on the left and the 4000 K LED is on the right.

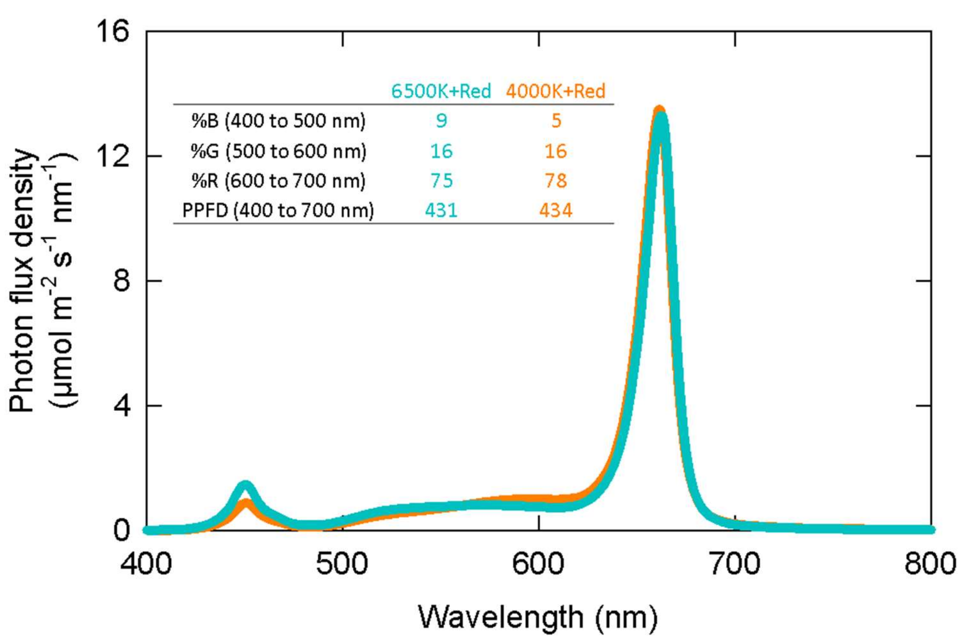

Figure 9. Measured spectral output inside a chamber at Utah State University. The input current was one ampere.

5. Concluding Remarks

These panels provide a demonstration of the high efficiency that LEDs can achieve. Although these LEDs are designed to output photons with high efficiency, they are still wasted if they are not absorbed by a plant, and instead hit the floor. Careful consideration in designing the rest of the system should be taken to maximize photon absorbance by the crop plants. Although we discuss their application for extraterrestrial agriculture, LEDs are regularly used in controlled environment agriculture, either greenhouses or plant factories. Therefore, these panels also demonstrate the capability of LEDs in these environments. These LED panels are lightweight and can readily be implemented in extraterrestrial applications. LED technology is expected to continue improving for the next few years, after which improvements will become increasingly difficult.

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