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Light emitting diode and metal halide supplemental lighting for greenhouse Bibb lettuce production in the Midwestern United States

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Abstract

Lettuce (*Lactuca sativa*) is one of the most common vegetable crops produced in greenhouses in the United States. Yet, it is difficult to maintain consistent production cycles in many areas due to seasonal variation in ambient light. This presents a challenge to profitability, so, many growers utilize supplemental lighting to provide more consistent production in greenhouse leafy crop operations. Research has frequently been carried out to investigate the relationships between light, temperature, and carbon dioxide (CO_2) in greenhouse lettuce crops to optimize production and profitability. Much of this work has been carried out using high intensity discharge lights (HID), specifically high pressure sodium (HPS) and metal halide (MH). Currently, growers are considering whether light emitting diode (LED) technology can augment or replace HID lighting for greenhouse-grown vegetables. To improve knowledge in this area, this study evaluated LED and MH lighting in Bibb lettuce crop in the Midwestern United States during low light seasons in 2014. Three lighting treatments were compared: 1) a naturally lighted control, 2) supplemental MH lighting, and 3) supplemental LED lighting. Three sequential runs comparing the three lighting treatments were carried out between January and April of 2014. At the conclusion of each run, fresh shoot weight for all plants was measured along with a chlorophyll content index and a subjective tipburn rating. Supplemental lighting increased biomass over naturally-lighted controls by 194%, 104%, and 39% in MH and 253%, 165%, and 55% in LED in runs one, two, and three, respectively across the two cultivars. Differences in the chlorophyll content index and tipburn rating were also observed in lettuce under both supplemental lighting treatments when compared to the naturally lighted control. This study illustrates that supplemental lighting can improve greenhouse lettuce yield during low light seasons, but suggests growers implementing supplemental lighting should carefully monitor and manage crop quality.

Key words: Hydroponic, protected culture, light emitting diode, metal halide, lettuce, *Lactuca sativa*, greenhouse, high intensity discharge lighting

Introduction

Greenhouses provide the opportunity to produce lettuce and other leafy vegetables year-round in many parts of the world. These controlled environments enable growers to more consistently produce high quality crops as well as manage pests and diseases that can reduce yield and profits in field production. Controlled environment greenhouses present the ability to maintain appropriate temperatures for year-round crop production even in cold climates (Albright *et al.*, 2000; Both *et al.*, 1997). While controlled environment production of leafy crops can have advantages in quality and consistency for local markets, seasonal fluctuations in ambient light are a challenge for many growers. Solar radiation varies throughout the year (Albright *et al.*, 2000) in many locations, and reductions in both duration and intensity of ambient solar radiation are a limitation. Even under closely controlled temperatures, low light can result in variations in production cycles, which can impact profitability.

Bibb lettuce is one of the most common crops grown in leafy crop greenhouses, and can generally be sold 5 to 6 weeks after seeding under optimum conditions. Under seasonal low light conditions, this production time frame may be lengthened by 2 or more weeks. Turns, or the number of crops produced per year in the hydroponic production greenhouse, is a common metric in determining profitability (Papadopoulos *et al.*, 2002). Often, plants spend at least 2 weeks in the seedling phase prior to transplanting, so 3 to 4 weeks is typically the length of time a crop is in the main production system. These timelines would conservatively produce 13 turns per year if growth was consistent. Two weeks added to the production cycle during 4 months of seasonally low solar radiation would result in approximately eleven and a half turns per year. For growers, this represents over a 10% yearly decrease in saleable crop. An added drawback is that demand for local greenhouse lettuce may be increased during cooler and lower light seasons due to reduced competition from outdoor producers. So, production declines often occur when demand and price potential may be highest.

For producers, reducing variability in seasonal production and increasing saleable product during low light periods is critical. Supplemental lighting systems, most commonly HPS and MH, have been used in greenhouses for decades. Research has focused on the implementation of these lighting systems in combination with temperature and CO_2 control. Models have been created to optimize and automate management of both light and CO_2 to efficiently produce a high quality crop (Albright *et al.*, 2000;

Research for this paper was conducted while N. Bumgarner was employed by CropKing, Inc. of Lodi OH, USA and J. Buck was employed by Hort Americas, LLC, Euless, TX, USA.

Both *et al.*, 1997; Ferentinos *et al.*, 2000; Gaudreau *et al.*, 1994; Ioslovich *et al.*, 2009). While these systems function well for many growers, the added capital and operational costs of supplemental lighting are challenging. Lighting continues to be one of the most expensive areas of controlled environment agriculture (Bourget, 2008), and future increases in efficiencies will likely be needed to expand controlled environment leafy production in some areas. Drawbacks of HPS and MH lights are the energy demand and inability to closely control the light spectrum delivered to the crop. These two issues can result in higher operating costs as well as added heat production.

Advances in lighting technologies, mainly LEDs, are changing the horticulture industry. This technology has been researched in various applications since the late 1980's (Morrow, 2008) and is likely to represent the dominant lighting system in greenhouses in coming years (Martineau *et al.*, 2012). Some key aspects of LED lighting in horticulture are the ability to tailor light spectrums for specific crops and purposes, and reduced heat output, which enables light placement closer to plants. Instant turn on, flexibility in application, and long operating life spans are other advantages of the technology in greenhouses (Bourget, 2008; Massa *et al.*, 2008; Morrow, 2008). Although currently more expensive than HPS and MH lighting, LED technologies are becoming more useful in regards to production and long-term cost efficiency.

Even with the benefits of LED technology, growers are hesitant to invest without thorough knowledge of optimum implementation. The initial criteria for application of new technologies in greenhouse lighting are the impact of the system on crop growth and yield. Many studies have been carried out to investigate aspects of growth under a range of LED wavelength combinations (Hoenecke, *et al.*, 1992; Son and Oh, 2013; Yorio *et al.*, 2001). In addition to these controlled environment tests, full-scale greenhouse comparisons have also been done (Martineau *et al.*, 2012; Pinho *et al.*, 2011). However, additional work is still needed to understand the yield impacts of LED lighting in leafy crop greenhouses in various climates and growing systems.

Another important factor for greenhouse lettuce producers is the impact of lighting systems on crop quality. One of the most common quality issues in lettuce crops is tipburn. Tipburn is necrosis on the margins of leaf tissue most common in the center of the expanding lettuce head. This condition can produce lower quality or unsaleable lettuce heads and is a significant concern for growers. Tipburn can be described as a localized deficiency of calcium (Ca) in the newly developing leaf tissue. However, this condition can occur in growing systems where Ca and other nutrients are not limiting, as is often the case in hydroponic production. In these systems, the deficiency is thought to result from suboptimum movement of Ca and/or increased demand rather than suboptimum nutrition in the solution (Barta and Tibbitts, 1991; Frantz *et al.*, 2004; Bangerth, 1979). While tipburn is a condition that impacts leafy crops in both controlled and field environments, rapid growth in greenhouse crops can increase the incidence of tipburn (Barta and Tibbitts, 1991). The combination of rapid growth and fluctuation in air movement and relative humidity in the greenhouse can induce tipburn by influencing water movement in the crop and water demand in the environment. Because of the role of light on growth rate and greenhouse environmental conditions, the impact of supplemental lighting on lettuce quality, specifically tipburn, should be investigated.

Supplemental lighting in greenhouse crops also has the potential to alter coloration and composition of the harvested leaves. Much of the research done in LED lighting has focused on the impact of specific light wavelengths on metabolism of secondary compounds including pigments and antioxidants. Specific wavelengths have been tested for their impact on pigments and secondary metabolites (Chen *et al.*, 2014; Li and Kubota, 2009; Samuoliene *et al.*, 2012) as well as sensory quality (Lin *et al.*, 2013). The ability to select light wavelengths to achieve desired appearance and crop composition could be an important aspect of greenhouse lighting in the future because it would allow growers to tailor crop attributes to buyer demands.

Although LED lighting development and research continue, questions regarding application and optimization still remain. An important current grower concern is whether LEDs should be purchased in place of HID lighting in greenhouse vegetable production. Therefore, this work was carried out to evaluate LED and HID lighting compared with natural lighting in Bibb lettuce crops in mid-latitude North American winter and spring production seasons. In addition to documenting the impact on lettuce yield, this study also sought to evaluate the effect of lighting systems on important visual aspects of crop quality as assessed through a chlorophyll content index and tipburn rating.

Materials and methods

Growing Environment: All crops were produced in a 19.0 x 6.7 x 4.0 m (L x W x H) double layer, polyethylene greenhouse (north-south orientation) located at the CropKing, Inc., facility in Lodi, OH, USA (41.03 latitude, -82.03 longitude). Greenhouse conditions were maintained at commercially appropriate temperature and humidity ranges for lettuce production (Table 1). Carbon dioxide enrichment was not carried out during the experiment, so conditions reported represent ambient CO_2 levels. Environmental conditions (Table 1) were monitored by a non-aspirated temperature and humidity sensor, solar radiation sensor (420-675 nm) and a CO_2 monitor logging continuously into an iGrow 1600 environmental control unit (Link4 Corporation, Yorba, CA, USA).

Crop Management: Two commercial Bibb lettuce cultivars ('Flandria' and 'Teodore') were grown using a nutrient film technique system (NFT; CropKing Inc. Lodi, OH, USA). Split-pellet lettuce seeds (Rijk Zwaan, De Lier, The Netherlands) were germinated in rockwool sheets (AO 25x40; Grodan, Roermond, The Netherlands). Rockwool was pre-moistened with reverse osmosis water and placed in 25 x 50 cm solid plastic seeding trays. Following seeding, trays were placed on an electric heating mat (53 x 152 cm; HydroFarm, Petaluma, CA, USA) thermostatically controlled at 23 °C for 96 h. After this germination period, seedlings were removed from the heat mat and placed in 23.0 cm x 4.0 cm x 2.4 m (W x H x L) open NFT channels under the experimental lighting treatments and grown for approximately two weeks under treatment levels of light and nutrient solution. These open-topped nursery channels remained in the lighted treatment area for all three experimental runs to enable transplants to be in production during the grow-

Table 1. Dates and environmental conditions for each of the three experimental runs carried out from January through April 2014, in Lodi, OH, USA

	Run 1	Run 2	Run 3
Dates of seeding	10 Jan, 2014	11 Feb, 2014	15 Mar, 2014
Date of transplant	29 Jan, 2014	28 Feb, 2014	31 Mar, 2014
Date of harvest	26 Feb, 2014	28 Mar, 2014	28 Apr, 2014
Average ambient air temperature (^{0}C)	19.6	19.7	19.9
Average ambient relative humidity (%)	65	68	71
Average ambient carbon dioxide (ppm)	452	450	461
Average ambient solar radiation (W m^{-2})	113	165	217

out phase of the previous experimental run as indicated by dates in Table 1. At transplant, individual plants in rockwool cubes were placed in 11.6 cm x 4.0 cm x 2.4 m (W x H x L) polyvinyl chloride (PVC) NFT channels. The two-piece grow-out channels had solid PVC top caps with 2.5 x 2.5 cm holes punched at 20 cm intervals to maintain plant spacing through harvest. Adjacent channels had offset hole spacing to stagger plants and provide for maximum leaf expansion. Plants were maintained in these grow-out channels for approximately four weeks from transplant to harvest.

All runs of the experiment were carried out in a 6.1 x 2.4 m section of NFT channels situated on the eastern side of the above described greenhouse. Thirty 2.4-m channels placed evenly at 0.2 m intervals were fed by a 950 L solution reservoir continuously controlled by single EC and pH controller (Fertroller; CropKing, Inc. Lodi, OH, USA) to ensure consistent solution conditions for all lighting treatments. Nutrient solutions were constantly flowing through the channels at a rate of approximately 300 mL min^{-1}. Nutrient solutions were prepared using a two-part concentrate formulated using background source water values and proprietary targets for individual macro and micronutrient elements (CropKing Inc., Lodi, OH, USA). Concentrates were mixed using greenhouse grade calcium nitrate, potassium nitrate, monopotassium phosphate, magnesium sulfate heptahydrate, potassium sulfate, chelated iron, solubor, copper sulfate, sodium molybdate, zinc sulfate, and manganese sulfate. Electrical conductivity (EC) was maintained at 2.0, 1.9, and 1.8 mS cm^{-1}, respectively in runs one, two, and three, and 5.9 pH in all runs. At two-week intervals during all experimental runs, approximately 75% of the tank was replaced with reverse osmosis water and the entire solution readjusted to meet target EC and pH levels. Nutrient solution temperature was not directly controlled, but was assumed to be close to ambient air temperature of the greenhouse.

Experimental design and layout: Three lighting treatments were compared in all three experimental runs. Each lighting treatment covered a 1.2 x 2.4 m area within the 6.1 x 2.4 m experimental treatment area and was separated by two 1.2 x 2.4 m buffer areas between the three lighting treatments. Each lighting treatment area contained six 2.4 m grow-out NFT channels (12 plant spaces in each channel) and one 2.4 m nursery channel at 0.2 m spacing. Therefore, each lighting treatment contained 72 plants in grow-out channels and enough nursery space to contain young plants for the next experimental run. The six channels in each lighting treatment area were divided into three blocks with one channel in each block randomly assigned to 'Flandria' and one to 'Teodore'. Each lighting treatment x cultivar combination comprised 36 plants.

The treatments included a naturally lighted control (1), which represented ambient solar radiation conditions present in the test greenhouse (Table 1). A supplemental MH lighting treatment (2) represented common greenhouse lighting equipment in use in many United States leafy crop hydroponic greenhouses. The LED treatment (3) represented current emerging technologies for greenhouse producers. Treatment (2) employed two PARSource electronic ballasts with 400W GE Multivapor Quartz metal halide bulbs, and GLX reflectors (PARSource, Petaluma, CA, USA). Each MH light covered a 1.2 x 1.2 m growing area. Treatment (3) employed ten 1.2 m x 40 mm Philips GreenPower LED production module deep red/blue 120 cm units (Fig. 1; Eindhoven, The Netherlands) suspended on an aluminum frame. The frame supported two 1.2 m LED units attached end to end and running parallel with the NFT channels to form five rows of LED lights spaced at 0.15 m intervals across the lighted area.

Supplemental lighting was installed and adjusted to provide average light intensity of 100 µmol m^{-2} sec^{-1} ± 5 µmol m^{-2} sec^{-1} across the treatment area. Light maps were prepared and intensities measured during dark periods. Photosynthetically active radiation (PAR) measurements (LI-190SA quantum sensor attached to a LI-250A light meter; Li-Cor Inc., Lincoln NE, USA) were taken under each of the lighting systems in a grid pattern to obtain lighted area averages prior to initiation of the study. This resulted in the MH and LED lights being suspended 86.4 and 24.4 cm, respectively, above the top of the NFT channel.

In each of the three sequential experimental runs, the location of each lighting treatment area was randomly assigned within the 6.1 x 2.4 m growing area. Additionally, the duration of lighting treatment was reduced in runs 2 and 3 to correspond to increased ambient light levels due to change in growing season between run 1 and run 3 (Table 1). Daily light integral (DLI) was adjusted through duration of lighting treatments. Lights were operated for 16 hours per day in run one, 12 hours per day in run two, and 8 hours per day in run 3 to provide an additional 5.8, 4.3, and 2.9 mol m^{-2} day^{-1}, respectively, for the three experimental runs in both the MH and the LED treatments (Table 2). Supplemental light intensity was not altered.

Data collection and analysis: Harvest was carried out in all experimental runs four weeks after transplanting (Table 1) during the early to mid-morning hours. All plants were removed from the channels by hand and the root material along with the rockwool media cube was removed. Individual heads were weighed to record fresh leaf biomass. Following this, two types of quality assessments were carried out on each lettuce head. First, two chlorophyll content index (CCI) measurements were taken from each plant using a CCM-200 chlorophyll content meter (Opti-Sciences, Hudson, NJ, USA). Measurements were taken on two separate leaves, including the second leaf in from the most mature outer leaf and the third leaf in from the most mature outer leaf on the opposite side of the plant. All measurement were taken approximately 1 cm from the leaf tip immediately to the right of the midrib. The final assessment was a subjective visual tipburn

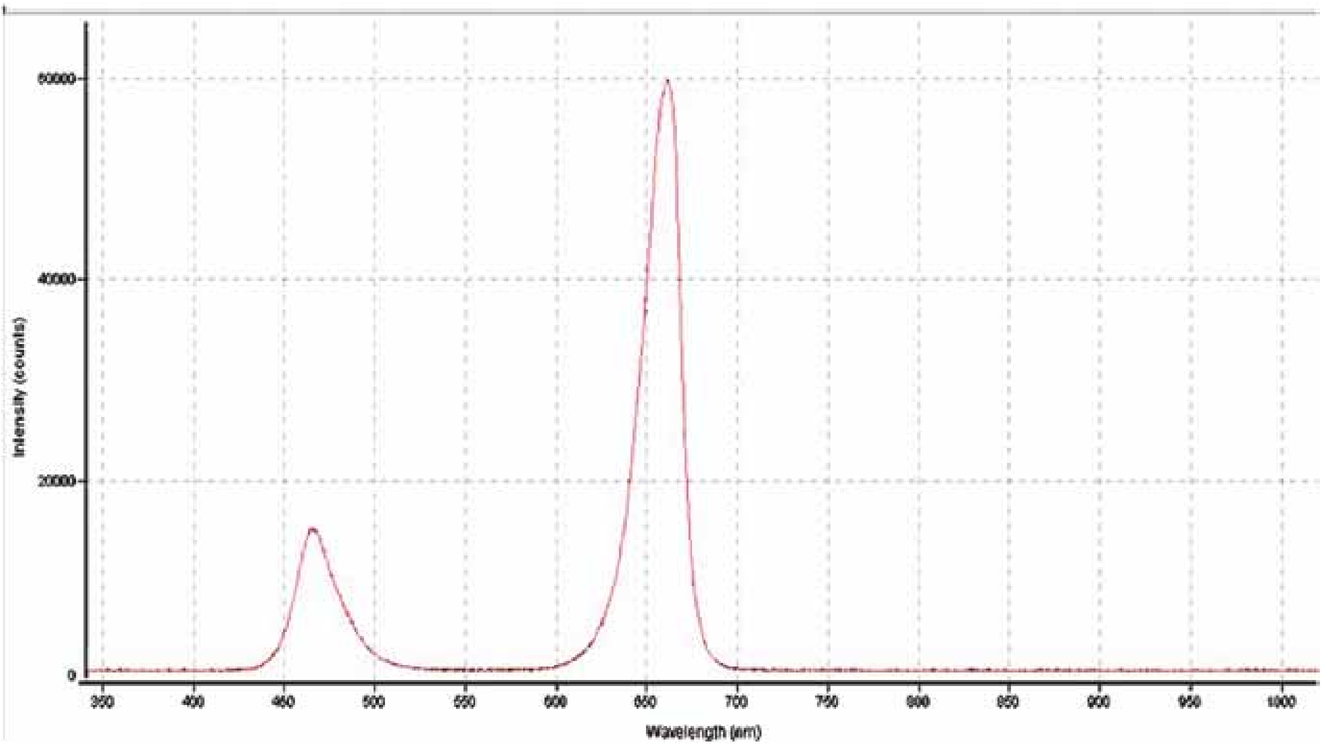

Fig. 1. Light spectrum delivered by the Phillips Deep Red/Blue 120 cm GreenPower Generation 1 for the LED lighting treatment as provided by Hort Americas LLC., Euless, TX, USA.

Table 2. Supplemental lighting treatment time periods and daily light integral (DLI) additions for each of the three experimental runs carried out from January through April 2014, in Lodi, OH, USA

	Run 1	Run 2	Run 3
Supplemental lighting application time	04:00 to 20:00 (16 h)	00:00 to 10:00 and 17:00 to 19:00 (12 h)	02:30 to 08:30 and 17:00 to 19:00 (8 h)
Daily light integral addition (mol m^{-2} day^{-1})	5.8	4.3	2.9

rating where each head was given a rating on a scale of zero to three. A rating of zero represented no visual signs of tipburn. A rating of one represented minor tipburn that was visible but not deemed serious enough to render the head unsaleable. A rating of two represented the presence of tipburn that would result in an unsaleable head. A rating of three indicated excessive tipburn resulting in significant tissue death and potentially subsequent secondary infection with a fungal pathogen.

Fresh weight, CCI, and tipburn ratings were collected from every Bibb lettuce head in both cultivars and all three lighting treatment in each experimental run. In each of these lighting x cultivar experimental units (n=36), means and standard deviations were calculated. From these means, standard deviations and n values, 95% confidence intervals were calculated for fresh biomass and tipburn rating. For chlorophyll content index measurements, the two values that corresponded to each head were averaged and then used to calculate means, standard deviations, and confidence intervals.

Results and discussion

Lettuce yield as affected by lighting treatment: The two experimental lighting systems provided significant increases over the control in all three runs of the experiment, but the percentage increase varied with run. Supplemental lighting showed biomass increases over controls of 194%, 104% and 39% in MH and 253%, 165% and 55% in LED in runs one, two, and three respectively across the two cultivars. Increases in fresh biomass under supplemental lighting have been consistently reported in greenhouse lettuce crops (Albright *et al.*, 2000; Both *et al.*, 1997; Ferentinos *et al.*, 2000; Martineau *et al.*, 2012; Papadopoulos *et al.*, 2002). However, much of the previous research has been conducted using HPS lights, rather than MH as used in this experiment. In all three runs, the MH treatment yielded significantly higher fresh biomass than the ambient lighting treatment. Additionally, in all three runs, the LED lighting treatment yielded higher fresh biomass than the MH and the ambient lighting treatment. As ambient light levels increased, supplemental light additions were decreased, but in all three runs significant increases in biomass were observed in the lighted treatments. The relative percentage of biomass increase was reduced in the second and third runs of the experiment as supplemental light levels decreased and ambient light levels increased.

One of the most important factors in determining utility of supplemental lighting and economy of these methods in greenhouse operations is the control of the lighting systems. This experiment was carried out using only timing devices to provide consistent addition of supplemental lighting for all treatments. Additionally, supplemental lighting in this project was applied without taking into account instantaneous ambient light levels. Large variations exist in the control systems and the capacity to manage lighting systems in greenhouses. In technologically advanced greenhouses, target cumulative light levels, referred to as DLI, can be programmed into environmental control systems (Albright *et al.*, 2000; Both *et al.*, 1997). Utilizing instantaneous light readings to track accumulation of light throughout the day, these sophisticated greenhouse control systems can provide

Table 3. Fresh biomass (g/head) and confidence intervals of two cultivars of greenhouse Bibb lettuce under three different lighting treatments (ambient, MH, and LED) in three experimental runs from January through April of 2014 in Lodi, OH, USA

Run n=36	Flandria			Teodore		
	Ambient	*MH*	*LED*	*Ambient*	*MH*	*LED*
Run 1	45.9 (44.0-47.8)*	125.4 (120.1-130.7)	138.9 (133.0-144.8)	29.8 (28.0-31.6)	96.8 (91.8-101.8)	128.0 (122.2-133.8)
Run 2	85.0 (80.8-89.2)	165.4 (157.2-173.6)	208.3 (199.7-216.9)	53.0 (50.2-55.8)	116.4 (110.2-122.6)	156.9 (150.0-163.8)
Run 3	165.5 (161.1-169.9)	234.1 (227.0-241.2)	249.0 (242.2-255.8)	110.0 (105.3-114.7)	147.6 (143.0-152.2)	176.7 (170.2-183.2)

* Denotes range of 95% confidence interval

consistent DLI by supplying supplemental lighting only when ambient light is insufficient to reach target levels. Many smaller growers do not possess such sophisticated control systems. In these lower technology operations, maximum lighting efficiency may not be attainable, but growth and productivity can still be significantly increased as demonstrated here. To aid smaller scale growers in utilizing supplemental lighting, simple control devices were used in this study.

In this study, supplemental lighting increased biomass over ambient in all three runs. However, biomass production under supplemental lighting in run one did not reach weights recorded under supplemental lighting in runs two and three. These yields indicate that although supplemental lighting increased biomass, the increase was not sufficient to standardize lettuce yield throughout the year. This result suggests that higher levels of supplemental light than were delivered in this trial may have further increased yield. However, quality, as discussed below, should always be considered.

Increased biomass across both lighting treatments in run three illustrates that yield gains are possible even under early to mid-spring conditions in the region. It would have been necessary to carry out additional runs to determine at what point supplemental light no longer produced yield gains in these lettuce crops. Such further experimentation could produce a threshold solar radiation value at which to discontinue supplemental lighting. This threshold would depend on other environmental conditions in the greenhouse, but an estimated value could still be useful to growers. Such target ranges could provide directly useable data for greenhouse growers who do not have environmental control systems that enable them to program lighting systems to target specific DLI in the production of their leafy crops.

Lettuce quality as affected by lighting treatment: The impact of the two experimental lighting systems on the two aspects of lettuce quality measured in this study were relatively consistent across the three runs. In 'Flandria', both MH and LED supplemental lighting increased the incidence of tipburn in all three runs. Crops grown under ambient light did not show signs of tipburn in any of the three runs. In all three runs, the tipburn incidence as reported on a 0 to 3 observational scale were similar for the two experimental lighting treatments. Similarly, 'Teodore' lettuce showed increased incidence of tipburn under supplemental lighting in all three runs. However, tipburn was observed in the ambient lighting treatment in run three. Additionally, in run three, LED lighting showed a higher tipburn rating than MH.

'Teodore' also showed signs of flower initiation and stem elongation in most of the heads that showed tipburn. This cultivar, a red-leaf lettuce, is reported by the seed supplier to be optimum for winter production. So, it may have been selected for performance under shorter day length conditions. Increased intensity and duration of light under the supplemental treatments may have induced flowering and resulted in the high incidence of bolting observed in the study. While supplemental light intensity was consistent in all three runs, lighting duration was decreased in runs two and three to reduce bolting potentially related to long days. However, bolting was still present even after daylength was decreased by altering the time periods of supplemental lighting. Future studies should investigate other red leaf cultivars for production suitability under supplemental lighting. These results illustrate the importance of cultivar selection, seasonality, and environmental management when supplemental lighting is added to greenhouse production systems (Gaudreau *et al.*, 1994).

Follow up work should also investigate whether yield impacts are attainable under lower light intensities to decrease the risk of tipburn. For smaller growers with less sophisticated environmental control systems, slightly lower growth rates under supplemental lighting than were observed in this study might still provide yield increases while mitigating the risk of quality deterioration. Lower target light intensities would also reduce the capital expense of

Table 4. Tipburn rating (0 to 3 scale) of two cultivars of greenhouse Bibb lettuce under three different lighting treatments in three experimental runs from January through April of 2014 in Lodi, OH, USA

Run n=36	Flandria			Teodore		
	Ambient	*MH*	*LED*	*Ambient*	*MH*	*LED*
Run 1	0.0	1.1 (0.9-1.3)*	0.9 (0.7-1.1)	0.0	1.5 (1.3-1.7)	1.3 (1.1-1.5)
Run 2	0.0	0.8 (0.6-1.0)	1.0 (0.8-1.2)	0.0	1.1 (0.9-1.3)	1.3 (1.1-1.5)
Run 3	0.0	0.4 (0.2-0.6)	0.1 (0.0-0.2)	0.5 (0.3-0.7)	1.2 (1.1-1.3)	1.9 (1.8-2.0)

* Denotes range of 95% confidence interval

Table 5. Chlorophyll content index (CCI) of two cultivars of greenhouse Bibb lettuce under three different lighting treatments in three experimental runs from January through April of 2014 in Lodi, OH, USA

Run	Flandria			Teodore		
	Ambient	MH	LED	Ambient	MH	LED
Run 1 n=36	9.6 (9.0-10.2)*	11.6 (11.1-12.1)	10.7 (10.2-11.2)	16.8 (16.2-17.4)	21.5 (20.3-22.7)	27.8 (25.5-30.1)
Run 2 n=36	7.2 (6.9-7.5)	9.2 (8.6-9.8)	9.7 (9.1-10.3)	13.8 (13.1-14.5)	20.8 (19.1-22.5)	26.0 (23.9-28.1)
Run 3 n=24	8.1 (7.7-8.5)	9.1 (8.8-9.4)	8.1 (7.7-8.5)	20.3 (19.1-21.5)	27.9 (25.8-30.0)	24.6 (22.3-26.9)

* Denotes range of 95% confidence interval

lighting system purchase. Martineau *et al.* (2012) reported that similar yields were attainable using lower light intensity in LED lighting than was provided in HID lighting. Such work indicates that lower LED intensity could provide biomass benefits while potentially decreasing quality reductions. Further work should focus on the question of optimum light intensities for growth and quality of lettuce crops in conjunction with humidity management and ventilation in the greenhouse. Providing growers with information on the optimum instantaneous and cumulative light levels to achieve increased lettuce productivity while maintaining a high quality saleable product is important for growers in both small and large operations.

Indices of pigment content, as described by CCI, showed different patterns than tipburn ratings. In ‘Flandria’, both MH and LED supplemental lighting increased the CCI in runs one and two and all lighting treatments had similar CCI in run three. There were no differences between the two types of supplemental lighting in any of the runs. ‘Teodore’ lettuce showed increased CCI under supplemental lighting in all three runs. In runs one and two, LED lighting treatments produced higher CCI numbers than both ambient and MH lighting while the two supplemental lighting treatments showed similar CCI in run three.

These results indicate a potential to alter pigment content when using supplemental lighting. However, reduced impact of supplemental lighting on CCI in run three could also be due to increases in ambient light. In ‘Flandria’ during run three, supplemental lighting increased yield over ambient lighting, but there was no difference in CCI. This suggests that threshold values for impacts on crop yield and pigment concentration may differ. While further investigation would be required to optimize supplemental lighting impact on CCI, these results do suggest that under low light conditions, darker green leaves may be possible using MH and LED lighting systems. Martineau *et al.* (2012), however, reported increased biomass from both HPS and LED lighting, but no significant impacts on chlorophyll and beta carotene. Together these reports indicate that a clearer understanding of wavelengths provided as well as intensities and durations of supplemental lighting in greenhouse production are needed to better assist producers in reaching yield and visual quality or crop composition goals.

Impacts of lighting types and intensity on crop tissue composition have been one of the most intensely studied aspects of supplemental lighting in completely controlled environments. Application in greenhouse settings is ongoing, but less well understood than the impacts in growth chambers where seasonal conditions are not a factor (Samouliene *et al.*, 2012). Using lighting spectrums to alter plant secondary metabolite composition may be important to crop production and human health in the future, but current economic realities of greenhouse production do not consistently and clearly reward growers for plant composition. Impacts on yield and cost efficiency of installation and operation are likely the most important current considerations for growers investigating lighting technologies. This study illustrates that increases in biomass yield can be achieved using supplemental lighting under northern latitude North American winter to spring conditions. However, crop quality issues, such as increased tipburn, may also accompany increases in biomass accumulation under some conditions. Therefore, especially for growers unable to precisely manage DLI, continued investigation of optimal lighting application (intensity, timing and control of lighting units) is needed. The integration of supplemental lighting with environmental management may provide opportunities to achieve increased biomass production and control of plant composition while reducing tipburn and other quality issues in these controlled environments.

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