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SPECTRAL PROPERTIES OF MICROWAVE-POWERED SULFUR LAMPS IN COMPARISON TO SUNLIGHT AND HIGH PRESSURE SODIUM/METAL HALIDE LAMPS [1,2]

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KRIZEK, D. T., MIRECKI, R. M., BRITZ, S. J., HARRIS, W. G., and THIMIJAN, R. W. *Spectral properties of microwave-powered sulfur lamps in comparison to sunlight and high pressure sodium/metal halide lamps.* BIOTRONICS **27**, 69–80. The spectral properties of 3.4 kW microwave-powered sulfur (MPS) lamps were compared with sunlight and with a combination of high-pressure sodium (HPS) and metal halide (MH) lamps. Photosynthetic photon flux (PPF) levels at 1.2 m from the MPS lamps (half and full power) and the HPS/MH lamps were 565, 1650, and 875 μmol $m^{-2} s^{-1}$, respectively, versus 2000 μmol $m^{-2} s^{-1}$ for sunlight. The percent of spectral irradiance from bare MPS lamps operated at full power was comparable to that of sunlight in the 400–500 nm (blue) and 600–700 nm (red) regions but was 60% higher in the 500–600 nm (yellow) region. On a percent distribution basis, HPS/MH lamps had 50% less blue, nearly 25% more red, and twice as much yellow irradiance as sunlight. On a percent basis, MPS and HPS/MH lamps emitted one third to one half as much 700–792 nm (far-red) irradiance as sunlight. At half power, there was a significant shift in spectral output of the MPS lamps from the red to the blue region. Measurements taken with a pyranometer and a pyrgeometer indicate that the biggest difference between MPS and HPS/MH lamps was in the 0.8 to 3.0 μm (near infrared, NIR) region; MPS lamps emitted one quarter as much NIR as HPS/MH lamps or the sun on a normalized basis (J μmol^{-1}). There was no appreciable difference in far IR (3 to 50 μm) between half power MPS and HPS/MH lamps, while at full power, MPS lamps had only one half as much far IR. Based on their spectral characteristics and high PPF, MPS lamps should provide an excellent source of radiant energy for use in plant growth chambers.

Key words: electrodeless lamps; high intensity discharge lamps; photosynthetic photon flux (PPF); plant growth chamber; spectral quality; Sunbrella.

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INTRODUCTION

Physiological studies on plants grown in controlled environments are frequently limited by the amount of photosynthetic photon flux (PPF) available. In many growth chambers, it is difficult to maintain PPF levels above 300 μmol $m^{-2} s^{-1}$.

Numerous efforts have been made to find a suitable radiation source for growing plants under controlled-environments that provides high amounts of PPF for photosynthesis and also satisfies spectral requirements for photomorphogenesis (*6, 9, 17, 20, 21*). In addition to having the proper spectral composition, the light source should also be cost effective. High-pressure sodium (HPS) and low-pressure sodium (LPS) lamps are cheaper to operate at equal PPF than are fluorescent lamps (*7*). The xenon arc lamp resembles natural daylight, but is seldom used in growth chambers because of its cost, short life, unreliability, low electrical efficiency, the need to filter excessive long-wave infrared (IR) radiation (*15*) and short wavelength UV, and the possible need to vent extraneous ozone when using a quartz envelope.

The standard HPS lamp has been used widely in horticultural lighting in the growth chamber and greenhouse (*1, 3*). It is very efficient as a source of PPF but its spectral output is primarily in the region between 550 and 650 nm and is deficient in the UV and blue region. Metal halide (MH) lamps on the other hand emit radiation in the UV and blue region but are deficient in the red and far-red portion of the spectrum. For this reason, many investigators have used a combination of HPS and MH lamps. A commercial lighting system housing a pair of these lamps, is known as the Sunbrella (Environmental Growth Chambers, Chagrin Falls, OH) and was used in the present study for a comparison with the microwave-powered sulfur (MPS) lamp and sunlight.

Electrodeless lamps have been used since 1975 as industrial sources of UV radiation (*11, 19, 23, 24*) and as experimental sources of visible radiation in a few studies (*4, 5, 10*), but thus far, there have been limited applications of these lamps for use as a high intensity light source for growing plants. In 1990, Fusion Systems Corporation (Rockville, MD, USA) developed a quartz MPS lamp that employs a unique plasma system (*11, 19*). The plasma-forming medium of this lamp consists of sulfur vapor which produces radiation upon molecular excitation by microwaves generated by magnetrons (*8*). These magnetrons are similar to those used in microwave ovens.

The basic components of the MPS bulb used in the present study are a spherical quartz envelope filled with argon and sulfur. The bulb is free of mercury (*12, 13*). Initial evaluation by Fusion Systems Corp. for projection applications in the semiconductor and printing industries indicates that the lamp has several attractive features, including high brightness and excellent stability (*8, 11*). The efficacy of this lamp for use in photosynthetic lighting, however, has not been clearly established, and the spectral characteristics of these lamps have not been described in detail.

The objectives of the present study were: a) to characterize the spectral properties of bare and filtered microwave-powered sulfur (MPS) lamps, operated at full and half power, as compared to a combination of high-pressure sodium (HPS) and metal halide (MH) (HPS/MH) lamps, and sunlight in the region of 250 to 792 nm; b) to compare the phytochrome photoequilibrium, yield photon flux, and effective blue quanta for each of these radiation sources; and c) to compare the amount of total radiation emitted by MPS and HPS/MH lamps in the 0.29 to 0.8 μm, 0.29 to 3 μm, 0.8 to 3 μm, and 3 to 50 μm bandwidths.

MATERIALS AND METHODS

Experimental set-up

Two EGC Model M-28 walk-in plant growth chambers (Environmental Growth Chambers, Chagrin Falls, OH) were used for comparison of light sources. One growth chamber was equipped with two 3.4 kW MPS lamps. The second growth chamber was equipped with ten Sunbrella lighting systems, each containing a 400W high pressure sodium (HPS) and a 400 W metal halide (MH) bulb.

The center of each MPS lamp was 0.6 m from the nearest side, front, or back wall, and 1.2 m apart. By means of operating one or two magnetrons per lamp, the MPS lamps were operated at either full or half power. The UV igniter lamp normally used to start the MPS lamps was found unnecessary and therefore not used in the present study. The MPS lamps were enclosed in a water-cooled light cap. Measurements were made of bare MPS lamps and of MPS lamps separated from the plant growing area by a filter consisting of a Plexiglas barrier and an acrylic diffuser to increase uniformity of PPF. The bulbs in each MPS fixture were air cooled. No adjustment was made in cooling of the bulb envelope in switching from full power to half power. The HPS/MH HID bulbs were enclosed in a water-cooled, porcelainized steel reflector with a glass barrier. No diffuser was used with these lamps. Radiation measurements were made at a distance of 1.2 m from the lamp banks.

PPF measurements

The amount of PPF emitted by the lamps (from 400 to 700 nm) was measured with a LI-COR Model 1000 quantum flux sensor (Lincoln, NE). Uniformity of PPF was determined by obtaining measurements in each growth chamber at each of 55 locations, spaced at 17.5×22.5 cm intervals (Fig. 1). The mean PPF levels for each chamber were calculated along with the coefficient of variance (CV).

Yield photon flux, effective blue quanta, and phytochrome photoequilibrium

Yield photon flux (YPF) was calculated using the relative quantum efficiency (RQE) spectrum for photosynthesis from McCree (*14, 15*) as modified by Sager *et al.* (*18*). Effective blue quanta for the blue light photoreceptor (BLP) was based on the action spectra for phototropism (*2*). Effective YPF and blue quanta were determined by convoluting the action spectra by the spectral

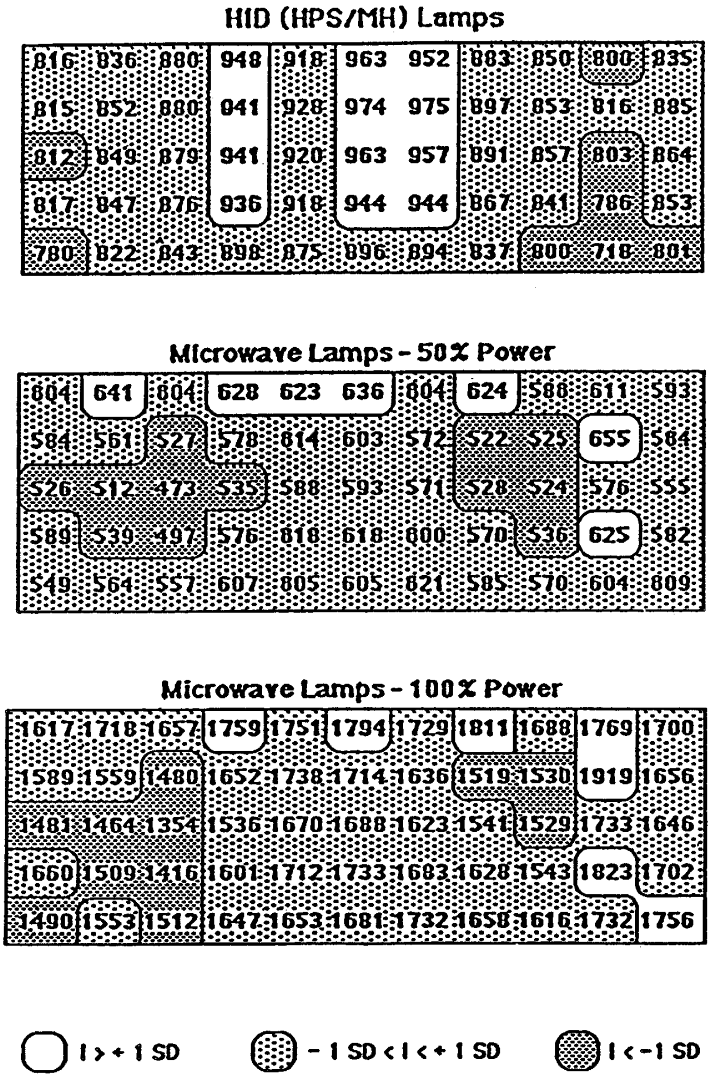

Fig. 1. Uniformity of PPF (μmol m^{-2}s^{-1}) in growth chambers under HPS/MH lamps and microwave-powered sulfur (MPS) lamps at half power and full power. Measurements made with a LI-COR quantum flux sensor at 17.5×22.5 cm intervals. Stippling and contours indicate areas less than or greater than one standard deviation from the mean.

irradiance emitted. Phytochrome photoequilibria were calculated for MPS, HPS/MH lamps, and the sun as defined by the ratio P_{fr}/P_{tot} in accordance with procedures described by Sager *et al.* (*18*).

Spectroradiometric measurements

Spectroradiometric measurements in the growth chambers were taken under MPS lamps at full and half power and under HPS/MH lamps. Measurements of sunlight were taken at Beltsville, MD (39°N) at solar noon on a clear, sunny day (June 26). Measurements were made every 2 nm from 250 to 792 nm with an Optronic Laboratories, Inc. Model 752 spectroradiometer (Orlando, FL).

Spectral curves are shown on both an absolute and on a normalized basis. Normalized data were based on the PPF level measured for sunlight (2000 μmol $m^{-2}s^{-1}$) as determined by the spectroradiometer.

Total radiation measurements

Total radiation measurements were made from 0.29 to 3 μm with two Eppley PSP pyranometers (The Eppley Laboratory, Inc., Newport, RI) and from 3 to 50 μm (far IR) with two Eppley PIR pyrgeometers. Means of each of the two pairs of instruments are reported. A Schott cut-off filter (Schott Glass Technologies, Inc., Duryea, PA) at 805 nm was used with the PSP pyranometer to determine the amount of near infrared (NIR) radiation (0.8 to 3 μm). Measurements with the Eppley PIR sensors were obtained by alternately taking light and dark readings and subtracting the dark values. Dark subtractions were not done for the Eppley PSP readings because measurements indicated they were negligible. A Styrofoam coffee cup covered with aluminum foil was placed over the sensor in order to obtain dark readings. Readings were taken with a Hewlett Packard Model 3457A multimeter (Loveland, CO).

RESULTS

PPF measurements

At full power, the MPS lamps in the uniformity study provided an average of 1642±15 μmol $m^{-2}s^{-1}$ of PPF and an average of 579±5 μmol $m^{-2}s^{-1}$ of PPF at half power; the average PPF under the HPS/MH lamps was 871±8 μmol $m^{-2}s^{-1}$ (Table 1). The range in PPF under HPS/MH lamps, MPS lamps at full power, and MPS lamps at half power was 718 to 975, 1354 to 1919, and 473 to 655 μmol $m^{-2}s^{-1}$, respectively (Fig. 1). The PPF at 1.2 m from MPS lamps operated at full power was over 80% of that of sunlight at solar noon on a clear summer day (Table 1).

Yield photon flux, effective blue quanta and phytochrome photostationary state

When normalized to 2000 μmol $m^{-2}s^{-1}$, MPS lamps operated at full power had almost the same yield photon flux (YPF) as those operated at half power (1724 vs 1682 effective μmol $m^{-2}s^{-1}$) (Table 2). HPS/MH lamps and June sunlight also had a similar YPF (1876 and 1803 effective μmol $m^{-2}s^{-1}$, respectively). In comparison to HPS/MH lamps, MPS lamps had 8% lower YPF at full power and 10% lower YPF at half power. In comparison to sunlight, the YPF for MPS lamps was 96% at full power and 93% at half power. The effective blue quanta (BLP) of MPS lamps at half power was 50% greater than that at full power (488 vs 328). In comparison to HPS/MH lamps, the BLP for MPS lamps at full and half power was 2.2 and 3.3 times greater, respectively. In comparison to sunlight, the BLP for MPS lamps was 19% less at full power and 20% more at half power. The phytochrome photostationary state (PSS) for MPS lamps was calculated at 0.76 at full power and 0.75 at half power as compared to 0.84 for HPS/MH lamps and 0.72 for sunlight (Table 2).

Table 1. Uniformity of photosynthetic photon flux (PPF) in a growth chamber containing two 3.4 kW microwave-powered sulfur (MPS) lamps at full or half power, filtered with a Plexiglas barrier and an acrylic diffuser, or ten Sunbrella light fixtures, each containing a 400 W high pressure sodium (HPS) and a 400 W metal halide (MH) lamp. PPF measurements were taken at 55 locations in each plant growth chamber at 17.5×22.5 cm intervals with a LI-COR quantum flux sensor. Coefficient of variance (CV) and standard error of the mean (SEM) based on n=55.

Radiation source	Range in PPF (μmol $m^{-2}s^{-1}$)	Mean PPF±SEM (μmol $m^{-2}s^{-1}$)	CV (%)
MPS lamps, full power	1354−1919	1642±15	6.8
MPS lamps half power	473−655	579±5	6.4
HPS/MH	718−975	871±8	6.8

Table 2. Yield photon flux (YPF), effective blue quanta (BLP), and phytochrome photostationary state (PSS) for microwave-powered sulfur (MPS) lamps at full and half power, HPS/MH lamps, and sunlight normalized to 2000 μmol $m^{-2}s^{-1}$. See text for details of measurements and calculations.

	Radiation Source			
	MPS full	MPS half	HPS/MH	June 26 Sun
YPF eff. μmol $m^{-2}s^{-1}$	1724	1682	1876	1803
BLP eff. μmol $m^{-2}s^{-1}$	328	488	148	407
PSS	0.76	0.75	0.84	0.72

Spectroradiometric measurements

A comparison of bare and filtered MPS lamps versus sunlight indicates clearly that the spectrum of the unfiltered MPS lamp extends as far into the UV region as does sunlight (Fig. 2) ; however, the sun emits much more UV-B than the MPS lamp (10^3 as much), on either a weighted (data not shown), or unweighted basis (Fig. 2 and Table 3). With a Plexiglas barrier and acrylic diffuser, the UV cut-off of the filtered MPS lamps was above 350 nm (at T=10%), so that all of the UV-B (280–320 nm) and some of the UV-A (320–400 nm) radiation was excluded (Fig. 2).

Based on a waveband breakdown of absolute irradiance obtained under filtered MPS lamps, HPS/MH lamps, and sunlight, most of the irradiance under filtered MPS lamps is in the 500–600 nm (yellow) region (Table 3). At half power, there was a significant spectral shift toward the 400–500 nm (blue) region (Fig. 3).

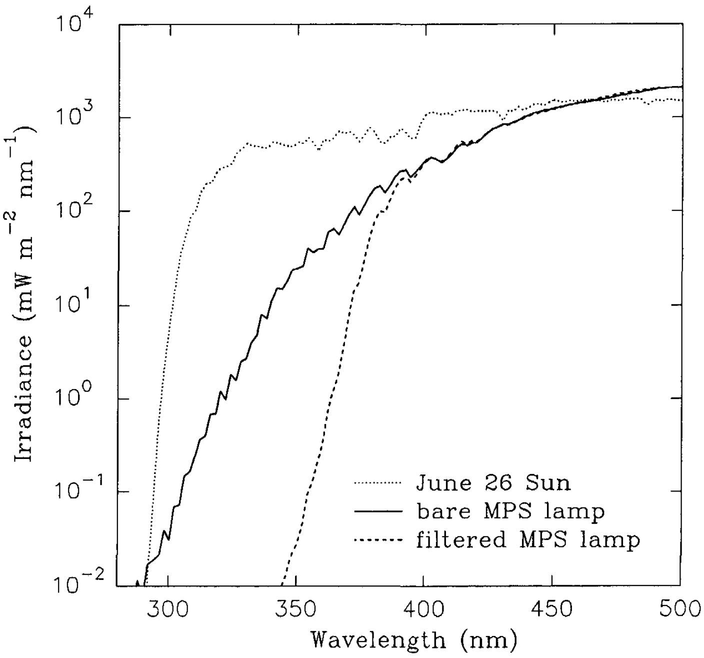

Fig. 2. Spectral irradiance from 290 to 500 nm (in mW $m^{-2} nm^{-1}$) of a bare and filtered (barrier and diffuser) microwave-powered sulfur (MPS) lamp (operated at full power) and sunlight (June 26) on a logarithmic basis. Data normalized to a PPF value of 2000 μmol $m^{-2} s^{-1}$ based on spectroradiometic measurements.

Table 3. Spectral irradiance (W m^{-2}) and percent of total irradiance (in parentheses) between 250 and 792 nm emitted by two bare 3.4 kW microwave-powered sulfur (MPS) lamps at full and half power, ten pairs of HID (high pressure sodium/metal halide) lamps (mounted in Sunbrella light fixtures) and sunlight. See text for details.

Waveband	Radiation Source			
	MPS full	MPS half	HPS/MH	June 26 sun
280–320	$5.9\times E^{-3}$ (0)	$8.1\times E^{-3}$ (0)	$3.8\times E^{-4}$ (0)	2.5 (0.4)
320–400	5.9 (1.4)	4.9 (3.4)	4.3 (2.2)	45.5 (7.8)
400–500	100.5 (24.6)	50.5 (35.3)	25.0 (12.6)	134.8 (23.0)
500–600	162.1 (39.7)	51.6 (36.0)	96.9 (48.8)	151.1 (25.8)
600–700	97.1 (23.8)	25.2 (17.6)	59.8 (30.1)	145.5 (24.8)
700–792	42.8 (10.5)	10.8 (7.5)	12.7 (6.4)	106.9 (18.2)
250–792	408.4 (100)	143.0 (100)	198.7 (100)	586.4 (100)

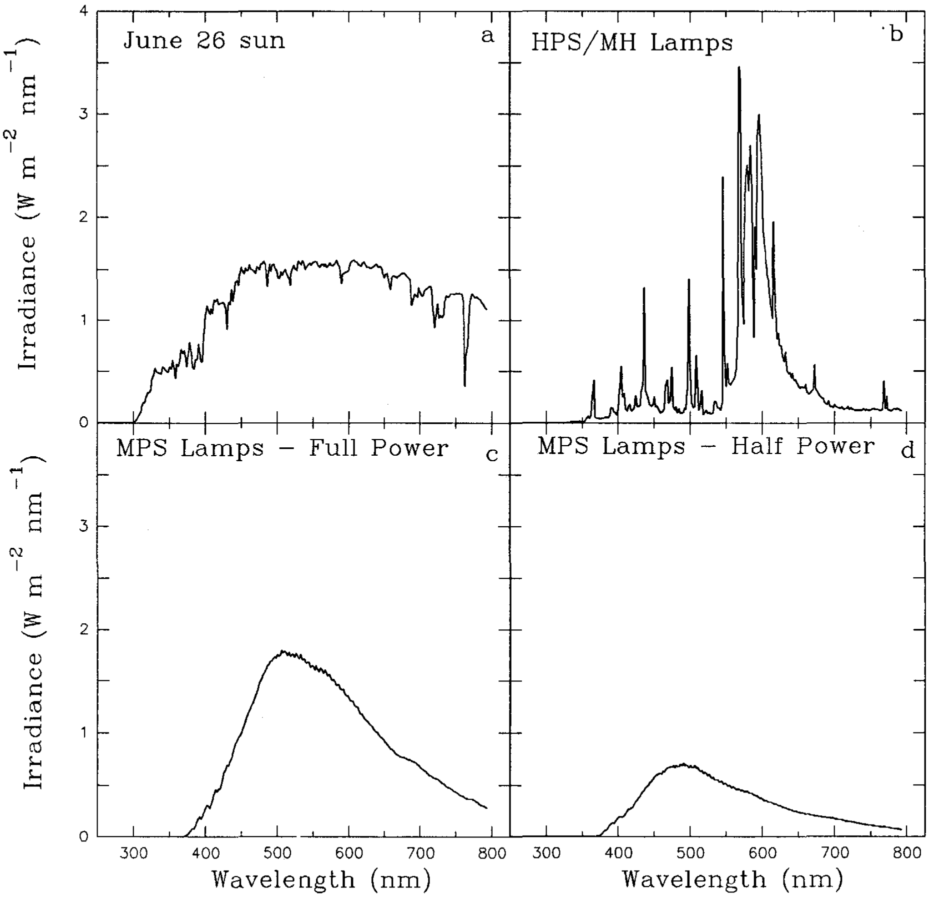

Fig. 3. Spectral irradiance of: a) sunlight (June 26); b) high pressure sodium/metal halide (HPS/MH) lamps; and filtered microwave-powered sulfur (MPS) lamps at c) full power and d) half power. PPF levels are listed in Table 2. Linear plots show data on an absolute basis.

Bare MPS lamps at full power were nearly comparable to sunlight in the percent of irradiance in the blue (400–500 nm) and the red (600–700 nm) regions, but had 60% more in the yellow (500–600 nm) region. At half power, the percent of irradiance for MPS lamps at half power was 50% greater in the blue (400–500 nm), one third less in the red (600–700 nm), and almost 50% more in the yellow (500–600 nm) region than for sunlight. In comparison to sunlight, the percent of irradiance for HPS/MH lamps was 50% less blue, nearly 25% more red, and nearly twice as much yellow. In comparison to sunlight, the percent of total irradiance in the 700 to 792 nm (far-red) region was 40% less under MPS lamps at full power, 59% less under MPS lamps at half power, and 65% less under HPS/MH lamps (Table 3).

Total radiation measurements

Measurements taken with a pyranometer (0.29 to 3 μm) and a pyrgeometer (3 to 50 μm) indicate that on a normalized basis, the biggest difference between

Table 4. Total radiation emitted by two 3.4 kW microwave-powered lamps (MPS) at full and half power (filtered with Plexiglass and an acrylic diffuser), and ten pairs of HID lamps (HPS/MH) mounted in Sunbrella light fixtures. Normalized data in parentheses expressed in J μmol^{-1}.

Radiation source	PPF (μmol m^{-2} s^{-1})	Irradiance (W m^{-2})			
		0.29–0.8 μm	0.8–3 μm	0.29–3 μm	3–50 μm
MPS lamp, full power	1786	419 (0.23)	92 (0.05)	510 (0.29)	44 (0.025)
MPS lamp half power	650	152 (0.23)	28 (0.04)	180 (0.28)	26 (0.040)
HPS/MH	1052	233 (0.22)	189 (0.18)	422 (0.40)	49 (0.047)

Measurements from 0.29 to 3 μm are means of readings taken with two separate Eppley PSP pyranometers. Measurements from 3 to 50 μm are means of readings taken with two separate Eppley PIR pyrgeometers. Irradiance from 0.80 to 3 μm was measured with an Eppley PSP pyranometer with a 805 nm Schott glass cutoff filter. Irradiance from 0.29 to 0.8 μm was calculated by taking the difference between column 3 and column 4. Measurements taken 1.2 m from the lamps.

filtered MPS lamps and HPS/MH lamps was in the 0.8 to 3 μm (NIR) region, where HPS/MH lamps emitted four times as much NIR as MPS lamps, on a relative basis (Table 4). There was a 43% increase in the 0.29–3 μm region between MPS and HPS/MH lamps on a normalized basis. Far IR (3–50 μm) radiation on a normalized basis was twice as large for the HPS/MH lamps as for the MPS lamps at full power and 17% greater than for MPS lamps at half power.

DISCUSSION

Light sources employing MPS and other types of electrodeless discharges provide a number of attractive features for both the lighting engineer and the plant scientist (*12, 13, 22, 24*). Since they are free of electrodes, MPS lamps are relatively fail-proof and have a long lamp life.

The lamps are relatively compact with integral electronics and are free of usual size constraints on lamp design, allowing innovative light sources, such as light pipes, to be created. Metal halide and other reactive gases may be used. In contrast to xenon arc lamps, MPS lamps and other electrodeless discharge lamps may be replaced easily at relatively low cost. Another important feature of these novel lamps is their extremely high efficacy. Since MPS lamps do not contain mercury, the degradation of materials by ultraviolet radiation is reduced and there is less environmental hazard involved in disposal.

One advantage of MPS lamps claimed by the manufacturer is the relatively low amount of IR radiation emitted. Our data on NIR measurements in the 0.8 to 3 μm region (Table 4) would tend to support this contention, since on a relative basis one quarter as much NIR was detected under MPS lamps as under

HPS/MH lamps enclosed in Sunbrellas. Similar findings were obtained by Both *et al.* (*4*) doing NIR and far IR radiation measurements under bare MPS lamps and bare HPS lamps that were either air or water cooled. The NIR value for sunlight derived from Thimijan and Heins (*20*) was almost identical to that of the HPS/MH lamps (0.19) in our study.

The broad band irradiances obtained by subtraction (0.29–0.8 μm) (Table 4) are only a little larger than our spectroradiometric measurements from 250 to 792 nm (Table 3), which are very close to those previously reported (*20*). The irradiance from 0.8 to 3.0 μm which they report, based on a review of published manufacturer's data, is only half as much as that measured in the present study and may be related to initial instrumentation error.

With the use of a Plexiglas barrier and acrylic diffuser in our experiments, there was proportionately less far IR (3–50 μm) emitted by MPS lamps than by HPS/MH lamps on a normalized basis. Measurements at the University of Wisconsin under bare MPS lamps (T. W. Tibbitts, 1997, personal communication) confirm our NIR results, but indicate somewhat higher levels of far IR than those obtained in our study with filtered MPS lamps. Since MPS lamps are free of electrodes and have a relatively small bulb envelope, they have minimal surface area from which to radiate IR radiation. This is in contrast to conventional lamps, which can radiate IR radiation from the plasma, the electrodes, and the quartz bulb envelope (*13*).

Although one might expect that the PPF level would be reduced in half by turning off one of the two magnetrons, our findings indicate that there was nearly a two-thirds decrease in PPF when the power was reduced without adjusting lamp envelope cooling. By reducing the power to the MPS lamps, there was a significant shift in the spectral output so that there was proportionally less of the radiation from 400 to 700 nm at wavelengths above 500 nm (62 vs 74%) and more radiation below 500 nm (38 vs 26%). If lamp cooling had been adjusted with a change in power, it is likely that the spectral shift would not have been as marked. Preliminary findings of the manufacturer indicate that there is virtually no shift in spectrum over the life of MPS lamps because of the use of a non-reactive fill material and the absence of electrodes (*12, 13, 22*). Further studies are needed to confirm this.

It is interesting to note, however, that the normalized YPF for the HPS/MH lamps (94%) is higher than that for either sunlight (90%) or for the MPS lamp at either full or half power (86% and 84%) indicating the greater photosynthetic efficiency of the PPF produced by HPS/MH lamps. The effective quanta of blue light and the PSS for phytochrome were nearly comparable for MPS lamps and for sunlight. In terms of photoregulation of shoot elongation, these features of MPS lamps would be desirable in terms of trying to simulate natural sunlight conditions.

Because of the point source nature of MPS lamps, it is important to have suitable reflective surfaces on the walls of the growth chambers and a suitable diffuser below the lamp. Installation of new polished aluminum on the chamber walls in the current set of studies undoubtedly contributed to the relatively high uniformity of PPF within the growing area.

Based on the spectral characteristics of MPS lamps and calculated values for phytochrome photostationary state, yield photon flux and effective blue quanta, MPS lamps should provide plant researchers with an excellent source of radiation for use in plant growth chambers. They should provide plant researchers with much higher PPF levels than are generally available. For physiological studies in plant growth chambers where high PPF is required, as in studies on UV-B radiation effects (to provide sufficient light for photorepair of UV damage), MPS lamps may be ideally suited.

For maximum utilization by plant scientists, it would be highly desirable to have MPS lighting systems with capabilities for programming and adjusting PPF levels and to have feedback control for those investigators interested in matching controlled environment lighting to ambient solar radiation.

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