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The Evaluation of LEDs for Illumination of Higher Plant Chambers: Lettuce NCER Response to Two Sources of Light

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In collaboration with

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Summary

Experiments were conducted investigating the Net Carbon Exchange Rate (NCER) responses of lettuce canopies to two lighting systems. The experiments were performed in 4 small, sealed plant growth chambers at the University of Guelph (Guelph, Ontario, CANADA). Hewlett Packard Light-Emitting Diodes (LEDs) (470nm, 620nm) were used in a 22.8 x 32.5 cm array to supply photosynthetic energy to lettuce (*Lactuca sativa* L. cv. Bellagreen) canopies. A broader spectrum High Pressure Sodium (HPS) lamp was used as the comparison light source. NCER was recorded by an on-line computerized infrared gas analysis system under a mean light intensity of 275 $\mu molm^{-2}s^{-1}$ at canopy height. Data indicated that HPS lighting resulted in higher instantaneous NCER values in the lettuce canopies as compared to the LED lighting. Improvements in the output intensity of both blue and red LEDs as well as a broader representation of spectra within the photosynthetically active region (PAR) can help to close the gap between plant NCER under the two lighting systems.

Introduction

Providing artificial lighting of sufficient quality and intensity is one of the major challenges of growing plants in space. (Salisbury and Bugbee, 1998; Dixon *et al*, 1999; Stasiak *et al* 1998). Considerable attention has been devoted to examining the utility of Light-Emitting Diodes (LEDs) as a radiation source for plant growth chambers. This is due to their small mass, volume, inherent safety and longevity. Furthermore, their spectral outputs can correspond directly to peaks in the photosynthetic action spectrum (Bula *et al*, 1991). One of the significant drawbacks of LED systems is the difficulty in obtaining LEDs with sufficient intensity (>15 $\mu molm^{-2}s^{-1}$ PPF) within the blue (400-500 nm) spectral range (Hoenecke *et al*, 1992). As a result, most studies have investigated the effects of LED arrays on plant growth and development under supplementation with blue light from fluorescent or other broader spectrum lamps (Brown *et al*, 1995; Schuerger *et al*, 1997).

A number of studies have investigated growth and morphological responses of plants to illumination by LED arrays (Ono *et al*, 1997; Goins *et al*, 1997; Brown *et al*, 1995; Schuerger *et al*, 1997; Goins *et al*, 1998). The Photosynthetic Photon Fluxes (PPF) of LED arrays used in these studies were modest, ranging well below expected canopy light saturation levels (Goins *et al*, 1997; Brown *et al*, 1995; Barta *et al*, 1992). While some studies have examined the influences of these types of LED arrays on plant photosynthesis (Goins *et al*, 1997; Tennessen *et al*, 1994) many have been conducted at leaf level only. Given the higher leaf area index (LAI) of full canopy systems, it is expected that Net Carbon Dioxide Exchange Rates (NCER) will be less favourable under illumination by LED arrays than under illumination by lamps with a broader spectral distribution and greater intensity such as High Pressure Sodium (HPS).

The purpose of this study was to investigate and compare plant canopy NCER responses to illumination by similar intensity LEDs and HPS lighting systems. A pre-requisite to meeting this objective was the development of an LED array having sufficient output in blue wavelengths so that supplementation of blue light by other lamps was not needed in order to reach the critical blue photon levels reported by other authors (Hoenecke *et al*, 1992).

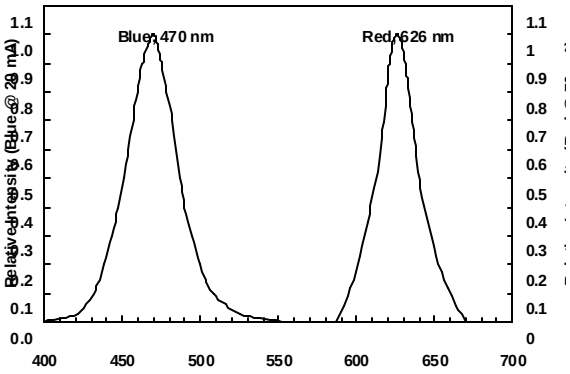
Methodology

Description of LEDs

The two LED panels used in this study were constructed with Hewlett-Packard Super Flux LEDs (Red-Orange, SunPower Series; San Jose, California) and 5mm Precision Optical Performance InGaN Blue LEDs. Table 1 summarizes the technical characteristics of the LEDs used. The spectral quality of each type of LED used is shown in Figure 1, while the dispersion of light from each LED lamp vertical axis is shown in Figure 2. The typical operating levels used in this study were 70mA and 20mA forward currents for red and blue LEDs respectively at approximately 25°C.

Description of LED Panel

The panel dimensions were 22.8 x 32.5 cm with a regular and even LED distribution (Figure 3). Blue LEDs constitute 12.5% of LED components used. The red LEDs were square in shape (0.81 x 0.81 cm) while the blue LEDs were circular in shape (0.58 cm diameter). A profile of panel intensity vs. time is shown in Figure 4. These measurements were made using red and blue LEDs separately, at their respective maximum outputs and indicate good stability in PPF output. The PPF output of red LEDs as a function of panel temperature is plotted in Figure 5. In order to maximize PPF output each panel was cooled with one 48 volt fan which consumed 4.32 watts of power. The LEDs were arranged on the circuit board in parallel "strings" in order to limit the voltage necessary to operate the panel to 39 volt. The current drawn by each panel at this voltage was 3.1 amperes. In addition to the power supplied directly to the panel, a 15 volt supply was necessary to power the current limiting circuit of the controller devices also used with the panel. The controllers also enabled graduated control of the current to be drawn by the red and blue LEDs separately. The combined power requirement of the panel, controller and cooling fan was 125 watts.



	Red LED	Blue LED
Material	Transparent Substrate AlInGaP	InGaN
Hewlett-Packard P/N	HPWT-MH00	HLMP-CB31
Peak Emission	626nm	470nm
Bandwidth (FWHM)	26nm	35nm
Max. operating intensity @ 5cm from panel surface	300 $\mu molm^{-2}s^{-1}$	15 $\mu molm^{-2}s^{-1}$

Table 1. Characteristic properties of Red and Blue LED components used in panel construction.

Figure 1. Spectral quality of red and blue LEDs (Copyright © 1998 Hewlett-Packard Co.).

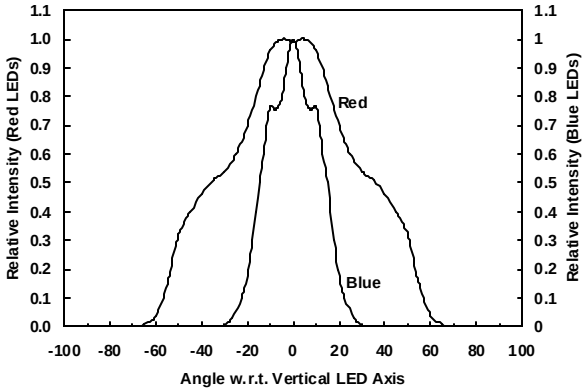


Figure 2. Dispersion characteristics of red and blue LED lamp light (Copyright © 1998 Hewlett-Packard Co.)

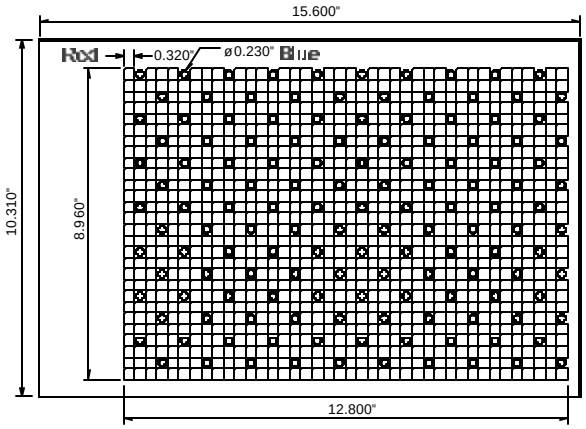


Figure 3. LED panel layout (12.5 % Blue LEDs).

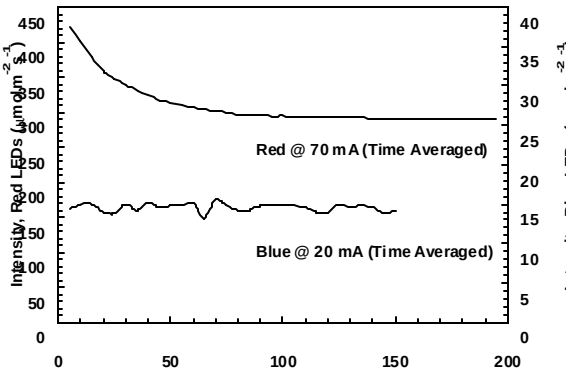


Figure 4. Time profile of LED panel light intensity at 5 cm away from panel surface.

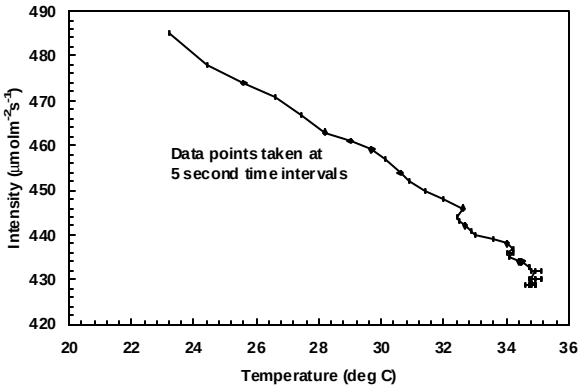


Figure 5. Temperature profile of panel intensity (red LEDs only @ 70mA).

Description of the HPS lighting system

The High Pressure Sodium lighting used consisted of a 1000W Lumalux lamp (Osram, Sylvania, Item # 67307) and a 17" Duraglow-c reflector (General Electric Canada, Cat. # HS-HP1000-12-43). The spectral quality of the HPS light in the photosynthetically active region is shown in Figure 6.

The power consumed by the lamp was 1000W while the fixture ballast consumed approximately 90 watts. Based on the reflector manufacturer's photometric data regarding the spatial light intensity distribution, the area of coverage under the HPS lamp at the plant canopy level and at the operating intensity level was ≅ 10 times the area covered by one LED panel. Accounting for this difference in illumination area, the combined power requirement of the HPS lamp and ballast was ≈109 watts. This confers an electrical vs. PPF efficiency which is 16% greater than the LED panel.

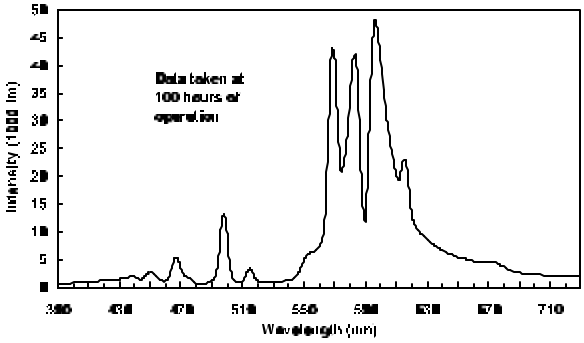


Figure 6. Spectral quality of HPS lamp (OSRAM, Sylvania, LU1000). (Copyright © 1998 OSRAM, Sylvania).

Net Carbon Dioxide Exchange Rates

NCER determinations were made using 3-week-old lettuce plants (*Lactuca sativa* cv. Bella-green) grown in greenhouses at the University of Guelph (Guelph, Ontario, CANADA). Following germination, plants were transferred to 4" pots filled with Pro-Mix© and were watered with 20-8-20 fertilizer solution, as required, for 3 weeks. Greenhouse demand temperature was 21°C day and 16°C night while the ambient light levels ranged from 100-1000 $\mu molm^{-2}s^{-1}$ (daylight). Ambient light levels were supplemented with HPS lamps (at 150 $\mu molm^{-2}s^{-1}$) to maintain a photoperiod of 18 hours. A total of 20 plants per replication were randomly selected and evenly allocated to one of the four sealed environment chambers used routinely in the determination of canopy NCER. These chambers are more fully described in the paper authored by Dutton

et al (1988). Three replications of the experiment were conducted. The average Leaf Area Index (LAI) over all chambers and replications was 2.50.

Two of the sealed chambers were illuminated with LED panels and two were illuminated with HPS fixtures. Temperature and humidity of the chambers were controlled by the use of a circulating fan and two heat exchangers. To estimate canopy NCER, pull-down of carbon dioxide in each chamber resulting from canopy photosynthesis was measured with an infrared gas analyzer (IRGA, LI-6262, LI-COR). With the chambers sealed, pure CO_2 was added with a mass flow controller (MKS Instruments) in order to compensate for losses due to canopy photosynthetic activity and to maintain CO_2 concentrations at 350 ppm (Leonardos *et al*, 1994). NCER was then calculated from measured CO_2 using the methods outlined in Dutton *et al* (1988).

Light measurements were made at the beginning and end of each treatment with a hand-held Quantum Meter (Apogee Instruments; Salt Lake City, Utah) positioned at the top of the canopy. Each chamber was insulated from external light so that the total area illuminated by each lighting system was constant (aprox. 440 cm^2). In order to avoid excessive heat transfer from the HPS fixtures to the chambers, tempered glass and water baths were used on the chamber tops. Furthermore, a neutral density screen was used to reduce the intensity of the HPS light to PPF levels identical or similar to those of the LED panels. Average light levels were determined from a series of measurements made at the top of the canopy. Minor differences in PPF following attenuation were accounted for in subsequent analyses.

The demand relative humidity of the chambers was 50% while the demand temperature was 21°C day and 16°C night. The mean light level at canopy height in all four chambers for all 3 replications was 275 $\mu molm^{-2}s^{-1}$. Photoperiod in each of the sealed chambers was 18 hours. NCER was determined over a period of 48 hours following an initial 24 hour period which allowed plants to acclimate to chamber conditions. Only post-equilibrated canopy NCER estimates obtained for the day periods were analyzed. Leaf areas were determined at the end of each replication using a portable leaf area meter (Model No. LI-3000, Lambda Instruments Corporation). Because of the nature of the experimental design, treatment with chamber interactions (treatment x chamber interactions) could not be assessed. Therefore, to compensate for chamber effects owing to differences in chamber leakage, a series of blanks (ΔCO_2 with no plants) were used as offsets in NCER calculations (Dutton *et al*, 1998).

Analysis of Data

Day-time canopy NCER estimates were pooled, by chamber, from all three replications of the experiment. Individual chamber NCER determinations normalized by leaf area were subjected to the Duncan's multiple range test (p=0.05) using chamber as the main effect. Since a clear influence of treatment (i.e. light source) on canopy NCER was detected, data from identical treatments were pooled and subjected to a subsequent analysis using a standard t-test. The null-hypothesis was $NCER_{LED}=NCER_{HPS}$, where $NCER_{LED\ or\ HPS}$ is the mean NCER determined for each lighting system.

Results

Treatment	N	Mean NCER	N	Mean NCER (Pooled)
HPS – Chamber 1	1255	1.94^a	2334	1.94^a
HPS – Chamber 2	1079	1.86^b		
LED – Chamber 1	1171	1.54^c	2428	1.60^c
LED – Chamber 2	1257	1.14^d		

Table 2. Mean canopy NCER by treatment and chamber and mean canopy NCER pooled by treatment. Mean NCER estimates assigned different letters are significant at the p=0.05 level. Comparisons between individual chamber NCER estimates were made using the Duncan's multiple range test using the main effect of chamber. Comparisons between NCER estimates pooled by lighting system were made using a standard t-test. N is the number of instantaneous NCER measurements collected at 6 minute intervals over the duration of all replications.

A representative NCER profile for each of an LED and HPS chamber is presented in Figure 7.

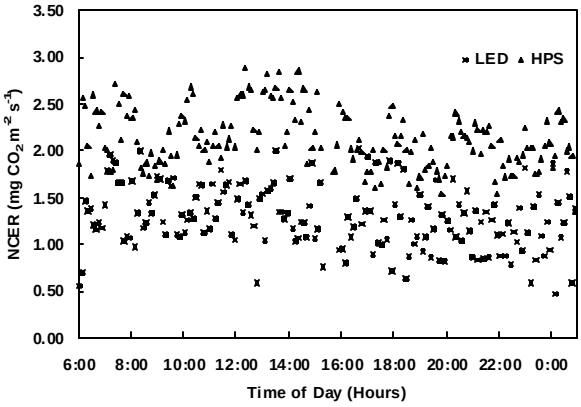


Figure 7. Full canopy NCER estimates for LED and HPS illuminated chambers. Data in this plot were collected at 6 min intervals over one 18 hr period during the third replication of the experiment.

This profile plots instantaneous canopy NCER as a function of the time of day for one 18 hour period obtained in the third replication of the experiment. Canopy NCER equilibrated rapidly, usually within 30 minutes of chamber illumination, and remained stable over the day period. Differences in canopy NCER were observed in the two types of chambers, with NCER being greater in chambers fitted with the HPS lamps. Variation in NCERs observed on the same plant canopy is attributed to instrumentation. Differences observed in instantaneous canopy NCER are presented in Table 2. Results of the Duncan's multiple range test conducted on data pooled for each chamber across all three replications indicated significant differences (p=0.05) between all treatments and chambers. Results of the pair-wise comparisons indicated that both chambers fitted with HPS lamps had significantly higher NCER than chambers fitted with LEDs. Observed differences in NCER between chambers of identical treatment were attributed to minor differences in leakage rate which could not be accounted for in the application of offsets or in leaf area measurements. Subsequently, NCER estimates obtained from chambers of identical treatment were pooled and analyses were performed using a simple t-test. Results of the t-test, also presented in Table 2, indicate that plants grown under HPS lamps had significantly higher (p=0.05) NCER than plants grown under LED arrays.

Conclusions and Discussion

Positive NCERs obtained under the LED treatments indicate that PPF levels (red and blue) were above the compensation point for the canopy and that net growth was possible under the current LED panel design. Further, measurements of the PPF output of the LED array indicated that blue light levels in the regions of 400-500 nm were at the critical intensities needed for proper plant development (Hoenecke *et al* 1992; Dougher *et al* 1998; Yorio *et al* 1998). Greater NCERs obtained under HPS lighting attenuated to the same PPF as LEDs are consistent with the broader spectral output of the HPS lamp. Since the photosynthetic action response in the blue and red regions of the spectrum is broad relative to the output of LEDs, it is not surprising that NCERs were lower than those obtained under lighting systems having wider spectral compositions. This implies that some improvement may be made in LED array design by integrating a series of LED types, each having maximum outputs at different wavelengths of the PAR range. A further improvement over the current design would be to include brighter blue LEDs. Blue LEDs with a mean output as high as 145 $\mu molm^{-2}s^{-1}$ have recently been investigated (Ono *et al*, 1998). Another improvement to the current panel design would be to correlate the peak output wavelengths of the LEDs used more closely to the chlorophyll absorption peaks of the species under treatment. At the time of panel construction, red LEDs at a wavelength of 626 nm were chosen due to intensity considerations.

These results are consistent with previous findings that the PPF conversion efficiency and photosynthetic efficiency of LED arrays is lower than most broader spectrum sources (Bula *et al*, 1991). While improvements in LED design may ultimately make their use more practical in full canopy situations, LED arrays, at present, seem most suitable for illumination of individual plants or canopies having very small leaf area indices. This study has shown that a broader spectrum, higher intensity lighting source, such as an HPS or microwave lamp, is more appropriate in cases where denser plant canopies are demanded. At this time, more practical applications of LED arrays may include illumination of micro-organism based autotrophic components of life support systems (Poughon, 1997). While LED technology develops to include high intensity lamps in the blue and red region, it is important to characterize plant responses such as NCER to currently available technologies. There is no doubt that, in time, superior lighting systems for space research and exploration applications based on LEDs will be available.

Acknowledgements

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References

Barta, D.J., T.W. Tibbitts, R.J. Bula, and R.C. Morrow. 1992. Evaluation of Light Emitting Diode Characteristics for a Space-based Plant irradiation Source. Adv. Space Res. 12(5):141-149.

Brown, C.S., A.C. Schuerger, and J.C. Sager. 1995. Growth and Photomorphogenesis of Pepper Plants under Red Light-emitting Diodes with Supplemental Blue or Far-red Lighting. J. Amer. Soc. Hort. Sci. 120(5):808-813.

Bula, R.J., R.C. Morrow, T.W. Tibbitts, D.J. Barta, R.W. Ignatius, T.S. Martin. 1991. Light emitting diodes as a radiation source for plants. HortScience 26:203-5.

Dixon M.A., B. Grodzinski, R. Cote, M.A. Stasiak. 1999. Sealed environment chambers for canopy light interception and trace hydrocarbon analysis. Adv. Space. Res. (in press)

Dougher, T.A., B.G. Bugbee. 1998. Is Blue Light Good or Bad for Plants? Life Support and Biosphere Science 5(2):129-136.

Dutton, R.G., J. Jiao, M.J. Tsujita, and B. Grodzinski. 1998. Whole plant CO_2 exchange measurements for nondestructive estimation of growth. Plant Physiol. 86:355-358.

Goins, G.D., N.C. Yorio, M.M. Sanwo, and C.S. Brown. 1997. Photomorphogenesis, photosynthesis, and seed yield of wheat plants grown under red light-emitting diodes (LEDs) with and without supplemental blue lighting. Journal of Experimental Botany, 48(312):1407-1413.

Goins, G.D., N.C. Yorio, M.M. Sanwo-Lewandowski, C.S. Brown. 1998. Life Cycle Experiments with Arabidopsis Grown Under Red Light-Emitting Diodes. Life Support and Biosphere Science, 5(2):143-150.

Hoenecke, M.E., R.J. Bula, and T.W. Tibbitts. 1992. Importance of 'Blue' Photon Levels for Lettuce Seedlings Grown under Red-light-emitting Diodes. HortScience 27(5):427-430.

Leonardos, E.D., M.J. Tsujita, and B. Grodzinski. 1994. Net Carbon Dioxide Exchange Rates and Predicted Growth Patterns in *Alstroemeria* 'Jacqueline' at Varying Irradiances, Carbon Dioxide Concentrations, and Air Temperatures. J. Amer. Soc. Hort. Sci. 119(6):1265-1275.

Ono, E., J.L. Cuello, and K.A. Jordan. 1997. Evaluation of high intensity light-emitting diodes as light source for plant growth. 1997 ASAE Annual International Meeting, Paper No. 974028.

Ono, E, J.L. Cuello, and K.A. Jordan. 1998. Characterizations of high-intensity red and blue light-emitting diodes (LEDs) as a light source for plant growth. Life Support and Biosphere Science, 5:403-413.

Poughon, L. 1997. Including a Higher Plants Chamber in the MELiSSA loop Description of a HPC for MELiSSA loop steady state simulations. V.1. ESA/ESTEC TN 32.3, ECT/FG/CB/95.205.

Salisbury, F.B., B. Bugbee. 1998. Plant productivity in controlled environments. HortScience, 23:293-9.

Schuerger, A.C., C.S. Brown, E.C. Stryjewski. 1997. Anatomical Features of Pepper Plants (Capsicum annuum L.) Grown under Red Light-emitting Diodes Supplemented with Blue or Far-red Light. Annals of Botany, 79:273-282.

Stasiak, M.A., C^tJ, R., Dixon, M.A., Grodzinski, B., 1998. Increasing plant productivity in closed environments with inner canopy illumination. Life Support and Biosphere Science, 5(2): 175-181.

Tennessen, D.J., E.L. Singsaas, T.D. Sharkey. 1994. Light-emitting diodes as a light source for photosynthesis research. Photosynthesis Research, 39:85-92.

Yorio, N.C., R.M. Wheeler, G.D. Goins, M.M. Sanwo-Lewandowski, C.L. Mackowiak, C.S. Brown, J.C. Sager, G.W. Stutte. 1998. Blue Light requirements for Crop Plants Used in Bioregenerative Life Support Systems. Life Support and Biosphere Science 5(2):119-128