OPEN ACCESS Int. J. Agr. Ext. 10 (02) 2022. 479-490 DOI: 10.33687/ijae.010.03.4237

Check for updates

Available Online at EScience Press
International Journal of Agricultural Extension
ISSN: 2311-6110 (Online), 2311-8547 (Print)
https://esciencepress.net/journals/IJAE

EVALUATION BETWEEN LIGHTING TECHNOLOGIES ON GROWING HYDROPONIC LETTUCE

Miguel Torres Jr, Stanley T. Omaye
Agriculture, Nutrition Department and Environmental Sciences and Health Graduate Program, University of Nevada, Reno, USA.

ARTICLE INFO

Article History
Received: May 13, 2022
Revised: September 5, 2022
Accepted: November 13, 2022

Keywords
Greenhouse
Circulating hydroponics
Nutrient flow technique
High-pressure sodium
Light-emitting diodes
Nutrient solutions
Technology

ABSTRACT

The use of lighting technologies combined with hydroponics has gained increased interest worldwide as a viable and integral horticultural solution to regions with limitations from geography or environmental conditions while offering scalability for rural cities, urban areas, and metropolitans alike. Unrelenting modern uncertainty with climate change, declining water and land supply; urbanization, and not to mention a population soon to exceed well over 8 billion in the coming decades will require innovative interdisciplinary solutions to secure sustainable food systems. In this study, we used a surrogate hydroponic garden to examine the difference in biomass yield from ambient sunlight (control) against supplemental High-Pressure Sodium (HPS) and Light Emitting Diodes (LEDs) lighting. Additionally, we determined the difference in irradiance, illuminance, and luminous intensity between the control and supplemental lighting treatments along with luminous efficacy between the latter. Both experimental groups exhibited higher total biomass of leaves and shoots than the control with measurement of wet and dry weight in grams. The LED group was found to have a significantly higher weight almost twice that of the HPS group. HPS and LEDs had significantly more luminous intensity, illuminance, and irradiance than the control but LEDs significantly outperformed HPS for all parameters including luminous efficacy.

Corresponding Author: Stanley T. Omaye
Email: Omaye@unr.edu

INTRODUCTION

Our changing world continues to provide a plethora of challenges to agricultural systems and future food security. It is estimated that up to 25% of the world's food production may become lost due to environmental breakdowns by 2050 unless action is taken (Nellemann and MacDevette, 2009; IPCC, 2021). It is projected that to meet global food demands, food system productivity will need to be increased by at least 50% and be year-round (Yamori, 2013). Greenhouse agriculture has the potential to increase food security (Gumisiriza *et al.*, 2022) and meet the yield goals of tomorrow despite less favorable environments (Paulitz and Bélanger, 2001). Hydroponic (soilless) crop production enables better control of cultivated crops and food safety through environmental control, nutrient, pest, and disease management. Moreover, continuous circulation systems like that of the Nutrient Flow Technique (NFT) have less of an environmental impact due to the minimum fertilizer input, waste, and decrease cost without sacrificing production output (Ferguson *et al.*, 2014). The addition of supplemental lighting offers hydroponic cultivation the possibility to accomplish year-round growing as these systems can be adapted to any condition arid, urban, or low light. This imparts the advantage of growing food closer to the consumer (Bellows *et al.*, 2003). Building in these infrastructural solutions behooves our civilization to reduce the vulnerability of our supply chain from biological (e.g., pandemic), natural disasters, industrial, terroristic, or climatic events alike (Kleindorfer and Saad, 2009; Chopra and Sodhi, 2004).

LEDs are unique as energy light sources composed of solid-state diodes which have a 50,000-hour plus lifespan and utilize small amounts of energy. They have minimal environmental impact needing no special disposal compared to previous light sources, and they effectively convert electrical energy losing little to the environment as heat (Massa *et al.*, 2008; Watanabe, 2011; Goto, 2012; Gonzalez, 2012). The lower heat load produced by LEDs allows them to be placed in closer proximity to crops (Ouzounis *et al.*, 2015). Not to mention that LEDs have been shown to accelerate (Chin, 2012) and increase plant growth in lettuce (Stutte *et al.*, 2009).

Lactuca sativa varieties were selected for this study for their quick turnover of a complete crop from start to finish in 28 days which made them ideal to replicate for a total of 4 trials during a season with a shorter photoperiod (December to March). Although there is a growing body of research evaluating supplemental HPS and LED lighting on hydroponic lettuce (Martineau *et al.*, 2012; Hernandez *et al.*, 2020), it has been limited in exploring whether these effects could be impacted by closer proximity to the canopy. In fact, the current body of knowledge shows indirect supplemental lighting at 6 feet or more above the canopy did not have a significant impact on lettuce biomass in HPS and LED compared to ambient light (Martineau *et al.*, 2012). However, Zhang *et al.* (2020) found that closer indirect light to the canopy just over 3 feet did result in equivalent HPS and LED lettuce biomass significantly more than ambient light. These mixed findings from previous studies present a unique opportunity to further explore and build on our knowledge of the potential benefit(s) of direct (1-foot) proximity of supplemental light to the canopy.

The first objective of the study was to determine the effects of different light sources on the wet and dry biomass of grown lettuce plants. Objective two was to determine the difference between light sources for irradiance, illuminance, luminous intensity, and the difference in luminous efficacy between the supplement light treatments. The last objective was to see if there was an interaction between lighting treatment and month grown on resulting biomass.

METHODOLOGY

Hydroponic plants were grown under three lighting treatments: ambient sunlight, HPS, and LEDs; and maintained at the University of Nevada, Reno (UNR) Agricultural Experimental Station Greenhouse Complex. The Complex offered automatic cooling and heating systems as a state-of-the-art facility. Supplemental lighting was utilized to extend the photoperiod of plants during a naturally shorter photoperiod to 16 hours of daily light.

A custom-designed Mobile Hydroponics Station (MHS) provided by Titaness Light, LLC was used to house the lighting fixture for the study as illustrated by the schematic in Figure 1. This equipment came readily furnished with a shelf for the hydroponic garden, a 6” exhaust fan for cooling, a power strip, and an adjustable dual-frame that held the lighting fixtures separated by a divider to allow for individual adjustment for growing treatments between devices. For the HPS treatment, one 600-Watt Hortilux Lamp was used in a dimmable A3V reflector with an attached ballast; while the LED treatment light was comprised of a mix of blue, red, far red, and white three-Watt heads for an equivocal output. The supplemental lighting fixtures were kept 12 inches above the plant canopy with each respective adjustable frame.

The greenhouse utilized a fan and pad system to maintain the temperature at 65° F during the day (5:30 AM to 6:30 PM) and 55° F at night (6:31 PM to 5:29 AM) with relative humidity averaging 32%. Two varieties of lettuce seeds Black Seeded Lettuce (*Lactuca sativa*) and Red Romaine Lettuce (*Lactuca sativa var. cimarron*) were purchased from Greenhouse Garden Center (Carson City, NV). Both plant varieties were grown from seed in small propagation trays using 1” cubes of rock wool (Cultilene Rockwool) to germinate seeds and kept moist with water at a pH between 6.0 and 6.4 for the first two to three weeks. Seeds were sown directly into 1” cubes of rock wool. Once roots were established and observed at the bottom of the rock wool cubes; 18 seedlings from each variety were transplanted into the hydroponic system in 3” net pots with hydroton clay pebbles. Their placements were randomized equally among the three light treatment groups into three rows of four for each group.

The experimental design employed the use of a 27-gallon (NFT) system which included six channels; three housed the supplemental treatment plants and three channels housed the control plants. These six channels were connected via a manifold to a single reservoir in which solution pH and nutrients could be adjusted. The reservoir allowed for constant recirculation and mixing of the growing solution which allowed for homogenization of the solution to be continuously applied via drip lines in the channels. These channels were attached to the manifold from the reservoir. The aqueous growing solution in the reservoir was continuously aerated using an all-purpose hydroponics 4" aeration disk.

The pH of the system was buffered to between 6.0 to 6.4, if necessary, three times a week using General Hydroponics pH Up and pH Down Solutions. A commercial nutrient solution series General Hydroponics Flora (Sebastopol, CA) was used to maintain an average concentration of average dissolved salts (mg/L) in a solution of 400 mg/L or 400 parts per million (PPM) adjusted three times a week as necessary. A low volume ratio of 1:1:1 of nutrients was added throughout each trial to titrate up to the 400 PPM range. Although this was considered low in the instructions by the manufacturer, Ferguson et al. (2014) findings indicate that lower nutrient solution concentrations do not affect plant yields in continuous flow systems.

The experiment consisted of four replicate trials of 28 days in December, January, February, and March. At the end of each trial, plants were individually harvested, weighed the wet weight of leaves and shoots; and placed in labeled brown paper bags. The samples were then placed in an oven and dried at 60° C for 72 hours and weighed again after drying. Following the collection of plant mass data, wet and dry weights were compared for each treatment to contrast the effect different light exposures had on the growth of lettuce plants' biomass.

Throughout each trial, Photosynthetically Active Radiation (PAR [W/m^2]) measurements were taken with a PMA 2100 Photometer, with an attached PMA 2131 quantum light detector, right over the canopy of each plant to record the total irradiance to each plant. These energy output readings (400 nm to 700 nm) from the lighting fixtures were then used to calculate the proceeding three calculations: illuminance, luminous intensity, and luminous efficacy for each device. These measurements indicate the perceived light brightness over the canopy, the light source's capacity to provide illumination, and the ability of the light source to convert electrical energy into visible light. When calculations were completed, irradiance, illuminance, and luminous intensity were compared between all lighting treatments while luminous efficacy was compared between the supplement lighting treatments.

Pest and System Management

Weekly hand inspections and physical removal were used with aphids and spider mites displacing them off plants. When it was ineffective a diluted mixture of five milliliters of Dawn® soap in one liter of water was used, applied to plants for 5 minutes, and rinsed afterward. The fungus gnats were managed with yellow sticky whitefly traps (Seagbright Laboratories, Emeryville, CA) around the setup. When spider mites persisted, PyGanic® insecticide (MGK, Minneapolis, MN) was applied bi-monthly to the greenhouse. The NFT Hydroponic System was screened three times a week for clogging in drip irrigation to all plants installed in each independent channel. The sump pump and aeration disk were checked for functionality three times weekly as well.

Statistical Analysis

The data collected were analyzed using descriptive, parametric, and nonparametric inferential statistics with Sigmaplot Version 14.5. Parametric tests could not be used widely in analyses in the current study where normality using the Shapiro-Wilk test or equal variance using the Brown-Forsythe test confirmed non-normality and unequal variance respectively at $p < 0.05$. A Kruskal-Wallis one-way analysis of variance (ANOVA) on ranks was performed to determine the differences among light treatments in wet biomass, dry biomass, irradiance, illuminance, and luminous intensity. The differences between treatments were isolated and tested using Dunn's post hoc method for multiple comparisons on ranks when significance was observed with Bonferroni adjustment ($p < 0.0167$).

A Mann-Whitney rank-sum test was used to determine differences in luminous efficacy between the HPS and LED light fixtures. Analysis on ranks for one-way ANOVA and sum test were used to account for the instances of confirmed non-normality and unequal variance (P <

0.05). A two-way ANOVA was performed to determine the interaction of lighting treatment and time on grown biomass. A Holm-Sidak post hoc method was used when significance was observed ($p < 0.05$) to perform all pairwise multiple comparisons with no adjustment due to its robustness to control family-wise (Type 1) error rate. Results are expressed as mean ranks (medians) and mean ± standard deviation (S.D.) on the analyses on ranks, while two-way ANOVA is expressed as mean and ± S.D.

RESULTS

Lettuce biomass

The median lettuce wet and dry biomass weights for all the light treatments are outlined in Table 1 and Table 2. LED lettuce had the highest yield for wet and dry biomass followed by HPS and then control with the least. A Kruskal-Wallis One-way ANOVA on Ranks showed that there was a statistically significant difference in wet biomass between the different light treatments, $H(2) = 36.84$, $P < 0.001$, with a mean rank wet biomass of 32.46 g for Control, 59.80 g for HPS, and 80.50 g for LED lighting treatments (Table 1). Pairwise comparisons using Dunn's test with Bonferroni correction indicated that LED lettuces were observed to be significantly different from Control ($p < 0.001$) but not HPS ($p = 0.025$, $p > 0.0167$); in addition, HPS lettuces were observed to be significantly different from Control ($p = 0.002$) which is shown in Table 3.

A Kruskal-Wallis One-way ANOVA on Ranks showed that there was a statistically significant difference in dry biomass between the different light treatments, $H(2) = 92.66$, $P < 0.001$, with a mean rank for dry biomass of 2.08 g for Control, 3.85 g for HPS, and 6.55 g for LED lighting treatments (Table 2). Pairwise comparison using Dunn's test with Bonferroni correction indicated that LEDs were observed to be significantly different from Control ($p < 0.001$) and HPS ($p < 0.001$); in addition, HPS treatment was observed to be significantly different from Control ($p < 0.001$) which is shown in Table 3.

Lighting Measurements

The median irradiance (watts per area [W/m^2]) over the canopy of each light treatment group is outlined in Table 4 along with illuminance and luminous intensity. A Kruskal-Wallis One-way ANOVA on Ranks showed that there was a statistically significant difference in irradiance between the different light treatments, $H(2) = 18.14$, $P < 0.001$, with a mean rank irradiance of 115 W/m^2 for Control, 145 W/m^2 for HPS, and 180 W/m^2 for LED lighting treatments. Pairwise comparison using Dunn's test with Bonferroni correction indicated that LEDs were observed to be significantly different from Control ($p < 0.001$) but not HPS ($p = 0.816$, $p > 0.0167$); in addition, HPS treatment was observed to be significantly different from Control ($p = 0.008$) which is shown in Table 5.

A Kruskal-Wallis One-way ANOVA on Ranks analyses supported that there were similar statistically significant differences in illuminance and luminous intensity between the different light treatments, $H(2) = 18.14$, $P < 0.001$. The mean ranks of illuminance were 78,497 lumens per area (lm/m^2) for Control, 99,035 lm/m^2 for HPS, and 122,940 lm/m^2 for LED lighting treatments; while luminous intensity mean ranks were 6,245 lm/sr for Control, 7,879 lm/sr for HPS, and 9,780 lm/sr for LED lighting treatments. Furthermore, pairwise comparisons using Dunn's test with Bonferroni correction mirrored the same patterns for illuminance and luminous intensity as irradiance with LEDs observing a significant difference from the Control ($p < 0.001$) but not HPS ($p = 0.816$) and HPS treatment as significantly different from Control ($p = 0.008$) shown in Table 5.

Finally, LEDs were observed to be better at converting energy readily into visible light for use with a higher luminous efficacy (lm/W) than HPS as shown in Table 6. A Mann-Whitney test indicated that luminous efficacy was greater for LEDs (213 lm/W) than HPS (150 lm/W), $U = 14$, $p = 0.019$ (Table 6).

Interaction between Time and Treatment on Wet Lettuce Biomass

Lettuce plants reached their highest wet biomass in January (Trial 2) and March (Trial 4) and lowest in December (Trial 1) and February (Trial 3). In December, all three groups had their lowest mean wet weight of 7.4 g (Control), 25.3 g (HPS), and 37.5 g (LED). The highest average wet weight means were 55.4g for control and 78.1 g for HPS in March; and 127.4 g for LED in January. A two-way ANOVA was conducted to examine the effect of time and treatment on the wet biomass growth of lettuce. There was a statistically significant interaction between the time lettuce plants were grown and the treatment on produced wet lettuce biomass, $F(6, 132) = 2.761$, $p = 0.015$. The main effect of time was significant,

$F(3, 132) = 41.997$, $p < 0.001$; and the main effect of treatment was also significant, $F(2, 132) = 49.257$, $p < 0.001$. Among the comparisons for the factor of time, all pairwise comparisons between months reached significance ($p < 0.001$) except for the January versus March pair shown in Table 7. This corroborates the data discussed in general for the wet biomass data with January and March as the months with the higher biomass of lettuce plants produced. When comparing across the factor of treatment, all pairwise comparisons between lighting treatments reached a significance of $p < 0.001$. Table 7 further illustrates the comparisons of treatment within time and comparisons of time within treatments.

Interaction between Time and Treatment on Dry Lettuce Biomass

Examining the dry biomass, the lettuce plants followed a slightly different trend with the control and HPS at their lowest in December at 1.4g and 2.3g respectively, while the LED dry biomass was lowest in February at 5.3 g. In February, the control and HPS had their highest dry biomass 2.7g and 4.3g respectively; and the LED in March at 8 g. A two-way ANOVA was conducted to examine the effect of time and treatment on the dry biomass of lettuce. A significant interaction was not observed between the time and treatment on dry lettuce biomass, $F(6, 132) = 2.071$, $p = 0.061$. The main effect of time was significant, $F(3, 132) = 12.754$, $p < 0.001$; and the main effect of treatment was significant, $F(2, 132) = 155.192$, $p < 0.001$. However, in the comparisons for the factor of time, two-thirds of pairwise comparisons between months reached significance ($p < 0.001$) except for the pairs January versus March and February versus December. This reflects the data discussed in general for the dry biomass data with variability in the weight of plants among groups for these months. When comparing across the factor of treatment, all pairwise comparisons between lighting treatments reached a significance of $p < 0.001$. Table 8 further reviews the comparisons of treatment within time and comparisons of time within treatments.

DISCUSSION

More attention has been garnered by integral agriculture methods utilizing hydroponic methods and technology such as supplemental lighting. These intersectional approaches offer a plethora of advantages and applications with few limits on location and scalability. This study exhibited that hydroponic lettuce grown under supplemental lighting resulted in greater wet and dry biomass compared to ambient light alone. LED lettuce produced the highest wet and dry biomass followed by HPS lettuce and control lettuce with the least. Lettuces produced less wet biomass in the early season likely due to lower levels of total solar radiation which provides ambient light. In contrast, lettuces grew larger later in the season when total solar radiation was higher.

Fresh (wet) biomass is a good indicator for water content in leaves of lettuce; whereas, dry biomass is a good indicator for photosynthetic production (Lefsrud *et al.*, 2008). Dry biomass is more stable than wet biomass, and it provides an understanding of how light affects plant growth. This study demonstrated that LEDs had the most significant effect on the growth of *Lactuca sativa* varieties followed by HPS than control as they both reached significantly higher biomass than control. In comparison, findings from Hernandez *et al.* (2020) observed similar with control but lettuces from the HPS were significantly bigger than the LED. One main difference in this study was the LED treatment was comprised of a combination of blue, red, and white LED lights while Hernandez *et al.* (2020) utilized an LED combination of blue and red.

According to Goins *et al.* (2001), greater far-red light (700 to 725 nm) was demonstrated to be outside of the range photosynthetically suitable for lettuce growth; while red light (660 to 690 nm) even far red combined with white light had pronounced effect on lettuce growth (Stutte *et al.*, 2009). In addition, blue light (400 to 476 nm) which when combined with red light stimulates lettuce biomass accumulation (Johkan *et al.*, 2010; Yorio *et al.*, 2001). As the supplemental LED lighting was a combination, this provides an inference as to the distinction in results in biomass from this study and Hernandez *et al.* (2020). Similar effects have been demonstrated in studies on bananas (Nhut *et al.*, 2003), cotton (Lin *et al.*, 2013), and strawberries (Nhut *et al.*, 2003) illustrating the opportunity to build our knowledge of the full range of benefits and uses for supplemental lighting.

When comparing these study's results back to findings from Martineau *et al.* (2012) and Zhang *et al.* (2020), a pattern was illustrated that as the distance between the supplemental light and canopy decreases the biomass could increase with LEDs. Furthermore, these implications signal an opportunity to determine how and when to best apply supplemental lighting to maximize their beneficial influence on biomass production and beyond based on application-dependent goals. This can extend our applications into small and general spaces with minimal lighting or environmental limitations by employing more interdisciplinary production methods. Not to mention that LEDs are exclusive in their ability to target specific wavelengths of light, and finer control over light intensity and periodicity (Davis and Burns, 2016).

For irradiance, LEDs had the highest output at 214.78 W/m^2, the second HPS (164.22 W/m^2), and then Control (114.92 W/m^2) with the least output. This supports previously reported data showing that increasing light irradiance increased plant mass (McAvoy and Janes, 1984). Light available to plants can be characterized in various ways, but the most relevant is the amount of irradiance available over the canopy (Pearcy, 2000). Similarly, illuminance and luminous intensity continued the same pattern as their calculations were derived from irradiance units. LEDs presented the highest average median illuminance of 122,940 lm/m^2, HPS second at 99,035 lm/m^2, and lowest at 78,491 lm/m^2 for the control (Table 4). Luminous intensity (lm/steradian [sr]) also followed the pattern with LEDs (9,780 lm/sr) having the highest intensity, HPS (7,878 lm/sr) and ambient light (6,245 lm/sr) with the lowest. Likewise, LEDs exhibited higher luminous efficacy than HPS demonstrating their ability to convert energy more readily into visible light for utilization and outperform HPS and control treatments on biomass throughout the four trials. This significantly higher efficacy of LEDs over HPS affirmed previous findings from Wallace and Both (2016) that conventional LED fixtures have a 40% higher efficacy than HPS.

These comparisons affirm the need to conduct further investigations into specialized production protocols to examine potential differences made in the biomass of plants with variable light sources in proximity to the canopy. There is still a lot of work to explore to fully understand the range of use and added benefits we can have from the utilization of technology across fields. Still, surrogate investigations like this study exploring the augmentation of environmental lighting in horticulture allow us to have a glimpse at the multitude of benefits of their use.

CONCLUSIONS

Integrative horticulture techniques coupling hydroponics and supplemental LED lighting technology offer a wide range of versatility and scalability from do-it-yourself setups to commercial food production. LEDs could provide a unique resource to optimize food production systems by significantly increasing the yield at harvest while utilizing fewer resources (energy, water, land, habitat). They offer the opportunities to easily set up anywhere in the world, a resilient buffer against intensifying uncertainties from environmental burdens which can threaten crops and the flow of supply chains; and an ability to impact plant growth and development by selecting desirable wavelength(s) of light, intensity, and proximity to the canopy of plants.

REFERENCES

Bellows, A. C., K. Brown and J. Smit. 2003. Health benefits of urban agriculture. Community Food Security Coalition Venice, CA, USA.

Chin, L. 2012. Study of high power light emitting diode (LED) lighting system in accelerating the growth rate of Lactuca sativa for indoor cultivation. International Journal of the Physical Sciences, 7.

Chopra, S. and M. Sodhi. 2004. Supply-chain breakdown. MIT Sloan management review, 46: 53-61.

Davis, P. A. and C. Burns. 2016. Photobiology in protected horticulture. Food and Energy Security, 5: 223-38.

Ferguson, S. D., R. P. Saliga III and S. T. Omaye. 2014. Investigating the effects of hydroponic media on quality of greenhouse grown leafy greens. International Journal of Agricultural Extension, 2: 227-34.

Goins, G. D., L. M. Ruffe, N. A. Cranston, N. C. Yorio, R. M. Wheeler and J. C. Sager. 2001. Salad Crop Production Under Different Wavelengths of Red Light-emitting Diodes (LEDs). SAE International. Place Published.

Gonzalez, E. G. 2012. LEDs for General and Horticultural Lighting: Final Project, Aallto University, Aalto. Place Published.

Goto, E. 2012. Plant production in a closed plant factory with artificial lighting. Acta Horticulturae: 37-49.

Gumisiriza, M. S., J. M. L. Kabirizi, M. Mugerwa, P. A. Ndakidemi and E. R. Mbega. 2022. Can soilless farming feed urban East Africa? An assessment of the benefits and challenges of hydroponics in

Uganda and Tanzania. Environmental Challenges, 6: 100413.

Hernandez, E., M. B. Timmons and N. S. Mattson. 2020. Quality, Yield, and Biomass Efficacy of Several Hydroponic Lettuce (Lactuca sativa L.) Cultivars in Response to High Pressure Sodium Lights or Light Emitting Diodes for Greenhouse Supplemental Lighting. Horticulturae, 6: 7.

IPCC. 2021. Climate change 2021: the physical science basis [M]// Lee J Y, Marotzke J., Bala G., et al. Future global climate: scenario-42 based projections and near-term information. Cambridge: Cambridge University Press, 2021: 1-195. Place Published.

Johkan, M., K. Shoji, F. Goto, S.-n. Hashida and T. Yoshihara. 2010. Blue Light-emitting Diode Light Irradiation of Seedlings Improves Seedling Quality and Growth after Transplanting in Red Leaf Lettuce. HortScience, 45: 1809-14.

Kleindorfer, P. R. and G. H. Saad. 2009. Managing Disruption Risks in Supply Chains. Production and Operations Management, 14: 53-68.

Lefsrud, M., D. Kopsell, C. Sams, J. Wills and A. J. Both. 2008. Dry Matter Content and Stability of Carotenoids in Kale and Spinach During Drying. HortScience, 43: 1731-36.

Lin, K.-H., M.-Y. Huang, W.-D. Huang, M.-H. Hsu, Z.-W. Yang and C.-M. Yang. 2013. The effects of red, blue, and white light-emitting diodes on the growth, development, and edible quality of hydroponically grown lettuce (Lactuca sativa L. var. capitata). Scientia Horticulturae, 150: 86-91.

Martineau, V., M. Lefsrud, M. T. Naznin and D. A. Kopsell. 2012. Comparison of Light-emitting Diode and High-pressure Sodium Light Treatments for Hydroponics Growth of Boston Lettuce. HortScience, 47: 477-82.

Massa, G. D., H.-H. Kim, R. M. Wheeler and C. A. Mitchell. 2008. Plant Productivity in Response to LED Lighting. HortScience, 43: 1951-56.

McAvoy, R. J. and H. W. Janes. 1984. The use of high pressure sodium lights in greenhouse tomato crop production. Acta Horticulturae: 877-88.

Nellemann, C. and M. MacDevette. 2009. The environmental food crisis: the environment's role in averting future food crises: a UNEP rapid response assessment. UNEP/Earthprint. Place Published.

Nhut, D. T., T. Takamura, H. Watanabe and M. Tanaka. 2003. Efficiency of a novel culture system by using light-emitting diode (led) on in vitro and subsequent growth of micropropagated banana plantlets. Acta Horticulturae: 121-27.

Ouzounis, T., E. Rosenqvist and C.-O. Ottosen. 2015. Spectral effects of artificial light on plant physiology and secondary metabolism: a review. HortScience, 50: 1128-35.

Paulitz, T. C. and R. R. Bélanger. 2001. Biological control in greenhouse systems. Annual Review of Phytopathology, 39: 103-33.

Pearcy, R. W. 2000. Radiation and light measurements. Springer Netherlands. Place Published. pp.97-116.

Stutte, G. W., S. Edney and T. Skerritt. 2009. Photoregulation of Bioprotectant Content of Red Leaf Lettuce with Light-emitting Diodes. HortScience, 44: 79-82.

Wallace, C. and A. J. Both. 2016. Evaluating operating characteristics of light sources for horticultural applications. Acta Horticulturae: 435-44.

Watanabe, H. 2011. Light-controlled plant cultivation system in japan - development of a vegetable factory using leds as a light source for plants. Acta Horticulturae: 37-44.

Yamori, W. 2013. Improving Photosynthesis to Increase Food and Fuel Production by Biotechnological Strategies in Crops. Journal of Plant Biochemistry & Physiology, 01.

Yorio, N. C., G. D. Goins, H. R. Kagie, R. M. Wheeler and J. C. Sager. 2001. Improving Spinach, Radish, and Lettuce Growth under Red Light-emitting Diodes (LEDs) with Blue Light Supplementation. HortScience, 36: 380-83.

Zhang, L., Z. Xu, D. Xu, J. Ma, Y. Chen and Z. Fu. 2020. Growth monitoring of greenhouse lettuce based on a convolutional neural network. Horticulture research, 7.

Appendix

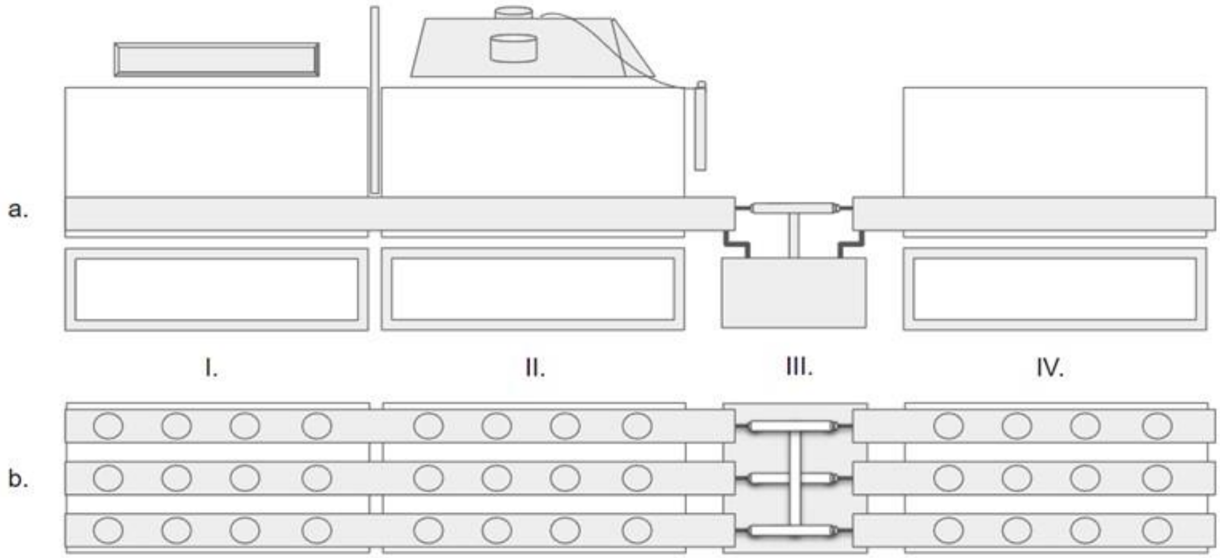

Figure 1. a.) Experimental setup from side view and b.) overhead view with treatments and water reservoir from left to right: LEDs (I), HPS (II), reservoir (III), and ambient sunlight (IV).

Table 1. Desriptive and two-way ANOVA on ranks results summary for comparison of median wet masses between Control, HPS, and LED lettuce biomass

	Total yield (n)	Median mass (g)	SD	P
Control Lettuce	48	32.46	22.580	<0.001
HPS Lettuce	48	59.8	34.72	
LED Lettuce	48	80.5	44.12	

[a] Significant at $p < 0.05$

Table 2. Desriptive and two-way ANOVA on ranks results summary for comparison of median dry masses between Control, HPS, and LED lettuce biomass

	Total yield (n)	Median mass (g)	SD	P
Control Lettuce	48	2.08	0.94	<0.001
HPS Lettuce	48	3.85	1.49	
LED Lettuce	48	6.55	1.99	

[a] Significant at $p < 0.05$

DOI: 10.33687/ijae.010.03.4237

Table 3. Dunn's Post Hoc Test results for all pairwise multiple comparisons of median wet & dry biomasses between Control, HPS, and LED lettuce.

	Wet		Dry	
	Difference of Ranks	P	Difference of Ranks	P
LED vs Control	51.54	<0.001	81.35	<0.001
LED vs HPS	22.52	0.025	49.30	<0.001
HPS vs Control	29.02	0.002	32.05	<0.001

[a] Significant at $p < 0.0167$ with Bonferroni adjustment

Table 4. Desriptive and two-way ANOVA on ranks results summary for comparisons of median irradiance over the canopy, illuminance, and luminous intensity between Control, HPS, and LED Lighting

	Irradiance (W/m^2)		Illuminance (lm/m^2)		Luminous Intensity (lm/sr)		Shared Statistic
	Median	SD	Median	SD	Median	SD	P
Control Lettuce	114.93	3.49	78,491.12	2,384.59	6,244.80	189.71	<0.001
HPS Lettuce	145.00	52.24	99,035.00	35,682.71	7,878.68	2,838.72	
LED Lettuce	180.00	83.72	122,940.00	57,181.40	9,780.43	4,549.04	

[a] Significant at $p < 0.05$

Table 5. Dunn's Post Hoc Test results for all pairwise multiple comparisons of median irradiance over the canopy, illuminance, and luminous intensity between Control, HPS, and LED lighting.

	Difference of Ranks	P
LED vs Control	15.39	<0.001
LED vs HPS	4.11	0.816
HPS vs Control	11.28	0.008

[a] Significant at $p < 0.0167$ with Bonferroni adjustment

Table 6. Overall comparison of median luminous efficacy between HPS and LED lighting

	Median	SD	P
HPS Light	150.05	54.06	0.019
LED Light	213.44	99.27	

[a] Significant at $p < 0.05$

Table 7. Holm-Sidak Post Hoc Test results summary for all pairwise multiple comparisons of means for wet biomass growth as a function of time and treatment between Control, HPS, and LED lettuce.

Comparison factor	Comparison	Difference of Means	t	P
Time	January vs December	58.893	9.980	<0.001
	March vs December	54.821	9.290	<0.001
	February vs December	31.549	5.346	<0.001
	January vs February	27.344	4.634	<0.001
	March vs February	23.272	3.944	<0.001
	January vs March	4.072	0.690	0.490
Treatment	LED vs Control	50.716	9.924	<0.001
	LED vs HPS	26.103	5.108	<0.001
	HPS vs Control	24.613	4.816	<0.001
Treatment within December	LED vs Control	30.112	2.946	0.011
	LED vs HPS	17.903	1.752	0.158
	HPS vs Control	12.209	1.195	0.234
Treatment within January	LED vs Control	82.649	8.086	<0.001
	LED vs HPS	52.612	5.147	<0.001
	HPS vs Control	30.037	2.939	0.004
Treatment within February	LED vs Control	44.291	4.333	<0.001
	LED vs HPS	27.855	2.725	0.015
	HPS vs Control	16.436	1.608	0.110
Treatment within March	LED vs Control	45.813	4.482	<0.001
	LED vs HPS	23.156	2.266	0.050
	HPS vs Control	22.657	2.217	0.028
Time within Control	March vs December	48.003	4.696	<0.001
	January vs December	37.336	3.653	0.002
	March vs February	24.497	2.397	0.070
	February vs December	23.506	2.300	0.068
	January vs February	13.830	1.353	0.325
	March vs January	10.667	1.044	0.299
Time within HPS	March vs December	52.757	5.162	<0.001
	January vs December	49.470	4.840	<0.001
	February vs December	33.457	3.273	0.005
	March vs February	19.299	1.888	0.173
	January vs February	16.013	1.567	0.225
	March vs January	3.287	0.322	0.748
Time within LED	January vs December	89.873	8.793	<0.001
	March vs December	63.703	6.233	<0.001
	January vs February	52.188	5.106	<0.001
	February vs December	37.684	3.687	<0.001
	January vs March	26.169	2.560	0.023
	March vs February	26.019	2.546	0.012

[a] Significant at $p < 0.05$

Table 8. Holm-Sidak Post Hoc Test results summary for all pairwise multiple comparisons of means for dry biomass growth as a function of time and treatment between Control, HPS, and LED lettuce.

Comparison factor	Comparison	Difference of Means	t	P
Time	March vs December	1.451	4.567	<0.001
	March vs February	1.440	4.533	<0.001
	January vs December	1.334	4.200	<0.001
	January vs February	1.323	4.165	<0.001
	March vs January	0.117	0.367	0.918
	February vs December	0.011	0.034	0.973
Treatment	LED vs Control	4.739	17.230	<0.001
	LED vs HPS	3.246	11.800	<0.001
	HPS vs Control	1.494	5.430	<0.001
Treatment within December	LED vs Control	5.261	9.563	<0.001
	LED vs HPS	4.213	7.659	<0.001
	HPS vs Control	1.047	1.904	0.059
Treatment within January	LED vs Control	4.924	8.951	<0.001
	LED vs HPS	3.273	5.950	<0.001
	HPS vs Control	1.651	3.001	0.003
Treatment within February	LED vs Control	3.453	6.277	<0.001
	LED vs HPS	1.841	3.346	0.002
	HPS vs Control	1.612	2.931	0.004
Treatment within March	LED vs Control	5.319	9.669	<0.001
	LED vs HPS	3.656	6.645	<0.001
	HPS vs Control	1.663	3.023	0.003
Time within Control	January vs December	1.245	2.263	0.142
	March vs December	1.226	2.228	0.130
	January vs February	0.820	1.491	0.449
	March vs February	0.801	1.456	0.381
	February vs December	0.425	0.773	0.688
	January vs March	0.019	0.035	0.972
Time within HPS	January vs December	1.848	3.360	0.006
	March vs December	1.842	3.348	0.005
	February vs December	0.990	1.800	0.265
	January vs February	0.858	1.560	0.321
	March vs February	0.852	1.548	0.233
	January vs March	0.007	0.012	0.990
Time within LED	March vs February	2.667	4.847	<0.001
	January vs February	2.291	4.164	<0.001
	December vs February	1.383	2.513	0.052
	March vs December	1.284	2.334	0.062
	January vs December	0.908	1.651	0.192
	March vs January	0.376	0.683	0.496

[a] Significant at $p < 0.05$