Next-Generation, Energy-Efficient, Uniform Supplemental Lighting for Closed-System Plant Production

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Abstract

Two relatively new, energy-efficient lamp types and light delivery systems for plant growth chambers were compared in matched 2.44 x 3.66 m walk-in plant growth chambers. The chambers were lit either by ninety-six 1.22 m long 54 W cool white HO T5 fluorescents arranged to cover the chamber ceiling, or by fourteen 315-watt ceramic metal halide HID lamps arranged in two rows. The fluorescents were contained in twelve 0.61 x 1.22 m luminaires (Sunlight Supply Systems, Model 960202), each containing a reflector and eight tubes. The HID lamps were housed in custom-designed luminaires (Cycloptics All-Bright 315W) with reflectors mounted above the ceiling of the chamber, opening into the chamber. Light intensities were measured at the centers of ninety-six (8 x 12) uniformly sized grid squares in five planes below the ceiling, from 0.76 to 1.98 m down, with the walls and floor of the chamber below the plane of measurement made non-reflective by covering it with black material, and keeping the chamber empty and the door closed. Wattage required by the lamps and ballasts showed the HID system provided 40% to 60% more light per watt than the T5 system, with light distributed more uniformly in the three lowest planes. A T12 fluorescent system (forty-eight 215-watt VHO cool white lamps,) with which the growth chambers were previously lamped, was also compared to the T5 fluorescent and HID systems, using measurements for single quadrants of the chambers. This was found similar to the T5 system in light distribution uniformity, but inferior to both in terms of energy efficiency. The T5 system provided nearly four times more light per watt than the T12 system, and the HID system provided five and a half to more than six times more light per watt.

INTRODUCTION

Electrical lighting for plant growth chambers poses several concerns. Expense is an overriding issue; light distribution uniformity is another and light quality is a third (Langhans and Tibbitts, 1997). Many existing growth chambers have T12 fluorescent lamps covering the ceiling, usually with VHO, cool white, 215-watt lamps. T12 lamps produce a wavelength distribution suitable for many plants, and covering the ceiling with light tubes is fairly effective in creating uniform lighting in the central area of a chamber, but T12s have low efficiency in converting electrical energy into light that plants can use (efficacy, or µmols PAR s^{-1} W^{-1}.) Improvements in fluorescent lighting technology have occurred recently with the advent of T8 and T5 lamps that have greater efficacy than T12s, longer lives, slower lumen depreciation, and less sensitivity to temperature.

HID lamp efficacy is generally higher than that of fluorescent lamps, and they generally produce higher light intensities. As a result, HID lamps are coming into common use in modern chambers. However, often only rudimentary efforts are made to achieve light distribution uniformity in chambers lamped with HIDs, such as making the ceiling and side walls highly reflective and spacing the lamps evenly. The difficulty of creating uniform lighting in a growth chamber with typical ceiling height, using HID luminaires, is illustrated by the data of Albright and Both (1994.) Because an HID luminaire array is comprised of point sources, it is difficult to achieve uniform light distribution, using conventionally designed reflectors, without creating hot spots. In this report, the HID lamp chosen was unusual in drawing only 315 W, while having an efficacy as high as that of 1000 W HPS lamps. Improved light distribution uniformity and system efficacy were anticipated, when combined with sophisticated design of the lamp reflector and luminaire layout.

METHODS

Two EGC walk-in chambers of dimensions 2.44 x 3.66 m, 2.18 m high, were refurbished in matching fashion with diffusely-reflective, white-painted sheet metal cladding on the walls. It was determined that the effective average reflectance of the chamber walls was approximately 0.8. One of the selected chambers served to evaluate the T12 system first, then the new HID system. It was initially equipped with forty-eight new T12 fluorescent lamps, (Sylvania, 215W, VHO, Cool White). After the tubes were "burned in" (at least 100 hours of operation under standard protocol), power use was measured and irradiation data was collected at four different levels above the floor (0.46 through 1.37 m in 0.30 m increments), the T12 fluorescents were removed and the light cap was modified to receive fourteen Cycloptics HID luminaires in an optimized layout. The Cycloptics luminaires were equipped with Phillips Elite Agro 315-watt ceramic metal halide lamps. The other chamber was retrofitted with twelve T5 luminaires (Sunlight Supply systems, Model 960202), with each equipped with a reflector and eight 1.2 m, 54 W, General Electric HO T5 Ecolux fluorescent lamps (for a total of ninety-six lamps). Each lighting system employed a transparent barrier between the luminaire space (light-cap) and the chamber space to facilitate heat removal from the luminaires. Operation of the growth chamber, and data collection and analysis protocols, were done in accord with the International Committee for Controlled Environment Guidelines (2004).

The T12 lighting system measurements were done on a platform the size of a growth chamber quadrant (1.22 by 1.83 m) in each chamber quadrant in turn, with light intensity measured in the centers of 0.093 m^2 square grid blocks marked on the platform, and repeating the procedure at successive levels. The platform surface was unfinished plywood. Two recently calibrated LI-COR quantum sensors and light meters (LI-250A) were used. One sensor was placed in a fixed position at the chamber center, on the corner of the platform, to serve as a reference while the other, with which local light intensity readings were taken, was used as a roving sensor. Light intensity at the reference sensor was recorded at the start and end of each set of roving sensor readings (four to eight per set) to observe and, if necessary, correct for luminaire light output drift over time.

Because the platform method had been used initially for the T12 chamber measurements, it was used in identical fashion for one set of measurements of the T5 and Cycloptics HID systems to compare the newer systems to the older under the same measurement method. For this purpose, just one quadrant of the chambers with the newer lighting systems was measured, that to the right and away from the chamber doors. The

T5 and Cycloptics HID measurements using the platform method were done twice - on the unfinished platform and on the platform with a thin black covering added - in order to evaluate the effect of platform surface reflectance on light intensity.

The platform method came to be considered less than ideal and a more easily duplicated and precise method of light mapping was developed to compare the two newer lighting systems. In this method, the reflectance of everything below the measurement plane was made as close to zero as possible. The floor, walls, and door below the plane of measurement were covered in black-out cloth (estimated reflectance less than 0.04) and all equipment within the chamber was painted in a flat black paint (reflectance less than 0.04, Benjamin Moore & Co, vinyl latex Flat Black 327-81). The reference sensor was set on a pedestal in the middle of the chamber. Rails were installed and leveled at appropriate heights down the sides of the chamber. A crossbar rested on rails spanning the chamber. Light readings were taken at eight positions on the cross bar, using the roving sensor. The procedure was repeated throughout the chamber and for five measurement planes ranging from 0.76 m to 1.98 m below the ceiling. The physical system is shown in Figure 1.

Additional light mapping was done for the HID system at 1.98 m below the ceiling with eight of the fourteen luminaires turned off, leaving a symmetric pattern of six luminaires. It was also done at 1.37 m below the ceiling with six of the fourteen luminaires turned off, leaving a symmetric pattern of eight luminaires. Electricity usage was measured while these subsets of luminaires were in use.

Electric power required to operate the lamps and their ballasts was determined in the chambers after lamps had undergone a minimum 100 hour burn-in period, using a standard procedure with a 14-hour logging period. True RMS wattage was recorded (Amprobe DM-II Pro Data Logger Recorder.)

The design process, through which the reflectors for the Cycloptics HID luminaires were developed, employed the software Photopia™, with additional proprietary software. The software permitted modeling the effects of varying wall, floor, and ceiling reflectances on light delivered to target planes, as well as losses in the reflector and overhead barrier. A major design goal was to distribute light as uniformly as possible near to the walls of the chamber and through a large vertical range. To achieve this goal, and provide light for plants coming from all directions, the chamber walls were deliberately incorporated in the design process, although it meant sacrificing efficacy to some extent. To maximize efficacy, the reflector was designed so as much light as possible left the reflector either directly or after only one reflection. Because the wall reflectance in the experimental chambers was lower than desired (c. 0.8), the effect of using more highly reflective walls was only modeled, pending installation and testing of more reflective wall materials in the T5 and Cycloptics HID chambers.

Data were analyzed using SPSS. ANOVAs were conducted on raw light intensity data without regard to the wattage required to operate the lamps, and also on the data normalized to take into account the differences in power used. In the comparison of T5 and Cycloptics HID lighting systems, the chamber lighting system was included with two levels, with distance below the ceiling another factor with five levels. In comparisons with the T12 system, there were three chamber lighting intensity levels and four distances below the ceiling.

RESULTS

The efficacies of the T12, T5, and Elite Agro lamps used in these chamber lighting system trials were previously determined to be 0.88, 1.24, and 1.91 µmol s^{-1} W^{-1}, respectively, (personal communication, R. Gelten and A. Dunaevsky, Phillips Lighting Co, 2011.) Based on the number and wattage of lamps with which the chambers were outfitted, values for total photosynthetic photon production by the lighting systems were calculated as 9113, 6402, and 8414 µmol s^{-1}, respectively, before any losses occurred in delivery. Given the poor reflector design of the T12 fluorescents, and the sophisticated reflector design of the Cycloptics HID luminaires, the expectation was that the rank order of average measured light intensity would be as follows: Cycloptics-HID, T5, and then T12 fluorescent (despite the T12 system generating more light at lamp level.) It was further expected that distance from the array of lamps would have a strong effect on light intensity and uniformity of light distribution within the chamber. Data presented in Tables 1 and 2 show these expectations were realized.

Despite requiring half the wattage of the T12 chamber, the average measured light intensity (PPF) in the T5 chamber was 50 to 60% more than in the T12 chamber, and the Cycloptics HID chamber provided more than twice the intensity. When the data are transformed to make comparisons equivalent, by multiplying the average PPF by the chamber area and dividing by the wattage to find delivered light efficacy (µmol s^{-1} W^{-1}), and its inverse, it can be seen the T5 system required one quarter of the electrical energy used by the T12 system to produce the same average PPF (ratios were 0.25 to 0.27, -- see Table 1 and Figure 2), and the HID system used even less energy (ratios of 0.16 to 0.18, depending on level). An ANOVA performed on the efficacy data showed the main effects of the chamber-lighting system, $F(2,69) = 1730$, $p < 0.0005$, partial $\eta^2 = 0.98$, and distance-below-ceiling, $F(3,67) = 460$, $p < 0.0005$, partial $\eta^2 = 0.95$, and a significant chamber x distance interaction, $F(6,136) = 19.6$, $p < 0.0005$, partial $\eta^2 = 0.46$. In measures of light uniformity, the Cycloptics HID system appeared to have an advantage over the fluorescent systems at the greater distances away from the light array, while the T5 system appeared to have a slight advantage closer to the lamp array, although the differences were not statistically significant.

The Cycloptics HID and T5 fluorescent systems were more closely compared at five distances below the light arrays, and with measurements throughout the chambers, as represented in Tables 2 and 3 and Figure 3. The HID system delivered 39 to 56% more PAR per second per watt than the T5 system, depending on distance below the luminaires. An ANOVA performed on the measured data, transformed to equivalent efficacies, showed the main effects of the chamber lighting system, $F(1,190) = 715$, < 0.0005, partial $\eta^2 = 0.79$ and distance-below-ceiling, $F(4,760) = 466$, $p < 0.0005$, partial $\eta^2 = 0.97$ and a significant chamber x distance interaction, $F(4,760) = 64$, $p < 0.0005$, partial $\eta^2 = 0.71$ The plot of mean efficacies against distance below ceiling in Figure 2 shows some waviness. This can be attributed to reduced reflectance lower on the walls when air circulation fans were exposed.

ANOVAs were performed on the data presented in Table 3, comparing reduced numbers of luminaires to the full complement. The slight efficacy increase when eight lamps instead of fourteen were used was just barely significant: $F(1,190) = 4.75$, $p = 0.031$, partial $\eta^2 = 0.024$, but this was possibly the result of imprecise wattage measurement over a shortened test period.

The coefficient of variation of the measured PPFs was distinctly smaller for the Cycloptics HID chamber than the T5 chamber in the three planes farthest from the luminaires. It was the same at the next highest level, and slightly higher than the T5 value at the closest plane to the luminaires. The other measures of uniformity, ratios of maximum and minimum values for PPF to the mean, corresponded. In order to test the significance of the differences in the coefficients of variation of the measured data, values were standardized to common means of 1.0, and then Levene's test for equality of variance was applied. For the three lowest planes of measurement, the variance of the PPFs was significantly different, $F(190) = 32$, or $F(190) = 49$, or $F(190) = 18$, $p < 0.005$ in all cases. The variances in standardized measures for the two highest planes were not significantly different.

DISCUSSION

T12 fluorescent lamps are becoming an obsolete technology and the observations made in this study amply explain why. Not only is their efficacy initially low, but it is difficult to deliver what light they do produce efficiently when they are crowded together. In this study, the comparison of most interest for the future of chamber lighting was between the T5 fluorescent and the Cycloptics HID options. Both these lamps use efficient electronic ballasts (less than 10% of the lamp's wattage required) and are dimmable, with little loss of efficacy, while providing the opportunity for savings through tailoring the amount of light provided and energy consumed to the needs of the research. These features also permit easy PPF-level and daily light integral control, thereby matching one of the hallmark advantages of LED lighting systems. Both lamps also have extraordinarily long lives with slow lumen depreciation. However, they are so new that end of life performance as yet remains to be reliably confirmed.

Given the starting difference in efficacies of T5 fluorescent and Elite-Agro ceramic metal halide lamps (1.24 and 1.91 $\mu mol\ s^{-1}\ W^{-1}$), and given that the HID reflector design and layout was specifically aimed at increasing light distribution uniformity, it was not unexpected that the Cycloptics HID system would outperform the T5 fluorescent system in terms of energy-use efficiency and uniformity, as proved to be the case. For safety reasons, this HID lamp is jacketed with a second glass sleeve, which reduces its efficacy 6% to roughly 1.83. The ratio of the lamp efficacies before reflector and other losses (1.83:1.24) is 1.48. As measured, the average efficacy for light delivered by the Cycloptics HID was 1.39 to 1.56 that of the T5 system, depending on distance from the luminaire, which is in accord with the ratio of lamp efficacies before losses.

The measured results were impressive for both systems, but prior modeling of the HID system had led to higher expectations for both magnitude and efficacy of delivered light than were reached. And although the uniformity of light distribution was better than or equal to that of the T5 system on four of the five planes measured, it was not as great an improvement as expected. Performance parameter changes were explored by computer simulation, changes that might be expected if the wall and ceiling reflectance above the plane of measurement were either 80% or 98%. The modeling suggested effective reflectance of existing chamber walls can be less than 80%, which is believable because the walls are not uncluttered surfaces, but include fans, vents, door framing, and numerous seams. The modeling also indicated that substantial benefits in efficacy of delivered light and improvements in light uniformity are possible for the Cycloptics HID system when wall and ceiling reflectance is increased, which is to be expected because the walls are used deliberately as a means of light delivery. Similar improvements can be expected for T5 fluorescent systems, although to a lesser degree because less light is directed to the walls.

As part of this research project, testing of biomass production (grams dry matter produced per mol of light imposed) using lettuce has begun. A variety of other plant species are also being comparatively tested in the chambers to ensure there is nothing anomalous in the quality of light produced by the various lighting systems.

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TABLES

Table 1. Comparison of T12 fluorescent, Cycloptics HID, and T5 fluorescent lighting, using the quadrant platform measurement method. Chamber wattages were, respectively, 13120, 4896, and 5528. Chamber floor area = 8.92 m^2 and n=24.

Meters below ceiling/luminaire:		1.727	1.422	1.117	0.812
Platform surface		Plain:black	Plain:black	Plain:black	Plain:black
Average μmol m^{-2} s^{-1}, all lamps	HID	590:537	657:596	730:646	814:706
	T5	460:424	498:454	536:480	578/509
	T12	289:n/a	323:n/a	330:n/a	349:n/a
Average PPF/Minimum PPF	HID	1.07:1.13	1.11:1.19	1.15:1.23	1.21:1.32
	T5	1.19:1.26	1.22:1.30	1.25:1.34	1.28:1.40
	T12	1.16:n/a	1.20:n/a	1.26:n/a	1.39:n/a
Maximum PPF/Average PPF	HID	1.06:1.09	1.10:1.17	1.13:1.19	1.20:1.27
	T5	1.12:1.16	1.12:1.16	1.11:1.16	1.11:1.15
	T12	1.12:n/a	1.14:n/a	1.17:n/a	1.23:n/a
Coefficient of Variation	HID	0.03:0.05	0.05:0.08	0.07:0.10	0.11:0.15
	T5	0.08:0.10	0.08:0.11	0.09:0.12	0.10:0.13
	T12	0.07:n/a	0.08:n/a	0.11:n/a	0.14:n/a
Average efficacy, μmol s^{-1} W^{-1}	HID	1.07:0.98	1.20:1.08	1.33:1.18	1.48:1.29
	T5	0.74:0.68	0.80:0.73	0.86:0.77	0.93:0.82
	T12	0.20:n/a	0.22:n/a	0.22:n/a	0.24:n/a
$Efficacy^{-1}$, W/(μmol m^{-2} s^{-1})	HID	0.93:1.02	0.84:0.92	0.75:0.85	0.67:0.78
	T5	1.35:1.46	1.24:1.37	1.16:1.29	1.07:1.22
	T12	5.08:n/a	4.55:n/a	4.46:n/a	4.21:n/a

Table 2. Fluorescent T5:Cycloptics HID comparisons, using black-out-below-plane measurement method. Chamber wattages were, respectively, 5528 and 4896 W. Chamber floor area = 8.92 m2 and n=96.

Meters below ceiling/luminaire:		1.981	1.676	1.372	1.067	0.762
Average µmol m^{-2} s^{-1}	HID	455	510	548	595	651
	T5	369	403	425	446	472
Average PPF/minimum PPF	HID	1.19	1.18	1.30	1.52	1.49
	T5	1.29	1.35	1.40	1.47	1.55
Maximum PPF/average PPF	HID	1.09	1.10	1.16	1.21	1.33
	T5	1.16	1.18	1.19	1.17	1.18
Coefficient of Variation	HID	0.06	0.06	0.08	0.12	0.17
	T5	0.10	0.11	0.12	0.13	0.14
Average efficacy, µmol m^{-2} s^{-1} W^{-1}	HID	0.83	0.93	1.00	1.08	1.19
	T5	0.59	0.65	0.69	0.72	0.76
$Efficacy^{-1}$, W/(µmol m^{-2} s^{-1})	HID	1.21	1.08	1.00	0.92	0.84
	T5	1.68	1.54	1.46	1.39	1.31

Table 3. Examples of reducing the number of operating Cycloptics HID luminaires on PPF, uniformity, and efficacy. Bilateral symmetry was retained in the combination of active lamps, and n=96.

Meters below ceiling/luminaire:	1.981		1.372	
Number of luminaires	6	14	6	14
Average PPF, µmol m^{-2} s^{-1}	198	455	309	548
Average PPF/minimum PPF	1.16	1.19	1.29	1.30
Maximum PPF/average PPF	1.11	1.09	1.16	1.16
Coefficient of Variation	0.057	0.060	0.08	0.08
Total watts	2092	4896	2457	4896
Average efficacy, µmol $m^{-2}s^{-1}W^{-1}$	0.84	0.83	1.12	1.00

FIGURES

Fig. 1. Growth chamber with Cycloptics luminaires; black cloth, side rails and crossbar in place; and showing the reference light sensor position.

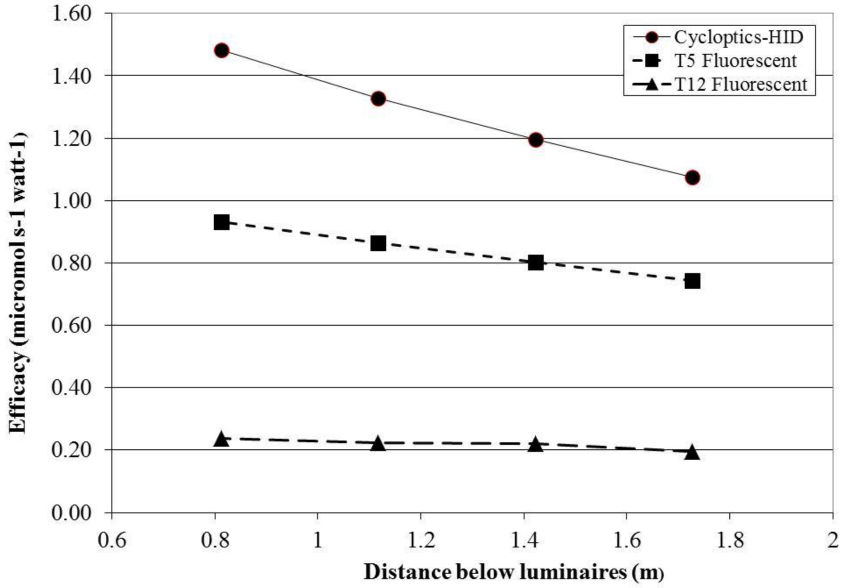

Fig. 2. Average efficacy of light delivery by three chamber lighting systems. Data determined for one quadrant, n = 24, using platform method

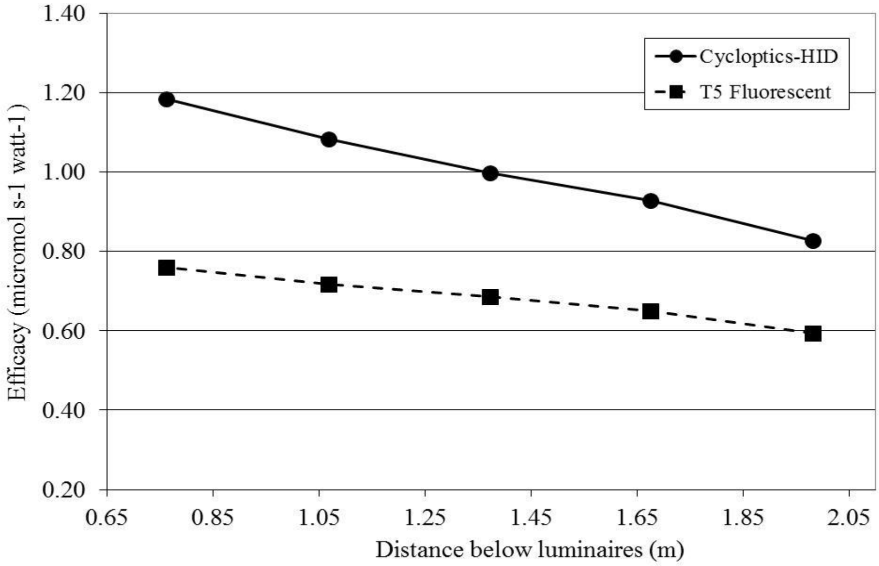

Fig. 1. T5 fluorescent compared to Cycloptics HID, in efficacy of light delivery to five planes below the luminaires. Data determined for chamber, n = 96.