Comparing Multiple Forms of Light on Different Cultivars of Swiss Chard in an Ebb and Flow Bench Aquaponics System

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EXECUTIVE SUMMARY

Due to the relatively new technology of aquaponics, there is a need for research regarding system optimization, particularly optimization of lighting. Lighting systems studied included natural light with supplemental HID, LED GrowPan, and LED LightStrip. Two cultivars of Swiss chard were chosen because of the quick growing time for Swiss chard: highly studied 'Bright Lights' and one heirloom 'Lucullus'. Suitability in aquaponics systems and light optimization were measured by plant growth and PAR measurement. Plant growth was measured by harvested fresh weights, dry weights, and leaf area. This study was conducted in an Ebb and Flow Bench style aquaponics system. Both cultivars were exposed to the different three lighting treatments. Differences in plant productivity were measured and the data was analyzed by ANOVA. A cost analysis was also performed to determine the cost effectiveness of each lighting system using the average energy cost for Minnesota. Through the study conducted, it was determined that, when possible, it is best to use natural sunlight along with supplemental lighting. Although the HID supplemental lighting was more expensive to run, the supplemental lighting system was used so infrequently that this system was still more cost effective. Additionally, it was found that when scaled properly, LED light systems are more cost effective than HID or fluorescence for systems requiring significant supplemental lighting. 'Lucullus' was more suitable for aquaponic production. This cultivar had statistically higher leaf areas and fresh weights than those of 'Bright Lights'.

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INTRODUCTION

Issue Description

Aquaponic growing "is the cultivation of fish and plants together in a constructed, recirculating ecosystem utilizing natural bacterial cycles to convert fish waste to plant nutrients. This is an environmentally friendly, natural food growing method that harnesses the best attributes of aquaculture and hydroponics without the need to discard any water or filtrate or add chemical fertilizers" (Bernstein 2011).

Studies involving many aspects of aquaponic production have been carried out, including common factors influencing crop yields and productivity. Studies involving multiple light intensity levels and planting density are also available (MacMaster, et. al. 2014). Other production factors such as type of growing substrate, fish feeding frequency, and photoperiod have also been the subject of scientific inquiry (Nuevaespana, et al. 2015). A study involving the direct comparison of various lighting in aquaponic systems, for example, High Intensity Discharge (HID), Light Emitting Diode (LED), etc., have yet to be researched. However, some studies mainly focusing on variables such as nutrient levels and yield suggest a need for supplemental lighting and to recognize the additional cost to the production system (Diessner 2013). Aquaponics is a relatively new field of food production and if early research suggests supplemental light is necessary, there exists a need to optimize use of supplemental light added to the system. Therefore it is important to inquire what light source is the most effective when used to supplement an aquaponic system. It will also be beneficial for both large and small scale growers to attempt to quantify the energy inputs and costs associated with different types of light.

When selecting a crop to test in our aquaponic system it was important to choose a species tolerant to hydroponic growing conditions with a relatively fast rate of growth due to time constraints. It was necessary to identify a species with two distinctly different cultivars. Two different cultivars will allow for comparison of plant performance over the various light treatments and also give insight into optimal cultivars for aquaponic production. *Beta vulargis* (Swiss chard) was chosen because it fits all the crop selection criteria for this research. Two cultivars of the species were readily available, these include 'Bright Lights', one cultivar commonly used in scientific study. One such study that uses 'Bright Lights' in quantitative research of the Betalains present in differently colored Swiss chard (Kugler 2004). In general, *Beta vulgaris* is tolerant of many growing conditions including hydroponics and even brackish water (Kotzen 2010). The species has a quick germination time (7-10 days) as well as time to maturity (approximately 60 days) with harvest possible halfway to maturity. The other cultivar, 'Lucullus', is an heirloom Swiss chard which added another variable to the study in order to determine a more productive variety for aquaponic systems.

Series Goals

A comprehensive, informational library is compiled through student research as part of an ongoing research project at the University of Minnesota in HORT 4601: Aquaponics: Integrated Fish and Plant Food Systems. The series mission is to supply interested parties with valuable information regarding aquaponics to expand the field and help provide sustainable, safe, healthy, and reliable products. These products may be physical, educational, or value based.

Chapter Goals

This chapter will attempt to convey the effects and consequences of different light types used in an “Ebb and Flow” aquaponics system obtained through University of Minnesota Horticulture 4601 course study. This chapter will additionally focus on the differences seen between two different cultivars of Swiss chard. Readers should understand the different effects seen between lighting types and cultivar differences. With this knowledge, readers should be able to utilize the authors recommendations based on crop growth rates, crop yields, and system inputs.

Objective

The objective for our research will be to identify the most profitable light sources and Swiss chard cultivars, ‘Lucullus’ and Bright Lights’, for further use in aquaponic systems. The most profitable method will be determined by comparing the productivity of each cultivar in terms of leaf area and plant weight, the light source’s impact on production capabilities, and the cost of operation for each supplemental lighting source. This research will help producers, both commercial and hobbyists, decide which light source and cultivar to use within their own system to maximize profitability.

Research Questions Tested

The research questions that will be tested through this research are the effects of different light types on the productivity of ‘Lucullus’ and ‘Bright Lights’ cultivars of Swiss chard.
The second research question being tested will be the different light types’ cost of operation compared to plant growth.

METHODS

Site Description

The following Site Description contains the greenhouse conditions under which the 2015 University of Minnesota HORT 4601 (Aquaponics) Spring Semester class conducted research. The only exception(s) to this are Chapter(s) that indicate(s) otherwise in their Study Design. The location for aquaponics research was in the Minneapolis – Saint Paul Metropolitan area, State of Minnesota, U.S.A., specifically located at the St. Paul Campus of the University of Minnesota (44°59'17.8" N lat., -93°10'51.6" W long.). Plant seeds were sown in 288 plug trays with a pasteurized Berger BM2 Germination Mix (Berger Peat Moss, Saint-Modeste, Quebec, Canada). For seed germination, a mist system in a greenhouse was used from sowing to germination (21±0.8/21±0.7°C, day/night, 16 hrs (0600–2200 HR) lighting at a minimum setpoint of 150 μmol m^{-2} s^{-1}, a mist frequency of 10 min. intervals (mist nozzles, reverse osmosis water) during 0600-2200 HR with a 7 sec. duration (Anderson, et al., 2011). The environmental conditions in this greenhouse were 24.4±3.0/18.3±1.5°C day/night and 16 hrs (0600–2200 HR) lighting at a minimum of 150 μmol m^{-2} s^{-1}. Greenhouses used for aquaponics experimentation were located in the Plant Growth Facilities, House Nos. 369-C2 and 369-C4. Greenhouse No. 369-C2 had 23.6±0.8°C (daily integral) whereas No. 369-C4 was at 21.7±0.4°C. Temperature setpoints were 23.5°C and 21.5°C for 369-C2 and 369-C4, respectively, while the photoperiod was long days (0600–2200 HR) with supplemental lighting supplied by metal halide high intensity discharge (HID) lamps at a maxima of 1377 μmol m^{-2} s^{-1}; electrical generators served as the electrical power backup system. Both greenhouses were adjacent, A-frame even-span construction sharing one inner wall; the roof, shared inner wall and interior wall adjoining the service walkway were glazed with double-strength float glass whereas the exterior walls had chambered acrylic (Exolite®; Cyro Industries, Mt. Arlington, NJ) glazing. Heating was delivered via hot water in perimeter pipes with galvanized fins for enhanced heat exchange. All environmental settings were controlled via an Argus Control Systems Ltd. computer (Surrey, British Columbia, Canada).

Water quality was monitored daily (5/wk excluding weekends) and fish measurements were sampled weekly by students and recorded in an interactive Google Doc® file. The measurements and safety protocols are detailed in Appendix A.
The aquaponics system in greenhouse No. 369-C4 consisted of four aluminum tanks (identical specifications as for No. 369-C2) with two tanks used for a two galvanized steel framed, adjustable shelving rack system; there were two shelves/rack. The same measurements and safety protocols (Appendix A) used in greenhouse No. 369-C2 were used. Temperature measurements averaged 23.5±0.9°C and approximated the air temperature setpoint. Fish species grown in this house were *Perca flavescens* (yellow perch) and *Carassius auratus* (goldfish) at varying densities, depending on fish age.

Study Design

To properly study the variables selected --supplemental light and specific cultivar of swiss chard--our research group has formulated a replicated study. This portion of the paper will describe the experimental design for the reported research.

Ebb and Flow System Overview

The specific aquaponic Ebb and Flow Bench System design constructed by Jay Maher was recreated accurately below in Figure 1. Two of these systems were used throughout the study. The two replicates will be described described as shelf A and shelf B. The top shelf of the system being designated as 1, with the bottom shelf being designated as 2.

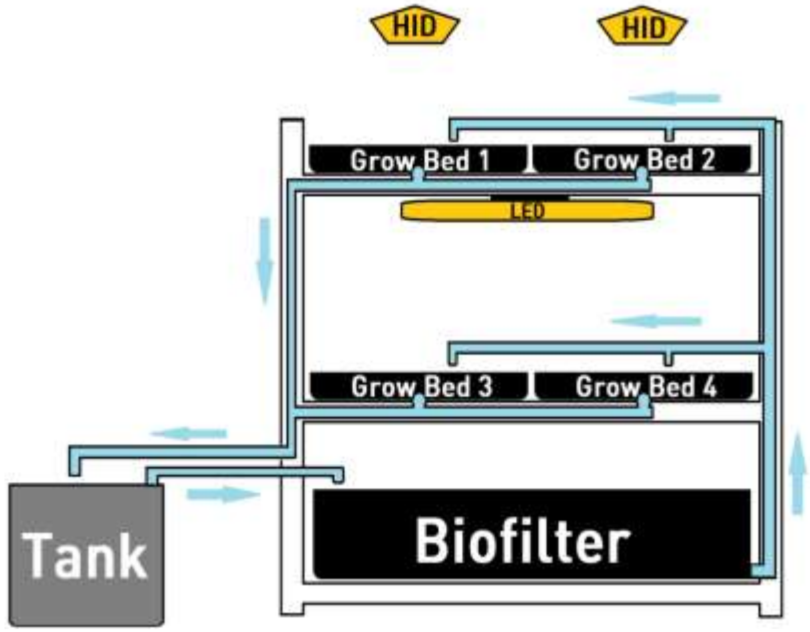


Figure 1: Diagram of the Ebb and Flow Aquaponic System set up in 369-C4 depicting the locations of supplemental light sources, grow beds, biofilter, and fish tank along with the direction of water flow represented by arrows.

This system's fish tank was held on the left side of the grow beds, biofilter was on the bottom shelf system, grow beds 1 and 2 were under HID lighting on the top shelf, and grow beds 3 and 4 were under LED lighting on the middle shelf. The shelf system was a galvanized steel framed, adjustable shelving rack system. In this study, two duplicates were used in the study design; they were referred to as shelf system A and shelf system B.

Fish Tank & Fish

The fish tank was an aluminum tank (193x77.5x75 cm, length x width x height; 6.5 cm thick walls) the water volume in each tank was ~550 L or 0.55 m^3. One system held *Carassius auratus* (goldfish), while another held *Perca flavescens* (yellow perch). Both species were stocked at varying densities, depending on fish age. Shelf system A's tank was stocked with goldfish while shelf system B's tank was stocked with yellow perch.

Biofilter

One plastic, rectangular tub (123x186x18 cm; Polytank Co., Litchfield, MN) served as a biofilter for each rack system, was filled with 3-4 cm diameter. lava rock (D-Rock Center, New Brighton, MN) and located on the concrete floor underneath the shelf system. To start the biofilter, ammonium carbonate (Hawkins Chemical Co., Roseville, MN) was added as needed to maintain ~1 mg/L ammonia while the nitrifying bacteria populations were established.

Water Circulation

Airlift pumps moved the water from the fish tank to the biofilter, where a float level control would allow the water depth to cycle between approximately 2 cm and 23 cm within the biofilter. At the high point, a Danner Supreme 700 GPH mag drive pump lifted the water from the biofilter to the plant beds on the two shelves above, from which point it would drain back to the fish tank via gravity. Flood and recede levels within the grow beds are 9 cm for shelf A and 4 cm in shelf B. Specific adjustments were made to the valves that control water flow and drainage back to the fish tank to allow for proper flood and recede levels. At the flood cycle, the water height in the growing trays was 5 cm. Approximate cycle time from low to high water levels was 1 hour.

Lighting

The top shelf of each rack system was exposed to natural and supplemental lighting (metal halide HID lights). For both shelf systems, the distance between the light fixture and the grow beds was 40 cm. For shelf system A, the lower shelf had a light emitting diode (LED) lighting supplied by Sunshine Systems GrowPan (450-470, 630 nm; 300 Watt; Sunshine Systems, LLC, Wheeling, IL). For shelf system B, the lower shelf had a light emitting diode (LED) lighting supplied by two Green Power LED (450-470, 660 nm; 32 Watt; 152x12 cm; 110v strips; Royal Philips N.V., Andover, MA).

For both shelf systems, the distance from the LED fixtures and the grow beds was 36 cm. All grow beds were subject to a While the photoperiod was long days (0600–2200 HR). For both the systems, the HID fixtures lighting the top shelves activated when natural sunlight fell below 200 µmol m^{-2} s^{-1}. For both the systems, the LED fixtures lighting the bottom shelves remained on for the full photoperiod.

Grow Beds & Tray Layout

The grow beds were composed of two plastic tubs per shelf (123x94x18 cm; Polytank Co., Litchfield, MN). Each grow bed was fitted with six 50.8x25.4 cm plug trays. Within each plug tray, a 4 x 8 (32 celled) 9 cm square-plug tray was used to grow the plants. In order to provide ample growing space for each plant, only every other plug was used. Figure 2 shows the experimental layout for each plug tray, the smaller squares represent the 9cm square plugs which were occupied by plants.

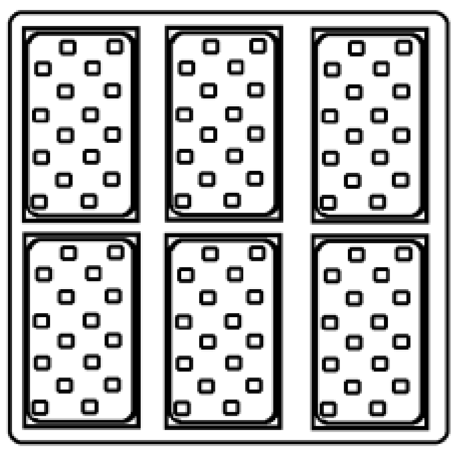


Figure 2 (right). Diagram showing the tray layout for the grow beds used in the Ebb and Flow aquaponics bench system in 369-C4. Small squares show the plugs with plants in the 9cm² plug trays.

Hypotheses Tested

1. In highly controlled greenhouse settings, HID and LED light types will have no measurable difference on operation cost and the production of Swiss chard.

2. The 'Bright Lights' Swiss chard cultivar will have the largest average fresh weight upon harvest of the two Swiss chard cultivars.
3. The Natural Lighting with HID supplemental light will result in the largest growth among the various supplemental lighting types.

RESEARCH TECHNIQUES

Growth Analysis

The cultivars planted for this experiment were sown in two plantings. The first planting included Swiss chard 'Bright Lights'. A total of 100 seeds were first sown on Julian day 49. The sown seeds were placed into the mist house for 3 weeks. A 90% germination percentage was observed for 'Bright Lights'. On day 62, 85 emerged seedlings were transplanted into alternating plugs in a 32 count 804, 9cm square plugs, plug tray (Figure 2). Rockwool was used as the substrate to hold the seedlings. On day 69, seedlings which did not survive the initial transplanting were eliminated. The trays were condensed so only surviving seedlings were in the aquaponics system.

The second planting included both Swiss chard cultivars 'Bright Lights' and 'Lucullus'. 100 seeds of each cultivar were sown on Julian day 62. The sown seeds were placed into the mist house for 1 week. A 92% germination percentage was observed for 'Bright Lights'. A 90% germination percentage was observed for 'Lucullus'. On day 69, 75 'Lucullus' and 65 'Bright Lights' seedlings were transplanted into alternating plugs in a 32 count 4x8, 9cm square plugs, according to Figure 2. Again, rockwool was used as the substrate to hold the seedlings. On day 83, plugs which contained seedlings which did not survive transplanting were eliminated. The surviving plants were condensed so only surviving seedlings were in the aquaponics system.

Twice a week, three days apart, the system was checked to determine flood and recede levels were as desired. At these times, any physiological changes -- color change, curling plant leaves, wilting, etc -- in the plants were additionally noted.

Through Julian days 100-122, mature leaves were harvested off individual plants on a weekly basis. Fresh and dry weights for each plant's weekly harvested leaves were measured to evaluate productivity.

On Julian day 122, all plants were harvested. At the end of the growth cycle, the total leaf area was measured as one determiner of productivity. To measure total leaf area of each plant, each flat subset first had the leaf area measured using a Leaf Area Meter. After leaf area was measured, fresh weight was measured in grams. After fresh weight was measured, plant biomass was placed into bags and dried to remove water. Next, the dry weight was weighed in grams and recorded as the biomass. Finally, average relative water content was calculated for each plant by subtracting dry weight from fresh weight.

Cost Analysis

This experiment tested 3 separate light systems. (1) Shelf 1A, Natural Light with 600 Watt HID supplemental lighting (2) Shelf 2A, 300 Watt LED GrowPan (3) Shelf 2B, Two 32 Watt Philips LED LightStrips.

To quantify the economic differences seen between systems, a PAR meter was used to find the distribution and intensity of the usable plant light for light system. For each system, under optimal (over 200 µmol m^{-2} s^{-1}) and cloudy (under 200 µmol m^{-2} s^{-1}) natural light conditions, the PAR meter was used to determine the average µmol m^{-2} s^{-1} which the plants were grown under. All of the following equations were derived from our group.

The following equation was used to calculate the total amount of usable plant sunlight between the 400-700nm light spectrum a plant received daily:

Equation 1:

$$\mu mol\ m^{-2}\ s^{-1}\ 1 \times 60\ sec1\ min \times 60\ min1\ hour \times 16\ hours1\ grow\ day1\ mol\ 1.0\ x\ 106\ \mu mol = Daily\ mol/m2$$

To quantify the cost to run each system, the actual energy draw from each light fixture was found. Each LED fixture only drew 65% of the rated wattage while each HID light consumed 600 watts. Next, we calculated the kWh per square meter for every growing day (16 hours) for each system. The following equation was used:

Equation 2:

$$Daily\ kWh\ Per\ m2 = 1kWh\ x\ 16\ Hours1\ Day\ /\ 2.31m2$$

Next, to receive a cost per day we used the result of the previous equation and multiplied by the average kWh price for the State of Minnesota; 0.10 / kWh (EIA 2015) The following equation was used:

Equation 3:

$$Cost\ per\ m2\ Per\ Day = kWh\ /\ m2Day\ x\ \$0.10kWh$$

Finally, to calculate the daily cost per plant we used the planting density of the equation and the calculated daily cost. The following equation was used:

Equation 4:

$$Cost\ Per\ Plant = Costm2 \div 124\ plants\ m2$$

A supplemental calculation was done to provide the cost per mol/day. The following equation was used:

Equation 5:

$$Cost\ Per\ Mol = Cost\ /\ m2\ Day \div mol/m2Day$$

Findings and Discussion

Economic Impacts of Lighting

In our experiment, the ranking of light fixture from least to most expensive is the following: HID supplemental, LED lightstrip (2), and finally the LED GrowPan. LED fixtures are much more efficient at providing plants with usable light (PAR, mol/day) per watt than conventional HID or fluorescent lighting, for that reason many LED fixtures cost significantly more to purchase when compared to conventional lighting.

System	Optimal Sunlight	Cloudy Sunlight	Optimal; Daily mol/m^2	Cloudy Daily mol/m^2
Shelf 1A	550 µmol m^{-2} s^{-1}	195 µmol m^{-2} s^{-1}	31.6 mol/m^2	11.23 mol/m^2
Shelf 2A	375 µmol m^{-2} s^{-1}	375 µmol m^{-2} s^{-1}	21.6 mol/m^2	21.6 mol/m^2
Shelf 2B	60 µmol m^{-2} s^{-1}	60 µmol m^{-2} s^{-1}	3.456 mol/m^2	3.456 mol/m^2

Table 1: PAR Measurements for light quanta for three systems (self 1A, 2A, 2B; Figure 1) for optimal sunlight for full sun and cloudy days and optimal daily light for both full sun and cloudy days as measured in Greenhouse 369-C4.

At optimal lighting, the light type which provided the most usable light would be shelf 1A. As previously noted, shelf 1A is under natural sunlight with HID supplemental light turning on after reaching a threshold of 200 µmol m^{-2} s^{-1}. Shelf 2A LED GrowPan was the second best performer under optimal light conditions. Shelf 2B LightStrips was last. Since shelves 2A and 2B are on the second lower shelf of the system, almost all of their light received is from the LED fixtures.

At cloudy lighting, measured when natural sunlight being under the 200 µmol m^{-2} s^{-1} threshold (level of light when supplemental light was activated by greenhouse management system). Under these conditions, Shelf 2A LED GrowPan provided the highest average µmol m^{-2} s^{-1}, with 1A HID supplemental second, and 2B LED LightStrips in third. It is important to recognize that both lower shelves 2A and 2B provide the same amount of usable light per day under all natural light conditions.

System	Optimal Sunlight	Cloudy Sunlight
Shelf 1A	0 kWh/m2	16.6 kWh/m2
Shelf 2A	2.59 kWh/m2	2.59 kWh/m2
Shelf 2B	0.41 kWh/m2	0.41 kWh/m2

Table 2: Energy used by various supplemental lighting systems (HID with sunlight, LED, and HID) in 369-C4 measured in kWh per m^2.

The following table below summarizes results from **Calculation 3 & 4**:

System	Optimum Sunlight Cost /Day (Per Plant)	Cloudy Sunlight Cost/Day (Per Plant)	Optimum Sunlight Daily Cost/Mol	Cloudy Sunlight Daily Cost/Mol
Shelf 1A HID+sun	$0.00/m2 ($0.00)	$1.60/m2 ($0.013)	$0.00	$0.15
Shelf 2A GrowPan	$0.259/m2 ($0.002)	$0.259/m2 ($0.002)	$0.01	$0.01
Shelf 2B LED lightstrip	$0.041/m2 ($0.0003)	$0.041/m2 ($0.0003)	$0.01	$0.01

Table 3: Calculated cost of operation for various supplemental lighting systems (HID with sunlight, LED GrowPan and LED lightstrip) calculated using Minnesota average energy cost for full sun and cloudy days. Calculations show energy cost calculated by plant and by mole.

Under optimal conditions, the cheapest light source was shelf 1A, the natural with HID supplemental; with $0.00 / m^2 daily cost. Conversely under cloudy conditions, shelf 1A was the most expensive system to run @ $1.60 / m^2. Shelf 2A cost $0.259 / m^2 per day. Shelf 2B cost $0.041 / m^2 per day.

Another important discussion point is to look further into shelf 2B, LED LightStrips. While it may appear that the LED light strips completely underperform when compared to the other light sources, we must look at the actual energy draw of the 2 LED Light Strips. These fixtures draw only 32 Watts each, or 64 Watts for the entire system. This is compared to 600 Watts for the HID light fixtures or 300 Watt for the LED GrowPan. To quantify the differences seen between the two LED fixtures, we can use the cost per mol of light provided in the table above. Both LED GrowPan and LED Light Strips had a cost of $0.01 / mol. While the HID (when activated) had a cost of $0.15 / mol. This suggests that the LED LightStrip could be scaled up to 300 watts and perform similarly to the LED GrowPan.

As many previous studies have already mentioned, the differences from light sources are easily quantified when considering initial investment cost, running cost, and total light output from the fixture. In this study, we found that the cost / m^2 and cost / mol /day of LED light fixtures was significantly lower than the conventional HID fixtures. While LED fixtures have a higher investment cost, it is clear from the results of this study that the LED fixtures provided a greater amount of usable light at a smaller cost compared to conventional lighting fixtures like HID.

Bright Lights 1	Final Harvest Leaf Area (cm²)	Leaf Area of Weekly Harvests (cm²)	Total Leaf Area (cm²)	Final Harvest Fresh Weight (g)	Fresh Weight of Weekly Harvest (g)	Total Fresh Weight (g)	Final Harvest Biomass (g)	Biomass of Weekly Harvest (g)	Total Biomass (g)	Leaf Area / Plant (cm²)	Total Fresh Weight / Plant (g)	Total Biomass/Plant (g)
Shelf 1A Sun&HID	1488	8505	9993	138.6	465.73	604.3	11.83	47.58	59.41	454.2	27.47	2.70
Shelf 2A GrowPan	1547	4820	6367	129.6	380.5	510.1	11.64	31.91	43.55	276.8	22.18	1.89
Shelf 2B LightStrip	1078	1890	2968	69.6	61.4	131	4.34	5.3	9.64	123.6	5.46	0.40

Table 4: Data for 'Bright Lights' Swiss Chard (First Replication) showing sums of leaf area, fresh weight, biomass for weekly harvest and final harvest.

Comparison of Light Type on Plant Growth

For various light types, the differences were best observed in the first replication of growing 'Bright Lights'. For each quantitative measurement, leaf area, fresh weight, and biomass per plant, HID lighting yielded the best results. This is disregarding cultivar and using the data collected over the longest period of time from the first transplanting of 'Bright Lights'. The lighting types were determined to be statistically different through ANOVA testing resulting in p-values of 0.024, 0.023, and 0.031 for leaf area, fresh weight and biomass per plant respectively. The chi-squared values were 7.8×10^{-8}, 0.936, and 0.99 also respectively. This suggests there is reason to question the statistical significance of difference in leaf area.

Additionally, it is important to define what the HID lighting treatment involves. As previously mentioned in cost analysis, this treatment is primarily natural sunlight only utilizing the HID lighting through the automated greenhouse management system when natural sunlight levels fall below 200 µmol m^{-2} s^{-1}. As calculated in the cost analysis it was found that in cloudy situations when the HID is actually turned on, total mol per day values are highest in the LED GrowPan treatment at 216 total mol per day. This study did not attempt to quantify the number of cloudy days in relation to their effects on indoor growing conditions. Future studies could attempt to focus on the outside environmental effects on the indoor greenhouse growing conditions.

Light source	Cv.	Final Harvest Leaf Area (cm^2)	Leaf Area of Weekly Harvests (cm^2)	Total Leaf Area (cm^2)	FInal Harvest Fresh Weight (g)	Fresh Weight of Weekly Harvest (g)	Total Fresh Weight (g)	Final Harvest Biomass (g)	Biomass of Weekly Harvest (g)	Total Biomass (g)	Leaf Area/ Plant (cm^2)	Fresh Weight / Plant (g)	Biomass/ Plant (g)
Sun&HID	BL	350	735	1085	24.2	25.8	50	1.87	1.57	3.44	217.0	10.00	0.69
	L	443	1470	1913	30.0	41.5	71.5	2.25	3.24	5.49	318.83	11.92	.92
LED GrowPan	BL	619	1155	1774	37.2	53.9	91.1	7.5	4.04	11.54	161.2	8.28	1.05
	L	442	315	757	30.8	23.3	54.1	2.8	2.06	4.86	151.40	10.82	.97
LED Light Strip	BL	247	0	247	12.8	0	12.8	0	1.12	1.12	16.47	0.85	0.07
	L	962	1000	1962	57.9	37.7	95.6	2.39	4.3	6.69	63.29	3.08	.22

Table 5: Leaf area, fresh weight, biomass data by Swiss Chard cultivar comparing 'Bright Light' (BL) and 'Lucullus' (L) showing sums of for weekly harvest and final harvest by light source for sunlight and HID, LED GrowPan, and LED lightstrip.

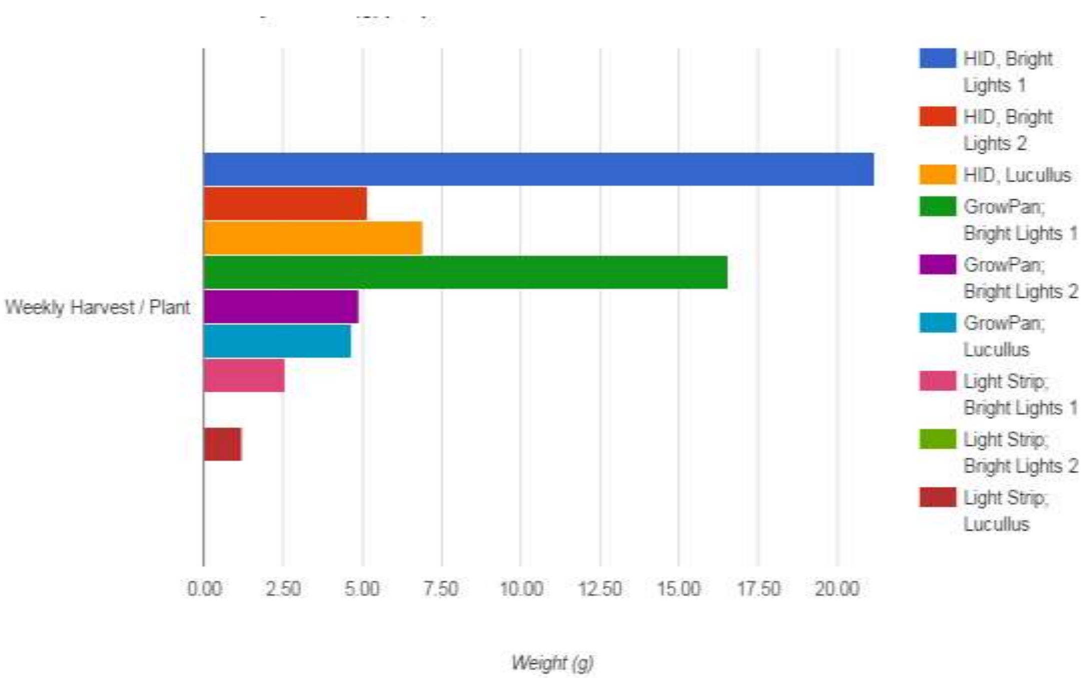
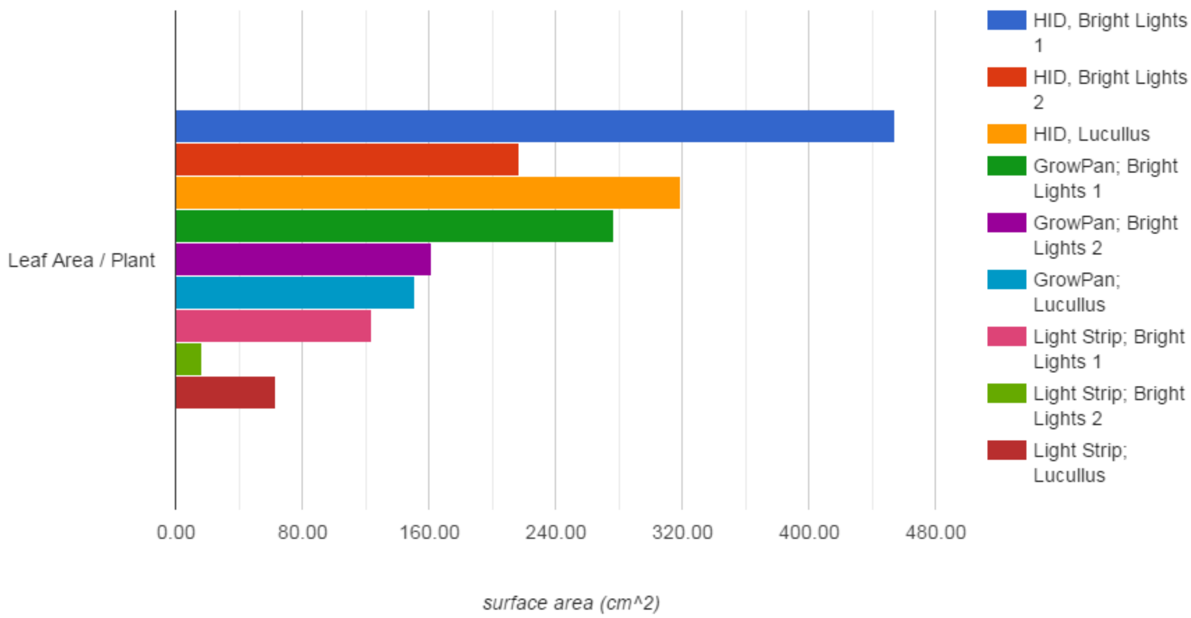


Figure 3: Bar graph showing the fresh weight per plant for both 'bright lights' and 'lucullus' Swiss Chard varieties under HID, GrowPan, and Lightstrip lighting sources in an Ebb and Flow Aquaponics bench system.



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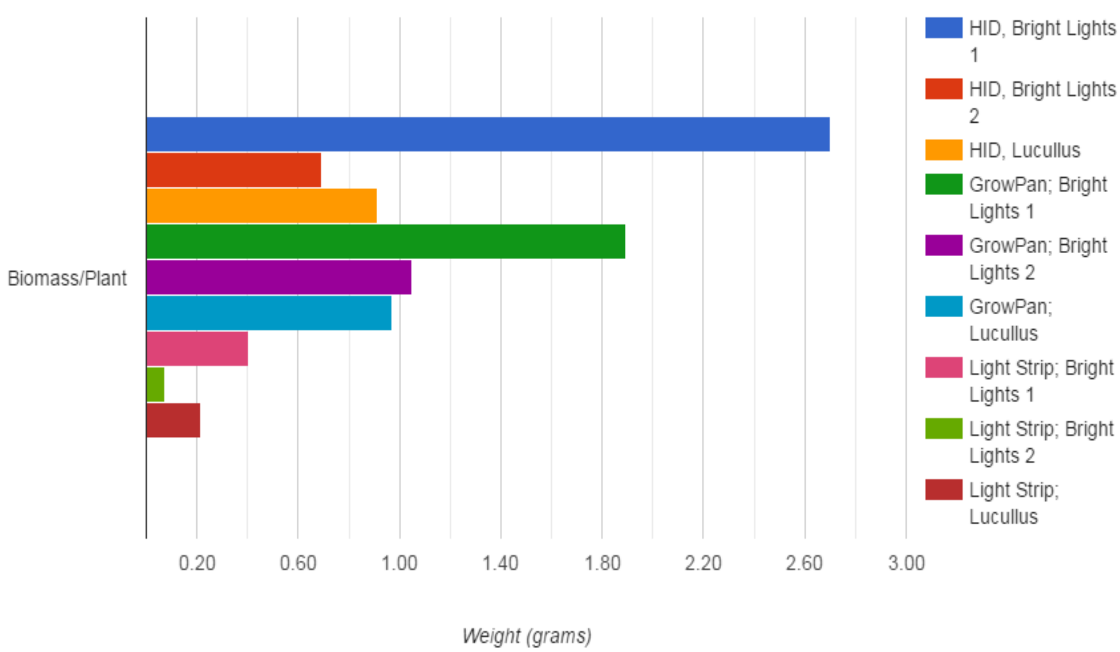

Figure 5: Bar graph showing the total biomass per plant for both 'bright lights' and 'lucullus' Swiss Chard varieties under HID, GrowPan, and Lightstrip lighting sources in an Ebb and Flow Aquaponics bench system.

Comparison of Cultivar Growth

Differences between cultivars were found to be significant when leaf area and fresh weight per plant were measured. This was supported by ANOVA tests resulting in p-values for leaf area and fresh weight being p=0.08 and p= 0.03 respectively. Final biomass of each cultivar was not shown to be statistically different indicated by p=0.39. If fresh weight and leaf area are of higher concern than biomass, which they often are in an aquaponics production system where plants are sold fresh, 'Lucullus' grown in this ebb and flow system resulted in largest leaf area and fresh weight between cultivars.   Figure 3 clearly shows the increased fresh weight of 'Lucullus' over each treatment in comparison to 'Bright Lights'.

The data for statistical analysis via ANOVA testing is found in appendix C.

Recommendations and Conclusion

Recommendation 1: Light Source Cost Analysis

Given the three tested options to light our systems, LED GrowPan, LED LightStrips, or natural light with HID supplemental light. From the perspective of cost of operation, this study recommends that an LED GrowPan is used as a light source. The LED GrowPan provided an ample amount of usable light (216 mol / day) over both optimal and cloudy natural light conditions in a cost effective manner.

Recommendation 2: Light Source Performance

Based on the results of this study, the natural light with HID supplemental light yielded the largest plants. This is due to the high PAR levels of natural light, with a moderate HID supplemental light level when natural light fell below a threshold. This study confirms that when possible, plants should be grown under natural sunlight.

An advanced recommendation from this study's results would be the use of LED GrowPan as a supplemental light source when the natural light levels fall below 200 $\mu mol\ m^{-2}\ s^{-1}$, combining both free, natural sunlight with the long term cost effective and powerful LED technology.

Recommendation 3: Swiss Chard Cultivar

In an ebb and flow shelf aquaponics system 'Lucullus' Swiss chard is more productive in producing leaf area and fresh weight, two important characteristics when considering the end consumer of the product.

Recommendation 4: Future Research

Further study should include quantification of cloudy and full-sun days to increase understanding of outside environment on the lighting cost effectiveness and plant productivity of aquaponics in a greenhouse.

Conclusion

Our study demonstrates the investment in LED GrowPan as a supplemental light source to natural sunlight within a greenhouse setting. The analysis of the productivity of each cultivar in terms of leaf area and plant weight, shows that it is most productive to grow ‘Lucullus’ Swiss chard. This research will help producers, both commercial and hobbyists decide which light source and cultivar to use within their own system to maximize profitability. However, there is further need for research on this topic to fully understand the potential of the system and its setup. Not only will this research impact aquaponic system managers, but it will help to expand the overall understanding of aquaponics as a whole.

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APPENDIX A: GREENHOUSE MAINTENANCE INSTRUCTIONS

Greenhouse Maintenance Instructions

- Wash your hands thoroughly prior to entering and after leaving each Aquaponics greenhouse (in accordance with the posting on the greenhouse doors).
- No food or drink in the greenhouses as well as no eating or drinking therein! Greenhouse water is NOT potable.
- Make sure that the water is flowing and being aerated. Water is pumped from each tank into the biofilters flows back into the tank via gravity. Aeration is via an air pump next to the window (one per room). Water should be flowing and aerated 24/7. If not, call Jay Maher IMMEDIATELY (his number is at the end of this document and posted outside of C2)! Stop feeding! Until help arrives, monitor the fish/water quality and mechanically aerate or exchange the water if necessary.
- Check the plants for visible growth issues. The plants will NOT require watering, but any pale green leaves may signal a lack of N. Watch for these signs or anything else that may seem abnormal. Report them to an instructor when these are noted.
- Measure water quality in half of the tanks each morning (even tanks on even days, odd tanks on odd days). Take these measurements PRIOR to feeding or measuring fish. We are interested in temperature, oxygen, pH, nitrite, ammonia, and alkalinity. Take all measurements/water samples from the front of each tank (i.e., the end of the tank that is closest to the center aisle). If a result is puzzling, take another measurement. If the result persists then record it and alert an instructor. If you break a glass sample tube, sweep up the area and put all glass in the sharps container.
    - o Temperature should be close to ambient (23^{o}C) unless the water is being experimentally heated: Turn on the temperature/pH probe and submerge the sensor end in the water (avoid getting the plastic housing wet). Record the equilibrium temperature in ^{o}C. When you are done, rinse the probe off in tap water, top up the storage solution inside of the cap well, and place the cap on the probe. Store upright.
    - o Oxygen (should be >6 ppm): Turn on the probe, remove the protective cap, and submerge the probe into the water up to the wire. Move the probe in a small circle (approximately the diameter of a penny) until the reading equilibrates. Record the oxygen concentration, rinse the probe off in tap water, and replace the cap.
    - o pH (should be 6.5-7.5): As per temperature.
    - o Nitrite (should be <0.75 ppm): Collect 5 ml of tank water in a small sample tube. Add 5 drops of the appropriate solution to the beaker. Cap/stopper and shake. After 5 minutes, use the color card to determine the approximate nitrite level (it is okay to sub-divide a category). Dispose of the solution in the sink in hall C and rinse both the cap/stopper and tube with tap water.
    - o Ammonia (should be <0.75 ppm): As per nitrite except that you add 8 drops from one bottle and 8 drops from another.
    - o Alkalinity (should be 3-4 drops): Collect 5 ml of tank water in a small sample tube. Add one drop of the appropriate solution, cap/stopper and shake for ~2 seconds. Repeat until the blue solution turns yellow. Record the number of drops

that you added. Dispose of the solution and clean the tube as per the nitrite protocol.

- Clean the pump filters in each of your tanks after sampling water quality. Lift the pump out of the water (don't be alarmed by the gurgling), slide the sponge filter off of the pump, and put the pump back into the water (so that it doesn't burn out). Then wring the filter out under running water in the hallway sink until clean and replace the filter. Do not swap filters among tanks.
- Feed the fish and check for pain/distress. Feed the fish in all tanks each morning (~8-9 a.m.) and afternoon (~3-4 p.m.) according to the rates and instructions from Jay Maher. There is fish feed in each greenhouse. Take this opportunity to check for pain/distress. Clinical signs are reduced or increased breathing (movement of the mouth and gill covering), darkening of the skin, altered swimming behavior (listlessness, surface breathing, loss of equilibrium), aggression, reduced feeding, and (in the case of an infection) sores. Report any dead fish to Jay Maher. Place them in a Ziplock bag and place the bag on the utility table; Jay will take care of disposal.
- Measure fish growth (and check for pain/distress) in four tanks once per week. Add tank water to a Green bucket and place the bucket on a scale. Zero the scale. Obtain 5 fish from a given tank as follows. First, gain access to the tank by placing the floating rafts on the biofilter and removing the air stones. If there is a tank heater attached to one of the air stones then turn off the heater and wait 10-15 minutes for the element to cool before removing the last air stone (the element can overheat very quickly if exposed to air). Then unplug the pump and place both the pump and weighted bucket on the floor. Second, use the PVC gate to concentrate fish at either the front or back of the tank. Be careful not to injure any fish during this procedure. Use the dip net for that tank to remove 5 fish from a given tank. Place these fish in the tared bucket and report mean mass in grams (mass of the fish in the bucket divided by number of fish in the bucket). Then transfer individual fish to the measuring board so that you can measure total length in mm. Return the fish to its original tank. When all fish have been processed, return the water to the tank and report mean fish length. Handle the fish gently and watch for any signs of pain/distress (see previous bullet). Before moving on to the next tank, wash the PVC gate, buckets, and measuring board.
- Clean up at the end of each day. Place any large plant parts (e.g., leaves/stems) that may have fallen onto the floors into the Orange bucket and then transfer them to the compost wheelbarrow. Sweep the floors clean. Properly store all equipment related to fish feeding/measuring and water quality.
- Complete the Maintenance Checklist and then report results via the Google sheet '4601.15 Aquaponics data record'.
- Color-coded buckets in the houses: Green buckets are for water/fish use only; Orange buckets are for compost plant materials; White buckets are for cleaning and disinfecting. Clear plastic bins are for plant harvest. Ziplock plastic bags are for any dead fish.

APPENDIX B: RAW DATA (NEXT PAGE)

Treatment	Harvest Leaf Area (cm^2	Leaf Area of Weekly Harvests (cm^2	Total Leaf Area (cm^2	Harvest Fresh Weight (g	Fresh Weight of Weekly Harvest (g	Total Fresh Weight (g
HID, Bright Lights 1	1488	8505	9993	138.6	465.73	604.33
HID, Bright Lights 2	350	735	1085	24.2	25.8	50
HID, Lucullus	443	1470	1913	30	41.5	71.5
GrowPan; Bright Lights 1	1547	4820	6367	129.6	380.5	510.1
GrowPan; Bright Lights 2	619	1155	1774	37.2	53.9	91.1
GrowPan; Lucullus	442	315	757	30.8	23.3	54.1
Light Strip; Bright Lights 1	1078	1890	2968	69.6	61.4	131
Light Strip; Bright Lights 2	247	0	247	12.8	0	12.8
Light Strip; Lucullus	962	1000	1962	57.9	37.7	95.6

Bright Lights 1						
Bright Lights 1	Harvest Leaf Area (cm^2	Leaf Area of Weekly Harvests (cm^2	Total Leaf Area (cm^2	Harvest Fresh Weight (g	Fresh Weight of Weekly Harvest (g	Total Fresh Weight (g
HID, Bright Lights 1	1488	8505	9993	138.6	465.73	604.33
GrowPan; Bright Lights 1	1547	4820	6367	129.6	380.5	510.1
Light Strip; Bright Lights 1	1078	1890	2968	69.6	61.4	131

Bright Lights 2			Extrapolated			
Bright Lights 2	Harvest Leaf Area (cm^2	Leaf Area of Weekly Harvests (cm^2	Total Leaf Area (cm^2	Harvest Fresh Weight (g	Fresh Weight of Weekly Harvest (g	Total Fresh Weight (g
HID, Bright Lights 2	350	735	1085	24.2	25.8	50
GrowPan; Bright Lights 2	619	1155	1774	37.2	53.9	91.1
Light Strip; Bright Lights 2	247	0	247	12.8	0	12.8

Lucullus						
Lucullus	Harvest Leaf Area (cm^2	Leaf Area of Weekly Harvests (cm^2	Total Leaf Area (cm^2	Harvest Fresh Weight (g	Fresh Weight of Weekly Harvest (g	Total Fresh Weight (g
HID, Lucullus	443	1470	1913	30	41.5	71.5
GrowPan; Lucullus	442	315	757	30.8	23.3	54.1
Light Strip; Lucullus	962	1000	1962	57.9	37.7	95.6

Treatment	Harvest Biomass (g)	Biomass of Weekly Harvest (g)	Total Biomass (g	Leaf Area / Plant	Weekly Harvest / Pl	Fresh Weight / Plant	Biomass/Plant
HID, Bright Lights 1	11.83	47.58	59.41	454.23	21.17	27.47	2.70
HID, Bright Lights 2	1.87	1.57	3.46	217.00	5.16	10.00	0.69
HID, Lucullus	2.25	3.24	5.49	318.83	6.92	11.92	0.92
GrowPan; Bright Lights 1	11.64	31.91	43.55	276.83	16.54	22.18	1.89
GrowPan; Bright Lights 2	7.5	4.04	11.54	161.27	4.90	8.28	1.05
GrowPan; Lucullus	2.8	2.06	4.86	151.40	4.66	10.82	0.97
Light Strip; Bright Lights 1	4.34	5.3	9.64	123.67	2.56	5.46	0.40
Light Strip; Bright Lights 2	0	1.12	1.12	16.47	0.00	0.85	0.07
Light Strip; Lucullus	2.39	4.3	6.69	63.29	1.22	3.08	0.22
Bright Lights 1							
Bright Lights 1	Harvest Biomass (g)	Biomass of Weekly Harvest (g)	Total Biomass (g	Leaf Area / Plant	Fresh Weight / Plant	Biomass/Plant	
HID, Bright Lights 1	11.83	47.58	59.41	454.23	27.47	2.70	
GrowPan; Bright Lights 1	11.64	31.91	43.55	276.83	22.18	1.89	
Light Strip; Bright Lights 1	4.34	5.3	9.64	123.67	5.46	0.40	
		Average	37.53	284.91	18.37	1.67	
		SD	25.42466191	165.4283848	11.48946712	1.166271714	
Bright Lights 2							
Bright Lights 2	Harvest Biomass (g)	Biomass of Weekly Harvest (g)	Total Biomass (g	Leaf Area / Plant	Fresh Weight / Plant	Biomass/Plant	
HID, Bright Lights 2	1.87	1.57	3.44	217.00	10.00	0.69	
GrowPan; Bright Lights 2	7.5	4.04	11.54	161.27	8.28	1.05	
Light Strip; Bright Lights 2	0	1.12	1.12	16.47	0.85	0.07	
		Average	5.37	131.58	6.38	0.60	
		SD	5.470661142	103.5116273	4.861344927	0.4926234239	
Lucullus							
Lucullus	Harvest Biomass (g)	Biomass of Weekly Harvest (g)	Total Biomass (g	Leaf Area / Plant	Fresh Weight / Plant	Biomass/Plant (g)	
HID, Lucullus	2.25	3.24	5.49	318.83	11.92	0.92	
GrowPan; Lucullus	2.8	2.06	4.86	151.40	10.82	0.97	
Light Strip; Lucullus	2.39	4.3	6.69	63.29	3.08	0.22	
		Average	5.68	177.84	8.61	0.70	
		SD	0.9296773634	129.8072075	4.814364791	0.4210996123	

APPENDIX C: STATISTICAL ANALYSES DATA

Source of Variation	SS	df	MS	F	P-value	F crit
Light Type	24841.67415	1	24841.67415	39.66656171	0.024295189	18.51282051
Cultivar	14252.1127	2	7126.05635	11.3787079	0.080783876	19
Error	1252.5247	2	626.26235			

Table 7: Leaf Area ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Light Type	298.0826889	2	149.0413444	9.998103794	0.027786559	6.94427191
Cultivar	244.1356222	2	122.0678111	8.188644902	0.038532496	6.94427191
Error	59.62784444	4	14.90696111			

Table 8: Fresh Weight ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Light Type	0.817233333	2	0.408616667	31.55341055	0.030718748	19
Cultivar	0.015	1	0.015	1.158301158	0.394402637	18.51282051
Error	0.0259	2	0.01295			

Table 9: Biomass ANOVA