BioChambers
PROVIDING GROWTH TO RESEARCH.

LED Lighting Options

By Patrick Friesen, PhD

1. Standard LED lighting option for general plant growth: PhytoFlux

BioChambers' PhytoFlux LED lighting system delivers a broad and balanced spectrum across the majority of our products. The light intensity (PPFD, Photosynthetic Photon Flux Density, 400-700nm) capabilities of PhytoFlux can grow everything from *Arabidopsis* to maize or hemp; it can be dimmed from 10 to 100% and easily provide PPFD ranging from 150 to 1200 or higher at leaf level.[1] The well-balanced color ratios and proportions of PhytoFlux provide a balanced spectrum for general plant growth and research (Table 1; Figure 1)[2]. PhytoFlux provides built-in spectral control; one channel provides PAR (400-700nm) and the other channel Far-Red (701-750nm). When set to a 1:1 intensity ratio, PhytoFlux provides a balanced spectrum, but can also provide a wide range of spectra and far-red PFD (Figures 2 & 3). Combined with our scheduling software, the wide range of spectra and achievable far-red PFD allow for custom light recipes or treatments from day to day or week to week. Light recipes or treatments can be used for production applications, such as aiding the transition to flowering and reproductive development (eg. speed breeding), controlling morphology, as well as other phytochrome-based research including the shade-avoidance syndrome (Figure 3).[3-5] To complement the PhytoFlux LED lighting system, a sensor that measures PPFD and far-red PFD independently is provided with every chamber and room. PPFD and far-red PPFD combined gives ePPFD, and the independent outputs can be used to infer a given spectrum.

Table 1: Comparison of light quality parameters (relative photon flux density, PFD) between BioChambers' PhytoFlux LED system and direct sunlight (spectra of Figure 1). PhytoFlux provides a balanced spectrum for general plant growth and research. For more information on light quality and plant growth, please read *How does the spectrum of my light source affect the growth of my plants?*[2]

	%Blue (400-500/ 400-750nm)	**Blue:Green**[6] (405-486/ 492-573nm)	**%Red** (600-700/ 400-750nm)	**Red:Far-red**[7] (655-665/ 725-735nm)	**%Far-red** (701-750/ 400-750nm)	**Phytochrome PhotoStationary State (PSS)**[8]	**Far-red Fraction**[9] Red = 645-665nm Far-red = 720-740nm
Direct Sunlight	23.7	0.78	31.7	1.14	14.6	0.72	0.47
PhytoFlux (PAR = 50%, Far-red = 50%)	15.0	0.51	38.1	1.84	11.7	0.80	0.36

1.1 Why does BioChambers include far-red capability standard for general plant growth?

BioChambers includes far-red standard to provide a broader light spectrum more similar to sunlight compared to fixtures that only provide radiation from 400 to 700nm. In several plant species, far-red enhances growth by stimulating leaf expansion and photosynthetic rate (net CO_2 assimilation) and regulates phytochrome based processes such as stem elongation, flowering time, and tillering in grasses.[10-14] Currently, extended PAR (ePPFD, sum of photons from 400-750nm) has been proposed as another light intensity measurement to report alongside PPFD.[15] To complement the PhytoFlux LED lighting system, a sensor that measures PPFD and far-red PFD independently is provided with every chamber and room. PPFD and far-red PPFD combined gives ePPFD, and the independent outputs can be used to infer a given spectrum.

For more information on how light quality and far-red affect plant growth and development, please read *How far-red photons affect plant growth and development: a guide to optimize the amount and proportion of far-red under sole-source electric lights*[4] and *How does the spectrum of my light source affect the growth of my plants?*[2]

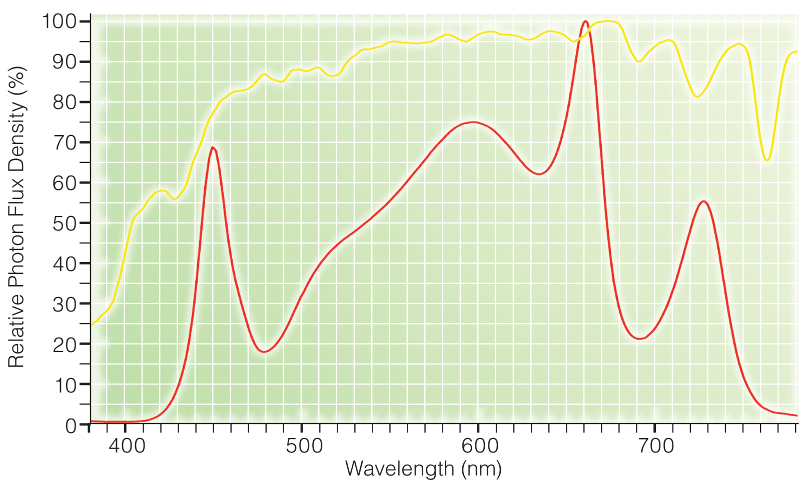

Figure 1: Spectral comparison of BioChambers' PhytoFlux LED system and direct sunlight. BioChambers' PhytoFlux LED system measurements are both channels PAR and far-red set to 50% intensity (1:1 ratio) inside a TPC-19 growth chamber. Measurement of direct sunlight taken September 6, 2019 in Winnipeg, Manitoba, Canada, midday, under a clear sky.

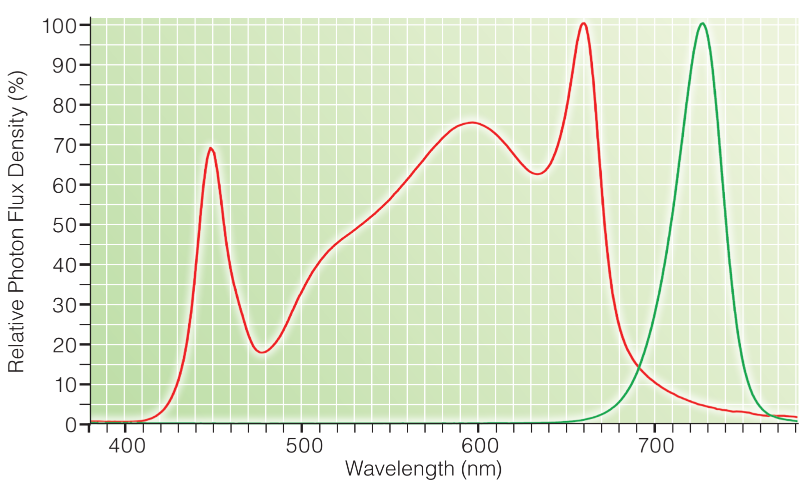

Figure 2: Spectral comparison of the two channels in isolation of BioChambers' Phytoflux LED system. Measurements were taken in a TPC-19 growth chamber at 20°C.

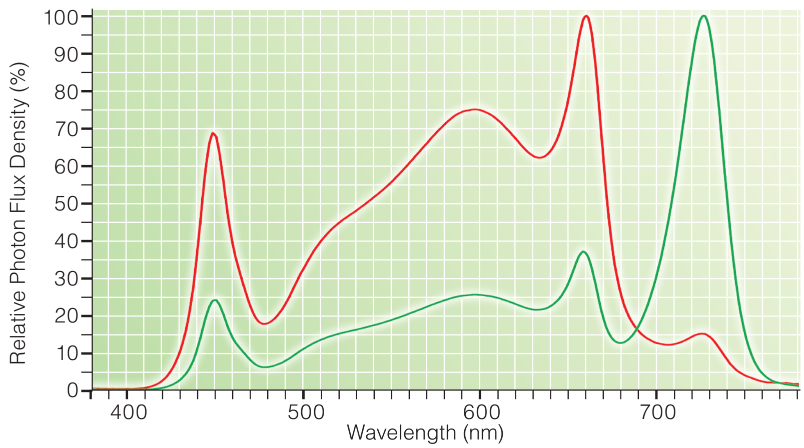

Figure 3: Comparison of the range of spectra possible with BioChambers' PhytoFlux LED system when both channels (PAR and far-red) are at their highest and lowest intensity set-points. Measurements were taken in a TPC-19 chamber at 20°C.

1.2 Lighting for plant tissue culture and micropropagation

Plant tissue culture is used for genetic engineering, and is integral to CRISPR/Cas9 gene editing.[16] Micropropagation is another tissue culture application with the goal of efficiently multiplying plant material into many more robust autonomous plantlets that are genetically identical to the mother plant material. Lighting is one factor in successful tissue culture operations, including growth medium composition, temperature, aseptic technique, and ventilation (especially for photoautotrophic micropropagation).[17, 18] Often the most important factor for successful plant tissue culture lighting is the ability to achieve uniform light intensities <100 PPFD.[17] These low light intensities are critical to develop shoots; to green up and begin to transition heterotrophic cultures into photosynthesizing autotrophic plants. During the 1960s and 1970s basic light quality requirements and their functions for tissue culture became known; blue light stimulates culture growth and shoot formation whereas red light can stimulate root formation.[17,19] We now know that light quality affects greening plant tissue cultures in similar ways as young seed started plantlets.[20,2] Broad spectrum white fluorescent lighting dominated plant tissue culture until the mid-2010s, when the switch to LEDs began in earnest.[21] As in fully functioning plants, white LEDs can produce comparable tissue culture outcomes to white fluorescents.[22-24] In general more comparable outcomes would be expected under lamps of similar color temperatures, with some caveats.[21] By combining white and monochromatic LEDs we now have virtually limitless spectral possibilities. Recent LED tissue culture studies have re-affirmed and built upon initial light quality work from the 1960s and 1970s, for example that red rich spectra can stimulate relatively greater root growth in some species.[25,26] The multitude of light qualities LEDs can provide is revealing that some tissue culture responses are species specific.[20,21] We still have much to learn in optimizing light quality for a given tissue culture goal for a given species, and about how light quality interacts with other environmental conditions.[21,27,28] Despite the diversity of light quality responses, successful transition of tissue cultured plantlets to other growing environments (growth chamber/greenhouse/field) requires gradually increasing the PPFD and vapor pressure deficit (VPD).[29] Currently we offer PhytoFlux, T5 LED, or Fluence RAZR systems for plant tissue culture equipment. (Table 3, Figure 4).

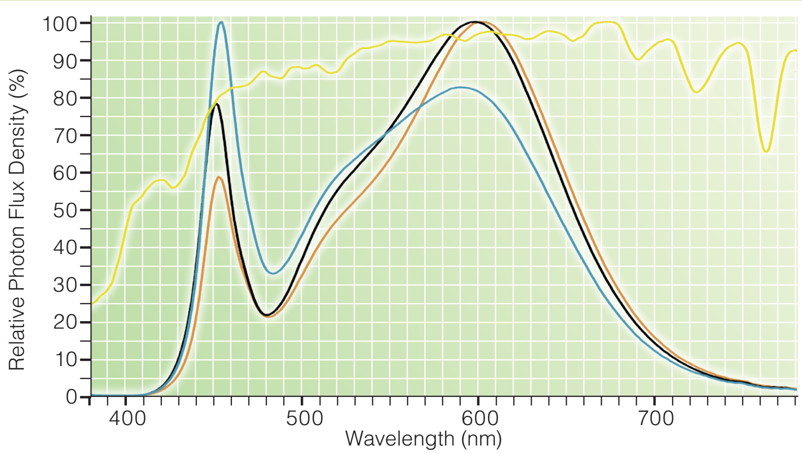

Figure 4: Spectral comparison of 3500K, 4000K, and 5000K Philips InstantFit T5 LED tubes (24W, type A) and direct sunlight. Measurement of direct sunlight taken September 6, 2019 in Winnipeg, Manitoba, Canada, midday, under a clear sky. Measurements of Philips T5 LED tubes are from limited sample sizes.

2. LED replacements for T5 and T8 fluorescent tubes

2.1 White T5 and T8 LED tubes

Driven by the increased efficiency and longevity of LEDs, several companies have developed white T5 and T8 LED lamps to replace white fluorescent tubes. White T5 and T8 LED lamps were developed to replace indoor lighting for humans, and because visible light and PPFD have overlapping wavelength ranges (400-700nm), fortunately white T5 and T8 LED fixtures can grow plants. T5 and T8 LED fixtures can likely be swapped with fluorescents in your existing equipment (verify ballast and lamp compatibility). We can also still build new equipment with a T5 lighting option, in situations where you want to swap out tubes of different color temperatures to change the spectrum, or are hesitant to move to LEDs. Our experience has shown T5 LED tubes provide similar PPFD as fluorescents inside growth chambers, while using only half the power, which is good for your facilities' electricity bill and the planet (Table 2)!

Table 2: Comparison of the average photosynthetic photon flux density (PPFD) between Philips InstantFit T5 LED tubes (Type A, 24W, 5000K white) and Sylvania T5 fluorescent tubes (54W, 4100K white). Measurements were taken 15cm (6") from the lights at 20°C.

	Philips InstantFit T5 LED tubes (24W)	Sylvania T5 fluorescent tubes (54W)
Chamber 1	1378	1373
Chamber 2	851	844
Chamber 3	542	548

With any T5 tube or E26 bulb, ensure product quality and safety through product reviews and certification (UL, CE, ETL, CSA).

2.1.1 How-to switch from white fluorescents tubes to white LED tubes

Step 1: Determine the best type of T5 or T8 LED tube for your needs and situation

T5 and T8 LED tubes come in three types: A, B, or C.[30] Type A tubes are the simplest and easiest to install and replace your fluorescents with, simply swap them with your existing fluorescent tubes. Aside from getting the appropriate tube length (4 ft. tubes on newer equipment), **you must check that your desired type A LED replacement tubes are compatible with your existing fluorescent light ballasts.** Occasionally, two or more growth chambers or rooms of the same model and lighting system may have different ballasts. Contact us with the serial numbers of all growth chambers or rooms you intend to retrofit; we will send you the ballast information. Finally, check the dimming compatibility of your desired LED tubes if you have a dimmable fluorescent lighting system.

Type B LED tubes bypass your existing fluorescent ballasts and require re-wiring of your lighting system by a qualified electrician. The advantages of type B LED tubes are greater efficacy (PPE) and the elimination of the ballast as a failure point for the lighting system.[31] Type C LED tubes come with their own external power driver and also require re-wiring of your lighting system by an electrician to bypass your existing fluorescent ballasts. Having their own external power driver gives type C LED tubes even greater efficacy (PPE) over type B tubes and gives them dimming capabilities. The drawback of type C LED tubes is their often greater cost compared to type A or B tubes.[30]

Step 2: Select the spectrum (color temperature) of your white LED replacement tubes

White LEDs, like fluorescents, come in a range of color temperatures. Color temperature is the color a perfect black body radiator would emit at a given temperature (in degrees Kelvin). Color temperatures range from 1000K to 10000K and are used to describe how "warm" or "cool" a light source is. The lower the color temperature, the warmer (more orange) a light source is, and the higher the color temperature the cooler (more blue) a light source is, with 5300K appearing almost perfectly white and balanced to our eyes. White LEDs are blue LEDs that are coated with yellow phosphor to varying amounts; more phosphor coating results in warmer (lower) color temperatures.[32] Our experience and the literature has shown white LEDs from 3500K to 5000K can grow healthy plants and *Arabidopsis* that are comparable to those grown under white fluorescents (Table 3, Figure 4).[33-35] White LEDs also generally have a high color rendering index (CRI), which means colors appear truer to our eyes the higher the CRI. Because of their greater CRI, plant health and pathogen identification can be easily assessed under white LEDs, and provides workers with a spectral environment similar to other indoor locations. In contrast to white LEDs, red + blue or high red + white LED systems have lower CRIs and are more prone to cause eye fatigue. Another metric, the color fidelity index (CFI) is being proposed as an improved measure for color perception over the more widely reported CRI.[36]

A white LED color temperature close to 4000K may be the most robust choice for consistent growth across a number of plant species. As you move from 3500K to 5000K white LEDs you increase the amount and proportion of blue at the expense of red, similar to fluorescents (Table 3, Figure 4). In this way, matching the color temperature of your new white LED replacement tubes to your existing fluorescents will generally best match plant growth. Certain aspects of plant growth may be different in plants grown under 3500K compared to 5000K white LEDs. Evidence suggests the biggest differences in plant growth between 3500K compared to 5000K white LEDs relate to the amount and/or proportion of blue. 5000K (more blue) white LEDs will stimulate cryptochrome based processes more than 3500K (less blue).[33,34] In house work with CANOLA has shown shorter hypocotyls under 5000K compared to 3500K, similar to what has been reported for other *Brassica*.[2, 37] Depending on the species, moving from 3500K to 5000K may cause other aspects of plant compactness to increase, however in some crops like CANOLA and radish, overall growth (dry biomass) is not statistically different > 20 days after emergence between 3500K and 5000K (reference 19, in house research). Across lettuce, radish, and pepper, 4000-4500K (blue peak close to but not higher than 600nm central hump) white LEDs may be most universally optimal for growth and dry biomass.[34] What all white LEDs have in common is a lack of appreciable far-red. Because they lack appreciable far-red, white LEDs have a low Far-red Fraction and high Phytochrome PhotoStationary State (PSS) (Table 3), and (like fluorescents), will show relatively low levels of far-red induced phytochrome effects.[4,2]

Table 3: Comparison of light quality parameters (relative photon flux density, PFD) between direct sunlight, white T5 LED tubes, a white fluorescent T5 tube, and a CFL bulb of different color temperatures. Similarly, for both white LEDs and fluorescents, the proportion of blue increases (at the expense of red) as color temperatures increase. For more information on light quality and plant growth, please read ***How does the spectrum of my light source affect the growth of my plants?***[2] Measurements of LED and fluorescent light sources are from limited sample sizes.

	%Blue (400-500/ 400-750nm)	**Blue:Green**[6] (405-486/ 492-573nm)	**%Red** (600-700/ 400-750nm)	**Red:Far-red**[7] (655-665/ 725-735nm)	**%Far-red** (701-750/ 400-750nm)	**Phytochrome PhotoStationary State (PSS)**[8]	**Far-red Fraction**[9] Red = 645-665nm Far-red = 720-740nm
Direct Sunlight	23.2	0.78	31.1	1.14	14.4	0.72	0.47
3500K Philips Type A T5 LED tube	14.6	0.42	39.3	6.86	2.8	0.86	0.12
4000K Philips Type A T5 LED tube	17.2	0.47	35.5	7.05	2.4	0.85	0.11
5000K Philips Type A T5 LED tube	23.2	0.60	30.0	6.42	2.2	0.85	0.12
4100K Sylvania T5 fluorescent tube	19.9	0.43	34.3	6.12	3.2	0.82	0.15
2700K Sylvania CFL fluorescent bulb	13.7	0.34	45.3	15.48	3.5	0.85	0.07

2.2 Multi-color and pure red T5 LEDs

Some manufacturers have integrated a range of white color temperatures, red, and possibly even far-red LEDs into a single T5 tube to create a variety of spectra to choose from. A red peak may be desirable to add to your spectrum, especially if you are adding far-red only LED flowering bulbs. Adding only far-red to white LEDs without a higher red peak can exacerbate far-red's phytochrome effects, potentially causing a strong shade avoidance syndrome (Figure 2 *in* reference 4). As discussed in the previous section, increasing the red fraction in a white LED background will reduce the color-rendering index (CRI) of the growth environment.[21] Finally, a red dominant spectrum at high PPFD can cause photobleaching in *Cannabis* sp..[38] How much other plant species are similarly photobleached and how this occurs is a current area of research.

3. LED replacements for halogen/incandescent (E26) sockets

For any E26 replacement lamp, you must ensure the wattage (W) of replacements do not exceed the rating of the chamber design. However, with replacement LED lamps it is unlikely to exceed the rated wattage.

3.1 Red + far-red and far-red only directional LED flowering lamps to replace halogens in vertically mounted halogen E26 sockets

If you have vertically mounted E26 sockets in your lighting system, there are several directional LED replacement lamps that could potentially replace halogens or incandescents. Here we focus on directional E26 LED lamps that provide appreciable far-red, which is in part what halogens provided. Some of these "flowering" lamps provide some white + red + far-red (eg. Philips Flowering 2.0 or 2.1), red + far-red (eg. Total Grow Pure Flowering 200), or only far-red (eg. Philips Flowering 1.0) (Figure 5). E26 LED lamps are called such due to phytochrome effects of appreciable far-red, which among other effects, hasten flowering in long-day plants.[4] These E26 flowering LED lamps use less power than halogens, but have substantially greater output in the red and far-red regions (Figure 5). These flowering lamps have the potential to dramatically alter your spectrum and provide too much far-red and/or red for your application and plant growth goals (Figure 5). It is important that these directional LED flowering lamps are only used in vertically mounted E26 sockets; even if they can physically fit in horizontally or angle mounted sockets/ lighting canopies, due to their directionality you will have poor spectral uniformity (Figure 6).

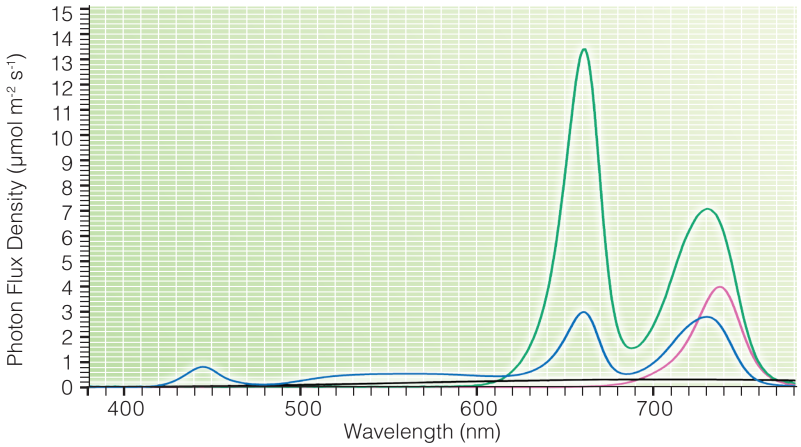

Figure 5: Comparison of spectra and output (PFD) between 25W halogen bulbs and various LED flowering lamps suitable for vertically mounted E26 sockets. Measurements were taken inside a reflective (mirrored) light box at the same distance from the vertically mounted socket (45cm) at room temperature. PFD far-red = sum 701-750nm. Measurements of LED and halogen light sources are from limited sample sizes.

- **Philips 13W GP LED Flowering Lamp 1.0** (PFD far-red: 140)
- **TotalGrow 17W Pure Flowering 200 Lamp** (PFD far-red: 296)
- **Philips 25W Halogen** (PFD far-red: 24)
- **Philips 11W GP LED Flowering Lamp 2.0** (DR/W/FR) (PFD far-red: 110)

Philips 9.3W GP Flowering Lamp 2.1 (DR/W/FR) (used in Figure 8) has the same spectrum and output as the GP Flowering Lamp 2.0

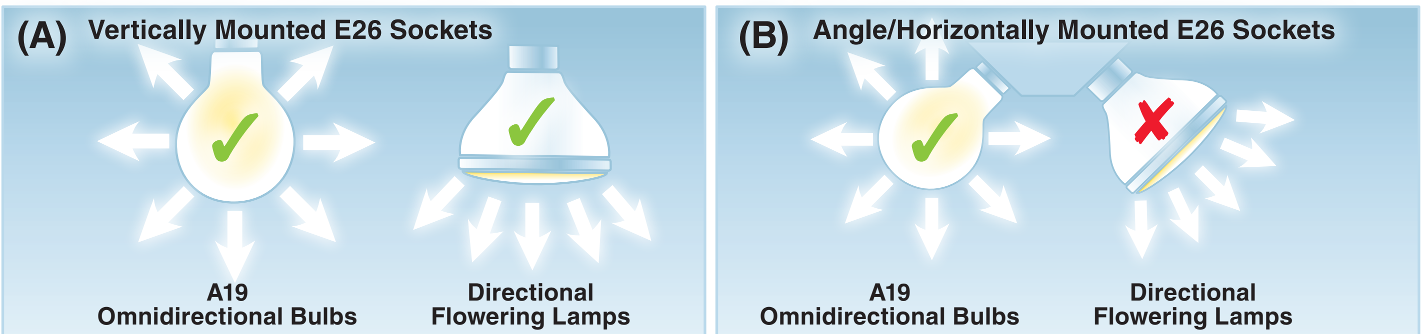

Figure 6: For vertically mounted E26 sockets (A), either A19 style omnidirectional bulbs or directional flowering lamps can be used. For angle or horizontally mounted E26 sockets (B), only use A19 style omnidirectional bulbs for uniform lighting/spectral conditions.

3.2 Very warm white (amber) and red omnidirectional (A19 bulb shape) LED replacements for horizontally, angle, or vertically mounted halogen E26 sockets

For horizontally or angle mounted E26 sockets you will need omnidirectional A19 bulbs to achieve good spectral uniformity. Again, here we focus on bulbs that provide some far-red to act as a sort of halogen replacement, although most or all major commercial lighting manufacturers also make these bulbs with white LEDs. The A19 LED bulbs that show the greatest far-red PFD are very warm white (2000K amber) and red bulbs. Among bulbs we could easily find, even the bulb with the greatest far-red PFD has somewhat less far-red PFD than a 25W halogen (Figure 7). Of the bulbs we tested, an omnidirectional 9.5W Anew A19 bulb from TCP has the greatest far-red PFD, closest to a 25W halogen (https://www.tcpi.com/anew/) (Figure 7). Some "white base" A19 LED bulbs may appear omnidirectional, but likely have some directionality from the white base (eg. https://www.lighting.philips.com/main/prof/led-lamps-and-tubes/led-bulbs/led-party-bulbs/929001997805_EU/product). Due to their lower overall and far-red PFD output, these amber and red A19 bulbs can be safely added to T5 white LED or fluorescent tubes in most lighting canopies without concern of having too much red or far-red. In fact, in most T5 dominant lighting canopies, these A19 bulbs will not greatly affect your growth spectrum, and merely provide a few extra red PFD, having little or negligible effects on plant growth.

With any T5 tube or E26 lamp/bulb, ensure product quality and safety through product reviews and certification (UL, CE, ETL, CSA).

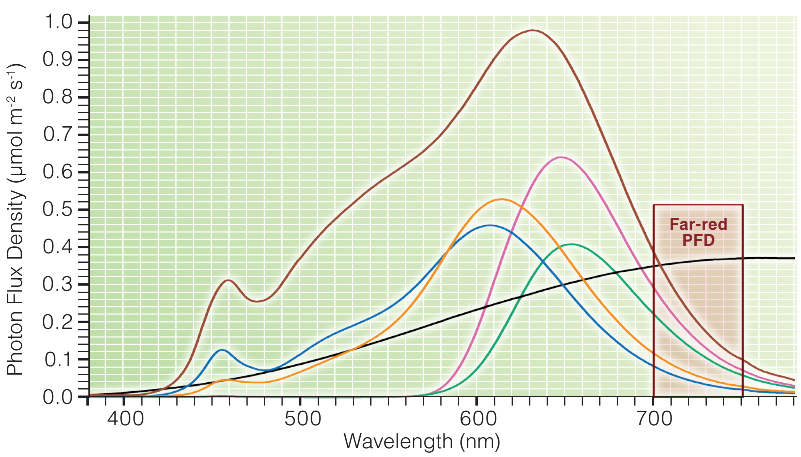

Figure 7: Comparison of spectra and output (PFD) between 25W halogen bulbs and various omnidirectional A19 or A15 LED bulbs suitable for angle, horizontally, or vertically mounted E26 sockets. Measurements were taken inside a reflective (mirrored) light box below the bulbs, at the same distance from the horizontally mounted socket (19cm) at room temperature. PFD far-red = sum 701-750nm. Measurements of LED and halogen light sources are from limited sample sizes.

- **Philips 4W Party Red** (PFD far-red: 8)
- **NOMA 4.5W Red** (PFD far-red: 7)
- **Philips 25W Halogen** (PFD far-red: 19)
- **Philips 4.5W Soft White (2700K)** (PFD far-red: 2)
- **Philips 4.5W Amber (2000K)** (PFD far-red: 3)
- **TCP 9.5W Anew** (PFD far-red: 11)

4. Combining T5 LEDs with vertically mounted E26 bulbs to create broader spectra

T5 LED tubes and LED lightbulbs for E26 sockets can be combined to broaden the spectrum of a predominantly white T5 LED system. If a desired horticultural T5 LED tube is incompatible with your existing T5 lighting system, or if it is more economical, you can combine T5 tubes and E26 lightbulbs by evenly distributing them across your lighting system. Here having an accurate spectrometer/spectroradiometer is essential for setting up your spectrum (https://www.licor.com/env/products/light/spectrometer, https://www.apogeeinstruments.com/spectroradiometers/, https://www.oceaninsight.com/products/systems/irradiance/wavego-vis-50/?qty=1). Again, T5 white LEDs grow healthy plants and several groups use only these. However if you wish to broaden your spectrum and include far-red for general plant growth, it is best to also include a red peak to balance the phytochrome response.

Step 1:

First verify the T5 LEDs of interest are compatible with your existing fluorescent ballasts. Next ensure the T5 LED tubes and E26 bulbs have safety certification relevant to your region (eg. UL, CE, ETL, or CSA). Purchase enough T5 tubes and E26 lightbulbs to reflect one filled chamber. Here we will use a high PPFD T5 lighting canopy in a TPC-19 as a case study. Each side of a TPC-19 T5 lighting canopy has 26 T5 tube sockets (4 ft. length) and 8 vertically mounted E26 sockets. This 26 T5 tubes:8 E26 sockets ratio can be reduced to 13:4, which is close to 12:4 or 6:2. Using 6 T5 white LED tubes and 2 E26 replacement LED bulbs evenly distributed over your spectrometer sensors, you can experiment with different combinations of tubes and bulbs to estimate what the spectrum will resemble in a filled T5 lighting canopy. Of course, in a filled chamber there will be some greater influence of the T5 tubes as 13:4 is slightly more than 12:4. There will also some spectral changes with distance and uniformity with directional flowering lamps, and finally some spectral change from reflectivity differences in a filled chamber that are challenging to predict.

Step 2:

After you have determined your desired spectral configuration with a handful of T5 tubes and E26 bulbs, purchase enough to fill one chamber and make sure your filled chamber spectrum is close to what you have estimated. Grow some test plants in this chamber and determine whether they meet or exceed your plant growth goals.

Step 3:

Retrofit all growth chambers or rooms of the same model and lighting system in your facility. Maintaining the same LED retrofits and spectrum across all chambers and rooms of the same model allows you to effectively replicate experiments through space (between chambers).[39] Keep in mind that as discussed in 3.1.1 (Step 1), occasionally chambers of the same model, both with T5 lighting systems, may have different ballasts, and therefore it is best practice to check the ballasts of all the chambers to retrofit to ensure compatibility of T5 LED tubes.

Figure 8 and Table 4 show an LED retrofit to a TPC-19, using 4000K Philips Type A T5 LED tubes as the primary white light source and a 1:1 combination of Philips Flowering 2.1 and Total Grow Pure Flowering 200 E26 LED flowering lamps.

Table 5: Comparison of light quality parameters (relative photon flux density, PFD) between direct sunlight and a TPC-19 LED retrofit (spectra of Figure 8).

	%Blue (400-500/ 400-750nm)	**Blue:Green**[6] (405-486/ 492-573nm)	**%Red** (600-700/ 400-750nm)	**Red:Far-red**[7] (655-665/ 725-735nm)	**%Far-red** (701-750/ 400-750nm)	**Phytochrome PhotoStationary State (PSS)**[8]	**Far-red Fraction**[9] Red = 645-665nm Far-red = 720-740nm
Direct Sunlight	23.7	0.78	31.7	1.14	14.6	0.72	0.47
T5 tubes: **4000K Philips Type A (24W)** **Vertically mounted halogen (E26) sockets** **50% Philips Flowering: 2.1 (9.3W), 50% Total Grow Pure Flowering 200 (17W) (1:1)**	16.62	0.48	42.1	1.91	10.6	0.80	0.35

These values are from an average of measurements taken at several distances from the lights, see Figure 8 caption for more information.

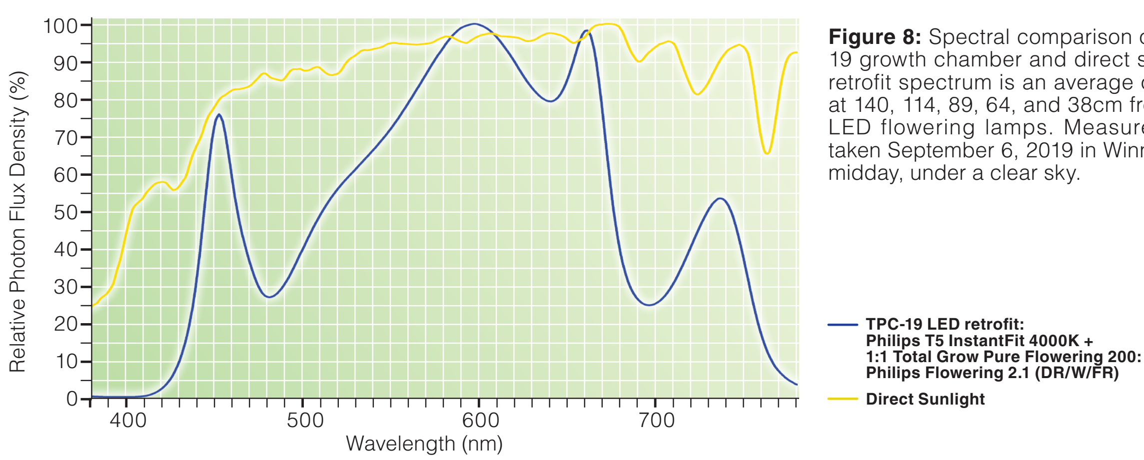

Figure 8: Spectral comparison of a LED retrofit of a TPC-19 growth chamber and direct sunlight. The TPC-19 LED retrofit spectrum is an average of 5 measurements taken at 140, 114, 89, 64, and 38cm from the bottom of the E26 LED flowering lamps. Measurement of direct sunlight taken September 6, 2019 in Winnipeg, Manitoba, Canada, midday, under a clear sky.

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