AgriEngineering

Article

On the Technical Performance Characteristics of Horticultural Lamps

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Abstract: Recent advances in light emitting diode (LED) technology have provided exciting opportunities for plant lighting applications, and it is expected that LED lighting will soon overtake the still common use of high-intensity discharge (HID) lighting technology. Because LED lighting offers novel capabilities, extensive research is needed to identify optimal lighting practices for the large number of crops grown by commercial greenhouse growers. Plant scientists and growers facing decisions about plant lighting systems do not always have sufficient information about lamp performance characteristics. In this paper, we reported on various technical performance characteristics for 18 lamp types commonly used for plant production, and compared these characteristics with the characteristics of sunlight. The results showed a substantial range of performance characteristics, highlighting the importance of a careful assessment before selecting a light source for horticultural applications. The data presented in this paper can be used to assess the suitability of a specific light source for a particular horticultural application.

Keywords: controlled environment agriculture; crop production; efficacy; extended photosynthetically active radiation; spectrum; supplemental lighting

Citation: Shelford, T.J.; Both, A.-J. On the Technical Performance Characteristics of Horticultural Lamps. *AgriEngineering* **2021**, *3*, 716–727. https://doi.org/10.3390/agriengineering3040046

Academic Editors: Francesco Marinello and Lin Wei

Received: 27 June 2021
Accepted: 23 September 2021
Published: 28 September 2021

1. Introduction

The rapid improvements in light emitting diode (LED) technology over the last three decades have resulted in a host of intriguing opportunities for plant lighting applications [1,2]. Before that, high-intensity discharge (HID) lighting systems were used as the most practical and cost effective option for commercial growers. As a result, the industry accumulated a lot of knowledge about how best to use HID lighting. However, LED technology has several advantages, e.g., flexibility in spectral output, higher electric conversion efficiency, and little radiant heat production. However, since LED fixtures for horticultural applications are still more expensive than comparable HID fixtures, the latter, and particularly high-pressure sodium (HPS) fixtures, are still the most dominant light source for plant lighting applications. Nevertheless, the expectation is that the use of LED lighting systems will overtake the use of HID lighting systems in the near future.

With the advances in LED technology come new opportunities to investigate plant responses to a host of lighting conditions that were previously difficult or impossible to study (e.g., light dimming, diurnal or seasonal changes in light spectrum, placing high-intensity light sources close to or inside the plant canopy). Not surprisingly, the scientific community has embraced LED technology and is investigating new ways to elucidate plant physiological responses (e.g., [3,4]) as well as economic benefits from potentially cheaper production practices (e.g., [5,6]). Promising results have been reported, but it will take some time before optimum lighting strategies have been worked out for the large variety of crops grown in greenhouses and indoor production facilities (e.g., [7,8]). Note that our study focused on the technical performance characteristics of lamps, and did not include any plant production trials.

Previous reporting by our research group [9–11] discussed the operating characteristics of select plant lighting sources, as well as how best to measure and report key technical metrics of light sources used for horticultural applications. The purpose of this paper was to present performance characteristics of the most commonly used light sources so that their differences in performance characteristics can be used to make better informed decisions about the most suitable light source for a particular plant production application.

Several of the light sources evaluated as part of this study are no longer manufactured (e.g., Illumitex and Lumigrow), or the specific models evaluated have been replaced by updated or new models. This issue is an important consideration for growers evaluating and selecting lighting systems and illustrates the importance of having meaningful technical data that can be used for comparisons. Instead of providing data on the latest light sources, the focus of this study was to provide performance metrics for the purpose of comparisons. Our laboratory is not a certified testing facility, nor does it have the capacity to test every lamp available in the market place. Instead, our test results attempted to fill knowledge gaps that may exist with end users of horticultural lighting technologies.

2. Materials and Methods

2.1. Light Sources

A variety of electric light sources commonly used for horticultural applications were evaluated. These sources included nine different LED lamps, three fluorescent lamps, three HPS lamps, a low-pressure sodium (LPS) lamp, a metal halide (MH) lamp, and a ceramic MH lamp (Table 1). While rarely used for horticultural applications, the LPS lamp was included because it has one of the highest luminous efficacy (lumen/W) values (based on lamp bulb wattage, not on fixture wattage that includes the power draw by the ballast), and has occasionally been reported on in the scientific literature when the performance of different lamp types was discussed (e.g., [12]). In addition to these electric sources, data describing sunlight were included for comparison. A scan of solar radiation was performed on a clear day close to the summer solstice at around solar noon (25 June 2015 in New Brunswick, NJ, USA).

Table 1. Light sources evaluated.

No.	Manufacturer and Model	Type	Code
1	GE Warm White 3000 K (electronic ballast, instant start)	Fluorescent, bare twin tubes, F32T8	FWW
2	GE Cool White 4100 K (electronic ballast, instant start)	Fluorescent, bare twin tubes, F32T8	FCW
3	GE Daylight 6500 K (electronic ballast, instant start)	Fluorescent, bare twin tubes, F32T8	FDL
4	Osram SOX (magnetic ballast)	LPS (90 W, bare bayonet bulb, horizontal)	LPS
5	Sun Systems LEC 315 (Ceramic Metal Halide)	CMH (315 W, mogul Elite Agro bulb, vertical)	CMH
6	iPower (electronic ballast)	MH (400 W, bare mogul GLBULBM400 bulb, horizontal)	MH
7	Gavita Pro 600e SE (electronic ballast)	HPS (600 W, mogul bulb, horizontal)	HPS-600
8	Gavita Pro 750e DE (electronic ballast)	HPS (750 W, double ended bulb, horizontal)	HPS-750
9	PARSource (electronic ballast)	HPS (1000 W, double ended Agrosun bulb, horizontal)	HPS-1000
10	Fluence VYPR X Plus	LED (passively cooled, white)	LED-PCW1
11	GE Arize Element L1000	LED (passively cooled, magenta)	LED-PCM
12	Philips GreenPower LED Toplight	LED (passively cooled, magenta, low blue)	LED-PCMLB
13	Valoya Model R150 NS1	LED (passively cooled, white)	LED-PCW2
14	Heliospectra LX602 G	LED (fan cooled; operated at 100% red, 100% blue, and 100% white output)	LED-FCRBW1

Table 1. *Cont.*

No.	Manufacturer and Model	Type	Code
15	Illumitex PowerHarvest 10 Series Wide	LED (fan cooled; F1 Spectrum)	LED-FCM1
16	Lumigrow Pro 650e	LED (fan cooled; operated at 100% red, 100% blue, and 100% white output)	LED-FCRBW2
17	Osram Zelion HL300 Grow Light	LED (fan cooled, magenta)	LED-FCM2
18	Lemnis Oreon Grow Light 2.1	LED (water cooled, magenta, operated with a water flow rate of 7.6 Lpm)	LED-WCM
	Sunlight	Solar noon, near summer solstice	SUN

2.2. Measurement Equipment

Light measurements were conducted in a 2-m diameter integrating sphere (Model LMS-760, Labsphere, North Sutton, NH, USA) connected to a spectroradiometer (Model CDS 2100, Labsphere, North Sutton, NH, USA) with a fiber-optic cable. The electric power used to operate the lamps or fixtures was conditioned using a programmable alternating current (AC) power source (Model 6460, Chroma, Foothill Ranch, CA, USA) and measured with a digital power meter (Model 66202, Chroma, Foothill Ranch, CA, USA). The electric power measured represents the "wall plug" or total power used by the lamp or fixture and includes any power drawn by a ballast, driver, or cooling fan.

Additional light measurements were conducted in a 3 by 4 m darkroom equipped with a spectroradiometer (Model PS-300, Apogee Instruments, Logan, UT, USA). The vertical distance between the bottom of the lamp bulb (or transparent cover in the case of some LED fixtures) and the sensor head was maintained at 61 cm. All measurements reported in this paper were measured directly below the center of the lamp bulb(s) or fixture.

2.3. Environmental Conditions

All lamp testing was performed at temperatures ranging between 20 and 25 °C, and relative humidity conditions ranging between 30% and 50%. The temperature inside the integrating sphere was maintained by closing the integrating sphere for only a short period of time (less than 20 s) during data collection. Immediately after data collection, the integrating sphere was opened again, allowing the inside temperature to return to laboratory conditions.

2.4. Calibration

All measurement equipment was calibrated according to manufacturer specifications and recommended frequency. When recommended, equipment was returned periodically to the manufacturer for recalibration.

2.5. Definitions and Calculations

Photosynthetically active radiation (PAR) was measured across the 400–700 nm waveband, while giving equal weight to each of the photons across that waveband. An equivalent measurement is the photosynthetic photon flux density (PPFD). Both have the units $\mu mol/(m^2 s)$. The photosynthetic photon flux (PPF) covers the same waveband, but has units of µmol/s [13].

The extended photosynthetically active radiation (ePAR) waveband was proposed by [14,15] and covers the 400–750 nm waveband. Note that a similar acronym (EPAR) was proposed by [16], who used the 290–850 nm waveband to define the term extended PAR. Using the concept of ePAR, the extended photosynthetic photon flux (ePPF) can be used to calculate the extended efficacy (ePPF divided by the electric power consumption) for a light source.

The yield photon flux (YPF) was calculated according to the definition used by [17]. It covers the 360 to 760 nm waveband and weighs each photon according to the relative quantum efficiency curve [18,19].

The phytochrome photoequilibrium (PPE) was calculated according to the method described in [19], and covers the 300 to 800 nm waveband. An equivalent term for this parameter is the phytochrome photostationary state (PSS). The calculation involves the spectral composition of light before it interacts with plant tissue. Note that [20] proposed to modify the calculation of the PPE so as to account for spectral distortions that occur as light interacts with leaf tissue.

The far-red (FR) fraction was calculated using an equation proposed by [21]: FR fraction = FR/(R + FR), with FR defined as the photon flux across the 730 ± 10 nm waveband, and red (R) as the photon flux across the 655 ± 10 nm waveband.

3. Results

Figures 1 and 2 show the normalized spectral output across the 300–800 nm waveband for the various lamps evaluated. Figure 3 shows the normalized spectral output across the 300–800 nm waveband for sunlight. The normalization was carried out by dividing all the spectral output values by the largest spectral output value across the 300–800 nm waveband. In Table 1, the various light sources evaluated are identified. Table 2 through 5 show the measurement values from the tests performed in the integrating sphere and the darkroom, as well as the measurement results from the solar scan.

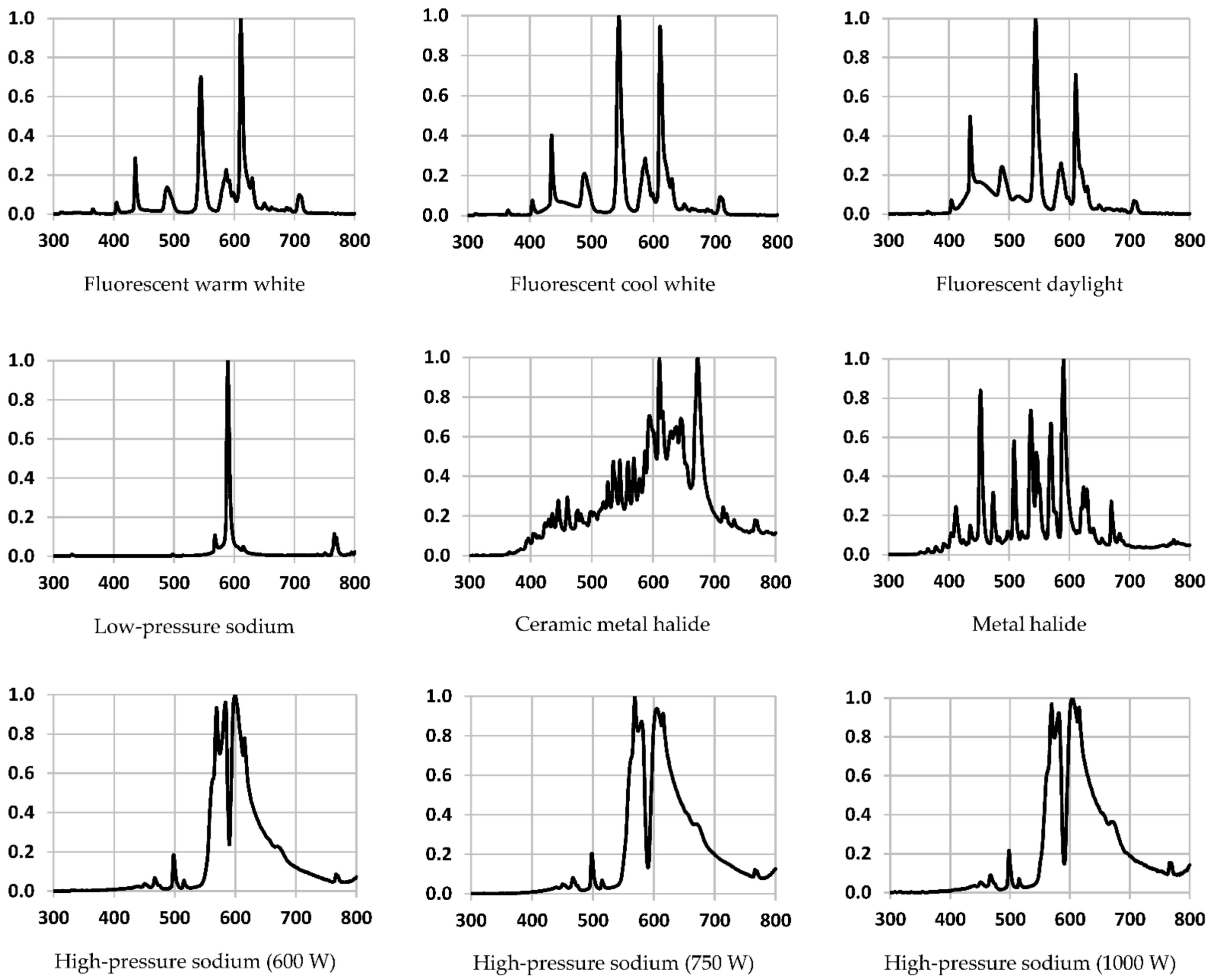

Figure 1. Normalized spectral output across the 300–800 nm waveband for nine different light sources. Original data measured as photon flux density with a spectroradiometer (Model PS-300, Apogee Instruments, Logan, UT, USA) in the units µmol/(m^{2}s) per nm. Horizontal axes: wavelength in nm, vertical axes: normalized spectral output (unitless).

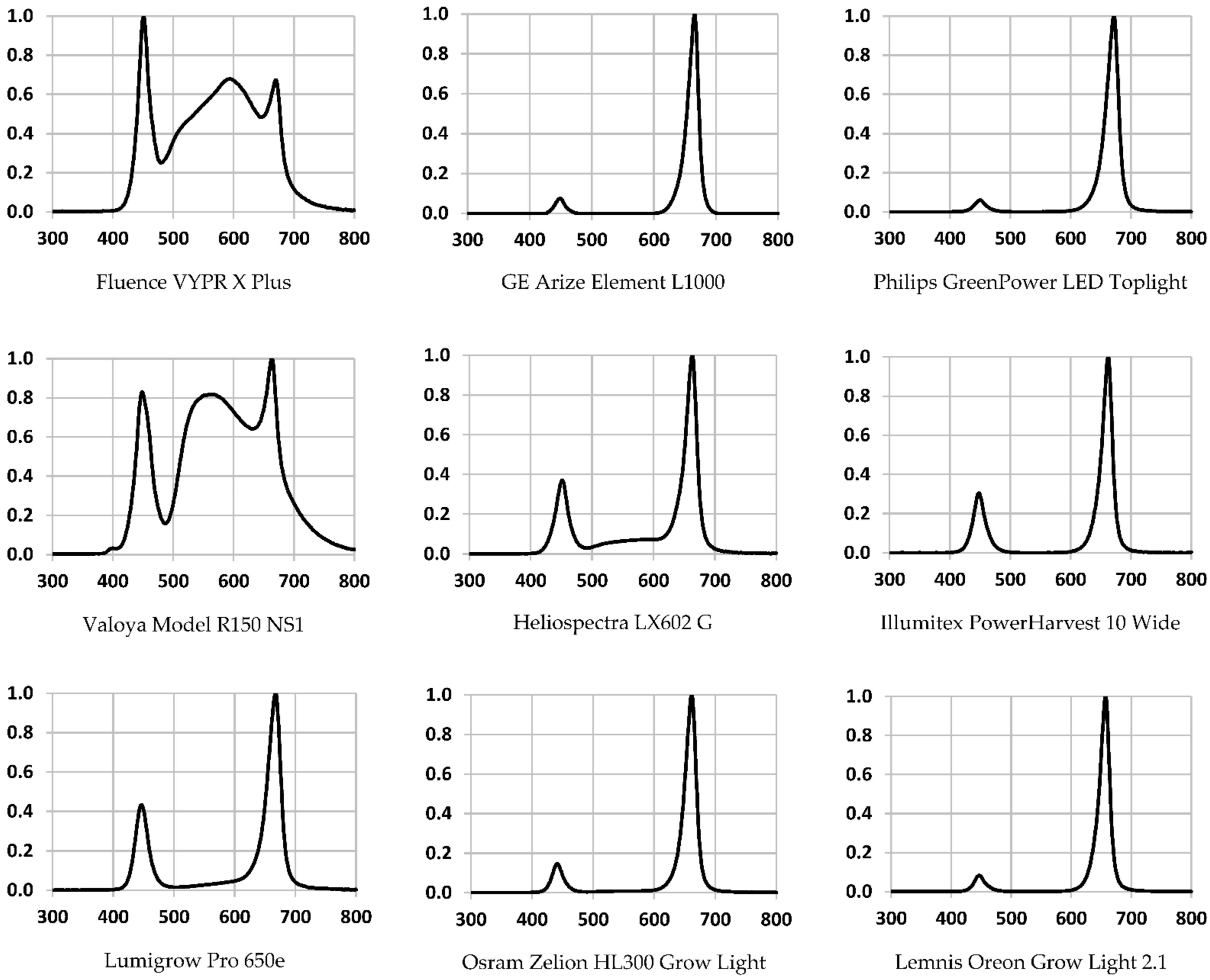

Figure 2. Normalized spectral output across the 300–800 nm waveband for nine different LED fixtures. Original data measured as photon flux density with a spectroradiometer (Model PS-300, Apogee Instruments, Logan, UT, USA) in the units μmol/(m^{2}s) per nm. Horizontal axes: wavelength in nm, vertical axes: normalized spectral output (unitless).

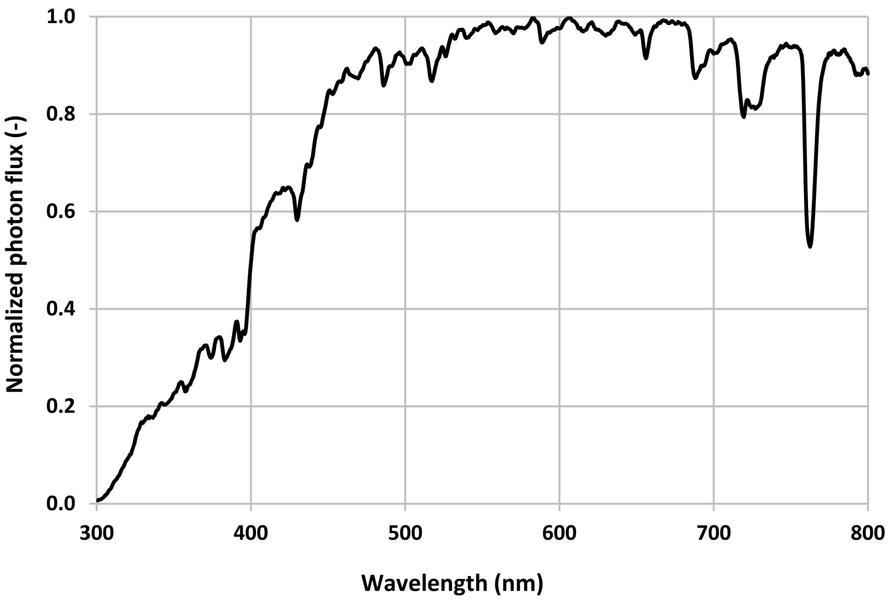

Figure 3. Normalized photon flux for solar radiation measured on a clear day near the summer solstice and around solar noon (25 June 2015 in New Brunswick, NJ, USA). Original data measured

as photon flux density with a spectroradiometer (Model PS-300, Apogee Instruments, Logan, UT, USA) in the units μmol/(m^2s) per nm. Total photosynthetically active radiation (400–700 nm): 1894 μmol/(m^2s).

Table 2. Measurement results from tests conducted in the integrating sphere. CCT = Correlated color temperature, CRI = Color rendering index, Ra = International standard for color rendering index (unitless), PPF = Photosynthetic photon flux.

No.	Code	Volt (VAC)	Current (Amp)	Power (Electric Watt)	Power Factor (-)	Luminous Flux (lm)	CCT (K)	CRI (R_a)	Radiant Watt (400–700 nm)	PPF (μmol/s) (400–700 nm)
1	FWW	120.0	0.8	56.7	0.58	4182	2980	85	11.3	53.0
2	FCW	120.0	0.8	55.9	0.58	4039	3975	82	11.3	51.6
3	FDL	120.0	0.8	56.2	0.58	3930	6462	83	12.4	54.5
4	LPS	120.0	1.3	154.3	0.98	12,238	1785	−43	23.5	115.9
5	CMH	277.0	1.2	339.4	0.99	29,508	2965	91	110.6	535.0
6	MH	120.0	3.7	441.8	1.00	28,990	5713	69	91.2	402.2
7	HPS-600	120.0	5.3	635.8	1.00	72,097	1922	36	193.6	968.8
8	HPS-750	208.1	4.3	888.5	0.99	95,598	2027	50	277.4	1395.4
9	HPS-1000	120.0	9.0	1076.7	1.00	121,425	1965	41	341.9	1714.1
10	LED-PCW1	120.0	4.3	513.8	0.99	64,773	5464	91	224.7	1036.0
11	LED-PCM	119.9	5.2	617.3	1.00	16,328	1000	−44	307.6	1635.2
12	LED-PCMLB	208.0	1.0	215.7	1.00	4906	1064	−83	98.3	515.9
13	LED-PCW2	120.0	1.1	133.3	1.00	12,480	4949	80	41.0	191.4
14	LED-FCRBW1	120.0	5.3	622.9	0.99	19,060	22,000	−6	152.7	749.0
15	LED-FCM1	120.0	4.3	510.4	1.00	8429	22,000	−282	175.7	873.7
16	LED-FCRBW2	120.0	4.8	566.3	0.99	10,660	22,000	−72	153.2	764.3
17	LED-FCM2	120.0	3.2	381.0	0.99	9016	1184	−3	135.4	704.5
18	LED-WCM	120.0	5.2	617.8	0.99	15,284	1000	−20	241.6	1282.3
	SUN	-	-	-	-	-	6500	100	-	-

4. Discussion

For this study, we evaluated single lamps or fixtures as the representative of a particular lamp type. We did not inform the manufacturers we were performing our tests, so we have no reason to believe that the specific lamps or fixtures we tested were selected for atypical performance. Nevertheless, it is not possible to draw conclusions about the typical performance of the lamps or fixtures we tested. The purpose of our tests was not to call out specific manufacturers about their products, but rather show the range of performance characteristics among light sources commonly used for horticultural applications. Additionally, since LED technology is developing rapidly, it is likely that the information on LED lamps presented here will be outdated in a few years.

The spectral output of the various lamps we evaluated were measured with spectroradiometers with calibrated detection ranges of approximately 300–1000 nm. As a result, little infrared (heat) radiation was detected. It is well known that some lamps (e.g., HID lamps) produce substantial amounts of infrared radiation, and this can be an important consideration when deciding on which lighting system is most appropriate for a particular installation. An approximation for the amount of infrared radiation produced by each lamp is the difference between the electric power consumed by the lamp and the radiant energy delivered (Table 2), but such an approximation neglects any passive or forced convective heat losses. However, any amount of radiant or convective energy produced by a lamp will eventually be converted into heat (first law of thermodynamics).

The scientific literature contains little information about the independent testing of a variety of lamp types used for horticultural applications. An exception is the report published by [22], who conducted an electrical and photometric evaluation of ten LED lamps, two HPS lamps, and one MH lamp. However, [22] contains only partial information about the spectral distribution across the 280–800 nm waveband.

The electrical metrics reported in Table 2 (volt, current, power, and power factor) can be used to assess the power requirements and performance characteristics of specific lamp types. Lamps operated with electronic ballasts (fluorescent, and HID lamps) or drivers (LED lamps) often can be operated at several different supply voltages. The higher the voltage used, the lower the current draw and this feature can be used to save on installation costs because smaller diameter wires can be used when the current draw is lower. The power factor indicates how much of the supplied power is used to do useful work. A value of 1 indicates that 100% of the supplied power performs useful work (i.e., operates the lamp), while lower numbers indicate that some percentage of the supplied power is lost (i.e., does not perform useful work).

Table 2 also reports on three performance characteristics that describe some of the visual aspects of light (lumen output, correlated color temperature, and color rendering index). These characteristics are not particularly useful for horticultural applications, but do allow for comparisons with light sources that are used for human vision applications (e.g., residential and commercial lighting). In addition, the color rendering index provides some insight into how easy it is to observe leaf color when the leaves are lit with a particular light source. This can be important when growers want to observe discolorations due to plant nutritional issues or damage due to insects or plant diseases.

Table 3 shows the lamp efficacy values that were calculated from the measurements performed in the integrating sphere. Efficacy data is one of the key performance metrics that are used to evaluate lamp performance. The numbers we report are not always as high as those reported by the manufacturers. There could be several reasons for this, but since our sample size was only one, it is not possible to determine which number is correct. Nevertheless, since our tests were performed using the same procedures and equipment, the relative differences among the various lamp types can be used for comparisons.

Table 3 also reports on performance characteristics that involve visible light. As mentioned before, assessing visible light for horticultural applications is not very useful, but the performance characteristics involving visible light that are included in Table 3 can be used to compare our measurements with those reported in the literature (e.g., [12]).

Table 3. Values derived from the measurements conducted in the integrating sphere. Values for sunlight in italics from [23], and in bold from [12]. PPF = Photosynthetic photon flux (400–700 nm), ePPF = Extended photosynthetic photon flux (400–750 nm), W_r = radiant Watt, W_e = electric Watt.

No.	Code	PPF Efficacy (µmol/J)	ePPF Efficacy (µmol/J)	PPF per Radiant Watt (µmol/s per W_r)	Luminous Efficacy (lm/W_e)	Lux per µmol/(m^2s) of PAR
1	FWW	0.94	0.96	4.71	73.8	78.9
2	FCW	0.92	0.94	4.59	72.2	78.3
3	FDL	0.97	0.97	4.41	69.9	72.1
4	LPS	0.75	0.76	4.92	79.3	105.6
5	CMH	1.58	1.70	4.84	86.9	55.2
6	MH	0.91	0.93	4.41	65.6	72.1
7	HPS-600	1.52	1.62	5.00	113.4	74.4
8	HPS-750	1.57	1.71	5.03	107.6	68.5

Table 3. *Cont.*

No.	Code	PPF Efficacy (µmol/J)	ePPF Efficacy (µmol/J)	PPF per Radiant Watt (µmol/s per W_r)	Luminous Efficacy (lm/W_e)	Lux per µmol/(m^2s) of PAR
9	HPS-1000	1.59	1.71	5.01	112.8	70.8
10	LED-PCW1	2.02	2.09	4.61	126.1	62.5
11	LED-PCM	2.65	2.65	5.32	26.5	10.0
12	LED-PCMLB	2.39	2.40	5.25	22.7	9.5
13	LED-PCW2	1.44	1.50	4.67	93.7	65.2
14	LED-FCRBW1	1.20	1.21	4.90	30.6	25.4
15	LED-FCM1	1.71	1.72	4.97	16.5	9.6
16	LED-FCRBW2	1.35	1.36	4.99	18.8	13.9
17	LED-FCM2	1.85	1.85	5.20	23.7	12.8
18	LED-WCM	2.08	2.08	5.31	24.7	11.9
	SUN	*2.08*	-	**4.57**	**107 ***	**54**

* Unit: lm/W_r.

Table 4 reports on several additional light parameters that are used by plant scientists to further qualify the light environment for plant production. These parameters include the yield photon flux (YPF), the ratio of the YPF and the photosynthetic photon flux (PPF), the phytochrome photoequilibrium (PPE), and three different ways to assess the amount of far-red that is present in the produced light spectrum. In each of these three different approaches, the definition (i.e., its waveband) of far-red light is different. Other definitions of far-red light have also been used, but the point here is to show that these different definitions can lead to quite different calculation results.

Table 4. Values derived from measurements conducted in the dark room with a spectroradiometer (Model PS-300, Apogee Instruments, Logan, UT, USA), except for the values for sunlight which were obtained from an outdoor spectral scan using the same spectroradiometer. YPF = Yield photon flux, PPF = Photosynthetic photon flux, PPE = Phytochrome photoequilibrium.

No.	Code	YPF (300–800 nm)	YPF/PPF (300–800)/(400–700) [Wave-Lengths in nm]	PPE (300–800 nm)	R:FR wide (600–699)/(700–800) [Wave-Lengths in nm]	R:FR Narrow (655–665)/(725–735) [Wave-Lengths in nm]	FR Fraction
1	FWW	18.0	0.92	0.85	8.4	5.3	0.14
2	FCW	17.3	0.89	0.84	9.5	5.8	0.13
3	FDL	17.0	0.85	0.82	10.1	6.4	0.12
4	LPS	14.5	0.98	0.84	1.0	1.3	0.45
5	CMH	542.9	0.91	0.82	3.7	2.4	0.26
6	MH	47.1	0.90	0.82	2.7	1.6	0.37
7	HPS-600	439.6	0.96	0.85	5.3	3.0	0.23
8	HPS-750	706.0	0.95	0.83	4.2	2.8	0.25

Table 4. *Cont.*

No.	Code	YPF (300–800 nm)	YPF/PPF (300–800)/(400–700) [Wave-Lengths in nm]	PPE (300–800 nm)	R:FR wide (600–699)/(700–800) [Wave-Lengths in nm]	R:FR Narrow (655–665)/(725–735) [Wave-Lengths in nm]	FR Fraction
9	HPS-1000	967.3	0.95	0.83	4.0	2.8	0.25
10	LED-PCW1	514.9	0.87	0.85	13.4	12.6	0.08
11	LED-PCM	1215.4	0.92	0.88	14,019	∞	0.00
12	LED-PCMLB	284.9	0.90	0.87	45.8	109.6	0.01
13	LED-PCW2	161.2	0.88	0.83	6.3	7.2	0.14
14	LED-FCRBW1	575.2	0.88	0.87	38.1	111.3	0.01
15	LED-FCM1	1703.5	0.88	0.87	74.9	265.4	0.01
16	LED-FCRBW2	396.0	0.87	0.86	29.4	69.9	0.02
17	LED-FCM2	336.3	0.91	0.88	66.3	226.3	0.01
18	LED-WCM	152.6	0.92	0.88	90.1	299.3	0.00
	SUN	1696.1	0.90	0.72	1.1	1.1	0.47

It is common for researchers to identify the blue, green, and red wavebands by the 400–500 nm, 500–600 nm, and 600–700 nm ranges, respectively. However, this practice double-counts the radiation output at 500 and 600 nm. Therefore, we used non-overlapping wavebands to report the radiation output across the various wavelength ranges (Table 5).

As this paper demonstrated, careful measurement of lamp characteristics is necessary so that sufficient information can be reported. Only reports with sufficient information will enable the repeatability of plant lighting research. Detailed reports will also help commercial growers make more informed decisions about plant lighting options. The range of performance characteristics disclosed in this paper highlight the importance of lamp selection for a particular horticultural application. In a perfect world, performance characteristics would be made available by lamp manufacturers, but that is not always the case, or the information is incomplete. Researchers and growers are encouraged to ask manufacturers for detailed information about the lighting products they are considering.

Table 5. Light distribution ratios as a percentage of the photon flux density across the 280–800 nm waveband as measured with a spectroradiometer (Model PS-300, Apogee Instruments, Logan, UT, USA). The values were calculated from measurements conducted in the dark room, except for the values for sunlight which were obtained from an outdoor spectral scan. UV = Ultraviolet, PAR = Photosynthetically active radiation, ePAR = Extended photosynthetically active radiation.

No.	Code	Photon Flux Density µmol/(m^2s) (280–800 nm)	UV-B (280–314 nm)	UV-A (315–399 nm)	Blue (400–499 nm)	Green (500–599 nm)	Red (600–699 nm)	Far-red (700–800 nm)	PAR (400–700 nm)	ePAR (400–750 nm)
1	FWW	20.9	0.2%	1.6%	15.3%	38.5%	40.0%	4.4%	93.8%	97.8%
2	FCW	20.5	0.2%	1.4%	22.2%	41.2%	31.7%	3.3%	95.1%	98.1%
3	FDL	20.6	0.1%	0.6%	33.0%	41.5%	22.5%	2.2%	97.1%	99.0%
4	LPS	17.5	0.4%	1.7%	2.0%	68.8%	13.8%	13.3%	84.6%	87.1%
5	CMH	690.8	0.03%	1.1%	13.1%	28.4%	45.2%	12.2%	86.8%	93.7%
6	MH	64.5	0.05%	2.0%	22.7%	48.2%	19.7%	7.3%	90.7%	93.8%
7	HPS-600	506.8	0.04%	0.4%	3.2%	40.4%	47.0%	8.9%	90.7%	96.1%
8	HPS-750	847.6	0.01%	0.2%	3.4%	32.7%	51.3%	12.4%	87.5%	94.9%
9	HPS-1000	1167.3	0.04%	0.3%	3.6%	32.1%	51.2%	12.7%	87.0%	94.2%
10	LED-PCW1	611.0	0.03%	0.2%	23.8%	38.4%	35.0%	2.6%	97.2%	99.3%
11	LED- PCM	1327.2	0.00%	0.00%	6.0%	0.0%	94.0%	0.0%	100%	100%
12	LED-PCMLB	324.3	0.02%	0.1%	5.3%	0.4%	92.2%	2.0%	98.0%	99.6%
13	LED-PCW2	195.4	0.04%	0.3%	18.0%	39.9%	36.0%	5.7%	94.0%	98.3%
14	LED-FCRBW1	666.1	0.04%	0.2%	23.2%	13.1%	61.9%	1.6%	98.2%	99.4%
15	LED-FCM1	1951.4	0.03%	0.2%	24.7%	0.5%	73.6%	1.0%	98.8%	99.6%
16	LED-FCRBW2	464.9	0.05%	0.2%	26.1%	5.8%	65.7%	2.2%	97.6%	99.3%
17	LED-FCM2	375.1	0.00%	0.1%	12.0%	2.7%	84.0%	1.3%	98.7%	99.6%
18	LED-WCM	167.3	0.01%	0.1%	8.0%	0.5%	90.4%	1.0%	98.9%	99.7%
	SUN	2658.4	0.1%	5.5%	20.4%	25.2%	25.5%	23.2%	71.2%	83.1%

5. Conclusions

- Every light source tested had unique performance characteristics, including their spectral outputs.
- The PPF efficacy of a light source is but one performance characteristic that should be considered.
- A spectroradiometer is needed in order to assess the spectral output of a light source.
- Changing the definition of PAR will make it more difficult to compare published results that used the current definition for PAR (400–700 nm) with results published based on the extended definition for PAR (ePAR, 400–750 nm).
- The sooner the scientific community can agree on definitions that describe key performance characteristics (e.g., waveband ranges, photosynthetically active radiation), the less confusion there will be when these performance characteristics are used to make plant lighting decisions.
- Due to the rapidly improving LED technology, it is critically important to have a consistent system for measuring and reporting lamp characteristics.
- Due to the challenges involved, commercial growers are encouraged to experiment with new light sources on a small growing area, before deciding to scale up to large production areas.

Author Contributions: Conceptualization, A.-J.B.; methodology, T.J.S. and A.-J.B.; data collection and analysis, T.J.S. and A.-J.B.; data curation, T.J.S. and A.-J.B.; writing—original draft preparation, A.-J.B.; writing—review and editing, T.J.S. and A.-J.B.; visualization, A.-J.B.; supervision, A.-J.B.; project administration, A.-J.B.; funding acquisition, A.-J.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the New York State Energy Research and Development Authority (Greenhouse Lighting and Systems Engineering–GLASE–project) and the New Jersey Agricultural Experiment Station.

Data Availability Statement: Original measurement data available on request from the authors.

Acknowledgments: The authors gratefully acknowledge the help they received from Claude Wallace who conducted several of the lamp evaluation tests.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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