Response of hydroponic baby leaf greens to LED and HPS supplemental lighting

N.S. Mattson[1,a], J.A. Allred[1], D. de Villiers[1], T. Shelford[1] and K. Harbick[2]

[1]School of Integrative Plant Science, Cornell University, Ithaca, NY, 14853, USA; [2]Application Technology Research Unit, USDA ARS, Toledo, Ohio, USA.

Abstract

The project objective was to determine the response of baby leaf greens to greenhouse supplemental lighting source. In the first experiment, plants were grown under five LED sources and two HPS sources for three crop cycles. In the second experiment, sequential crops were grown in a greenhouse for one year under one HPS and LED fixture type selected from experiment 1 based on crop biomass and energy efficacy (Philips GreenPower LED Toplighting Deep Red/Blue – Low Blue and HPS Gavita Pro 6/750e FLEX DE). In both experiments seeds of arugula (*Eruca sativa* 'Astro'), kale (*Brassica napus* subsp. *napus* var. *pabularia* 'Red Russian'), lettuce (*Lactuca sativa* 'Outredgeous') were sown at 1550 seeds m^{-2} density into a peat-based substrate in Speedling rafts. Rafts were placed in a germination chamber for 2 days and then floated on hydroponic ponds with a modified Sonneveld's nutrient solution in a greenhouse where they received lighting treatments for 11-14 days. Light quantum sensors under each treatment were connected to a light and shade control algorithm to achieve a daily light integral (DLI) of 17 mol m^{-2} d^{-1}. In experiment 1 only subtle differences were found in plant biomass and morphology in response to seven lighting treatments. The fresh mass (FM) of arugula, kale, and lettuce averaged 2.7, 1.9, and 3.0 g plant^{-1} across lighting treatments. For arugula FM, one LED source performed significantly better than two other LED sources. For kale FM, no significant differences were found based on treatment. For lettuce FM, two HPS sources and one LED source performed better than one LED source. In experiment 2, while DLI was controlled, some seasonal patterns were found. Overall, FM, dry mass (DM), and total yield was greater in the fall and lower in the winter and early spring. In winter there was a slight increase in FM/DM under HPS. In fall there was a slight FM/DM benefit to LED. Averaged over the calendar year, arugula and lettuce did not exhibit differences in FM/yield based on light source, while kale had a slight increase in FM/yield under HPS. The monthly differences in biomass based on light source may be due to light effects on plant temperature.

Keywords: greenhouse supplemental lighting, light emitting diodes, high pressure sodium, arugula, kale, lettuce, hydroponics

INTRODUCTION

Baby leaf greens have grown in popularity as a greenhouse hydroponic crop for salad mixes. Baby leaf vegetables are harvested at the stage between two and seven true leaves (Di Gioia et al., 2017) and common crops include: arugula, beet, kale, lettuce, mustard, pac choi, and spinach (Thornton et al., 2015). As compared with mature leafy greens (such as head lettuce), baby leaf greens are seeded at a much higher density and have shorter crop cycles. Supplemental light is commonly used in hydroponic leafy greens production as, within bounds, light intensity is linearly correlated with plant mass (Kitaya et al., 1998; Albright et al., 2000) and supplemental light is an important tool to reduce seasonal variability in yield which can be found in greenhouse production (Kroggel et al., 2012).

Traditionally, high intensity discharge (HID) fixtures such as high pressure sodium (HPS) lights have been used in greenhouse supplemental lighting. In the US in 2017 it was estimated that 98% of greenhouse lit area was from HID fixtures (Stober et al., 2017).

[a]E-mail: nsm47@cornell.edu

However, as costs of horticultural light emitting diode (LED) fixtures decreases and energy efficacy increases, the adoption of LEDs for supplemental lighting is becoming more common. Some potential benefits of LEDs, beyond electrical efficacy, include the ability to target/adjust wavebands of light to impact changes in crop morphology, nutrition, or yield (Ouzounis et al., 2015; Pocock, 2015) and a lower heat load directed toward the crop due to decreased longwave radiation as compared to HPS fixtures allowing for LED fixtures to be placed close to a crop or operated during warmer ambient temperatures without increasing leaf surface temperature (Morrow, 2008; Ouzounis et al., 2015).

Light quality is known to impact leafy greens. A higher ratio of blue or UV light lead to head lettuce that was more compact though slightly denser (Ouzounis et al., 2015). Under sole-source lighting, red leaf lettuce exposed to ultraviolet-A or blue light exhibited greater anthocyanin content (Li and Kubota, 2009). In the same experiment far-red treatment led to a 28 and 15% increase in fresh mass (FM) and dry mass (DM), respectively. This may be due to a greater leaf area and increased light interception with far-red radiation. Use of green or far-red radiation in place of blue led to increases in diameter and biomass of lettuce and kale (Meng et al., 2019). Light intensity and ratio of red, green, and blue light affected some nutritional characteristics of brassica microgreens (Craver et al., 2017).

While a body of literature exists on light source/quality effects of leafy greens under sole-source lighting, relatively less exists on the effect of light source under greenhouse supplemental lighting conditions. Boston head lettuce was provided greenhouse supplemental lighting from either HPS or an LED containing a large red peak (along with smaller peaks at ultraviolet, blue, green, and far-red) (Martineau et al., 2012). Plant biomass per mole of supplemental lighting was the same between HPS and LED treatments. Several phytochemicals were unaffected by light treatment, however violaxanthin was greater in the HPS vs. LED treatment. When supplemental lighting was supplied by HPS or red/blue LED fixtures providing the same light intensity, FM of several lettuce cultivars was increased from ambient controls and was unaffected by light treatment (Zhang et al., 2019). Based on the limited literature HPS vs. LED sources have similar growth impacts when there is a background of ambient sunlight. However, to our knowledge, effect of HPS or LED light source has not been evaluated for baby leafy greens in greenhouse supplemental lighting.

The overall goal of this project was to determine the response of baby leaf greens to LED or HPS supplemental lighting sources to guide adoption of energy efficient light fixtures without compromising plant yield or quality. In the first experiment, plants were grown under five LED sources and two HPS sources for three crop cycles. In the second experiment, sequential crops were grown in a greenhouse each month for one year under the most energy efficacious HPS and LED fixtures identified in experiment 1.

MATERIALS AND METHODS

The project consisted of two phases. In experiment 1, FM of baby leaf greens was examined in response to seven light sources (two HPS and five LED). Based on FM and photosynthetically active radiation (PAR) efficacy, one HPS and one LED fixture were selected to grow larger crop stands during each month of a calendar year. Plant culture was similar for both experiments, seeds of arugula (*Eruca sativa* 'Astro'), kale (*Brassica napus* subsp. *napus* var. *pabularia* 'Red Russian'), lettuce (*Lactuca sativa* 'Outredgeous') (seed source: Johnny's Selected Seeds, Fairfield Maine) were sown at 1550 seeds m^{-2} density into a peat-based substrate (LM-1, Lambert Peat Moss, Rivière-Ouelle, Quebec, Canada) in Styrofoam seedling trays with a cell volume of 14.75 mL (Model TR338A, Speedling, Ruskin, FL). Prior to seeding the substrate had been incorporated with water at a ratio of 3:1 water:substrate by weight. Seedling trays were placed in plastic bags that were closed and placed into a germination chamber at 23°C for 48 h. Following germination, trays were floated on mini hydroponic ponds for 11, 13, and 14 days for arugula, kale, and lettuce, respectively. The hydroponic ponds contained a modified Sonneveld's nutrient solution for leafy greens providing (in mg L^{-1}): 142-N, 31-P, 215-K, 90-Ca, 24-Mg, S-18, 1.12-Fe, 0.14-Mn, 0.13-Zn, 0.16-B, 0.02-Cu, and 0.02-B prepared in reverse osmosis water (Brechner and Both, 2013). Aquarium pumps connected to airlines and air stones kept the nutrient solution at saturated dissolved oxygen. The pH was adjusted with 1 M nitric acid to maintain pH at 5.8 and electrical conductivity (EC) was maintained at 1.30 dS m^{-1}. During the experiments, the glasshouse temperature set points were 20/18.5°C DT/NT.

In experiment 1, the seven light sources listed in Table 1 were set up in a common glass greenhouse in Ithaca, NY (42.4°N, latitude). For the Philips GreenPower light sources, 3 fixtures were used and for all other light sources one fixture was used. The fixtures were hung ca. 1.2-2.0 m above benches so as to supply ca. 200 µmol m^{-2} s^{-1} at crop canopy height where light quantum sensors (LI-190R, LI-COR, Lincoln, Nebraska, USA) were placed under each treatment. Each light treatment area was located at least 2 m away from other treatments so that there would be minimal light interference. The experiment was conducted in April and May, and a 50% aluminum shade curtain was left closed for the duration of the experiment to necessitate greater need for supplemental light. Each light source was controlled based on quantum sensors located at crop canopy according to the LASSI (Light and Shade System Implementation) algorithm (Albright et al., 2000) set to a target daily light integral (DLI) of 17 mol m^{-2} d^{-1}. An ambient light (no supplemental light) treatment was also included. Averaged over the experiment, crops received 9 mol m^{-2} d^{-1} from ambient light and 8 mol m^{-2} d^{-1} from supplemental light. Under each light source, mini hydroponic ponds (28 L volume) contained Styrofoam rafts with 40 cells (seeds) for each species. At harvest, plants were cut at the substrate line and weighed to determine average fresh mass per 40 cell raft. The experiment was replicated over time for a total of three crop cycles. Student's T-Test was used to compare average FM for each light treatment. All statistical analysis for this project used JMP version 13 (SAS Institute Inc., Cary, NC, USA).

Table 1. Operating characteristics of light fixtures included in experiments 1 (all) and 2 (Gavita Pro 6/750e Flex and Philips GreenPower toplighting DR/B – Low Blue). Fixture measurements took place in an integrating light sphere (*n*=1) at Rutgers University as described by Wallace and Both (2016).

Light fixture	Lamp type	Supply voltage (V)	Power consumption (W)	PAR output (µmol s^{-1})	PAR efficacy (µmol J^{-1})	PAR efficacy (mol kWh^{-1})
Gavita Pro 600e SE[a]	HPS	120.10	660	1030	1.56[b]	5.62
Gavita Pro 6/750e Flex[c] US DE	HPS	207.96	656	1030	1.57	5.64
Heliospectra LX602-G[d]	LED	119.98	460	603	1.31	4.7
Illumitex PowerHarvest 10 Series W	LED	119.99	510	872	1.71	6.16
LumiGrow Pro 650[d]	LED	120.05	495	703	1.42	5.1
Philips GreenPower toplighting DR/B - Low Blue	LED	208.02	198	481	2.43	8.76
Philips GreenPower toplighting DR/B - High Blue	LED	208.02	206	482	2.34	8.41

[a]The lamp bulb used in the Gavita Pro 600e SE fixture was Philips MASTER GreenPower Plus 600W EL (mogul base).

[b]PAR efficacies were calculated based on Plank's equation (photon energy content at specific wavelengths).

[c]The fixture was characterized using the 600 W setting (as used during the plant experiments).

[d]Operated with 100% of red and blue output (as used during the plant experiments).

Based on energy efficacy and plant response, one HPS fixture (Gavita Pro 6/750e Flex US DE) and one LED fixture (Philips GreenPower toplighting DR/B - Low Blue) were selected for experiment 2 in which crops were grown each month over a calendar year and with a greater crop canopy. Lights (16 Philips GreenPower bars and 11 Gavita Pro 6/750e fixtures) were hung in a common glass greenhouse using a design to optimize spatial light uniformity to achieve an average PPFD of 185 and 189 µmol m^{-2} s^{-1} for LED and HPS, respectively, at crop canopy height. For each light source a 15 m^2 area was lit and treatment areas were separated from each other by 3 m to minimize light interference. Centered under each treatment area were three replicate hydroponic ponds (530 L volume) in which one 156 cell Styrofoam

Speedling tray for each species was placed. Each month during a calendar year a new crop was germinated as before in a germination chamber and grown on in the hydroponic pond, again for an additional 11, 13, and 14 days for arugula, kale, and lettuce, respectively. A quantum sensor was placed under a representative location under each light source and the LASSI algorithm was used to control the on/off times of each light source as well as a retractable shade curtain in the greenhouse to achieve a DLI of 17 mol m^{-2} d^{-1}. At harvest, plants from the inner nine rows (each with 8 cells) were harvested and FM and DM for each plant was recorded. For each flat, representative hypocotyl length (from substrate surface to cotyledon) from 3 representative plants was taken and yield was calculated (g m^{-2}) based on the FM of each row. Analysis of Variance revealed significant effect of light source, month, and a light by month interaction for each species. Tukey's HSD was used to compare months to each other within a light source and a T-test was used to compare HPS to LED within each month.

RESULTS AND DISCUSSION

In experiment 1, FM under ambient light was half or less than with supplemental light (Table 2). During experiment 1 ca. 53% of the DLI came from ambient light and 47% from fixtures. Some differences in FM were observed in response to lighting treatment for the three species. The FM of arugula was greatest under Illumitex PowerHarvest which was greater than the Heliospectra and Lumigrow fixtures. The FM of kale was not affected by light treatment. For lettuce, the Philips GreenPower Low Blue had greater FM than Heliospectra and Lumigrow, and the two Gavita HPS fixtures had greater FM than Heliospectra.

Table 2. Fresh mass (g $plant^{-1}$) of baby leaf greens in response to light fixture in exp. 1. Data are means ± SE of 3 crop cycles (each with 40 cells per species) replicated over time.

Light treatment	Fresh mass (g $plant^{-1}$) Arugula 'Astro'	Kale 'Red Russian'	Lettuce 'Outredgeous'
Ambient (no supplemental light)	1.42±0.10 c	0.95±0.05 NS	1.97±0.17 d
Gavita Pro 600e SE	3.17±0.26 ab	3.10±0.96	3.72±0.27 ab
Gavita Pro 6/750e Flex US DE	3.22±0.29 ab	3.33±0.90	3.68±0.36 ab
Heliospectra LX602-G	2.59±0.22 b	2.60±0.61	2.78±0.15 cd
Illumitex PowerHarvest 10 Series W	3.39±0.27 a	3.17±0.84	3.11±0.24 abc
LumiGrow Pro 650	2.63±0.26 b	2.63±0.64	2.94±0.18 bc
Philips GreenPower toplighting DR/B - Low Blue	2.97±0.27 ab	3.03±0.75	3.75±0.36 a
Philips GreenPower toplighting DR/B - High Blue	2.71±0.25 ab	2.9±0.86	3.35±0.23 abc

Mean separation comparison by light fixture within a species using Student's T-test (α=0.05).

In experiment 2, for arugula, measured parameters were substantially influenced by month (Table 3). For example, FM of arugula was greatest for HPS in November and for LED in September and FM was nearly two-fold that of the lowest months (February-April). Low plant performance in February, March, and April was evident for all three species under both light sources and we believe this correlated to poor substrate moisture content which reduced and delayed germination. Hypocotyl length was greatest for September and April for HPS and in August, September, and May for LED and lowest in January and February for both light sources. Yield was greatest for HPS in September through November (2,060-2,140 g m^{-2}) and least for February and March (810-940 g m^{-2}). For LED, yield was greatest in September (2410 g m^{-2}) and lowest in February through April and June (920-1,180 g m^{-2}). Within the same month, hypocotyl length was significantly affected by light source for only two months, while the other parameters were affected by light source for several of the months. For example FM of HPS arugula was greater than LED in October, November, December, January, and June, while LED had greater FM in July, August, September, and March. Yield exhibited similar patterns, where with the exception of June, HPS yield was favored in cooler months while LED yield was favored in warmer months. When months were grouped together, light source did not significantly impact the measured parameters, i.e., averaged over the year, light source did not impact yield.

Table 3. Harvest parameters of Arugula 'Astro' in experiment 2. Monthly data are means ± SE of 27 (fresh and dry mass) and 9 (hypocotyl length) measurements per light source and fresh yield was calculated based on 27 harvested rows (each with 8 plants) with a density of 1,550 plants m^{-2}.

Month	Fresh mass (g $plant^{-1}$)		T-test	Dry mass (g $plant^{-1}$)		T-test
	HPS	LED		HPS	LED	
July	0.88±0.02 fg[a]	0.93±0.02 ef	*[b]	0.055±0.001 cd	0.059±0.001 d	NS
August	1.05±0.02 e	1.24±0.02 c	***	0.059±0.001 cd	0.074±0.003 bcd	***
September	1.38±0.03 b	1.63±0.03 a	***	0.073±0.003 bc	0.091±0.003 b	***
October	1.34±0.03 bc	1.14±0.03 cd	***	[c]		
November	1.61±0.04 a	1.4±0.03 b	***	0.105±0.005 a	0.117±0.007 a	NS
December	1.22±0.04 cd	1.1±0.03 cd	*	0.103±0.005 a	0.061±0.009 cd	***
January	1.24±0.04 cd	1.05±0.08 de	*	0.105±0.008 a	0.082±0.006 bc	*
February	0.73±0.02 h	0.76±0.02 g	NS	0.056±0.007 cd	0.055±0.001 d	NS
March	0.67±0.01 h	0.77±0.02 g	***	0.054±0.001 d	0.057±0.004 d	NS
April	0.76±0.01 gh	0.79±0.01 fg	NS	0.067±0.001 bcd	0.065±0.004 cd	NS
May	1.13±0.02 de	1.12±0.03 cd	NS	0.08±0.001 b	0.08±0.002 bc	NS
June	0.88±0.02 f	0.7±0.02 g	***	0.071±0.002 bcd	0.053±0.002 d	***
All months	1.07±0.02	1.05±0.02	NS	0.075±0.002	0.072±0.002	NS

Month	Hypocotyl length (cm)		T-test	Yield (g m^{-2})		T-test
	HPS	LED		HPS	LED	
July				1310±39 cd	1420±28 cd	*
August	2.66±0.04 b	2.69±0.07 a	NS	1600±47 b	1780±59 b	*
September	3.11±0.08 a	2.94±0.06 a	NS	2060±58 a	2410±52 a	***
October	2.08±0.05 c	2±0.06 bc	NS	2050±48 a	1680±51 bc	***
November	1.96±0.07 c	1.85±0.07 bc	NS	2140±67 a	1820±72 b	**
December				1520±55 bc	1450±55 cd	NS
January	1.08±0.05 e	1.41±0.05 d	***	1300±68 cd	1620±128 bc	*
February	1.34±0.07 de	1.43±0.15 d	NS	940±39 ef	1020±41 e	NS
March	1.45±0.04 d	1.68±0.05 cd	***	810±31 f	920±47 e	*
April	2.15±0.12 c	2.11±0.06 b	NS	1110±32 de	1180±24 de	NS
May	2.88±0.08 ab	2.68±0.07 a	NS	1700±38 b	1670±49 bc	NS
June	2.05±0.04 c	2.06±0.07 b	NS	1350±33 c	1040±32 e	***
All months	2.07±0.04	2.08±0.04	NS	1490±27	1500±28	NS

[a]Mean separation comparison across months within a lighting treatment using Tukey's Honestly Significant Difference (HSD, α=0.05).

[b]T-test comparing HPS to LED light for a given month, NS, *, **, *** are non-significant or significant at $P\leq0.05$, 0.01, or 0.001, respectively.

[c]Missing data were not recorded for the month due to an oversight.

Similar to arugula, measured parameters for kale were influenced substantially by crop cycle month (Table 4). For HPS, greatest FM and DM occurred in November and was three-fold greater than March. For LED, greatest FM occurred in September and November and was lowest in March. Monthly patterns in yield were similar to FM. Kale DM for HPS was greatest in November and December and was three-fold DM in March. For LED, DM was greatest in November and December and least in March and June. Hypocotyl length varied by month and was greatest in September and two-fold shorter on its lowest months (January and February). When comparing light sources within a month, FM was greater for LED in July through September and March and was greater for HPS for October through January and June. Yield followed a similar pattern as FM but was not significant for some months. Again, with the exception of June, HPS may favor yield in cooler months, while LED may favor yield in warm ambient months. When months were grouped together, FM and yield were a bit greater under HPS (about 5% greater than LED), while DM and hypocotyl length were unaffected by light source.

Table 4. Harvest parameters of Kale 'Red Russian' in experiment 2. Monthly data are means ± SE of 27 (fresh and dry mass) and 9 (hypocotyl length) measurements per light source and fresh yield was calculated based on 27 harvested rows (each with 8 plants) with a density of 1,550 plants m^{-2}.

Month	Fresh mass (g $plant^{-1}$)		T-test	Dry mass (g $plant^{-1}$)		T-test
	HPS	LED		HPS	LED	
July	2.05±0.04 d[a]	1.99±0.03 d	NS[b]	0.111±0.002 de	0.112±0.002 cd	NS
August	2.09±0.05 d	2.37±0.05 bc	***	0.109±0.003 de	0.133±0.003 b	***
September	1.99±0.05 d	2.52±0.06 ab	***	0.105±0.008 e	0.127±0.009 bc	NS
October	2.71±0.09 b	2.33±0.05 bc	***	[c]		
November	3.16±0.1 a	2.75±0.08 a	**	0.191±0.007 a	0.167±0.006 a	**
December	2.44±0.06 bc	2.24±0.06 c	*	0.172±0.017 ab	0.147±0.004 ab	NS
January	2.49±0.07 bc	1.94±0.08 d	***	0.155±0.005 bc	0.134±0.006 b	*
February	1.57±0.05 e	1.52±0.04 ef	NS	0.099±0.003 e	0.095±0.003 de	NS
March	0.8±0.02 f	0.93±0.02 g	***	0.055±0.003 f	0.065±0.002 f	**
April	1.64±0.02 e	1.66±0.03 ef	NS	0.103±0.004 e	0.111±0.002 cd	NS
May	2.4±0.06 c	2.43±0.05 bc	NS	0.138±0.005 cd	0.142±0.003 b	NS
June	1.83±0.05 de	1.39±0.03 f	***	0.111±0.003 de	0.084±0.002 ef	***
All months	2.1±0.04	2.0±0.03	*	0.123±0.003	0.12±0.002	NS

Month	Hypocotyl length (cm)		T-test	Yield (g m^{-2})		T-test
	HPS	LED		HPS	LED	
July				3030±81 ef	3010±57 d	NS
August	3.83±0.05 c	3.29±0.07 c	***	3160±82 def	3190±94 cd	NS
September	4.43±0.05 a	4.2±0.04 a	**	3020±79 ef	3730±117 ab	***
October	2.36±0.07 e	2.3±0.05 e	NS	4120±133 b	3500±111 bc	***
November	2.26±0.04 e	2.33±0.05 e	NS	4670±142 a	3960±139 a	***
December				3600±120 cd	3320±96 bcd	NS
January	1.92±0.04 g	1.72±0.29 f	*	3300±132 def	3000±125 d	NS
February	2±0.04 fg	1.78±0.33 f	**	2280±83 h	2200±70 e	NS
March	2.21±0.05 ef	2.22±0.26 e	NS	1130±41 i	1260±46 f	*
April	3.23±0.07 d	3±0.29 d	*	2540±57 gh	2490±58 e	NS
May	4.15±0.07 b	3.89±0.34 b	**	3820±127 bc	3680±97 ab	NS
June	3.83±0.06 c	3.82±0.39 b	NS	2820±66 fg	2050±56 e	***
All months	3.02±0.06	2.86±0.06	NS	3130±27	2950±51	*

[a]Mean separation comparison across months within a lighting treatment using Tukey's Honestly Significant Difference (HSD, α=0.05).

[b]T-test comparing HPS to LED light for a given month, NS, *, **, *** are non-significant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

[c]Missing data were not recorded for the month due to an oversight.

Lettuce growth parameters followed similar patterns to arugula and kale with large month-to-month variation and times where light source affected FM, DM, and yield within a month (Table 5). For HPS, greatest FM was in November and least was in March. For LED, greatest FM was in August and lowest was in March and June. Yield followed similar patterns to FM for both HPS and LED. The highest DM occurred in December through January for HPS and lowest was in March. DM was greatest in November and least in March and June. When comparing light sources within a month, FM and yield were greater for LED than HPS in August and September. FM was greater for HPS than LED in October through December, February, and June. Again, with the exception of June, HPS FM and yield was favored during cooler months and LED attributes were favored during warmer months. Overall, when comparing HPS to LED across all months there were not any significant differences in the measured attributes.

Overall, in the 12-month study we found substantial seasonal variation in yield even though DLI was controlled. Such effects may be due to other parameters such as substrate moisture (which influences germination) or greenhouse air temperature. Seasonal effects on yield were also found by Kroggel et al. who found that lettuce yield varied greatly during the year with some correlation with DLI, an R^2=0.32, suggesting that 68% of the variability in yield could not be explained by DLI. Our finding that, averaged over a year, light source had no (arugula and lettuce) or minimal (kale) impact on FM/DM/yield corroborates other studies with greenhouse supplemental lighting (Martineau et al., 2012; Zhang et al., 2019).

Table 5. Harvest parameters of Lettuce 'Outredgeous' in experiment 2. Monthly data are means ± SE of 27 (fresh and dry mass) and 9 (hypocotyl length) measurements per light source and fresh yield was calculated based on 27 harvested rows (each with 8 plants) with a density of 1,550 plants m^{-2}.

Month	Fresh mass (g plant^{-1})		T-test	Dry mass (g plant^{-1})		T-test
	HPS	LED		HPS	LED	
July	1.43±0.02 cd[a]	1.39±0.03 de	NS[b]	0.054±0.001 cd	0.054±0.001 e	NS
August	1.38±0.06 cd	1.98±0.05 a	***	0.051±0.003 cde	0.07±0.003 cd	***
September	1.14±0.06 ef	1.61±0.05 bcd	***	0.04±0.003 e	0.065±0.002 de	***
October	1.99±0.07 b	1.73±0.06 b	**	[c]		
November	2.35±0.07 a	1.68±0.08 bc	***	0.085±0.004 ab	0.104±0.004 a	**
December	1.87±0.04 b	1.43±0.04 de	***	0.088±0.002 a	0.079±0.003 bc	**
January	1.45±0.05 cd	1.3±0.06 ef	NS	0.079±0.003 ab	0.084±0.004 b	NS
February	1.29±0.05 de	1.14±0.04 fg	*	0.058±0.003 c	0.06±0.003 de	NS
March	0.37±0.02 h	0.42±0.02 h	NS	0.024±0.001 f	0.027±0.001 f	NS
April	0.97±0.04 fg	0.93±0.04 g	NS	0.058±0.002 c	0.06±0.004 de	NS
May	1.59±0.06 c	1.49±0.06 cde	NS	0.075±0.005 b	0.065±0.003 de	NS
June	0.83±0.03 g	0.54±0.02 h	***	0.042±0.002 de	0.026±0.001 f	***
All months	1.39±0.03	1.31±0.03	NS	0.06±0.001	0.063±0.002	NS

Month	Hypocotyl length (cm)		T-test	Yield (g m^{-2})		T-test
	HPS	LED		HPS	LED	
July				2200±43 c	2100±50 d	NS
August	0.36±0.02 bc	0.36±0.01 bc	NS	2010±101 c	3070±80 a	***
September	0.6±0.03 b	0.45±0.02 b	***	1590±89 de	2290±81 bcd	***
October	0.14±0.01 c	0.2±0.01 bc	**	2890±130 b	2590±101 b	NS
November	0.17±0.02 c	0.17±0.02 c	NS	3410±119 a	2510±118 bc	***
December				2720±69 b	2080±73 d	***
January	0.28±0.03 c	0.26±0.02 bc	NS	1910±77 cd	1490±99 e	**
February	1.38±0.2 a	1.06±0.17 a	NS	1870±91 cd	1590±72 e	*
March	0.1±0.02 c	0.08±0.01 c	NS	560±29 f	610±27 g	NS
April	0.13±0.02 c	0.16±0.02 c	NS	1290±71 e	1090±71 f	NS
May	0.24±0.05 c	0.2±0.06 bc	NS	2180±86 c	2150±107 cd	NS
June	0.45±0.06 bc	0.32±0.04 bc	NS	1290±48 e	830±29 fg	***
All months	0.4±0.03	0.33±0.02	NS	2000±48	1870±46	NS

[a]Mean separation comparison across months within a lighting treatment using Tukey's Honestly Significant Difference (HSD, α=0.05).

[b]T-test comparing HPS to LED light for a given month, NS, *, **, *** are non-significant or significant at $P\leq$0.05, 0.01, or 0.001, respectively.

[c]Missing data were not recorded for the month due to an oversight.

CONCLUSIONS

In experiment 1, over 3 crop cycles greenhouse supplemental light source had a subtle but significant effect on FM. In experiment 2, when averaged over a year, there was minimal effect of light source on FM/DM/yield. However, biomass was significantly affected by light source for some specific months. This may be due to the impact that light source had on crop temperature as biomass was favored by HPS in winter/early spring months and favored by LED in late summer/early fall. Light source effects on temperature should be carefully considered in future research as well as when commercial greenhouses consider adoption of LEDs. Future research should also explore hybrid lighting (combined HPS and LED) approaches to balance possible yield impacts that light source has on plant temperature.

ACKNOWLEDGEMENTS

Funding for this research was received from the New York State Energy Research and Development Authority grant 40322. The data on fixture power consumption, PAR output and efficacy was collected by the laboratory of A.J. Both, Rutgers University.

Literature cited

Albright, L.D., Both, A.J., and Chiu, A.J. (2000). Controlling greenhouse light to a consistent daily integral. American Society of Agricultural Engineers *43* (*2*), 421–431.

Brechner, M., and Both, A.J. (2013). Hydroponic Lettuce Handbook. (Cornell CEA). http://cea.cals.cornell.edu/attachments/Cornell%20CEA%20Lettuce%20Handbook%20.pdf

Craver, J.K., Gerovac, J.R., Lopez, R.G., and Kopsell, D.A. (2017). Light intensity and light quality from sole-source light-emitting diodes impact phytochemical concentrations within Brassica microgreens. J. Am. Soc. Hortic. Sci. *142* (*1*), 3–12 https://doi.org/10.21273/JASHS03830-16.

Di Gioia, F., Renna, M., and Santamaria, P. (2017). Sprouts, microgreens and "Baby Leaf" vegetables. In Minimally Processed Refrigerated Fruits and Vegetables (Boston, MA: Springer), p.403–432.

Kitaya, Y., Niu, G.H., Kozai, T., and Ohashi, M. (1998). Photosynthetic photon flux, photoperiod, and CO_2 concentration affect growth and morphology of lettuce plug transplants. HortScience *33* (*6*), 988–991 https://doi.org/10.21273/HORTSCI.33.6.988.

Kroggel, M., Lovichit, W., Kubota, C., and Thomson, C. (2012). Greenhouse baby leaf production of lettuce and komatsuna in semi-arid climate: seasonal effects on yield and quality. Acta Hortic. *952*, 827–834 https://doi.org/10.17660/ActaHortic.2012.952.105.

Li, Q., and Kubota, C. (2009). Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. Environ. Exp. Bot. *67* (*1*), 59–64 https://doi.org/10.1016/j.envexpbot.2009.06.011.

Martineau, V., Lefsrud, M., Naznin, M.T., and Kopsell, D.A. (2012). Comparison of light-emitting diode and high-pressure sodium light treatments for hydroponics growth of Boston lettuce. HortScience *47* (*4*), 477–482 https://doi.org/10.21273/HORTSCI.47.4.477.

Meng, Q., Kelly, N., and Runkle, E.S. (2019). Substituting green or far-red radiation for blue radiation induces shade avoidance and promotes growth in lettuce and kale. Environ. Exp. Bot. *162*, 383–391 https://doi.org/10.1016/j.envexpbot.2019.03.016.

Morrow, R. (2008). LED lighting in horticulture. HortScience *43* (*7*), 1947–1950 https://doi.org/10.21273/HORTSCI.43.7.1947.

Ouzounis, T., Rosenqvist, E., and Ottosen, C. (2015). Spectral effects of artificial light on plant physiology and secondary metabolism: a review. HortScience *50* (*8*), 1128–1135 https://doi.org/10.21273/HORTSCI.50.8.1128.

Pocock, T. (2015). Light-emitting diodes and the modulation of specialty crops: light sensing and signaling networks in plants. HortScience *50* (*9*), 1281–1284 https://doi.org/10.21273/HORTSCI.50.9.1281.

Stober, K., Lee, K., Yamada, M., and Pattison, M. (2017). Energy savings potential of SSL in horticultural applications (No. DOE/EE-1723) (EERE Publication and Product Library). https://doi.org/10.2172/1418429.

Thornton, T., Grahn, C.M., Miles, C.A., and Benedict, C. (2015). Baby-leaf salad green production guide for western Washington. WSU Extension Bull, p.1–25.

Wallace, C., and Both, A.J. (2016). Evaluating operating characteristics of light sources for horticultural applications. Acta Hortic. *1134*, 435–444 https://doi.org/10.17660/ActaHortic.2016.1134.55.

Zhang, M., Whitman, C.M., and Runkle, E.S. (2019). Manipulating growth, color, and taste attributes of fresh cut lettuce by greenhouse supplemental lighting. Sci. Hortic. (Amsterdam) *252*, 274–282 https://doi.org/10.1016/j.scienta.2019.03.051.