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LED Interlighting Improves Leaf Level Photosynthesis but not Yield or Quality of Hydroponic Greenhouse Tomatoes

Colorado State University
Specialty Crops Program
Horticulture Center Greenhouses

LED Interlighting Improves Leaf Level Photosynthesis but not Yield or Quality of Hydroponic Greenhouse Tomatoes

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Abstract. Recent technological advances have led to light-emitting diode (LED) light fixtures becoming more readily available. They are becoming established as a way to supplement light in controlled environment crop production and are typically installed above the canopy. Due to their unique characteristics, LED lighting infrastructure and fixtures can also be placed within the canopy (interlighting bars); a location that has typically been hard to reach with traditional high-pressure sodium (HPS) or ceramic discharge lamps (CDL) due to the amount of heat HPS and CDL's produced (Dzakovich et al., 2015). Currently, there is little research on the overall effects of interlighting on plant growth and productivity. Therefore, four studies were conducted to measure the impacts of interlighting on the growth of hydroponically grown greenhouse tomatoes in Colorado. The tomato plants were grown to maturity in Experiments 1-3 to analyze the effects of the interlighting on vegetative biomass, fruit quality, and fruit quantity. LED interlighting was evaluated for a 16-h photoperiod under both naturally increasing and naturally decreasing daylengths. Experiment 4 (Distance Experiment) was conducted to evaluate if increasing or decreasing the distance of the tomato plants to the lights influenced young tomato plant growth. Tomato plants were grown in perlite and trained to a single leader on an overhead support system. Flowers were hand pollinated twice a week to ensure fruit set. Data collected included dry lower leaf biomass, dry upper leaf biomass, dry above ground vegetative biomass, marketable individual ripe fruit weight, marketable total ripe fruit weight, individual green fruit weight, total green fruit weight, soluble solids content, pH, and leaf gas exchange to assess tomato vegetative and reproductive growth and physiological parameters. In addition, the photosynthetic photon flux density (*PPFD*; 400-700 nm) of the interlighting bar was measured to create an energy distribution map. Lastly, a distance experiment was conducted to measure the effects of the proximity of the interlighting bars on early tomato vegetative growth. Across Experiment 1-3 we observed that interlighting significantly increased the photosynthetic rate in individual lighted leaves, however, overall vegetative growth and fruit yield did not increase. Although individual

leaves responded to the additional light resource located in the canopy, it did not significantly increase overall yield or quality of greenhouse-grown tomato fruits.

Introduction

Greenhouse tomato production accounts for over $400 million in sales in the United States annually and occupies over 390 hectares of controlled environment space (U.S. Census of Agriculture, 2012). Tomatoes are the second most economically important vegetable crop in terms of sales in the United States, and the greenhouse vegetable industry is expanding (Pena, 2005). Greenhouse-grown vegetables are continuing to gain popularity as the population grows and the demand for year-round fresh local produce increases. In countries with shorter growing seasons (i.e., higher latitude in the Northern hemisphere), tomatoes are grown almost entirely in greenhouses (Brazaitytė et al., 2009). In an effort to build the most efficient system, and therefore allow growers to receive the highest capital for their labor, new greenhouse technologies, such as light-emitting diodes (LED) has emerged.

With the development of LED lighting, greenhouse production has become more energy efficient and therefore more cost effective (Urrestarazu et al., 2016). In addition, LED lights produce significantly less heat and have a longer lifespan than traditional high-pressure sodium (HPS) and ceramic discharge lamps (CDL) (Dzakovich et al., 2015). Although results have shown varying outcomes, it is possible that the cooler, more energy-efficient LED lights could replace HPS and CDL in the future (Bergstrand et al., 2016; Urrestarazu et al., 2016). In addition, LED lights are the first supplemental lights that can be manufactured to emit specific wavelengths of radiation, allowing growers to optimize the lighting environment within the greenhouse and, for the first time, place the lights within the canopy of the crop (Dzakovich et al., 2015; Nelson and Bugbee, 2014). Previous research has evaluated the effects of different overhead supplemental lighting spectrum combinations in an effort to optimize greenhouse-grown vegetable (tomato and pepper) and flower (geranium, petunia, and snapdragon) production (Deram et al., 2014; Poel and Runkle, 2017). For example, one study evaluated the effects of five different supplemental lighting red:blue light ratios on tomato growth and fruit production, but found that none of the LED combinations had a significant effect on early tomato yield (Brazaitytė et al., 2009). Tomatoes are a C_3 plant and have an average light compensation point between 20 and 40 $\mu mol \cdot m^{-2} \cdot s^{-1}$ *PPFD* (Tartachnyk and Blanke, 2007). However, with traditional overhead supplemental lighting, bottom leaves of the plants become shaded by new growth causing lower leaves to drop below the light compensation point and senesce (Guo and Gan, 2005). By placing the supplemental lighting system within the canopy, lower leaves that would have been shaded by newer leaves can now be illuminated. This, in turn, can add to the overall photosynthetic rate of individual lighted leaves and, hypothetically, to the overall yield and quality of the crop.

There are few published studies that describe the full life cycle of a tomato crop, including vegetative biomass and fruit yield and quality, under LED interlighting. For example, researchers have studied the effect of interlighting on hydroponically-grown tomatoes and found little effect on the overall yield. However, tomato fruit quality and total plant biomass were not collected in that experiment (Gomez and Mitchell, 2016). In another related study, researchers compared high pressure sodium (HPS) top-lighting and LED vertical towers effects on tomato quality (chromaticity, Brix, titratable acidity, electrical conductivity, pH, and a sensory panel) and found that Brix was significantly increased in the LED treatment, but only in one of the three experiments (Dzakovich et al., 2015). However, that study did not measure overall fruit yield or vegetative biomass. Although many manufacturers provide a light map for their products, no unbiased published studies exist that describe the PAR pattern generated by LED interlighting. In addition, no studies have evaluated the effect of distance from the interlighting bars on young plant growth.

Therefore, the object of this study was to determine if interlighting influences the growth, quality, and productivity of hydroponic greenhouse tomatoes. We aim to add to the published literature on the effects of supplemental LED interlighting on tomato vegetative growth, fruit yield, and quality. We also generate an interlighting PAR distribution “map” to help and evaluate the impact of distance to the interlights on young tomato plants. Our goal is to fill in these gaps in the literature and, through this work, broaden the knowledge of the effects of interlighting on vegetative growth, tomato leaf gas exchange, and fruit yield and quality in a greenhouse environment.

Materials and Methods

Site Description, Greenhouse and Hydroponic System Description, Experimental Design, and Cultural Practices. The research experiments were conducted at the Colorado State University (CSU) Horticulture Center in a twin-wall polycarbonate greenhouse located in Fort Collins, Colorado. The greenhouse was equipped with LED top lights (GreenPower LED® toplighting system, Philips Lighting, Netherlands, Kingdom of the Netherlands) with a red:blue light ratio of 9:1 providing a *PPFD* of 85 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Interlighting bars (GreenPower LED® interlighting system; Philips Lighting) with a red:blue light ratio of 13:3 were suspended horizontally from the ceiling and consisted of two bars spaced 32 and 93cm (Figure 1).

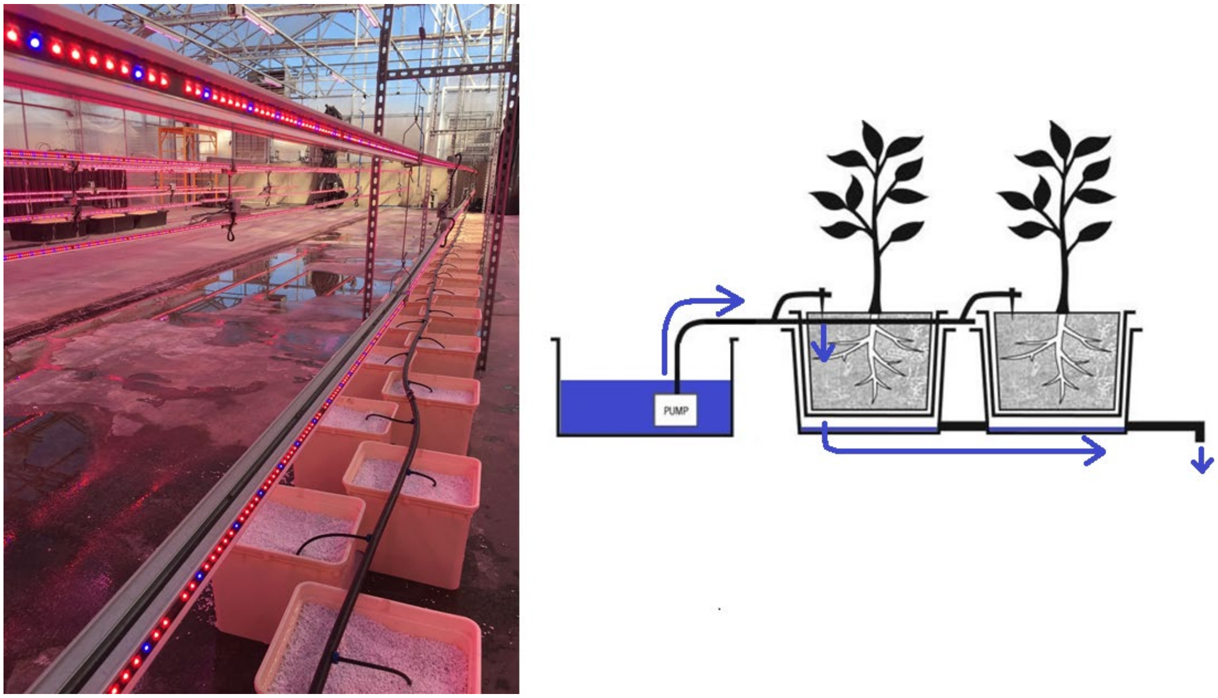


Figure 1. Interlighting system with two sets of light bars (13:3 red:blue diodes per 23cm) and perlite-filled Bato buckets prepared for hydroponic production of greenhouse tomatoes. Example of a drain-to-waste hydroponic system. Blue arrows indicate the flow of water and nutrients into and out of the system.

Tomato seeds were sown in potting mix (Sunshine® Mix #4, SunGro, Massachusetts, United States) and grown at the CSU Horticulture Center for four weeks prior to being transplanted singly into the middle of a Bato bucket (experimental unit) approximately 23cm away from the interlighting bars (Figure 1). Bato buckets were filled with medium grade perlite and connected to a drain-to-waste hydroponic system (Figure 1). Plants were grown with a 16-h photoperiod (light:dark) with top lights until plants were as tall as the top interlighting bar (approximately 84cm). Once plants reached the top of the interlighting bar; the interlights were turned on for the entirety of the 16-h photoperiod and the top-lights were turned off for both treatments for the duration of the experiment.

Tomatoes were pruned to a single leader and trained up to an overhead support system and lowered and leaned as needed. Bato buckets were flushed with fresh water once a week to remove excess accumulated salts from the media. Flowers were removed until the treatments began (i.e., tomatoes reached the top interlighting bar). Tomatoes were hand pollinated with a pollination wand (Garden Pollinator Express, VegiBee, Missouri, United States) twice a week until two weeks before the termination of each experiment. Tomatoes were harvested for approximately three weeks.

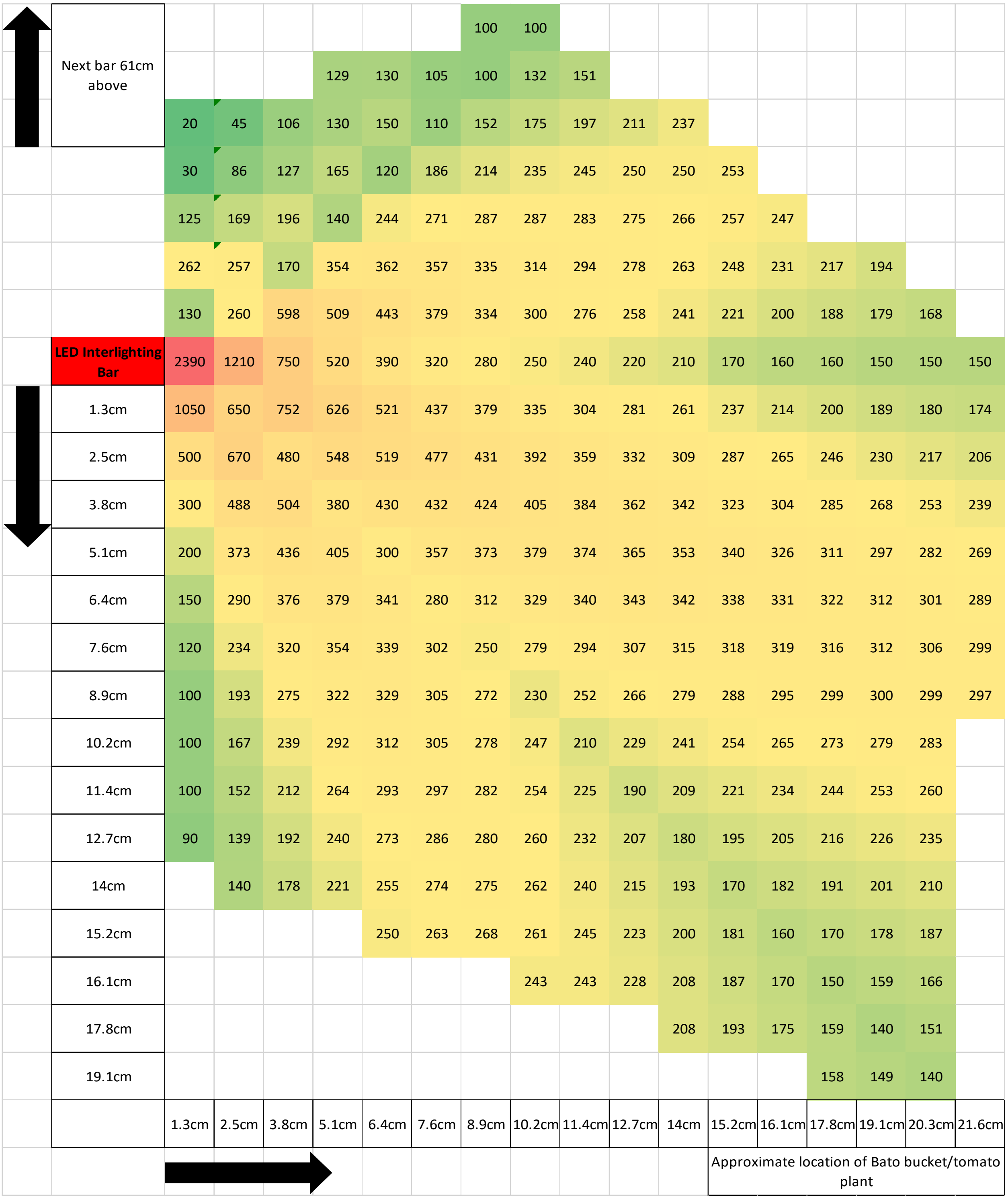
The temperature in the greenhouse was set to heat at 18.3°C and cool at 22.8°C during both the day and night. Relative humidity was not directly controlled in this experiment. Experiments 1 and 3 were conducted under naturally increasing day lengths (December to June) and Experiment 2 was conducted under naturally decreasing day lengths (June to November). Experiment 1 had an average DLI in the greenhouse of 12.1, Experiment 2 had an average DLI of 17.4, and Experiment 3 had an average DLI of 11.8. Tomato cultivars Jet Star and Crimson Sprinter were grown for the first experiment, and only Jet Star was grown for the second and third experiments. Crimson Sprinter was not used for the second and third experiment due its low marketable yield during the first experiment; most of the fruit developed significant blossom end rot.

Nutrients (FloraSeries®, General Hydroponics, California, United States) were added to a 1000L water bulk tank once a week and plants were fertigated with all macro and micronutrients according to the manufacturer’s drain-to-waste recommendations. Tomato leaves affected by powdery mildew were sprayed with a potassium bicarbonate fungicide (GreenCure Organic Gardening Fungicide, GreenCure®, New York, United States) according to the manufacturer’s recommendations. If the fungicide treatment was ineffective, lower leaf material was removed to increase air flow and reduce inoculum.

Four tomato growth experiments were conducted from January 2017 to June 2018. Experimental units (single Bato buckets) were arranged in a randomized complete block design (RCBD) with three replications of two treatments: natural light (unlighted) only and supplemental LED interlighting (lighted). Experiment 1 was conducted from January 2017 to May 2017 under naturally increasing daily light integral (DLI). Experiment 2 was conducted from June 2017 to November 2017 under naturally decreasing DLI. Experiment 3 was conducted from December 2017 to May 2018 under naturally increasing DLI and a Distance Experiment was conducted from December 2017 to March 2018 under naturally increasing DLI. The Distance Experiment was designed to determine if the placement of the tomato plants impacted fresh and dry biomass during early vegetative growth.

The first three experiments were set up in a RCBD and each treatment was replicated three times (with the exception of Experiment 1, which only had two replications of the unlighted treatment) and each block contained ten experimental units. Experiment 1 had five plants of each cultivar represented in each block. The Distance Experiment contained one experimental unit of each of the three treatments in a block and eight replications.

Before beginning the four experiments, the *PPFD* of the LED lights was measured and recorded using a full-spectrum quantum meter (MQ-500, Apogee Instruments, Utah, United States). Measurements were made at a 180°, 135°, 90°, 45°, and 0° angle from the interlighting bars every 1.3cm away until the PAR measurement read the same value for three consecutive measurements (3.9cm). From these measurements, averages were calculated to create a PAR distribution “map” (Figure 2).



Next bar 61cm above							100	100									
				129	130	105	100	132	151								
	20	45	106	130	150	110	152	175	197	211	237						
	30	86	127	165	120	186	214	235	245	250	250	253					
	125	169	196	140	244	271	287	287	283	275	266	257	247				
	262	257	170	354	362	357	335	314	294	278	263	248	231	217	194		
	130	260	598	509	443	379	334	300	276	258	241	221	200	188	179	168	
LED Interlighting Bar	2390	1210	750	520	390	320	280	250	240	220	210	170	160	160	150	150	150
1.3cm	1050	650	752	626	521	437	379	335	304	281	261	237	214	200	189	180	174
2.5cm	500	670	480	548	519	477	431	392	359	332	309	287	265	246	230	217	206
3.8cm	300	488	504	380	430	432	424	405	384	362	342	323	304	285	268	253	239
5.1cm	200	373	436	405	300	357	373	379	374	365	353	340	326	311	297	282	269
6.4cm	150	290	376	379	341	280	312	329	340	343	342	338	331	322	312	301	289
7.6cm	120	234	320	354	339	302	250	279	294	307	315	318	319	316	312	306	299
8.9cm	100	193	275	322	329	305	272	230	252	266	279	288	295	299	300	299	297
10.2cm	100	167	239	292	312	305	278	247	210	229	241	254	265	273	279	283	
11.4cm	100	152	212	264	293	297	282	254	225	190	209	221	234	244	253	260	
12.7cm	90	139	192	240	273	286	280	260	232	207	180	195	205	216	226	235	
14cm		140	178	221	255	274	275	262	240	215	193	170	182	191	201	210	
15.2cm					250	263	268	261	245	223	200	181	160	170	178	187	
16.1cm								243	243	228	208	187	170	150	159	166	
17.8cm											208	193	175	159	140	151	
19.1cm														158	149	140	
	1.3cm	2.5cm	3.8cm	5.1cm	6.4cm	7.6cm	8.9cm	10.2cm	11.4cm	12.7cm	14cm	15.2cm	16.1cm	17.8cm	19.1cm	20.3cm	21.6cm

Approximate location of Bato bucket/tomato plant

Figure 2. A light map of the amount of photosynthetically active radiation (PAR) produced by LED interlights. Values are in µmol photons/m^2/sec.

Tomato Fruit Yield and Quality Measurements. Upon maturity, tomatoes were harvested twice a week for a period of four weeks before the termination of each experiment (Figure 3).

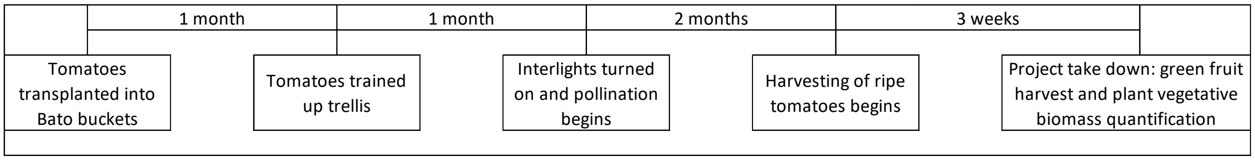


Figure 3. Approximate experimental timeline from transplant to take down for greenhouse grown hydroponic tomatoes. Experiment 1 and 3 were grown from January to June. Experiment 2 was grown from June to November.

Ripe fruits were harvested, numbered, sorted as marketable or unmarketable, and weighed individually. At the final harvest, all the green fruit above five grams were also harvested, counted, and weighed together for an average immature fruit yield. In addition to fruit weight, soluble solids content (Brix), and pH were measured to evaluate fruit quality. Three random plants from each block and treatment were selected, and two representative tomatoes from that plant were frozen to -10°C for one week and then allowed to thaw in sealed plastic bags. The thawed tomatoes were then thoroughly crushed by hand in the bag to homogenize. Soluble solids content was measured by straining the homogenized juice though a cheesecloth and placing a sample on a digital, temperature-adjusted refractometer (AR200 Refractometer, Reichert Technologies, New York, United States). pH was measured by placing a pH probe (MC110 pH Meter, Milwaukee, North Carolina, United States) into the bag of homogenized juice and recording the values.

Vegetative Growth and Physiological Parameters. After the LED interlights were turned on, gas exchange measurements were taken using an infrared gas analyzer (LI-6400KT, LI-COR, Nebraska, United States) once during each experiment. Measurements were taken in the morning (between 8:00-11:00am) on randomly assigned plants within each block and treatment combination. Two individual leaves that were near the top interlighting bar were selected on each plant and averaged. Leaves were selected based on height (i.e., the top interlighting bar) and location to the interlighting bar to ensure that the leaves measured were close to the same age. In addition, at the final fruit harvest, the total above ground vegetative biomass was collected. Lower leaves that were in direct contact with the LED lights were collected and bagged separately (i.e., lower leaf biomass) from the rest of the vegetative biomass (i.e., upper leaf biomass). Bags of plant material were then dried in a 40°C oven for two weeks prior to weighing.

For the Distance Experiment, the three treatments were based on the distance from the interlighting bar. Tomato plants were placed within a Bato bucket on either the edge closest to the interlighting bar (~7.5cm away from the interlighting, “near”), in the middle of the bucket (~15cm away from the interlighting, “middle”), or on the edge furthest from the interlighting bar (~23cm away from the interlighting, “far”). The interlights were turned on for the entire duration of the experiment. Plants were pruned to a single leader and trained up a string to an overhead support as in Experiments 1-3. Pruned fresh biomass was weighed within a half hour after harvest before drying; dry weights were also recorded. Flower clusters were removed and discarded to encourage vegetative growth. Once the tomato plants reached the top bar, plants were destructively harvested. Fresh weights were recorded for each plant before being dried and weighed again.

Statistical Analysis. The data gathered was analyzed using R statistical software (R Studio®, Massachusetts, United States). R packages “plyr”, “lsmeans”, “multcompView”, “dunn.test”, and “car” were used for the analysis. A Two-Sample t-test was performed after basic assumptions were met (i.e., normal distribution of residuals, independent simple random sampling, appropriate sample size, and blocking). If data was not normally distributed, the data was log transformed to satisfy the Shapiro-Wilks test. If data transformation did not produce a normal distribution, either Wilcoxon or Kruskal-Wallis Rank Sum Test was performed. In Experiment 1, the main effects of treatment and cultivar were analyzed as well as their interaction. Since there was only one cultivar evaluated in Experiments 2, 3, and the Distance Experiment, only the main effects of treatments and blocks were tested. Blocks were treated as a random effect while treatment, and cultivar were fixed effects in the model. The p-value was set at 0.05.

In Experiments 1, 2, and 3 the response variables measured and analyzed were dry lower leaf biomass, dry upper leaf biomass, dry total vegetative biomass, marketable individual ripe fruit weight, marketable total ripe fruit weight, marketable and unmarketable individual ripe fruit yield, marketable and unmarketable total ripe fruit weight, individual green fruit weight, total green fruit weight, soluble solids content, pH, and leaf gas exchange. In the Distance Experiment, both fresh and dry measurements were taken for the vegetative sucker weight and total plant biomass weight.

Results

Photosynthetically Active Radiation Map. Using the values recorded with the quantum sensor at various distances and angles, a PAR distribution map of the interlighting bars (Figure 2) was created. The map was colored by conditionally formatting these values from “greatest” (red) to “least” (green) PAR. Since tomatoes typically have a compensation point of 20 to 40 $\mu mol \cdot m^{-2} \cdot s^{-1}$ *PPFD* (Tartachnyk and Blanke, 2007) and a light saturation range of 1600-2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Bolaños and Hsiao et al., 1991; Yu et al., 2015) all red and yellow shaded values were coded as being within the useful range for photosynthesis. Tomato plants were placed in the Bato buckets approximately 15cm from the interlighting bar and the side of the plant that was facing the LEDs had access to a lighted area of approximately 230 cm^2 per bar. The interlighting bars were placed 61cm apart from each other vertically, which resulted in very little overlap in lighting. This created a lighted area of approximately 460 cm^2 total.

Experiment 1. Gas exchange measurements of supplemental lighted ‘Crimson Sprinter’ leaves were significantly higher than unlighted leaves. *PPFD* had an average reading of 160 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for lighted plants and 58 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for unlighted plants, which resulted in an almost three times greater photosynthetic rate on illuminated leaves. However, neither cultivar showed statistical differences in plant vegetative growth including lower leaf biomass, upper leaf biomass, or total shoot biomass. Neither cultivar showed statistical differences in fruit yield or quality (i.e., marketable individual ripe fruit weight, marketable total ripe fruit weight, marketable and unmarketable individual ripe fruit yield, marketable and unmarketable total ripe fruit weight, individual green fruit weight, total green fruit weight, soluble solids content, and pH (Table 1)).

Table 1. Summary of the effects of intercanopy lighting on tomato fruit quality and yield, biomass, and gas exchange in Experiment 1, conducted during naturally increasing day lengths (Januaruy to May). Values with differing letters within a column are statistically significant at α=0.05. NS stands for non-significant.

Experiment 1 ('Jet Star' and 'Crimson Sprinter')

	Brix	pH	Lower Leaf Biomass (g)	Upper Leaf Biomass (g)	Total Shoot Biomass (g)	Marketable Individual Fruit Weight (g)
Lighted - Jet Star	4.5 ± 0.1 b	ns	ns	176 ± 16 b	243 ± 19 bc	189 ± 10 a
Unlighted - Jet Star	4.3 b	ns	ns	172 ± 23 b	224 ± 27 c	171 ± 15 ab
Lighted - Crimson Sprinter	6.2 ± 0.3 a	ns	ns	259 ± 17 a	312 ± 21 a	139 ± 14 b
Unlighted - Crimson Sprinter	5.5 ± 0.3 a	ns	ns	248 ± 21 a	304 ± 25 ab	153 ± 13 b

	Marketable Total Fruit Weight (g)	Market and Unmarket Individual Fruit Weight (g)	Market and Unmarket Total Fruit Weight (g)	Green Individual Fruit Weight (g)	Green Total Fruit Weight (g)	Gas Exchange (µmol CO_2/m^2.sec)
Lighted - Jet Star	1370 ± 1125 a	131 ± 4 a	4608 ± 312 a	105 ± 4 a	2429 ± 180 a	N/A
Unlighted - Jet Star	1675 ± 1305 a	129 ± 6 a	3345 ± 441 a	106 ± 4 ab	2472 ± 267 a	N/A
Lighted - Crimson Sprinter	480 ± 153 b	105 ± 5 b	3005 ±334 b	91 ± 7 b	1749 ± 162 b	8.1 ± 0.6 a
Unlighted - Crimson Sprinter	497 ± 153 b	114 ± 5 b	3566 ± 395 b	93 ± 9 ab	1844 ± 230 b	2.7 ± 0.5 b

Experiment 2. Unlike Experiment 1, unlighted plants had a mean soluble solids content (4.55° Brix) that was significantly higher than lighted plants (3.96° Brix). In addition, unlighted plants had significantly higher lower leaf (83.8g) and total shoot biomass (i.e., 206.7g) than lighted plants (i.e., 56.3g and 162.0g, respectively). Similar to Experiment 1, lighted leaves showed significantly higher gas exchange measurements than leaves on unlighted plants (i.e., 9.9 and 0.3 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively). The PAR values for the lighted and unlighted plants averaged 262.3 and 31.1 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively. There were no significant treatment impacts on dry upper leaf biomass, marketable individual ripe fruit weight, marketable total ripe fruit weight, marketable and unmarketable individual ripe fruit yield, marketable and unmarketable total ripe fruit weight, individual green fruit weight, total green fruit weight, and pH (Table 2).

Table 2. Summary of the effects of intercanopy lighting on tomato fruit quality and yield, biomass, and gas exchange in Experiment 2, conducted during naturally decreasing day lengths (June to November). Values with differing letters within a column are statistically significant at α=0.05. NS stands for non-significant.

Experiment 2 (Only 'Jet Star')

	Brix	pH	Lower Leaf Biomass (g)	Upper Leaf Biomass (g)	Total Shoot Biomass (g)	Marketable Individual Weight (g)
Lighted	4.0 ± 0.1 b	ns	56.3 ± 6.5 b	ns	162 ± 11 b	ns
Unlighted	4.6 ± 0.1 a	ns	83.8 ± 5.7 a	ns	207 ± 16 a	ns

	Marketable Total Weight (g)	Market and Unmarket Individual Weight (g)	Market and Unmarket Total Weight (g)	Green Fruit Individual Weight (g)	Green Fruit Total Weight (g)	Gas Exchange (µmol $CO_2/m^2.sec$)
Lighted	ns	ns	ns	ns	ns	12.8 ± 3.0 a
Unlighted	ns	ns	ns	ns	ns	-0.1 ± 0.4 b

Experiment 3. Similar to the previous two experiments, lighted leaves showed significantly higher net photosynthetic rate than unlighted leaves (i.e., 3.2 and 7.4 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively). PAR was over 3.5 times greater in lighted leaves compared to unlighted leaves (i.e., 213.7 and 69.8 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively) which resulted in over a 3.5 times greater photosynthetic rate on illuminated leaves. However, there were no significant differences for any of the other parameters measured (i.e., dry lower leaf biomass, dry upper leaf biomass, dry total vegetative biomass, marketable individual ripe fruit weight, marketable total ripe fruit weight, marketable and unmarketable individual ripe fruit yield, marketable and unmarketable total ripe fruit weight, individual green fruit weight, total green fruit weight, soluble solids content, and pH (Table 3).

Table 3. Summary of the effects of intercanopy lighting on tomato fruit quality and yield, biomass, and gas exchange in Experiment 3, conducted during naturally increasing day lengths (Januaruy to May). Values with differing letters within a column are statistically significant at α=0.05. NS stands for non-significant.

Experiment 3 (Only 'Jet Star')

	Brix	pH	Lower Leaf Biomass (g)	Upper Leaf Biomass (g)	Total Shoot Biomass (g)	Marketable Individual Weight (g)
Lighted	ns	ns	ns	ns	ns	ns
Unlighted	ns	ns	ns	ns	ns	ns

	Marketable Total Weight (g)	Market and Unmarket Individual Weight (g)	Market and Unmarket Total Weight (g)	Green Fruit Individual Weight (g)	Green Fruit Total Weight (g)	Gas Exchange (µmol $CO_2/m^2.sec$)
Lighted	ns	ns	ns	ns	ns	7.5 ± 0.3 a
Unlighted	ns	ns	ns	ns	ns	3.2 ± 0.7 b

Distance Experiment. Plants placed in the middle of the Bato buckets (middle treatment) showed significantly higher total dry biomass compared to both near and far plants (Figure 4). The contrast of the middle to near had a p-value of 0.0271 and the contrast of the middle to far had a p-value of 0.0196. However, fresh total weight did not differ (data not shown). In addition, fresh and dry sucker weight did not show a statistical difference between any of the treatments.

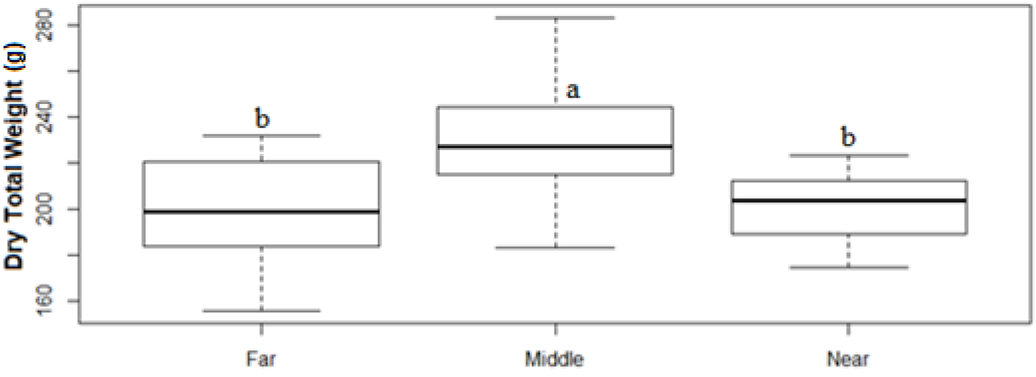


Figure 4. The effects of distance from interlighting bars on 'Jet Star' tomato dry vegetative biomass (grams) in young plants. 'Near' represents plants ~7.5cm away from the light source, 'Middle' represents plants ~15cm away from the light source, and 'Far' represents plants ~23cm away from the light source.

Discussion

The interlighting bars used in this experiment had little effect on the overall growth and productivity of greenhouse grown, hydroponic tomatoes. In the two naturally decreasing day length experiments (Experiments 1 and 3), there were no significant differences between the lighted and unlighted treatments for any of the growth parameters measured. In the naturally increasing day length experiment (Experiment 2), unlighted plants produced significantly higher lower leaf biomass, total shoot biomass, and Brix. However, in Experiment 2 the plants on the northern most block, which was one of the lighted treatments, were also impacted by powdery mildew. Therefore, the differences observed in lower leaf and total shoot biomass were likely due to powdery mildew and its management impacts (i.e., leaf removal, spraying), rather than a treatment effect. The powdery mildew may have also been the cause for significantly higher Brix in unlighted plants compared to the lighted plants since lighted plants experienced higher stress and increased trimming of lower leaves.

In all three experiments, gas exchange, which was measured using a transparent chamber, was significantly higher in individual lighted leaves nearest to the LED bars, but this did not correspond to a difference in the overall growth, yield, or quality of the crop. Several factors could explain why this was the case. First, the ambient lighting in the greenhouse, which illuminated the whole side of the plant not facing the bar, had a *PPFD* reading between 800-1400 $\mu mol \cdot m^{-2} \cdot s^{-1}$ which, while not reaching the saturation point for tomato plants, was significantly higher than the 200-400 $\mu mol \cdot m^{-2} \cdot s^{-1}$ produced by the LED interlights. Since the plants were grown in a greenhouse environment, natural solar radiation during the day provides sufficient light to the tomato plants (Dzakovich et al., 2015). In Experiment 1, 2, and 3 the plants received an average Daily Light Integral (DLI) of 29, 34, and 27 $mol \cdot m^{-2} \cdot s^{-1}$, respectively. Greenhouse tomato plants are considered a high light requirement crop and typically require a DLI between 20-30 $mol \cdot m^{-2} \cdot s^{-1}$. Therefore, the DLI requirement was met on solar radiation alone, without the addition of interlighting (Morgan 2013). In addition, the increased photosynthesis of a small number of individually lighted leaves may have been too small to create an overall increase in plant growth. As seen in the PAR distribution map, the supplemental radiation produced by the LEDs decreases quickly as the distance increases from the source which may have resulted in only the leaves closest to the interlighting receiving benefit. A vertical configuration of the LEDs could possibly provide better results if more of the canopy could be illuminated. However, the cost and effectiveness of vertical lighting towers is still being evaluated at this time.

In the Distance Experiment, the plants in the middle of the Bato buckets produced more dry total vegetative biomass than either the near or far plants. These results could indicate that there is an optimal placement of the tomato plants from the interlighting bars. In this manuscript, we report the full life cycle of tomatoes grown with interlights. We measured a comprehensive set of parameters which adds to the existing literature. As reported in the existing literature (Dzakovich et al., 2015; Gomez and Mitchell, 2016), there were few significant increases in any of those parameters due to supplemental lights placed in the crop canopy.

Conclusion

In this series of four experiments (i.e., Experiment 1-3 and the Distance Experiment), we sought to determine the effects of interlighting on greenhouse grown hydroponic tomatoes. Our results demonstrated that although individual leaves closest to interlighting bars do increase their photosynthetic rate (i.e., within 15cm of the light source), the overall plant vegetative growth, fruit production, and quality was not significantly increased by the supplemental interlighting. This is likely due to the interlights PAR measurement dropping off quickly as seen in the PAR light map and in the Distance Experiment, as well as from effects being "washed out" by natural solar radiation. The only significant differences seen in Experiment 2 (e.g., a decrease in lower leaf biomass of lighted plants) were likely due to complications with powdery mildew, rather than an effect seen from the treatment. In conclusion, the LED interlighting system utilized in this project did not increase tomato productivity as expected.

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