Growing food in space:

A comparison of LED and solar-fiber-optic technologies

Paul Kusuma, J. Matthew Hardy & Bruce Bugbee

Utah State University – Crop Physiology Laboratory

Abstract

Growing food on Mars for long-term space exploration has many benefits including reduced fuel and cost requirements for lift-off, improved nutrition and psychological benefits for astronauts, air purification, and oxygen and water regeneration. However, complications are caused by the thin atmosphere on Mars, which would force production underground or into a heavily armored shelter. Providing the massive number of photons necessary to grow food is expensive and careful consideration must be made regarding the most promising technologies. The two most promising options are a combination of either concentrating mirrors coupled to solar-fiber-optics (SFO), or photovoltaics (PV) coupled to light-emitting diodes (LEDs). Here we discuss the efficiency, equivalent system mass, and photobiological potential of both systems. Recent advances in PV and LEDs mean that they have caught up to SFO technology and now appear to be the superior technology.

Introduction

Providing food to crew members on a manned mission to Mars remains a logistical problem. There are two options: bring it or grow it. For a long mission to Mars, there is an opportunity for substantial savings by relying on self-sufficiency, as growing food can decrease launch weight and therefore save fuel and money. Determining how much to grow and how much to ship is dependent on many factors including, system productivity, system mass and crop perishability. Prepackaged foods currently have a shelf-life of 1.5 to 3 years (Anderson *et al.* 2018). Shelf-life is dependent on the crop, and certainly fresh leafy green crops are not available for astronauts unless they are grown.

Additional considerations include the general benefits of bringing plants on a long-term space mission include natural air purification, regeneration of oxygen and water, and psychological benefits. Several astronauts have reported the therapeutic benefit of having plants on the International Space Station (Odeh and Guy, 2017).

While there are advantages to growing food on a long extraterrestrial mission, there are abundant complications. The thin atmosphere of Mars transmits dangerous short wave radiation with wavelengths below 320 nm. Ozone in Earth's atmosphere absorbs most of this dangerous radiation. Additionally, the thin atmosphere on Mars does not provide protection from incoming meteorites. Together these factors indicate that the best solution for habitation is to grow plants below ground or in a heavily armored station.

In this closed, controlled environment, we consider two potential technologies to provide photons for plant production: concentrating

mirrors/solar fiber-optic (SFO) or photovoltaic/ Light-emitting diode (LED). These technologies will be analyzed by their current and near term equivalent system masses, an analysis that includes the system efficiency. Further, we will consider the photobiological potential of both systems including the factors of photon duration, intensity and color.

Efficiency

SFO system

Concentrating mirrors and fiber-optics do not require intermediate conversion into electrical energy and therefore have a high efficiency. An SFO system was 37.4% efficient in 2015 according to Nakamura *et al*. (2015), and it was predicted that the efficiency of this system could reach 64.6%. More recent estimates have estimated that it can be 76% efficient (Nakamura, personal communication).

LED system

LED technology has made huge advancements in the last two decades (DOE SSL 2017). Under the operating conditions of 100 mA mm^{-2} and low junction temperature of 25 C, cool white (6500 K), blue (peak 450 nm), red (peak 660 nm) and far-red (peak 730 nm) LEDs are now 76, 93, 81 and 77% efficient, respectively (Kusuma *et al.* 2020). Further decreasing the drive current density and temperature of the LEDs can further improve the efficiency by small but potentially significant amounts.

Incorporating LEDs into a lighting system introduced further decreases in efficiency, but with careful design these decreases can be minimized. Work is being done to design and demonstrate a high efficiency/efficacy (µmol of photons[A] per J of input energy) fixture for NASA. This system may be able to reach 80% efficiency, with an efficacy of 3.7 µmol per J (Wouter Soer, personal communication).

Photovoltaics have also improved but at a slower rate. The best PV technology on satellites can achieve an efficiency of 39.2%, but current technology on Earth has efficiencies less than 30% (NREL 2020).

The efficiency of both LED and PV subsystems are important to reach high overall system efficiency. One important consideration of this system is the direct current (DC) power produced by the PV system and required by the LED system. On Earth, power supplies (drivers) are used in LED lighting fixtures to convert alternating current (AC) to DC, as well as regulate the voltage and current to the LEDs. Good drivers are about 95% efficient, while medium grade drivers are about 80% efficient (Kusuma *et al.* 2020). If both subsystems run off direct current, this power conversion is unnecessary, and the overall system does not suffer this decrease in efficiency, but voltage and current regulation may still reduce efficiency. Wire length and subsequent wire mass need to be taken into consideration when considering the necessity of AC power.

If this system provided DC to DC power, then light would only be provided when natural light was supplied to the PV. Batteries for power storage could be an option to increase day lengths, but these are very massive. Unless otherwise stated, we will not assume energy storage in batteries.

[A]Photons, not energy, drive photobiology. This is due to the Stark–Einstein Law, which states that for every photon absorbed, only one molecule can react. This Law can be restated to say that one photon excites one electron.

Equivalent system mass analysis

Drysdale *et al.* (2008) used equivalent system mass analysis to determine an SFO system would be superior to an electric lighting system. This was largely due to the low efficiencies of electric lights and PVs, but technology has come a long way in 12 years. Additionally, they estimated the break-even time of an SFO system compared to shipping food to be as little as four years for a Martian base.

Not only must the relative efficiencies of each of these systems considered, but also the total mass of the system. This is called equivalent system mass (ESM), and it is calculated by the following equation (Levri *et al.* 2003):

$$ESM = M + V \cdot V_{eq} + P \cdot P_{eq} + C \cdot C_{eq} + CT \cdot D \cdot CT_{eq}$$

Where M is the system mass (kg), V is the volume requirement (m^3), V_{eq} is the volume mass equivalency (kg/m^3), P is the power requirement (kW_e), P_{eq} is the power mass equivalence (kg/kW_e), C is the cooling requirement (kW_{th}), C_{eq} is the cooling mass equivalency (kg/kW_{th}), CT is the crew-time requirement (CM-h/yr), D is the mission duration (y) and CT_{eq} is the crew-time mass equivalency (kg/CM-h/y). This equation converts all system requirements into a single mass term. The mass of a system is proportional to cost of the system, due to the enormous cost of fuel for liftoff. Volume and crew-time will be the same for both systems that we are comparing, so they can be removed from the equation. Additionally, any external power requirements (i.e. equipment that is outside of the system on the surface of Mars, like concentrating mirrors and PV) will rely on passive radiative cooling, and therefore will not be considered in the cooling calculations.

The photosynthetic photon flux density (PPFD, 400 to 700 nm) is normalized to 1000 µmol m^{-2} s^{-1} in both systems. This photon flux density, the driver of photosynthesis, must be converted to

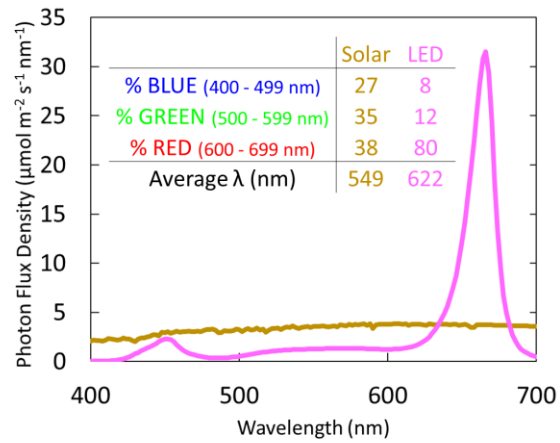

Figure 1: Assumed spectral photon distribution for the SFO and LED systems. Percentages and average wavelengths are also provided for each spectral trace. Notice the shift to longer wavelengths in the LED system. The LED system may be further tuned with continued photobiology.

an energy flux for ESM analysis. This calculated with Planck's equation (E = hc / λ), with requires an assumption of spectral photon distribution (SPD). The analysis for the SFO system assumes an SPD of sunlight on Mars (provided by Aaron Berliner). This spectral distribution is slightly different from the spectral distribution on Earth due to differences in atmospheric make-up and therefore absorbance (see below). However, it still has an average wavelength of about 550 nm. The LED system assumes a lighting system that has a 1:1 ratio of cool white (6500 K) and red (peak 660 nm) LEDs. This LED lighting system would provide about 80% of the PPFD as red photons (600 to 700 nm). Both the Martian solar spectra and the LED spectra used in this model are shown in Figure 1. The LED spectra is notably shifted to longer wavelengths compared to the solar spectra, which means for the same number of photons, it will introduce less photon energy into the system (192 vs 218 W m^{-2}). However, the SFO system is 100% efficient at transferring photons into the system, whereas the LED system in this model is only about 80% efficient

Table 1: Assumptions and calculations for ESM analysis. The ratio of the LED to SFO ESM is provided at the bottom of the table for both current and near term technologies. PAR refers to photosynthetically active radiation.

	Current Technology		Near-term	
	LED	SFO	LED	SFO
Energy in PAR (W)	192	218	192	218
Lighting efficiency	0.8	1	0.9	1
Power requirement (P and C)(W)	240	218	213	218
Collection (kg per kW)	26	53	20	35.9
Transmission (kg per kW)	8	136	8	21.2
Emission (kg per kW)	5	0	5	0
Total P_{eq} (kg per kW)	39	189	33	57.1
M_L (kg)	9.4	41.2	7.0	12.4
Total C_{eq}(kg per kW)	77	77	77	77
M_C (kg)	18.5	16.8	16.4	16.8
ESM (kg)	27.8	58.0	23.4	29.2
LED : SFO ESM	0.48		0.80	

with current technology, meaning it will also introduce heat.

The mass equivalencies of the SFO system were provided by Dr. Takashi Nakamura.

Our assumptions for current and near-term mass equivalencies, efficiencies and incoming radiation of both technologies on Mars are shown in Table 1. Additionally we demonstrate a calculation of the ESM for both systems using current and near-term assumptions in Table 1, and just near-term assumptions in Figure 2.

It is difficult to determine exactly how quickly technology will advance and how accurate our predctions for near-term mass equivalencies/ efficiencies are, especially for a system like the SFO. We note that there are many more people working to improve LED technology compared to SFO technology. Additionally, little work has been done to optimize LEDs for low mass.

The conclusions of Drysdale *et al.* (2008) have now been reconsidered with newer technology for both electric light (LED) and SFO systems. Our analysis demonstrates that rapid advancements in LED technology and slower advancements in PV tehnology have made this system much more competitive. Based on our analysis, the LED system is 52 and 20% less massive than the SFO system with current and near-term technology respectively. Sensitivity analysis is conducted in a forthcoming paper (Hardy *et al.* 2020).

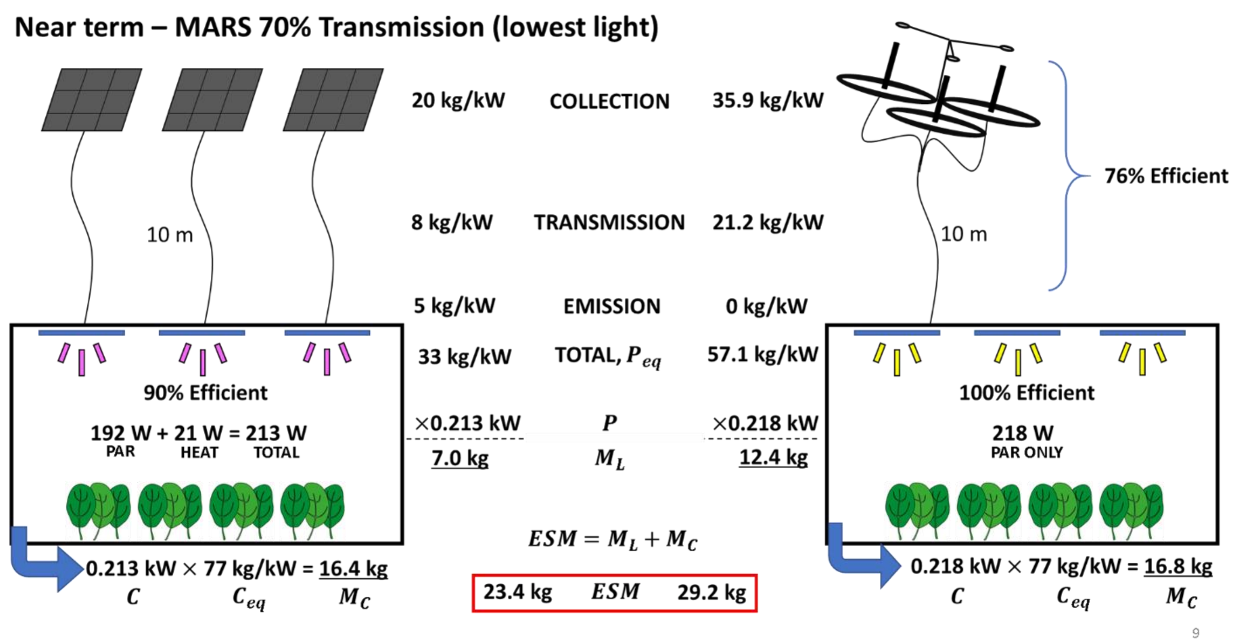

Figure 2: Model of ESM for both the LED and SFO system. Mass equivalencies and energy fluxes are provided in this diagram and an example calculation is performed.

Photobiology

Three aspects of light (photons) are important for plant growth and development: photoperiod (duration), quantity (intensity) and quality (color). These three parameters will now be considered for both the SFO and LED systems.

Photoperiod

Photoperiod is important for two main reasons: flowering and daily photon integral (DPI).

Short days plants (SDP) only flower if the day length is shorter than some critical photoperiod. Examples include soybeans and rice. Long day plants (LDP) only flower if the day length is longer than some critical photoperiod. Examples include lettuce and wheat. The critical photoperiods are species specific. Day neutral plants flower regardless of photoperiod. Examples include cucumber and tomato.

DPI, often called DLI (daily light integral) in the literature, is well correlated with yield. DPI is the integration of all the photons (400 to 700 nm) provided to an area during the entire day. Photosynthetic quantum yield (moles of carbon fixed per mole of photon absorbed) decreases as light intensity increases. There is a potential to increase growth rates and yield with the same total number of photons by lengthening the photoperiod and simultaneously reducing the instantaneous light intensity.

Wheat can tolerate constant light, but many other species, like tomato, suffer from constant light. For a crop like wheat, which will flower under constant light without a reduction in yield, it may be beneficial to grow plants for a longer photoperiod under a lower light intensity. Unfortunately the day-lengths in the system are heavily dependent on the natural day length on Mars.

The length of a day on Mars, called a sol, is about 40 minutes longer than a day on Earth. In addition to rotational speed, the tilt of Mars is surprisingly similar to the tilt of Earth's axis, at 25 degrees compared to 23.5 degrees. By contrast, a year on Mars is a little less than double an Earth year. Altogether, these factors will provide environmental day-length conditions similar to Earth at any given Martian latitude, but 'seasons' will last longer. It is hard to determine how dust storms will affect the photoperiod. These factors, all of which influence photoperiod, should be considered when determining the location of the base.

In a SFO system, the maximum photoperiod is entirely dependent on the natural photoperiod, but the minimum photoperiod can easily be shortened by removing the light into the system. This would reduce the overall photons provided to the plant, but this is an issue with all short day crops.

The LED system would be under similar constraints as the SFO system because the electrical power in our general model is provided by PV, which can only be provided during the day.

One important additional consideration is that the LED system can be electrically powered from sources other than sunlight. Nuclear power is one such option. Kilopower, a NASA nuclear power technology, is expected to produce 10 kW of power at a power equivalency of 150 kg/kW (Gibson 2018). This could supply constant power for LED lighting, and would allow for much greater manipulation of photoperiod.

Photon quantity

Yield increases with increasing light intensity. Intensity in both systems is constrained by the ability to collect solar power. Then, both systems concentrate the light to any desired intensity. As mentioned previously, quantum yield is higher at lower intensities. There is an important tradeoff, therefore, between growing area and light intensity. As photon quantity increases area

required to grow the food declines non-linearly (Wheeler 2002). The optimum between area and intensity is heavily dependent on the previously discussed ESM modelling, however both systems could be optimized in the same way, so it is not further considered here.

The intensity on the surface of Mars is about half the intensity on Earth (Clawson 2007). This is based on the inverse square law and differences in atmospheric constituents including dust storms. It estimates of radiation incident on Mars on the average day ranges between 19 to 26 mol m^{-2} sol^{-1}, depending on spatial and environmental conditions. This only really contributes to the total number of concentrating mirrors or PV.

Photon quality

Photons excite electrons and thus photobiology is driven by the number of photons, not energy or lumens. Biologically active photons must have sufficiently high energy to excite pigment

Table 2: Approximate ratios of wavelengths on Earth and Mars. These values can vary depending on environmental conditions and the time of day. Values for Earth come from the ASTM standard and values for Mars were supplied by Aaron Berliner.

	Percent of PPFD (400-700) Earth	Percent of PPFD (400-700) Mars
UV-B (280-319)	0.2	2
UV-A (320-399)	10	9
BLUE (400-499)	25	27
GREEN (500-599)	35	35
RED (600-699)	40	38
FAR-RED (700-749)	19	18
FAR-RED (750-800)	19	17

photoreceptors, and there are multiple photoreceptors with weighting functions for wavelengths, which are biophysically or empirically derived. Lumens are an example of a weighting function applied to a photon flux and spectral distribution for human visual function.

The effect of spectral quality on plant shape is synergistic among wavelengths, interacts with intensity, varies among species (Snowden *et al.* 2016), and may vary over the plant life cycle. Some principles, however, apply across all species.

In plant biology, spectra are traditionally separated into the following coarse categories: ultra-violet, blue, green, red and far-red. Ultra-violet and far red can be divided into further subcategories (Table 2).

In a SFO system, the base-line spectra is the solar SPD on the surface of Mars. The solar SPD of Earth and Mars are compared as percentages in Table 2. These percentages are normalized to photosynthetic photons (400 to 700 nm), and therefore blue, green and red percentages add up to 100%. There are minimal changes in the quality of the radiation between Earth and Mars, except for UV-B radiation, which is several times higher[B] on Mars as both a percent and as an absolute flux.

From this initial solar spectra, ratios of wavelengths can be altered with filters or beam splitting. Filters reduce system efficiency because they block the radiation, thereby requiring more concentrating mirrors for the same intensity. Because of this, it is unlikely that this technique would be deployed. Alternatively, the parabolic concentrating mirrors can be tuned with selective beam splitters to transmit or reflect certain wavelengths. Much of the

[B] The value for UV-B radiation (280 to 320 nm) on Mars is estimated from a model for values from 300 to 320 nm. This is because as the wavelength decreases the computational expense of scattering calculations increases exponentially.

infrared radiation (above 800 nm) in sunlight introduces an unwanted heat load, but some of this radiation is still useful for PV. These wavelengths are still concentrated by the mirrors and can be converted into electrical power using low band-gap PV cells (Nakamura *et al.* 2010). The wavelengths just above and just below the photosynthetic photons (ultra-violet and far-red) have the potential to be either beneficial or detrimental. The SFO system can include or exclude these wavelengths. This aspect of the technology has potential for increased optimization of the whole plant growth system.

Unfortunately, the fiber-optic cables have a fairly high absorbance at lower wavelengths (below 500 nm), and this effect is potentiated as the wavelength decreases. This means that these wavelengths will be reduced in the system compared to surface fluxes. The extent of reduction depends on the length of the fiber optic cables as absorbance is a function of path length. This is demonstrated in Figure 3. The impact this could have on plant growth is discussed below.

By contrast, LED technology provides the ability to dramatically alter SPD, but this can have a

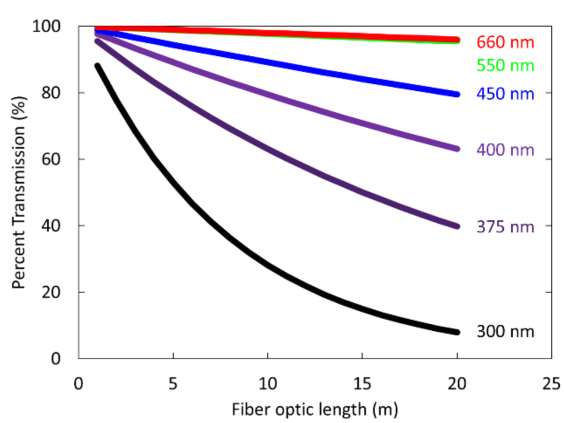

Figure 3: The decrease in transmission of specific wavelengths as fiber-optic cable length increases. Notice that the issue is much worse as 300 nm compared to 400 nm.

fairly large impact on efficiency. Assuming the sources of photons are 100% efficient, a spectra with all the photons at 400 nm would introduce 43% more heat into the system compared to a spectra with all the photons at 700 nm for the same photon flux density. Of course, different LEDs have different efficiencies, but this demonstrates the theoretical potential of choosing a longer wavelength spectra for food production, assuming photons can be efficiently produced. Based on the following discussion of spectral effects on plant growth and development, we conclude that the 'optimal' fixture is one that contains mainly red photons (centered at 660 nm) with a small addition of blue and green photons. Ultra-violet and far-red photons can also be added, but they must be applied with caution. It is for this reason that we assume an LED output that uses a combination of red and cool white LEDs at a 1:1 ratio in our analysis above.

Based on the literature, the following broad conclusions can be made regarding the five broad categories of wavelengths mentioned above.

Ultra-violet photons are separated into three broad categories: UV-C (100–280 nm), UV-B (280–315/320 nm), and UV-A (315/320–400 nm). The wavelength at which UV-C and UV-B are separated (280 nm) is determined by the shortest wavelength of solar radiation that reaches the surface of Earth. UV-C does, however, reach the surface of Mars due to its thinner atmosphere (Patel *et al.* 2002). The wavelength at which UV-B and UV-A are separated (315 or 320 nm) is generally determined by the effect of sun on human skin sunburn (315 nm) or skin cancer (320 nm). There is no universal agreement on the wavelength transition between UV-B and UV-A, both are equally used.

UV-C photons are ionizing and therefore they are dangerous to biological organisms.

UV-B photons are strongly weighted for biological effects including growth responses, DNA damage and sunburn (Flint and Caldwell, 2003; McKinlay and Diffey, 1987). They can be damaging, but they can also have beneficial effects including increased production of secondary metabolites like antioxidants (Dou *et al.* 2019). Further, UV-B appears to be required to reduce the physiological disorder intumescence, sometimes called Oedema. Symptoms appear as tumor-like growths on leaves and stems (Figure 4), which cause a decrease in photosynthesis and an increase in desiccation. It is a disorder that only appears in closed controlled environments, which led Lang and Tibbitts (1983) to test factors that had the potential to induce it. They found that the problem is reduced by the addition of ultra-violet radiation. Kubota *et al*. (2017) reported that 12.3 to 14 mmol m^{-2} d^{-1} of UV-B was required for completely removing intumescence in Beaufort tomato. Studies out of our laboratory have confirmed that UV-B completely removes intumescence, but it is very difficult to apply UV-B without causing damage. Further studies out of our laboratory found that the same amount of UV-B (14.7 mmol m^{-2} d^{-1}) was beneficial for tomato (cv. Maxifort), but detrimental to pepper (cv. Triton), two intumescent prone species. Clearly, there are different response thresholds for different species, and the thresholds of damage are still unknown.

Intumescence is actually somewhat uncommon, and only occurs in certain cultivars. Perhaps the easiest solution for avoiding intumescence in closed controlled environments is to avoid using the species that are known to get it. Similar to humans, the question as to whether UV-B is beneficial or harmful heavily depends on the wavelength, intensity, duration and species.

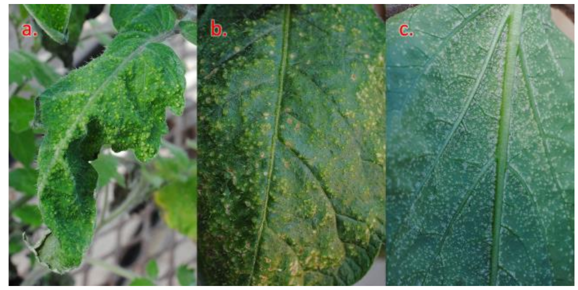

Figure 4: Intumescence on tomato cv. Maxifort (a), potato cv. Russet Burbank (b), and pepper cv. Triton(c).

UV-A photons are less damaging than UV-B, and can have either stimulatory or inhibitory effects on plant growth, depending on species and interacting environmental factors (Verdaguer *et al.* 2017). Studies out of our laboratory have demonstrated that UV-A may also be able to reduce intumescence, without the danger of being damaging.

In a separate study out of our laboratory, our data suggests that longer wavelength UV-A photons including violet photons are less effective at altering plant photobiology (anthocyanin accumulation and reduced leaf area) than blue photons at 450 nm.

Based on studies by McCree (1971, 1972), photosynthetic photons are only considered to be the photons with wavelengths between 400 and 700 nm. However, McCree's studies show significant differences in the photosynthetic efficiency of species at wavelengths below 425 nm. One example to demonstrate this is the drop in photosynthesis at 375 compared to blue photons (400 to 500 nm). Radish was shown to have approximately equal photosynthesis at 375 compared to blue, while sunflower was shown to have an 85% decrease in photosynthesis. McCree's data demonstrated that photons between 350 to 400 nm can be photosynthetic, but a high fraction are typically absorbed by non-photosynthetic pigments.

Photons in the UV-B region of the spectrum would be difficult to apply in a SFO system because they are highly absorbed in the fiber optic cables. In an LED system UV-B/UV-C LEDs are only about 3% efficient at 25 C and 350 mA (Kusuma *et al.* 2020). Therefore, both systems would have difficulty applying this radiation to plants, but small doses of UV-B can have large biological effects.

UV-A is also highly absorbed in the SFO system. Using a cable length of 10 m, as our ESM model assumes, the fiber-optic cables would absorb about 40% (60% transmission) of the photons with wavelengths at 375 nm. However, these photons are freely provided by the Sun and probably ought to be added, unless they reduce photon capture and decrease yields. At 25 C and 700 mA, the efficiency of UV-A LEDs increases from 50 to 60% as the peak wavelength increases from 370 to 395 nm. A violet LED with a peak at about 405 nm is about 65% efficient, and has 15 to 30% of its photons below 400 nm. Unlike the SFO system, these photons are not free, so much more careful consideration needs to be made as to whether or not to add them.

Blue photons (400–500 nm) reduce plant height and leaf expansion in many species (Snowden *et al.* 2016; Hernandez and Kubota 2016; Wang *et al.* 2016; Meng *et al.* 2019). Because of absorption by inactive pigments (e.g., anthocyanin), blue photons are about 20% less photosynthetically efficient than photons from the most common red LED (660 nm) (McCree 1971, 1972). However, the blue-induced decreases in leaf area (reducing photon capture) may have a larger effect on overall plant growth than the blue-induced reduction in photosynthetic rate (Snowden *et al.* 2016). Recent data out of our laboratory has suggested that photons at 450 nm are more effective at reducing leaf area than photons at 400 or 425 nm.

Overall, it can be generally concluded that lower blue is better, but these photons are also required for normal plant development. Adding about 10% blue photons to red LEDs achieved between 1.5 and 3 times more dry mass (Yorio *et al.* 2001). Goins *et al.* (1997) found similar results, but found that 1% blue was too little to induce this improvement in growth. Studies have determined that the minimal amount of blue required for 'normal' plant development is about 20 to 30 µmol m^{-2} s^{-1} (Yorio *et al.* 1998), but it is unknown how much this range of value interacts with intensity and other wavelengths.

In the SFO system, blue photons, like UV photons, are absorbed by the fiber optic cables, albeit to a lesser extent. It is possible that this overall reduction in PPFD, by only reducing the blue photons, will increase growth rates via an increase in leaf area and photon capture. However there is not much data behind this theory.

The most efficient common LED is a blue LED with a peak at about 450 nm (about 93%). The advancements in blue LEDs has been driven by the need for efficient indoor lighting, as blue LEDs are converted into white LEDs with a material called a phosphor (see below). Besides the 450 nm peak LED there are other blue LEDs, but they are less efficient and they appear to be less photobiologically potent. Due to the reduced plant size at high ratios of blue, the optimal LED spectra would likely only contain about 5 to 15% blue.

Green photons (500–600 nm) are typically thought to be non-photosynthetic because leaves reflect green photons and extracted chlorophyll appear to have minimal absorbance in the green region. However, they are up to 90% as photosynthetically efficient as photons from the most common red LED (660 nm) (McCree 1971, 1972), and they penetrate deeper into plant canopies than blue or red photons

(Brodersen and Vogelmann 2010).This means that the ‘effective’ PPFD is reduced on the leaf level basis, which has the potential to increase the leaf level quantum yield and increase overall canopy yields. This is because the leaves that are lower in the canopy are also photosynthesizing at the higher quantum yield. The higher absorbance of blue and red photons on the leaf level mean that the leaves at the top of the canopy have a low quantum yield and leaves at the bottom of the canopy are contributing to photosynthesis.

The effect of green photons on plant shape is generally much less than an equivalent number of blue or far-red photons. Studies in *Arabidopsis* suggest that green photons can reverse blue photon responses like the inhibition of hypocotyl elongation (Bouly *et al.* 2007; Sellaro *et al.* 2010), and further, other studies suggest green photons induce shade avoidance like increased stem elongation or reduced branching (Zhang *et al.* 2011; Wang *et al.* 2015). Some studies suggest that green-induced shade avoidance also occurs in food crops and other economically valuable plants (Snowden *et al.* 2016; Meng *et al.* 2019; Park and Runkle 2018), but many other studies show minimal effects (Snowden *et al.* 2016; Hernandez and Kubota 2016; Park and Runkle 2018; Li and Kubota 2009; Son and Oh 2015; Chen *et al.* 2016; Kang *et al.* 2016).

The most important reason to add green photons is to improve human perception of plant color, which aid in the identification of nutritional disorders (via human or machine vision). Furthermore, the psychological benefits mentioned in the introduction would not apply if the astronauts could not see the green color of the plants.

The SFO system does absorb a small amount of green photons in the fiber-optic cables, but even at 20 m, this is only about 5% (Figure 3). Therefore this system would supply an ample amount of green.

Unfortunately, monochromatic direct emitting (non-phosphor-converted) green LEDs have low efficiency of 42% (Kusuma *et al.* 2020). White LEDs are thus used to provide the green photons that are important to human vision; and they have the added benefit of providing blue and red photons. White LEDs are blue LEDs with a fluorescent material (called a phosphor) that absorbs some of the blue photons and re-emits them at longer wavelengths. There are two common phosphors used in white LEDs, a green phosphor with a florescence peak around 550 nm and red phosphor with a fluorescence peak around 630 nm. The green phosphor is typically more efficient than the red phosphor, but at low photon outputs (low drive current densities) the difference between the two types of phosphors is small. Our example spectra in the ESM analysis uses white LEDs with a correlated color temperature of 6500 K. This is colloquially referred to as a cool white LED. For maximum efficiency, the LEDs in the system would be run at low drive currents. It may be beneficial to further consider the amount and type of phosphor to use on the blue LEDs to achieve white light. Two main factors that would go into this consideration include color rendering and optimal amount of blue.

As technology improves, it is possible to create an improved LED system that uses direct green emitting diodes. These photons have lower energy than blue photons so the energy flux at the same PPFD would be lower with direct emitted green photons compared to phosphor-converted green photons (following the Stark-Einstein Law, one photon fluoresces one photon. White LEDs that only contain direct emitting LEDs are called color-mixed white, as opposed to phosphor-converted white. Color-mixed white light would also be created by amber (peak 590 nm) and red/orange LEDs (peak 630 nm).

Photons from these LEDs have even lower energy than green photons, and therefore they have the potential to further reduce the energy flux into the system. Their addition would improve the color rendering over blue/green/red alone. Unfortunately green, amber and red/orange LEDs are all currently inefficient. This is called the “green-gap” and it is difficult to determine how rapidly the technology will improve.

Red photons (600–700 nm) are well absorbed by leaves, and they are photosynthetically efficient.

The classical paradigm has been that red and far-red act antagonistically to inhibit or induce shade avoidance symptoms, such as stem elongation, hyponastic leaf orientation, and/or reduced branching (Smith 2000; Casal 2012). However, the high absorbance of red photons by chlorophyll means that the impact of red on shade responses may be overestimated (Morgan and Smith 1978). Replacing green photons with red photons has minimal effects on plant shape (Son and Oh 2015; Kang *et al.* 2016). These lower relative effect of red photons compared to blue photons may be explained by the fact that most studies start with a high portion of red photons as the ‘background’ and therefore altering the spectra only changes the percentage of red by 20 to 30%, whereas the amount of blue is doubled or even tripled in a study. Plants grown in the complete absence of red and green photons (sole-source blue LEDs) can rapidly elongate (Snowden *et al.* 2016; Hernandez *et al.* 2016; Kong *et al.* 2018).

Like with green photons, red photons would be easily provided by a SFO system, and in fact, they would be the largest portion of the total flux (Table 2). There is an efficient red LED with a peak at about 660 nm. These red LEDs would make up a large portion of the growing spectra because the LEDs are efficient, the photons are energetically low compared to shorter wavelengths, and they have a high photosynthetic efficiency. However there may be a few reasons to be slightly wary of such a high portion of red in the plant growing spectra including poor color rendering index for human vision and possible photo-bleaching at high light intensities.

Far-red photons (700–800 nm) can have powerful effects on plant shape. Chlorophyll heavily absorbs radiation in the 400 to 700 nm region and transmits much of the radiation beyond 700 nm. Plants have evolved to sense this relative increase in far-red to tell them if they are in the shade. Plants are often categorized as either shade avoidant or shade tolerant. While definitions may vary, it is useful to categorize plants as shade avoidant if they increase stem length more than leaf area and shade tolerant if they increase leaf area more than stem length. These categories inform whether it would be advantageous to apply this radiation on a crop in a controlled environment. An increase in leaf area increases photon capture and therefore also increases yield and growth rates, while an increase in stem length decreases structural strength, which leads to a higher chance of physical damage. In addition, longer stems mean carbon is allocated to organs (stems) that are not beneficial. Generally, shade avoidance has been associated with decreases in yield (Robson *et al*. 1996; Sawers *et al*. 2005).

Lettuce and other leafy greens are generally shade tolerant. Because these crops have a short shelf-life, are nutritious and have a high harvest index (meaning a high portion of their total produced biomass is edible), they are some of the first choices for off-world agriculture. Many agronomic crops (e.g. rice and wheat) have generally appeared to be far-red insensitive. While agronomic crops have the benefit of being calorically rich, they can be much more easily stored and brought rather than grown.

Despite the classically defined range of photosynthetic photons (400 to 700 nm), recent studies indicate that far-red photons (700 to 750 nm) are photosynthetically synergistic with shorter wavelength photons (Zhen and Iersel 2017; Zhen and Bugbee 2020). These photons are thus being reconsidered for their role in photosynthesis. Recent data out of our lab has shown a slight decrease in quantum yield in lettuce with an increasing amount of far-red photons from far-red LEDs, but due to an increase in leaf area there was an overall increase in yield. Like with ultraviolet, far-red must be used with caution. But, because of the value described here, and because of the low energy of these photons, they are a promising addition.

Like with ultra-violet photons, the SFO system can be tuned to include or reject far-red photons. And, as with ultra-violet, these photons are free, so there is a good argument for their inclusion. The reason to exclude them is if they increase stem elongation too much in certain species, but greenhouses transmit these wavelengths without much issue.

Far-red LEDs (with a peak at 730 nm) are readily available and are 77% efficient at 25 C and 100 mA mm^{-2} (Kusuma et al. 2020). These LEDs peak right where the photoreceptor that senses far-red is most responsive. They would likely be included in the optimal LED spectra, but more work needs to be done to see what the optimal amount is under different conditions, and therefore, for now, they should be applied with caution.

Conclusion

Overall, we believe our analysis shows that advancements in technology mean that an electric system that utilized LEDs will be superior for growing plants on Mars compared to a solar-fiber-optic system. This is due to the lower ESM and the ability to optimize the spectrum with the LED system.

Some estimates by nutritionists suggest that a healthy diet for astronauts may require upwards of 100 kinds of vegetables. A majority of the diet will come from high calorie agronomic crops, but it is still important to optimize the system for all crops. This can be achieved with a manipulation of the spectrum using LEDs. Further research is required to understand how wavelengths interact with each other, and how spectral quality interacts with photon intensity and species.

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