UNIFORMITY OF PHOTOSYNTHETIC PHOTON FLUX AND GROWTH OF 'POINSETT' CUCUMBER PLANTS UNDER METAL HALIDE AND MICROWAVE-POWERED SULFUR LAMPS

Krizek, D. T.
Climate Stress Laboratory Natural Resources Institute Agricultural Research Service U. S. Department of Agriculture

Mirecki, R. M.
Climate Stress Laboratory Natural Resources Institute Agricultural Research Service U. S. Department of Agriculture

Bailey, W. A.
Climate Stress Laboratory Natural Resources Institute Agricultural Research Service U. S. Department of Agriculture

出版情報：BIOTRONICS. 27, pp.81-92, 1998-12. Biotron Institute, Kyushu University

BIOTRONICS **27**, 81–92, 1998

UNIFORMITY OF PHOTOSYNTHETIC PHOTON FLUX AND GROWTH OF 'POINSETT' CUCUMBER PLANTS UNDER METAL HALIDE AND MICROWAVE-POWERED SULFUR LAMPS[1, 2]

D. T. KRIZEK[1], R. M. MIRECKI and W. A. BAILEY

Climate Stress Laboratory, Natural Resources Institute, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, MD 20705–2350, USA

(Received September 11, 1998; Accepted October 1, 1998)

KRIZEK, D. T., MIRECKI, R. M. and BAILEY, W. A. *Uniformity of photosynthetic photon flux and growth of 'Poinsett' cucumber plants under metal halide and microwave-powered sulfur lamps.* BIOTRONICS **27**, 81–92. The uniformity of photosynthetic photon flux (PPF) and vegetative growth of *Cucumis sativus* L. ('Poinsett' cucumber) were examined using growth chambers equipped with either six 400 W metal halide (MH) lamps or with a single 1000 W microwave -powered sulfur (MPS) (LIGHTDRIVE™ 1000) lamp mounted on a polished stainless steel reflector with secondary screening for microwave protection. PPF levels in each growth chamber were set initially at 500 μmol m^{-2} s^{-1}. Pots were placed at equal distance from one another in ten columns of six rows each (n=60). Growth measurements were only taken on the center six columns of plants (n=36). The uniformity of PPF was greater in the MPS than in the MH chamber for both the 36 and the 60 pot arrangement. However, growth measurements showed similar variance in the MH as in the MPS chamber. Plants grown for 14 days under MPS lamps had significantly greater growth than those under MH lamps. Petiole length, total stem length, and leaf enlargement were 90%, 44%, and 34% greater, respectively, in plants grown under MPS lamps than under MH lamps. Similar differences were obtained in biomass; dry weights of tops and roots of MPS grown plants were 28% and 36%, greater, respectively, than those of MH grown plants. These findings demonstrate the potential of using sulfur lamps for accelerating seedling production under controlled environments and validate the concept that sulfur lamps have a better spectral quality for plant growth than metal halide lamps. These results should be of interest to growers and researchers involved in protected cultivation. The LIGHTDRIVE™ 1000 sulfur lamp should also provide a useful tool for studying the photocontrol of shoot development.

Key words: cucumber; *Cucumis sativus* L.; electrodeless lamps; high intensity discharge lamps; shoot growth; spectral quality; controlled environment.

---

[1]Corresponding author: Donald T. Krizek, USDA Climate Stress Laboratory, Bldg. 046A, BARC-West, Beltsville, MD 20705–2350, USA; Tel: (301) 504–5324, Fax: (301) 504–6626; e-mail address: dkrizek@asrr.arsusda.gov

[2]Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

INTRODUCTION

Controlled-environment studies are frequently constrained by a lack of commercially available sources of radiant energy that provide a stable level of photosynthetic photon flux (PPF) at 500 μmol m^{-2} s^{-1} or more while at the same time providing a spectrum close to that of sunlight. Recent studies indicate that electrodeless microwave-powered sulfur (MPS) lamps may satisfy both requirements (*1, 2, 6, 8*).

General reviews of electrodeless lamps have been written by Waymouth (*17*) and Wharmby (*18*). The principal design features of electrodeless sulfur lamps have been summarized by MacLennan *et al.* (*9, 10*) and Turner *et al.* (*15*). The basic sulfur lamp consists of a spherical quartz envelope filled with argon and sulfur vapor and surrounded by a primary RF screen. This vapor serves as the plasma forming medium of the MPS lamp which produces radiation upon molecular excitation by microwaves generated by a magnetron (*10*).

Preliminary studies done at Beltsville, MD (*2, 8*) and Ithaca, NY (*1*) using a prototype 3.4 kW lighting system developed by Fusion Systems Corp. (the forerunner of Fusion Lighting Inc., Rockville, MD, USA) have demonstrated the efficacy of using microwave-powered sulfur lamps as a high intensity source of visible radiation for growing selected horticultural and agronomic plants under controlled environments. In a recent study conducted in Japan, Kozai *et al.* (*6*) reported that they were able to grow rice plants for three months from seed to harvest in a growth chamber containing a 3.4 kW microwave-powered lamp.

Measurements taken at Beltsville, MD with a quantum sensor indicated that PPF levels up to 80 percent of full sunlight could be obtained in a growth chamber at a distance of ca. one meter from the prototype MP sulfur lamp, when the magnetron was operated at full power (*8*).

Since 1992, scientists at Fusion Lighting Inc. have made a number of improvements in the design of electrodeless sulfur lamps in order to develop a self contained lighting system and to improve the spectral output of these lamps (*9, 10, 15, 17*). One of the first commercial products to become available was the SOLAR 1000™ lamp. This lamp is currently referred to as the LIGHTDRIVE™ 1000 lamp. Although this lamp is normally sold as a packaged unit with lamp, ballast and reflector assembled (*10*), we constructed our own reflector housing with secondary screening in order to be able to install a single lamp in the light cap of one of our small experimental growth chambers. Our goal in doing so was to be able to determine whether the distribution of irradiance from a single 1000 W MPS lamp was adequate for growing a uniform stand of plants and to compare plant responses with those obtained under a bank of six 400 W metal halide (MH) lamps set initially at an equal PPF level.

Until recently, most growth chamber studies have been conducted using 1500 mA fluorescent lamps. Depending upon the arrangement and number of such lamps used, it is often difficult to maintain an irradiance much above 300 μmol m^{-2} s^{-1} of PPF. The possibility of using a single LIGHTDRIVE™ 1000 sulfur lamp to achieve a PPF level of at least 500 μmol m^{-2} s^{-1} made it seem attractive to test this new lamp.

To evaluate the suitability of this system, a study was conducted to determine the amount of pot to pot variation in PPF and vegetative growth of cucumber plants grown for 14 days from seed under MH and MPS lamps and to compare the irradiance and growth under the two radiation sources.

MATERIALS AND METHODS

Plant material and cultural conditions

Seeds of cucumber (*Cucumis sativus* L. cv. Poinsett) were presoaked for 1–2 h in distilled water at room temperature and then planted in 7.6 cm diameter white plastic pots containing a peat–vermiculite mix (Jiffy Mix, Jiffy Products of America, West Chicago, IL, USA). Plants were given distilled water during the first 3–4 days; thereafter they were fertilized 1–2 times daily with a complete nutrient solution as described by Silvius *et al.* (*13*).

Pots were spaced equidistant from one another in ten columns of six rows each (n=60) by placing them in a specially constructed frame made of aluminized metal (Coilzac, Environmental Growth Chambers Inc., Chagrin Falls, OH, USA). Duplicate experiments were conducted and the data were combined for statistical analysis.

Plants were grown in specially designed plant growth chambers (0.76×1.24 m) with temperature and relative humidity controlled by Aminco–Aire Environmental Controllers (Parameter Generation and Control, Inc., Black Mountain, NC, USA) as described previously (*7*). Environmental conditions common to both growth chambers were as follows: 16 h photoperiod (0900–0100), day/night temperature of 25±1℃, relative humidity of 60±5%, and ambient CO_2.

Experimental setup

Plants were grown in two separate growth chambers. One growth chamber was equipped with six 400 W MH lamps (Philips Lighting Co., Somerset, NJ) mounted in the light cap (0.48 m×0.76 m) in two rows of three lamps each, with the base of the lamps mounted 20 cm from the sides of the chamber. A second growth chamber contained a single 1000 W MPS lamp (LIGHTDRIVE™ 1000 formerly designated SOLAR 1000™) (Fusion Lighting Inc., Rockville, MD, USA) placed in a polished stainless steel reflector with the magnetron mounted at a 45 degree angle onto the side of the reflector (Fig. 1). The distance from the lamps to the top of the pots was 0.7 m in the MH chamber and 0.75 m in the MPS chamber. The doors and walls of the growth chambers were lined with polished aluminum (Coilzac, Environmental Growth Chambers, Chagrin Falls, OH) to increase their reflectivity.

To prevent stray microwave radiation, secondary screening was installed at the bottom of the reflector, using a piece of hardware cloth (5 mm×5 mm screen) having a 0.7 mm diameter wire. The screening reduced the amount of PPF by ca 12% but was suitable for blocking extraneous microwave radiation and allow sufficient air ventilation for cooling of the lamp.

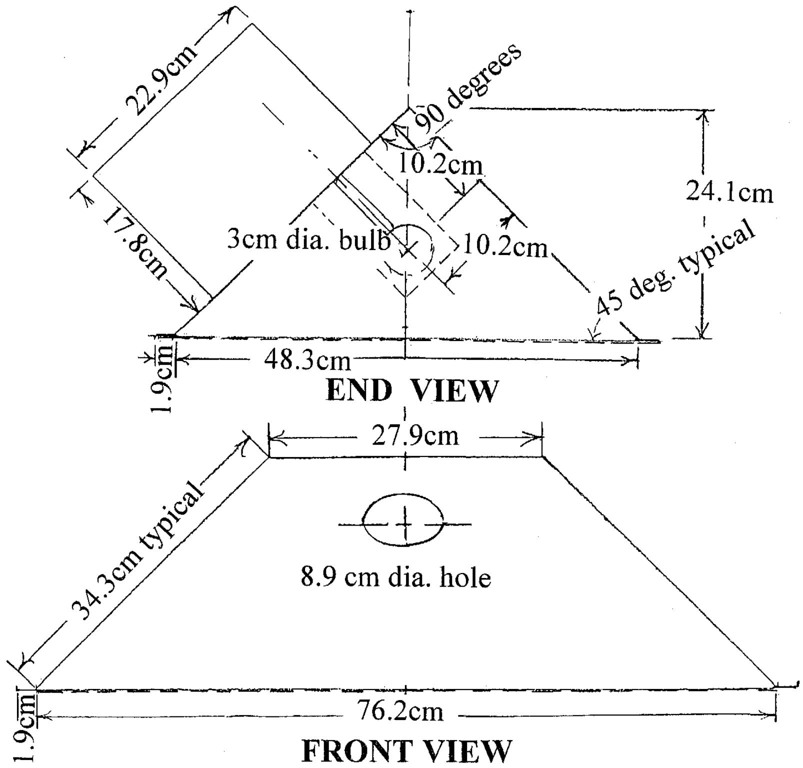

Fig. 1. Schematic of polished stainless steel reflector used to mount a 1000 W microwave-powered sulfur (MPS) lamp (LIGHTDRIVE™ 1000, formerly called SOLAR 1000™ lamp) in the light cap. End view shows the lamp assembly mounted on a fabricated reflector. A secondary screen of galvanized hardware cloth (5 mm×5 mm grid) was mounted on a 1.9 cm flange around the bottom of the reflector.

Radiation measurements

The level of PPF (400–700 nm) in each growth chamber was set initially at 500 μmol m^{-2} s^{-1} by means of a LI-COR (Lincoln, NE, USA) quantum flux sensor. Duplicate PPF measurements were taken at each pot location to assess uniformity of PPF under MH and MPS lamps. Plots of PPF distribution are only shown for the center six columns of plants, since these were the ones from which data were collected.

Spectroradiometric measurements (250–792 nm) were made every 2 nm from 250 to 792 nm in the center of each growth chamber with an Optronic Model 752 (Orlando, FL, USA) UV-VIS spectroradiometer. For purposes of comparison, spectral irradiance for the two radiation sources was adjusted to 500 μmol m^{-2} s^{-1} and tabulated in selected band widths (Table 1).

Total radiation measurements from 300–3000 nm were made with a Kipp and Zonen Model CM3 pyranometer (Delft, Holland). Microwave radiation levels were monitored with a H-1501 Microwave Survey Meter (Holaday Industries, Inc., Eden Prairie, MN, USA).

Table 1. Integrated spectral irradiance (W m^{-2}) under metal halide (MH) and microwave-powered sulfur (MPS) lamps adjusted to 500 μmol m^{-2} s^{-1} of photosynthetic photon flux (PPF) and red/blue band and red/far-red band ratios. Ratio of irradiance under MPS/MH lamps shown to highlight similarities and differences in selected bandwidths.

Rad. Source	Waveband (nm)							
	280–320 UV-B	320–400 UV-A	400–500 Blue	500–600 Yellow	600–700 Red	700–792 Far-red	R/B ratio	R/FR ratio
MPS	0.017×10^{-3}	0.374	29.67	51.77	27.30	11.61	0.73	2.35
MH	0.159×10^{-3}	7.587	31.42	59.57	19.48	5.16	0.62	3.78
MPS/MH	0.11	0.05	0.94	0.87	1.40	2.25	1.18	0.62

Comparative growth measurements

Growth measurements were only taken on the center six columns of plants (n=36) with the other columns serving as border plants. After 14 days, plants were photographed, harvested, and data taken on total height, hypocotyl length, petiole length, number of leaves, fresh weight of tops, and total leaf area. Leaf area was determined using a LI-COR Model LI-3000 leaf area meter. After drying the samples in a forced draft oven for at least 48 hr at 70C, data were taken on dry weight of the leaves, stems, hypocotyl, petioles, and roots. Total dry weight of the tops was determined by summing the weights of the individual fractions.

Statistical analysis

Uniformity of PPF and growth responses were analyzed using data combined from duplicate experiments run in succession. Differences referred to as significant were at $p\leq0.05$ as determined by Analysis of Variance (Anova) using PC SAS version 6.11 PROC MIXED procedure. Means and standard errors were calculated for the combined data in the two experiments based on n=72 or 120 for PPF values and n=72 for growth measurements.

RESULTS AND DISCUSSION

Comparative measurements of irradiance

Qualitative differences in spectral irradiance under MH and MPS lamps were evident on both a linear (data not shown) and on a logarithmic (Fig. 2) basis in terms of the shape of the curves and in the spectral cutoff. These differences were especially marked in the UV, blue (B), red (R) and far-red (FR) regions.

Quantitative differences were most striking in the 320–400 nm (UV-A), 600–700 nm (R), and 700–792 nm (FR) band widths (Table 1). MPS lamps emitted only 5% as much UV-A, 40% more R, and 125% more FR radiation as MH lamps. Spectral irradiance in the 400–500 nm (B) and 500–600 nm (yellow) bands were fairly comparable; MPS lamps emitted 5% less B and 13% less yellow than MH lamps. The R/B ratio and the F/FR ratios also differed under MH and MPS

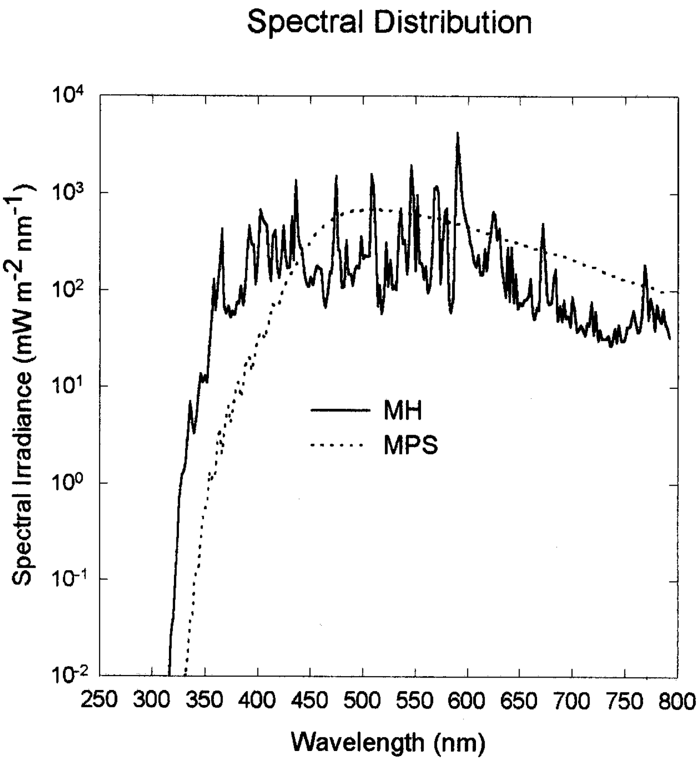

Fig. 2. Spectral irradiance (mW m^{-2} nm^{-1}) under metal halide (MH) and microwave–powered sulfur (MPS) lamps plotted on a logarithmic scale. The initial photosynthetic photon flux level was set at 500 μmol m^{-2} s^{-1} in each growth chamber.

lamps (Table 1). MPS lamps had a 62% lower red/far–red (R/FR) ratio than MH lamps which could account for the increase in stem and petiole elongation, in view of the well known effect of FR radiation in promoting elongation responses (*12*).

The range in PPF under the MH and MPS lamps was from 383.1 to 615.4 vs 455.5 to 548.1 μmol m^{-2} s^{-1}, respectively, for the 36 pot arrangement, and from 383.1 to 615.6 vs 428.0 to 548.1 μmol m^{-2} s^{-1}, for the 60 pot arrangement. Although there were no differences in mean PPF between the two growth chambers for the 60 pot arrangement, the mean PPF for the 36 pot arrangement was 7.8% greater under MH than under the MPS lamp ($p \leq 0.0001$).

The overall variance in PPF was greater under the MH lamps than under the MPS lamp for both the 36 pot arrangement (459.4±11.5 vs 495.9±3.7 μmol m^{-2} s^{-1} and for the 60 pot arrangement (496.6±6 vs. 489.3±3.3 μmol m^{-2} s^{-1}). This was a reflection of the spatial distribution of the MH lamps being primarily along each side of the chamber rather than toward the center of the chamber. Consequently, the overall uniformity of PPF was greater in the MPS than in the MH chamber. The comparative distribution of PPF under the two radiation sources for the 36 pot arrangement is shown in three dimensional plots (Figs. 3 and 4).

Although MH lamps emitted lower levels of FR radiation than MPS lamps

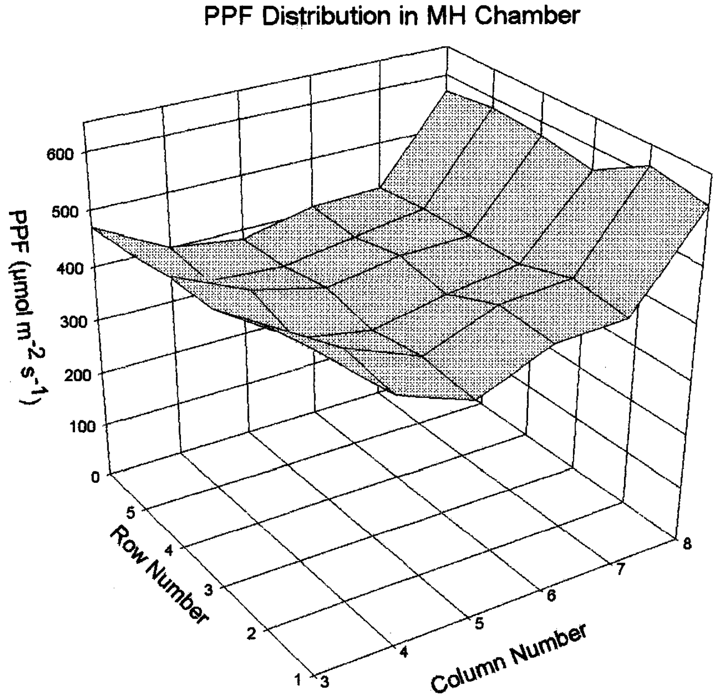

Fig. 3. Distribution of photosynthetic photon flux (PPF) in a growth chamber containing six 400 W metal halide (MH) lamps. Plot measurements made at every pot location in six columns (left to right) and six rows (front to back).

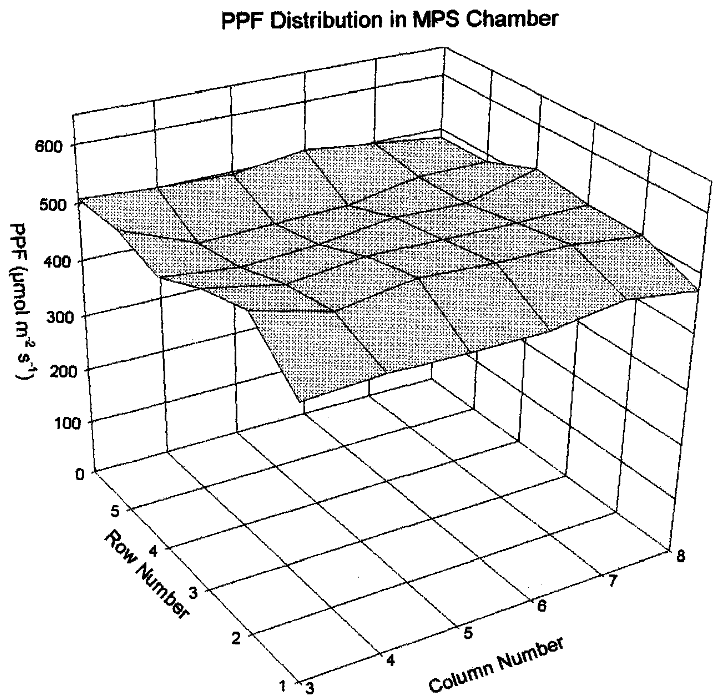

Fig. 4. Distribution of photosynthetic photon flux (PPF) in a growth chamber containing a single 1000 W microwave-powered sulfur (MPS) lamp (LIGHTDRIVE™ 1000). Plot measurements made at every pot location in six columns (left to right) and six rows (front to back).

based on spectroradiometric readings, they emitted twice as much net radiation from 300–3000 nm based on pyranometer readings; this difference in long-wave radiation was obvious when working in the two growth chambers. There was no evidence of extraneous microwave radiation when the secondary screen was installed in the MPS growth chamber.

Comparative growth measurements

Despite a high degree of variance in PPF under MH lamps, because of a large drop off of PPF in the center of the growth chamber (Fig. 3), this was not reflected in an obvious difference in growth (Fig. 5A). This was unexpected and suggests that plants are better integrators of PPF than physical measurements might otherwise indicate. The variance in growth under MH and MPS lamps was similar. For example, in the case of dry weight of tops, the mean and SEM was 629.9 ± 12.7 vs. 492.2 ± 8.9 mg while the percentage of variance was 2.0 vs 1.8%, respectively.

Regressions of total height, petiole length, total leaf area and dry weight of tops indicated that there were no significant relationships between PPF and growth response (data not shown). Although the regression coefficient between PPF and dry weight of tops for MPS and MH treated plants was not significant ($r^2 = 0.11$ and 0.47, respectively), the rate of growth of MPS treated plants based on mg dry weight per μmol m^{-2} s^{-1} of PPF was twice as great as that of MH treated plants (1.58 vs 0.75 respectively).

For the first 6 days there were no visual differences in growth between the two sets of seedlings. However, by day 10–12, plants under MPS lamps began to show increased stem and petiole elongation and increased leaf enlargement. By 13 days, MPS grown plants had become crowded and had grown above the pot labels while those of MH grown plants were shorter and less crowded. These differences were even more marked at time of harvest, both in the overhead views (Figs. 5A, 5B) and in the close-up (Fig. 6).

These visual differences were confirmed by quantitative data (Table 2). For every growth parameter measured, plants grown 14 days under MPS lamps had significantly greater leaf number, stem and petiole elongation, leaf expansion, and biomass of leaves, petioles, hypocotyls, stems, and roots than those grown under MH lamps.

Differences in petiole growth between the two treatments (illustrated in Fig. 6) were particularly marked; petiole length was 90% greater in plants grown under MPS lamps than under MH lamps, while hypocotyl length and total stem height were 29 and 44% greater, respectively. Similar differences were obtained in biomass; fresh and dry weights of tops of MPS grown plants were 43 and 28% greater, respectively, than those of corresponding fractions from MH grown plants. Dry weight of roots and total plant dry weight were 36% and 31% greater, respectively, under MPS lamps. MPS treated plants had 34% greater leaf area than MH treated plants.

These findings demonstrate the potential of using sulfur lamps for accelerating seedling production under controlled environments. On a 60 pot

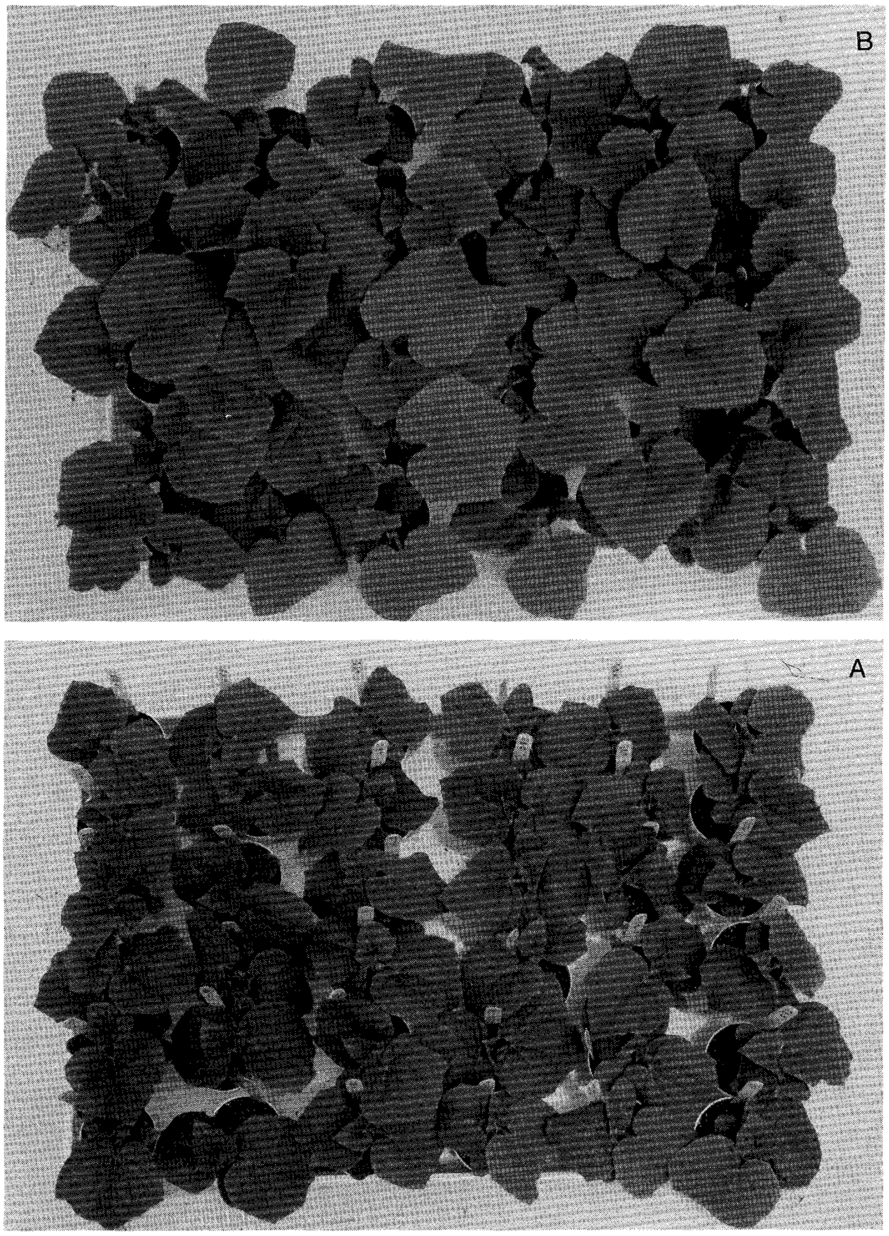

Fig. 5. Appearance of 'Poinsett' cucumber plants grown for 14 days in a growth chamber under six 400 W metal halide (MH) lamps (Fig. 5A) or under a single 1000 W microwave-powered sulfur (MPS) lamp (Fig. 5B) . Note space between MH grown plants and the absence of space between MPS grown plants and the fact that pot labels are still visible among the MH grown plants but not the MPS grown plants.

basis, the mean PPF in the MH and MPS growth chambers was nearly the same, viz, ca 500 μmol m^{-2} s^{-1}; however, on a 36 pot basis, the mean PPF in the MPS growth chamber was about 50 μmol m^{-2} s^{-1} higher than the mean PPF in the MH growth chamber. Since linear growth, leaf enlargement, and biomass were 30 to 90% greater in MPS treated plants, it is unlikely that PPF differences alone could

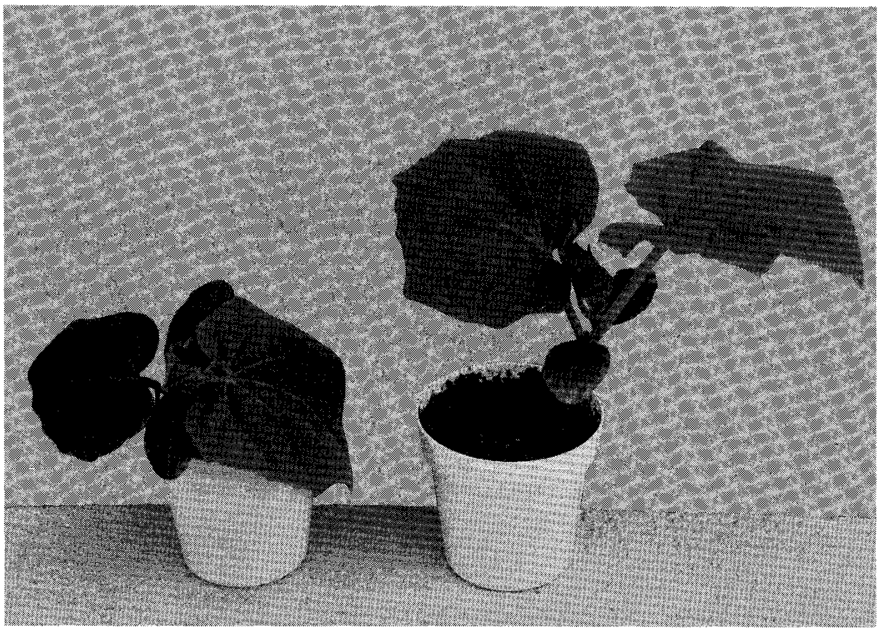

Fig. 6. Comparative growth of 'Poinsett' cucumber plants grown for 14 days from seed under (left) six metal halide (MH) lamps or (right) a single microwave-powered sulfur (MPS) lamp. Note greater stem and petiole length and leaf area in MPS grown plant.

Table 2. Growth of 'Poinsett' cucumber plants after 14 days in a growth chamber under six 400 W metal halide (MH) lamps or a single 1000W microwave -powered sulfur (MPS) lamp. Data presented for F values and means±SEM. Lamp means for all growth parameters were significantly different at $p \leq 0.0001$ based on LSMEANS (n=36 observations per treatment).

Parameter	Rad. source MH lamps	Rad. source MPS lamps	F value
total leaf no.	4.3±0.1 b	4.5±0.1 a	8.44
total height, mm	38.4±0.4 b	55.2±0.8 a	375.14
petiole length, mm	26.3±0.3 b	50.0±1.0 a	657.02
hypocotyl length, mm	26.2±0.3 b	33.9±0.5 a	186.74
total leaf area, cm^2	147.3±2.1 b	196.7±3.1 a	186.45
fresh wt tops, g	6.0±0.1 b	8.6±0.1 a	263.59
dry wt blades, mg	431.3±8.0 b	514.3±10.1 a	46.07
dry wt petioles, mg	24.1±0.5 b	50.3±1.5 a	392.44
dry wt hypocotyl, mg	20.1±0.4 b	38.5±1.0 a	346.94
dry wt stems, mg	16.8±0.5 b	26.2±0.7 a	130.82
dry wt tops, mg	492.2±8.9 b	629.9±12.7 a	90.87
dry wt roots, mg	201.7±7.0 b	273.7±9.1 a	45.01
total dry wt, mg	691.2±12.2 b	902.1±14.5 a	125.32

have accounted for these differences.

Our findings validate the concept that sulfur lamps have a better spectral quality for plant growth than metal halide lamps. These results should be of interest to growers and researchers involved in protected cultivation. These new sulfur lamps should also afford a useful tool for photobiologists interested in studying the photocontrol of shoot development.

Numerous studies have been conducted to find a radiation source for use in growth chambers that provides suitable levels of visible radiation for photosynthesis and normal development of the plant (*3, 4, 5, 11, 12, 14, 16*). The present study indicates that the LIGHTDRIVE™ 1000 lighting system should be ideal for accomplishing these objectives with even a single lamp. For increased irradiance (e.g., 1000 μmol m^{-2} s^{-1} or higher), it would be necessary to install at least a pair of these lamps in a small reach-in growth chamber.

To improve the commercial value of seedlings propagated under MPS lamps, it may be desirable to alter the spectral emission of the lamps to increase the R/FR ratio and/or add supplemental irradiance in the B and in the UV-A portion of the spectrum, thereby reducing stem and petiole elongation.

ACKNOWLEDGMENTS

The authors extend grateful acknowledgments to Donald A. MacLennan, Frank Sowers, and Brian Turner, Fusion Lighting, Inc., Rockville, MD for providing the sulfur lamp used in this study and for their helpful discussions and to Jay Cline for his help in data collection and analysis.

REFERENCES

1. Both, A. J., Albright, L. D., Chou, C. A. and Langhans, R. W. (1995) A microwave-powered light source for plant irradiation. *Acta Hort.* **440**, 187–192.

2. Britz, S. J., Krizek, D. T., Lee, D. R., Harris, W. G., Hungerford, W. E. and Bailey, W. A. (1993) Soybean growth under microwave-powered sulfur lamps, high irradiance discharge lamps, or solar radiation at ambient or elevated CO_2. *HortScience* **28**(5), 538.

3. Bubenheim, D. L., Bugbee, B. and Salisbury, F. B. (1988) Radiation in controlled environments: Influence of lamp type and filter material. *J. Amer. Soc. Hort. Sci.* **11**, 468–474.

4. Cathey, H. M. and Campbell, L. E. (1980) Light and lighting systems for horticultural plants. *Hort. Rev.* **2**, 491–537.

5. Hartmann, K. M. and Kaufmann, W. F. (1990) Solar simulation for growth chambers. Pages 279–293 *in* H. D. Payer, T. Pfirrmann, and P. Mathy (eds). *Environmental research with plants in closed chambers. Air Pollution Research Report 26.* Commission of the European Communities. E Gu ot SA, Brussels, Belgium.

6. Kozai, T., Kitaya, Y. and Oh, Y. S. (1995) Microwave-powered lamps as a high intensity light source for plant growth. *Acta Hort.* **399**, 107–112.

7. Krizek, D. T., Kramer, G. F., Upadhyaya, A. and Mirecki, R. M. (1993) UV-B response of cucumber seedlings grown under metal halide and high pressure sodium deluxe lamps. *Physiol. Plant.* **88**, 350–358.

8. Krizek, D. T., Mirecki, R. M., Britz, S. J., Harris, W. G. and Thimijan, R. W. (1998) Spectral properties of microwave-powered sulfur lamps in comparison to sunlight and high pressure sodium/metal halide lamps. *Biotronics* **27**, 69–80.

9. MacLennan, D. A., Turner, B. P., Dolan, J. T., Ury, M. G. and Gustafson, P. A. (1994) Efficient, full spectrum, long-lived, non-toxic microwave lamp for plant growth. Pages 243–254 *in* T. W. Tibbitts (ed) *Proceedings International Lighting in Controlled Environments Workshop.* Held at the University of Wisconsin, Madison, March 27–30,

1994. NASA Report. NASA CP-95-3309.
10. MacLennan, D. A., Turner, B. P. and Shanks, B. E. (1996) Sulfur lighting for plants in controlled environments. Pages 97–105 *in Proceedings of 17th Conference, Hydroponic Society of America*. Held at San Jose, California, June 1996.
11. Sager, J. C., Edwards, J. L. and Klein, W. H. (1982) Light energy utilization efficiency for photosynthesis. *Transactions of the ASAE* **25**, 1737–1746.
12. Sager, J. C., Smith, W. O., Edwards, J. L. and Cyr, K. L. (1988) Photosynthetic efficiency and phytochrome photoequilibria determination using spectral data. *Transactions of the ASAE* **31**, 1882–1899.
13. Silvius, J. E., Kramer, D. F. and Lee, D. R. (1978) Carbon assimilation and translocation of soybean leaves at different stages of development. *Plant Physiol.* **62**, 54–58.
14. Tibbitts, T. W., Morgan, D. C. and Warrington, I. J. (1983) Growth of lettuce, spinach, mustard, and wheat plants under four combinations of high-pressure sodium, metal halide, and tungsten halogen lamps at equal PPFD. *J. Am. Soc. Hort. Sci.* **108**, 622–630.
15. Turner, B. P., Ury, M. G., Leng, Y. and Love, W. G. (1997) Sulfur lamps-progress in their development. *J. Illum. Eng. Soc.* **26**(1), 10–16. Winter 1997.
16. Warrington, I. J., Mitchell, K. J. and Halligan, C. (1976) Comparison of plant growth under four different lamp combinations and various temperature and irradiance levels. *Agric. Meteor.* **16**, 231–245.
17. Waymouth, J. F. (1993) Applications of microwave discharges to high-power light sources. Pages 427–443 *in* C. M. Ferreira and M. Moisan (eds) *Microwave Discharges-Fundamentals and Applications*. NATO ASI Series. Series B: Physics. Vol. 302. Plenum Press, New York.
18. Wharmby, D. O. (1993) Electrodeless lamps for lighting: a review. *IEE Proceedings A* **140**(6), 465–473.