EFFECT OF AQUAPONIC VS. HYDROPONIC NUTRIENT SOLUTION, LED LIGHT INTENSITY AND PHOTOPERIOD ON INDOOR PLANT GROWTH OF BUTTERHEAD, ROMAINE AND KALE (*L. SATIVA, B. OLERACEA*)

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TITLE:	Effect of Aquaponic vs. Hydroponic Nutrient Solution, LED Light Intensity and Photoperiod on Indoor Plant Growth of Butterhead, Romaine and Kale (*L. sativa, B. oleracea*)
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ABSTRACT

Effect of Aquaponic vs. Hydroponic Nutrient Solution, LED Light Intensity and Photoperiod on Indoor Plant Growth of Butterhead, Romaine and Kale (*L. sativa, B. oleracea*)

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Vertical farming has been proposed as a solution for providing food security for an increasing, urbanized human population. Light-emitting diode (LED) technology has become increasingly affordable and efficient, making it an ideal choice as artificial lighting for indoor farms. Still largely undiscovered parameters are the optimal plant varieties and types of production systems for plant growth, profit, and human nutrition. Aquaponics may be able to provide sustainable animal protein for vertical farms, increasing their ability to provide more substantial nutrition to consumers. This research aimed to better understand vertical farming as a food production system, and to determine if aquaponics can be an appropriate and applicable fit for it. The experiment was a randomized, factorial design with three independent variables: (1) LED photoperiod interval (2) LED-plant distance, and (3) nutrient solution, as well as several dependent variables to assess both plant yield and quality. A 4-tiered shelving unit was constructed for nutrient film technique (NFT) plant production, and treatments were assigned to each row: (1) LED experiment: Row A, 12/12hr reduced photoperiod with adjustable LEDs 4in. above plant surface; Row B, 2/1hr altered photoperiod interval relative to the control; Row C (control), 16/8hr "standard" photoperiod. (2) Nutrient experiment: Row C, aquaponic nutrient solution; Row H, hydroponic nutrient solution. Rows C and H had matched photoperiod and light intensity. Kale from Row A had significantly lower fresh and dry plant yield relative to the control, Row C ($p<0.05$). Hydroponic romaine, Row H, had significantly higher plant yield relative to aquaponics, Row C ($p<0.05$). Butterhead yields were not significantly different in any treatments ($p>0.05$). Future research may implement a larger sample size of only one plant variety, harvest plants earlier, limit light intensity variation, effectively "balance" the aquaponics system, and have more measures of plant "quality."

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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Indoor vertical farming is a hydroponic plant production method with claims of substantial yield increases, water savings, environmental control, year-round production, as well as a more consistent and successful product compared to conventional in-field farming. However, its feasability as a sustainable food solution for a growing human population is limited by its limited crop success and high operational costs – namely electricity.

Aquaponics is a hydroponic growing method that promotes water and nutrient conservation by integrating fish and beneficial bacteria in the same recirculating system. Fish are grown in a recirculating tank; nutrient-rich water is diverted through mechanical and biological filters and then supplied to plants in a hydroponics system before cycling back into the fish tank. This growing method has the added benefit compared to hydroponics systems in vertical farms of producing a sustainable protein source – fish – in addition to leafy greens. Aquaponics diversifies the grower's market potential and decreases the reliance on synthetic fertilizers and chemicals. However, it remains disputed whether aquaponics can produce the same quality greens as hydroponics because of the different conditions required by fish, bacteria and plants. A compromise must be made in water quality and nutrient load to benefit all organisms.

Light-emitting diode (LED) technology has become increasingly popular for indoor farms as it becomes more affordable and efficient; however, lighting electricity remains the major cost of an indoor growing operation. The success of vertical farms in the future as food

producers (rather than being condemned to the specialty restaurant sector) will be highly dependent on both energy efficiency and ability to grow a wider range of foods to provide more substantial nutrition to consumers.

1.2 Overall Research Goal

Indoor hydroponic plant production allows for higher control and optimization of nutrient requirements and ratios, foliar applications, air quality and light conditions relative to in-field farming. However, indoor vertical farming systems have been met with criticism because of the limited range of food they can produce for a growing human population. Still largely undiscovered parameters include matching plant varieties with an ideal indoor system for growth, profit and nutrition (Huett, 1994; Kopsell and Sams, 2013; Hashida *et al.*, 2014; Bian *et al.*, 2015; Wortman, 2015). One of the major limitations to the scalability of indoor farms is the cost due to electricity requirements. LEDs have become increasingly more affordable in recent years, and also provide the highest efficiency among artificial lighting for growing plants (Morrow, 2008). Research over the past 10 years has assessed different light cycles and spectra in order to maximize plant growth and drive down costs (Massa *et al.*, 2008; Kang *et al.*, 2013; Son and Oh, 2013; Chen *et al.*, 2014; Cope *et al.*, 2014; Bian *et al.*, 2015; Kunoi *et al.*, 2017). The aim of this research is to gain a better understanding of vertical farming as a food production system, and evaluate if aquaponics can be appropriate and applicable for it. In addition, it is to provide a working system in the BRAE department at Cal Poly to engage and interest students in this exciting new field.

1.3 Research Objectives

The experiment was divided into two parts: (1) nutrient solution treatments, and (2) light treatments. The first part of the experiment was a comparative study between hydroponics and aquaponics to determine the effect of nutrient source on plant yield and quality. This entailed constructing two systems with different nutrient sources: (1) hydroponics system supplied by synthetic fertilizers, and (2) aquaponics system supplied almost entirely by fish feed. Artificial lighting is an evolving field for indoor plant production, as well as a major energy cost. Lighting variation was the second research objective that focused on optimizing LED lighting for multiple plant varieties. Specifically, plant yields due to variation in both LED photoperiod and light intensity were investigated. Three plant varieties were used to determine if any effects between treatments varied by plant type. Three plant varieties – butterhead and romaine lettuce (*L. sativa*), as well as dwarf Siberian kale (*B. oleracea*) – were chosen for nutrient solution and light treatments because of their success in aquaponics and hydroponics systems in a pilot study conducted prior to this experiment. The following research objectives were made:

1. Compare plant growth of three plant varieties – butterhead, romaine and kale – in aquaponics vs. hydroponics nutrient solutions.
2. Determine if altering the photoperiod interval for LEDs (e.g. 16/8hr vs. 2/1hr) impacts growth in any of three varieties grown in the aquaponics system.
3. Determine if decreasing distance of LEDs to the plant surface (i.e. providing higher relative intensity) as well as reducing photoperiod impacts plant growth.

1.5 Thesis Statement

The two parts of the experiment addressed issues with vertical farming: (1) human nutrition, and (2) energy usage. Thesis statement: (1) Aquaponics can provide more substantial nutrition for vertical farms compared to conventional hydroponics without decreasing plant yield or quality, and (2) (a) decreasing LED photoperiod intervals from 16/8hr to 2/1hr will result in higher plant yields, (b) decreasing the LED-plant surface distance by using adjustable lighting will provide higher relative light intensity than the other treatments with fixed lighting, allowing for a lower photoperiod – and likewise less energy usage – relative to the control, and will not result in lower plant yields.

1.6 Scope

1.6.1 Time

A pilot study was conducted from 10/17 – 12/17, giving insight as to which plant varieties performed best in the aquaponics system, as well as indicated relative light and nutrient requirements of each species. Most of winter break (12/9/17 – 12/28/17) was dedicated to making design changes to the system based on shortcomings of the pilot study. Plants were germinated from seed from 1/1/18 – 1/14/18. Plants were transplanted on 1/14/18 and grown in the main system until 2/15/18. Plants were harvested, data was collected, and plant matter was dried for yield data over the next week (2/15/18 – 2/22/18).

1.6.2 Location

The system was constructed in Lab 4, Building 8A, of the BRAE department at California Polytechnic State University, San Luis Obispo, CA. All parts of the experiment were

conducted in Lab 4, from seed germination to harvest. This building did not have sophisticated HVAC control, so both air temperature and relative humidity (RH) were monitored to graph the environmental conditions in both the system and Lab 4 building.

1.6.3 Assumptions

First, it was assumed that the nutrient content of water entering the system compared to when it left the system was negligibly different. In other words, that the plants at the head of the system were supplied with the same amount of nutrients as the plants at the tail-end. Likewise, it was assumed that plants across treatments in the same location received the same amount of nutrients. Second, water in the aquaponics system was completely isolated from the hydroponics system (and vice versa). Third, probes and sensors used for daily monitoring performed at their rated accuracies. Multiple experimenters helped with daily monitoring, so it was also assumed that variation between experimenters over time was negligible. Fourth, it was assumed that any plant growth variation between rows was due to the experimental treatment alone, and not due to extraneous variables such as environmental conditions. Each treatment was conducted in different rows of a vertical grow system; it had to be assumed that differences in plant growth in – for example – the top-most row vs. a lower row, was due to the treatment and not from a different environment higher up in the Lab 4 building. Last, every LED light bar from every row was assumed to provide consistent photosynthetic photon flux density (PPFD) to plants throughout the experiment. One comprehensive light test was done prior to the start of the experiment to measure light variation between plant locations throughout each system; it was assumed light delivery did not change from time of light test to time of plant harvest.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Food is one of life's fundamental necessities. Humankind has learned throughout millennia to control and manipulate its environment – the development of agriculture being the pinnacle of these discoveries. Indeed, entire civilizations were built from the ability to cultivate food. Advances in agriculture through modern science and engineering has coincided with exponential increase in human population. As the population grows, agricultural innovations must continue in order to feed the planet.

Urbanization is occurring throughout the world, rural communities declining rapidly as people move to cities for better jobs, healthcare, and opportunities (UN FAO 2008). With the global population growing exponentially – estimated to reach 9.7 billion by 2050 (UN DESA 2015) – overpopulation has become a serious public concern. Current infrastructure in cities has not been able to support population increases sustainably, particularly in developing countries, resulting in chronic food insecurity (UNFAO 2008). Consequently, "food deserts" have formed in urban communities: urban regions without reasonable access to affordable and nutritious food (Larsen, K. & Gilliand, J. 2009). "Urban farming" has become a movement in recent years to bring more produce into the city through rooftop greenhouses (Buehler and Junge, 2016), family gardens (Orsini *et al.*, 2013), and even hydroponically indoors (Besthorn, 2013). The average distance food travels from farm to table in the U.S. is about 1500 miles (Pimentel *et al.*, 2008). The world population is already outpacing the global food supply, and by 2050 this "food gap" is projected to increase further due to an aging agricultural workforce (USDA 2012). The only feasible

way to reduce transportation and still deliver more food than currently supplied is to grow more food in less space, and closer to where it will be eaten.

The following review outlines current food production methods as they pertain to feeding an increasingly populated and urbanized planet. Topics include agricultural advancements from controlled environments and hydroponics, sustainable animal protein provided by aquaculture, waste recycling and water reduction with "aquaponics," an overview of plant nutrient requirements in hydroponics systems, and LED technology applied to indoor plant production. This information provides an understanding of alternative farming practices and their potential place in the future of agriculture.

2.2 Controlled Environment Agriculture (CEA)

2.2.1 Introduction to CEA

In-field agriculture has many factors to consider that impact plant yields, including weather, climate, soil variability and pests. These factors make running a profitable and predictable farming operation difficult, especially in a world with a changing climate. Controlled Environment Agriculture (CEA) is the use of enclosed greenhouses or indoor facilities to produce a "microclimate" environment within its walls for optimizing plant production (Coelho *et al.*, 2005; Panwar *et al.*, 2011). CEA, as the name implies, has benefits over other forms of farming because of the added ability to "control" the system. Several parameters can be controlled with sensors and mechanical hardware including air flow, temperature, relative humidity, CO_2 levels, water delivery and quality, pH and electrical conductivity (EC) (Coelho *et al.*, 2005; Panwar *et al.*, 2011; Duarte-Galvan *et*

al., 2012). Having this added level of control potentially results in substantial yield increase and overall quality, as well as less water and fertilizer consumption (Duarte-Galvan *et al.*, 2012). Being able to control and manipulate environmental and chemical parameters have resulted in new discoveries in terms of ideal growing conditions for different plant cultivars, making CEA operations increasingly popular in universities and R&D sectors. However, the large investment required for running a successful and profitable CEA operation has limited its commercial growth. Environmental control platforms are being optimized in order to decrease energy usage in CEA operations, particularly HVAC (Coelho *et al.*, 2005; Duarte-Galvan *et al.*, 2012).

2.2.2 Environmental Control in CEA Facilities

Growing plants in fully-enclosed structures has many advantages, including reduced pest and disease risks (Despommier, 2011; Panwar *et al.*, 2011). CEA structures are often equipped with some level of Heating, Ventilation, and Air Conditioning (HVAC) system that supplements air flow and adds temperature control, regardless of the climate outside of the enclosure. Sufficient air flow and conditioning in an enclosed system increases O_2 and CO_2 gas exchange, regulates temperature, prevents excess humidity, minimizes disease pressure, and reduces pest issues (Fath and Abdelrahman, 2005). By nature of plant metabolism, carbon dioxide from the air is taken up and oxygen is released, resulting in CO_2 in the enclosure depleting over time. Plant growth is limited by CO_2 levels (Fath and Abdelrahman, 2005), so the manual addition of CO_2 and/or periodic exchanges of outside air are required. Air temperature, relative humidity, and atmospheric pressure are directly and positively correlated with “dew point”, the temperature at which water condenses from

gas to liquid (Korner and Challa, 2003). An increase in air temperature and/or humidity increases the dew point; any object within the enclosure that is cooler than the dew point will collect dew – including plant surfaces. Moisture on leaves of plants increases disease pressure significantly from fungi and fungus-like organisms such as downy mildew, powdery mildew and botrytis (Mashonjowa *et al.*, 2013). Overall, it is crucial for CEA operations to carefully manage air flow and conditioning for high yields of healthy plants.

2.2.3 Indoor Vertical Farming

Another type of CEA facility that has been a growing trend for urban areas is indoor vertical farming. Vertical farming has increased in popularity in recent years due to more affordable and efficient artificial LED lighting (Morrow, 2008; Stutte, 2015), as well as the demand from consumers to have their food grown closer to home. Extending crop production to the vertical dimension can produce 4-30 times higher yields than conventional in-field agriculture per unit area, and installation in city centers can greatly reduce or even eliminate distribution costs (Cicekli and Barlas, 2014; Touliatos *et al.*, 2016). Existing "agtech" startups in the U.S. claim to have reduced water usage by 90-99% with no pesticide applications, doing this in a fraction of the land area and with year-round production (ref: AeroFarms, Freight Farms, Garden Fresh Farms, Plenty, Urban Produce). Indoor vertical farms have even more control than CEA greenhouses in temperature and light delivery; however, this comes at the cost of increased energy costs. Vertical farms have been limited in the range of produce they can profitably grow, relying mostly on leafy greens because of their high market value and proven success indoors. For these reasons, vertical farms have been met with skepticism in their ability to provide sustainable food security.

2.3 Aquaculture, Nitrification, Recirculating Aquaculture Systems (RAS)

2.3.1 Introduction to Aquaculture

Aquaculture is the farming of fresh and saltwater animals for human or animal consumption. Aquaculture currently meets the production needs for over half of global fish consumption, and is the fastest-growing among all animal food-production sectors (Naylor *et al.*, 2009). However, in order to meet protein requirements for human nutrition in the next two decades, fish farming would have to increase five-fold (UN FAO: SWA 2006). Approximately 75% of feed nutrients – namely nitrogen – remain as waste in the water (Piedrahita, 2003). Nitrogen in the form of ammonia can be highly toxic for fish, making frequent water exchanges necessary. Continued growth of the aquaculture industry, as well as a sustainable approach to waste and water reduction, will be critical for the coming years.

2.3.2 Aquaculture Systems: RAS

There are four major types of aquaculture systems: (1) open ponds, (2) cages or "net-pens", (3) flow-through "raceways", and (4) recirculating aquaculture systems (RASs). Type of system is largely dependent on location, available inputs and resources, and type of aquatic species. These operations range from "extensive" operations with few inputs to "intensive" systems with many inputs, high stocking densities, and higher control over production (Klinger and Naylor, 2012). RASs incorporate mechanical and biological filtration to treat and reuse water, decreasing the frequency of exchanges to < 10% of total volume of water per day (Blidariu and Grozea, 2011). RASs have the least frequency and volume of exchanged water of any aquaculture system. A typical flow-through system requires >50,000 liters of water per kilogram of feed, while a RAS ranges from <100 – 1,000 L/kg

feed (Martins *et al.*, 2010). RASs utilize bacteria to convert waste nutrients into nitrite and nitrate, but even these forms of nitrogen are toxic to fish in varying amounts (Martins *et al.*, 2010). In addition to water use reduction, RAS technology reduces or eliminates issues that other systems have: waste management and nutrient recycling (Piedrahita, 2003; Crab *et al.*, 2007), controlled and precise disease management (Summerfelt *et al.*, 2009), and no fish escapes or ecological disruption (Martins *et al.*, 2010).

2.3.3 General Constraints for Productivity of Aquaculture Systems

There are a set of general constraints in aquaculture that limit productivity, the most determining one being water quality. Five of the most important water quality parameters are (1) dissolved oxygen (DO), (2) total ammonia nitrogen (TAN), (3) pH, (4) alkalinity (as mg/L $CaCO_3$), and (5) temperature (Somerville *et al.*, 2014). Sufficient DO levels in an aquaculture system are of paramount importance, especially in an intensive system such as a RAS because of high stocking densities and feed load. Aeration systems provide either blown air or pure oxygen to typically maintain a DO of 5-6 ppm or 8 ppm, depending on whether it is a warm or cold water system, respectively (Malone, 2013). Redundancy in design must be implemented in the form of a backup system, as dissolved oxygen in the tank will reach critical concentrations within 30-60 min in the event of aeration or flow failure (Brune *et al.*, 2003; Malone, 2013).

Optimal temperatures for fish depend on the species; however, warmer temperatures generally result in higher fish productivity. Biofilters containing nitrifying bacteria perform best at warmer temperatures of 25-29ºC (Rakocy *et al.*, 2006). Heating coils are commonly

installed in RAS designs to keep temperature within a desired range regardless of changing environmental conditions (Malone, 2013). Increased temperature increases fish respiration as well as bacterial metabolism, resulting in more oxygen consumed by both classes of organisms and thus a higher demand for DO (Summerfelt and Sharrer, 2004). Oxygen's solubility in water becomes lower as water temperature increases (Bewtra *et al.*, 1970). In addition to temperature's effect on DO, feed rate increases fish respiration and bacterial metabolism, which further decreases DO and increases ammonia production. Thus, it is important to appropriately size a biofilter and aeration system to account for desired feed rate and temperature. Alkalinity is the buffering capacity of a solution – or resistance to pH change – expressed in mg/L of calcium carbonate, $CaCO_3$. It is necessary maintain sufficient carbonate levels in solution to prevent large swings in pH from both bacterial and fish metabolisms. Fish produce carbon dioxide, forming carbonic acid in water, decreasing pH and inhibiting nitrification (Summerfelt and Sharrer, 2004):

$$H_2CO_3 \leftrightarrow CO_2 + H_2O \leftrightarrow H^+ + HCO_3^- \quad \text{(Eq. 2.1)}$$

Nitrifying bacteria "consume" alkalinity from the production of hydronium ions as ammonia and nitrite are oxidized into nitrate, destroying alkalinity (Ebeling *et al.*, 2006):

$$NH_4^+ + 1.83O_2 + 0.094CO_2 + 0.024HCO_3^- \rightarrow \quad \text{(Eq. 2.2)}$$
$$0.024C_5H_7O_2N + 0.977NO_3^- + 0.953H_2O + 1.95H^+$$

It has been reported that for every 1 gram of ammonia-nitrogen oxidized to nitrate, 7.14 grams of alkalinity is consumed, as well as 4.6 grams of dissolved oxygen (Ebeling *et al.*, 2006). Low alkalinity causes rapid swings in pH that inhibit nitrification, resulting in a

buildup of ammonia, which can ultimately kill fish and bacteria. Carbonates must be manually added to match both feed rate and expected nitrifying capacity.

A pH between 7-9 is optimal for most fish, as well as nitrifying bacteria (Rakocy *et al.*, 2006). Small deviations from this optimal range result in lower nitrification rates (Ebeling *et al.*, 2006); larger deviations can result in bacterial colony loss, as well as increased disease pressure and deaths for fish. Total ammonia nitrogen (TAN) is comprised of both unionized ammonia, NH_3, and ammonium ions, NH_4. Both forms of ammonia are in equilibrium in any given solution. The proportion of unionized ammonia (NH_3) and ammonium ion (NH_4^+) in equilibrium depends on both pH and temperature (Ebeling *et al.*, 2006). This relationship between pH and temperature is further shown in Table 2.1, where an increase in pH and temperature result in an increase in toxic, unionized ammonia (NH_3) relative to relatively non-toxic ammonium ions (NH_4) (Emerson *et al.*, 1975). When designing a system, it is important to keep pH and temperature within manageable ranges.

Table 2.1. Fraction of toxic, unionized ammonia (NH_3) in solution at different pH and temperature. Increases in pH and temperature are positively correlated with a higher fraction of toxic ammonia. Source: Emerson et al. 1975.

	Temperature (°C)						
pH	**18**	**20**	**22**	**24**	**26**	**28**	**30**
7	0.003	0.004	0.005	0.005	0.006	0.007	0.008
7.4	0.009	0.010	0.011	0.013	0.015	0.017	0.020
7.8	0.021	0.024	0.028	0.032	0.037	0.042	0.048
8.2	0.051	0.059	0.068	0.077	0.088	0.100	0.113
8.6	0.120	0.136	0.154	0.174	0.195	0.218	0.242
9	0.255	0.284	0.314	0.346	0.783	0.412	0.445

Ultimately these water quality parameters both determine – and are affected by – the feed rate for fish. Recommended feed rates vary based on many parameters including the type and size of fish, as well as temperature of the system (Foltz, 1982). Table 2.2 outlines the recommended feed rates for channel catfish, a commonly farmed freshwater fish, based on size and temperature of the system. Amount of feed fed daily, expressed as a percentage of fish biomass, decreases as fish grow larger and as temperature decreases in the system.

Table 2.2. Feed rates for channel catfish based on fish size and temperature of the system. Feed rate decreases with larger fish in cooler water. Source: Foltz, 1982.

Fish size (g)	**% Biomass fed/day at Varying Temperature (ºC)**				
	18	**21**	**24**	**27**	**30+**
56.2	1.6	1.9	2.2	2.5	2.8
164	1.2	1.4	1.7	1.9	2.1
283	1	1.2	1.4	1.5	1.7
450	0.8	1	1.1	1.3	1.4
553	0.7	0.9	1	1.1	1.3

2.3.4 Nitrification Process in RAS and Aquaponics Systems

Biological filters ("biofilters") are physical units containing "fixed film" or substrate with high specific surface area (SSA) for beneficial bacterial attachment to treat water (Summerfelt and Sharrer, 2004; Malone, 2013). Integration of an appropriately sized biofilter in a RAS is necessary to prevent toxic ammonia and nitrite accumulation. Fluidized sand and bead filters are commonly used because of their low cost, relatively high SSA for bacterial attachment, and mechanical filtration ability (Malone, 2013).

There are two main classes of nitrifiers that are grown in biofilters of RAS and aquaponics systems: (1) ammonia-oxidizing bacteria (AOB), and (2) nitrite-oxidizing bacteria (NOB) (Ebeling *et al.*, 2006). Ammonia is first excreted through the gills of fish; thus, AOB are

the first colonizers in biofilters that are first being established (Somerville *et al.*, 2014). NOB are the next class of bacteria that colonize the biofilter, oxidizing accumulated nitrite into nitrate. CO_2, O_2 and alkalinity are consumed during this process (Eq. 2.2); however, there is a net production of CO_2 in the system. The nitrification process results in biomass formation, H^+ production (and pH reduction), DO reduction, and NO_3 accumulation. Bicarbonate and other alkaline bases must be added frequently to both buffer and raise pH to stable levels (Rakocy *et al.*, 2006). CO_2 accumulation and DO consumption by fish are compounded by bacteria. It is estimated that 5.9 mg/L of CO_2 is produced and 4.6 mg/L of O_2 is consumed for every 1 mg/L of TAN oxidized by bacteria alone (Summerfelt and Sharrer, 2004). Sufficient aeration must be supplied to maintain DO levels $\geq$ 5 mg/L (Summerfelt and Sharrer, 2004; Malone, 2013); for commercial scale systems at least 80% DO saturation, or $\geq$ 6-7mg/L, is maintained (Rakocy *et al.*, 2006).

2.4 Hydroponics and Aquaponics

2.4.1 Introduction to Aquaponics

One of the largest costs for a RAS – aside from energy inputs – is waste removal (Klinger and Naylor, 2012). An emerging technology that can make fish farming an even more sustainable food production system is "aquaponics." Aquaponics is a food production system that combines aquaculture with hydroponics: fish and plants are grown in the same RAS to decrease waste and minimize water use (Tyson *et al.*, 2011). Integrating plants with a RAS decreases daily water exchanges from ~10% to less than 2% total volume per day (Rakocy *et al.*, 2006). Some of the major problems associated with traditional aquaculture can be mitigated by incorporating plants including biosolids, total ammonia nitrogen

(TAN) and water usage reduction (Somerville *et al.*, 2014). Though much less toxic than ammonia and nitrite, chronic exposure to high levels of nitrate (NO_3) has been shown to reduce growth and health of fish in RASs (Monsees *et al.*, 2017). NO_3 accumulation can be mitigated with an appropriately sized plant production area. Nitrate is a primary macronutrient essential for plant growth and needed by plants in higher concentrations than any other mineral nutrient (Bugbee, 2004). As such, the nitrification process forms a mutualism between fish, nitrifying bacteria and plants in aquaponics system.

Plants both reduce accumulation of waste nutrients and provide sellable produce, increasing the diversity and amount of food that can be grown in the system. This creates new consumer markets and can potentially increase the economic value of the RAS (Rakocy *et al.*, 2006). Interestingly, plant production becomes the major cash crop when integrated with aquaculture rather than the fish, despite their primary function being the removal of nitrogen and saving water. Certain leafy greens are able to reach marketable size in as little 30 days – compared to about 6 months for tilapia, a commonly farmed freshwater fish – and can be grown indoors year-round (Rakocy *et al.*, 2006). Unfortunately, most of the current aquaponics systems are small-scale and reports are lacking in scalability (Somerville *et al.*, 2014). In order for aquaponics to be a sustainable solution for food security in the future, more substantial studies must be done.

2.4.2 Introduction to Hydroponics

"Hydroponics" is a plant production method without soil as a rooting medium; instead, plants are grown with added soluble nutrients in either drip irrigated soilless media, or in a

water column. Benefits of hydroponic farming over soil growing systems include: (1) elimination of soil borne pathogens and the need for soil sterilization, (2) reduced pesticide applications, (3) precise control of plant nutrients, (4) water usage reduction, (5) adherence to environmental policies through nutrient recycling and closed systems that reduce and eliminate environmental contamination, respectively (Savvas, 2003). A fertigation injection board and tank system is installed – often with ion-sensitive electrodes and automated dosing systems – that delivers specific ratios of all necessary plant macro- and micronutrients (Savvas and Adamidis, 1999; Jung *et al.*, 2015). In a completely closed hydroponics system, nutrient ratios are constantly changing based on the type of plant and its growth cycle. Thus, models have been established that replenish recycled effluent with specific nutrients (Savvas, 2002). Hydroponics systems have developed exponentially in recent years, quickly approaching $1 billion in revenue with an annual growth rate of 4.5% (IBIC 2016). A major inhibitor to even more profound growth in commercial hydroponic greenhouses is the investment cost per unit growing area to provide complete environmental and nutrient control; thus, they are particularly well-suited for areas with soil issues, limited water resources, salt buildup, and/or environmental pollution from nitrate and phosphate leaching (Savvas, 2003). Increased automation of both water and nutrient supply will help scale these systems in the future.

2.4.3 Hydroponic Units: Nutrient Film Technique (NFT)

The hydroponic units in aquaponics systems vary based on the size of the operation and its application. There are three main types of hydroponic water columns, from most-to-least common: deep water culture (DWC), media beds (flood and drain or “ebb and flow”), and

nutrient film technique (NFT) (Somerville *et al.*, 2014; Goddek *et al.*, 2015; Love *et al.*, 2015). DWC utilizes floating rafts that are made of polystyrene that carry plants with their roots suspended in water beneath. This method is preferred for growing a single crop type on a commercial scale because of its ability to be mechanized (Somerville *et al.*, 2014). Because of the high initial investment and heavy infrastructure – vertical farms, small-scale operations, and hobbyists tend to steer away from DWC (Somerville *et al.*, 2014). Media beds contain soil alternatives, such as shale or clay pebbles ("Hydroton"), that act as the substrate for plants; water is delivered via a "flood-and-drain" (aka "ebb-and-flow") irrigation method (Love *et al.*, 2015). Media beds are the most popular systems for small-scale aquaponics – especially in developing regions – because of their low initial cost, space efficiency and simplicity (Somerville *et al.*, 2014).

NFT systems consist of channels that a "film" of nutrient-rich water passes through; plants are set in slots in the channels with their roots partially immersed in water (Goddek *et al.*, 2015). The large air-to-root contact area resulting from the nutrient film provides more oxygen to roots which aids in respiration (Bugbee, 2004). However, sufficient flow must be provided to prevent root zones from becoming anaerobic. NFT systems are much lighter than DWC and media bed systems because of plastics used for the channels, substantially less water volume, and no substrate. NFT systems are popular for rooftop systems as well as vertical farming because of their lightweight and scalable design (Somerville *et al.*, 2014). All three systems share basic components: a sump for collecting downstream water, pump(s) for water circulation, plumbing, fish tank, aeration, biofiltration and mechanical filtration (Somerville *et al.*, 2014; Goddek *et al.*, 2015; Love *et al.*, 2015).

2.4.4 "Balancing" Aquaponics Systems

Regardless of the type of aquaponics system, productivity – or overall output – of the system is ultimately limited by three trophic levels: (1) fish, (2) plants, and (3) bacteria. Figure 2.1 illustrates a simplified diagram of these interrelated parts of an aquaponics system (Goddek *et al.*, 2015). Each trophic level complements the other, resulting in a cyclical relationship: fish feed is first processed by fish and excreted as waste in the form of ammonia nitrogen; ammonia is oxidized by nitrifying bacteria into nitrite and then nitrate; nitrate is taken up by plants and assimilated into biomass. It is paramount in designing any aquaponics system that each component is properly sized because of the interdependency of each process involved.

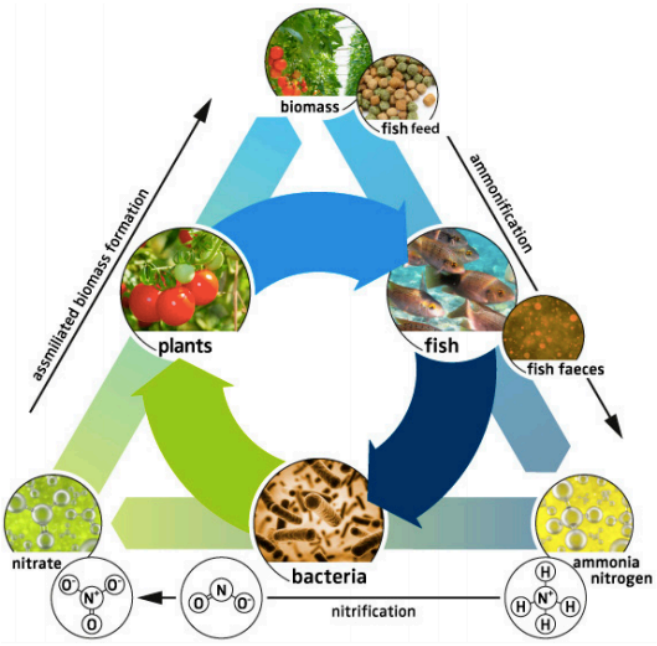


Figure 2.1. The three major trophic levels involved in aquaponics. Fish feed is processed by fish and excreted as waste in the form of ammonia nitrogen; ammonia is oxidized by nitrifying bacteria into nitrite and then nitrate; nitrate is taken up by plants and assimilated into biomass. Source: Goddek et al. 2015.

Fish productivity in an aquaponics system is limited by water quality, waste removal, tank size, fish stocking density, and feed rate (Rakocy *et al.*, 2006; Danaher *et al.*, 2013; Somerville *et al.*, 2014). The parameters for fish productivity influence and determine the amount of plants that are able to be grown. In addition, the density of bacteria in the system dictate the feed rate; toxic ammonia will accumulate if the feed rate exceeds the nitrification rate (Meade, 1985). The UN Food and Agriculture Organization (UN FAO) technical paper on small-scale aquaponics illustrates this balance:

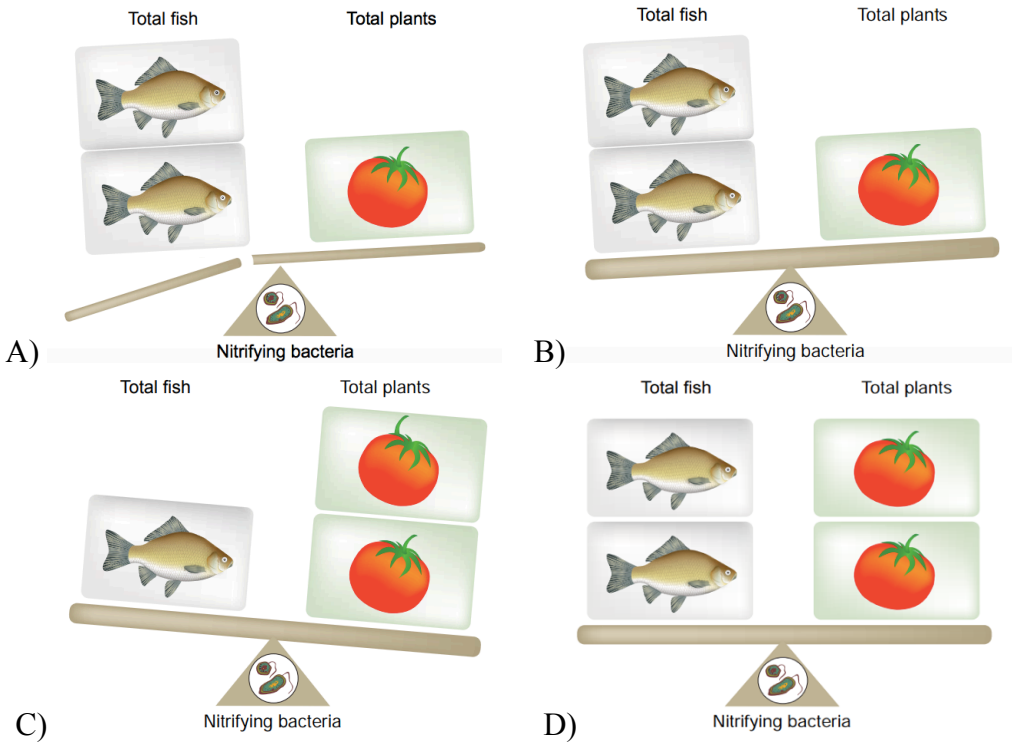


Figure 2.2. Left-right, top-down: A) Fish biomass exceeding the biofilter carrying capacity, resulting in accumulation of toxic ammonia. B) Fish and biofilter correctly sized with too few plants, resulting in accumulation of nitrate. C) Fish and biofilter correctly sized with too many plants, resulting in nitrate deficiency. D) Correctly-balanced system, resulting in dynamic equilibrium between fish, plants and bacteria. Source: Somerville et al. 2014.

2.5 Plant Nutrient Requirements in Hydroponics and Aquaponics Systems

2.5.1 Introduction to the Essential Elements for Plant Nutrition

What constitutes an element as "essential" for any plant has been disputed over time. The emergence of hydroponics in the mid-1800's and into the 1900's enabled researchers to grow plants in different nutrient profiles to determine element essentiality (Barker and Pilbeam, 2015). According to Barker and Pilbeam in *Handbook of Plant Nutrition*, there are currently seventeen elements that are designated as essential plant nutrients: carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), Magnesium (Mg), sulphur (S), boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni) and zinc (Zn) (Table 2.3).

Table 2.3. The seventeen essential elements for plant nutrition divided into macro- and micronutrients. Macronutrients are further divided into "structural," "primary" and "secondary" nutrients. Source: Barker and Pilbeam, 2015.

Macronutrients

Structural		**Primary**		**Secondary**	
C	Carbon	N	Nitrogen	Ca	Calcium
H	Hydrogen	P	Phosphorus	Mg	Magnesium
O	Oxygen	K	Potassium	S	Sulphur

Micronutrients

B	Boron	Mn	Manganese
Cl	Chlorine	Mo	Molybdenum
Cu	Copper	Ni	Nickel
Fe	Iron	Zn	Zinc

Carbon, hydrogen and oxygen are structural elements obtained from the atmosphere and water, while the other fourteen elements are obtained as mineral nutrients in soluble fertilizers (Epstein and Bloom, 2005). The fourteen mineral nutrients are further classified as either primary or secondary "macronutrients", or as "micronutrients", based on quantity of the nutrient required by plants (Barker and Pilbeam, 2015). Deficiencies of individual mineral nutrients often elicit unique deformities in plant growth, which allows for visual diagnoses and appropriate nutrient adjustments in the system (Harper and Sellek, 1987).

2.5.2 Nutrient Requirements in Hydroponics vs. Aquaponics Systems

Table 2.4 outlines the recommended concentrations of mineral nutrients that need to be supplemented in hydroponics systems (Epstein and Bloom, 2005). Though fertilizers exist that provide individual mineral nutrients for plants, general two-part nutrient solutions (e.g. "A" and "B") are available that contain all essential macro- and micronutrients.

Table 2.4. Generally recommended mineral nutrient concentrations for plants in standard hydroponics systems. Source: Epstein & Bloom 2005.

Macro-nutrient	**Concentration (mg/L)**	**Micro-nutrient**	**Concentration (mg/L)**
N, total	321 ± 130	Fe^{2+}	5.18 ± 1.79
PO_4^{3-}	36.9 ± 6.2	Cu^{2+}	0.042 ± 0.017
K^+	340 ± 101	Zn^{2+}	0.455 ± 0.374
Ca^{2+}	160 ± 10	Mn^{2+}	1.83 ± 0.96
Mg^{2+}	40.9 ± 3.3	$B(OH_4)^-$	0.573 ± 0.134
SO_4^{2-}	134 ± 53	MoO_4^{2-}	0.087 ± 0.037

Mineral nutrient availability for plants in aquaponics systems is dependent on many factors including the type of system, fish species and growth stage, stocking density, feed rate and composition, and microbial nitrification rate (Rakocy *et al.*, 2006; Wortman, 2015). Among these factors, fish feed and composition are particularly important because the type and quantity of nutrients in the feed ultimately determine what nutrients the plants will receive. Commercial fish feeds typically do not contain sufficient amounts of potassium (K^+) or iron (Fe^{2+}); it is necessary to supplement with potassium bicarbonate/hydroxide ($KHCO_3$ or KOH) and chelated iron (e.g. Fe-EDDHA) to prevent deficiencies (Rakocy *et al.*, 2006). Fish feeds are optimized for fish rather than plants, so the essential mineral nutrient concentrations for plants tend to be lower in aquaponics systems than what is targeted in hydroponics systems (Wortman, 2015; Goddek *et al.*, 2016). Increasing the

stocking density of fish as well as feed rate and composition can reduce deficits of plant nutrient availability in aquaponics systems.

2.5.3 Nutrient Solution Parameters and their Effect on Nutrient Uptake

Nutrient solution parameters in soilless systems can be managed more precisely than in field agriculture, potentially increasing productivity and quality of crops. These parameters include (1) electrical conductivity (EC), (2) pH, (3) temperature, and (4) dissolved oxygen (DO) (Trejo-Tellez and Gomez-Merino, 2012).

EC is a vital nutrient solution parameter because it is a quantitative measure of the ionic concentration of nutrients in solution that determine growth and development of plants (Trejo-Tellez and Gomez-Merino, 2012). It estimates osmotic pressure – a measure of the force exerted by dissolved solutes on water – which indicates the amount of ions, or dissolved nutrients, available to plants in the root zone (Nemali and van Iersel, 2004). Ions that contribute to EC include (1) macronutrients: NO^{3-}, PO_4^{3-}, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, (2) acid/base ions: H^+, OH^-, (3) alkalinity: HCO_3^-, as well as (4) sodium (Na^+) and chloride (Cl^-) (Trejo-Tellez and Gomez-Merino, 2012). As micronutrients are supplied in much lower quantities, they do not significantly contribute to EC (Sonneveld and Voogt, 2009). Ideal EC varies by crop and environmental conditions, but generally a range of 1.5 – 2.5 mS/cm is desired for common hydroponic crops (Sonneveld and Voogt, 2009). Leaf lettuces (*L. sativa*), for example, grow optimally from 1.4 – 2.0 mS/cm (Samarakoon *et al.*, 2006). EC below 1.4 mS/cm results in decreased yields due to nutrient deficit, while EC above 2.0 mS/cm begins to prevent nutrient uptake because of increased osmotic pressure

(Samarakoon *et al.*, 2006). As seen in Table 2.5, crops have been assigned to different "salinity" groups (plant mineral nutrients = salts, hence "salinity") based on their threshold EC values (Jensen and Collins, 1985; Wallender and Tanji, 2011):

Table 2.5. Threshold EC (mS/cm) of various crops assigned into salinity groups. Sources: Trejo-Tellez and Gomez-Merino, 2012; Wallender and Tanji, 2011.

Salinity group	**Threshold EC (mS/cm)**	**Crop examples**
"Sensitive"	1.4	*L. sativa* (e.g. butterhead, romaine), carrots, strawberries
"Moderately sensitive"	3.0	*B. oleracea* (e.g. kale, broccoli, cabbage), tomato, cucumber, pepper
"Moderately tolerant"	6.0	soybean, ryegrass
"Tolerant"	10.0	sugarbeet, cotton, bermuda-grass

EC does not selectively measure individual mineral nutrients; rather, a sum of all ions in solution. It provides a number that is representative of a known composition of added nutrients. The nutrient solution composition in a hydroponics system has the potential to be more directly managed than in aquaponics because it often comes from a synthetic fertilizer or stock solution (e.g. 2-part "A&B") of a known concentration. Nutrient solution composition can be much more difficult to determine in aquaponics systems because added nutrients are not plant-available when first introduced (Rakocy *et al.*, 2006); fish feed must first be consumed and metabolized by fish and/or solubilized by bacteria before nutrients are available to plants. Both hydroponics and aquaponics systems have dynamic nutrient compositions over time because plants uptake nutrients in different ratios and amounts based on plant type and life cycle (Bugbee, 2004). Periodic water and tissue sampling must be done to get a specific breakdown of mineral nutrients in solution and taken up by plants, respectively Trejo-Tellez and Gomez-Merino, 2012.

pH directly influences the availability of mineral nutrients to plants. The composition, elemental speciation and bioavailability of the nutrient solution are affected by changes in pH (De Rijck and Schrevens, 1999). In other words, essential mineral nutrients can change forms based on pH to become more or less soluble (and likewise more or less bioavailable to plants, respectively). pH must be measured and adjusted daily to prevent unwanted fluctuations that can result in decreased plant yields because of the lower buffering capacity that is typical in hydroponic soilless cultivation (Trejo-Tellez and Gomez-Merino, 2012). A pH 5.5 – 5.8 is recommended for hydroponic culture, though plants can grow equally as well at a range up to pH 7.0 as long as nutrients do not become limiting (Bugbee, 2004). Fig. 2.3 illustrates a Troug diagram of the plant availability of different macro- and micronutrients at different pH levels.

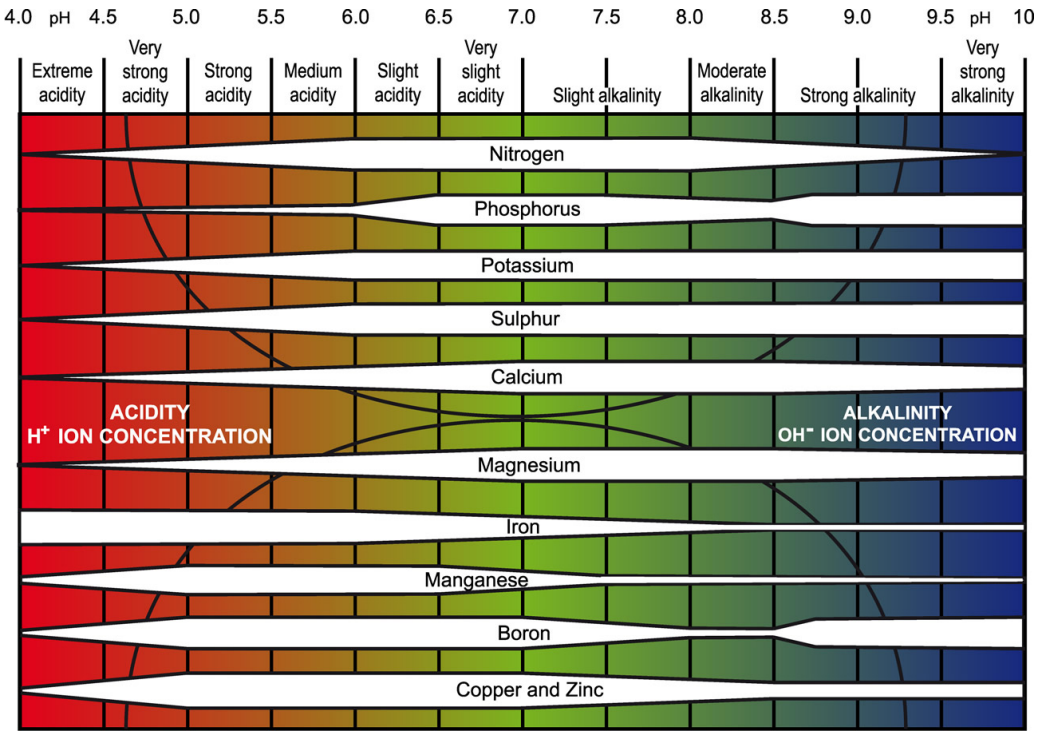


Figure 2.3. Troug diagram of plant availability of different macro- and micronutrients based on pH. Band thickness is proportional to availability. Source: Potash Development Association (PDA) & Troug, E. 1946.

Nitrification rates in biofilters of aquaponics systems are optimal at slightly alkaline pH levels up to 8.5 (Tyson *et al.*, 2007). As pH is lowered, nitrifying bacteria are less productive, resulting in potential buildup of toxic ammonia for fish in the system. For this reason, aquaponics systems cannot operate within the optimal pH range of 5.5 – 5.8 for plants. Instead, a neutral pH near 7.0 can be maintained that allows for both plant nutrient uptake and bacterial nitrification (Wortman, 2015).

Temperature of the nutrient solution has a direct effect on plants' water and nutrient uptake, as well as oxygen solubility (i.e. DO) (Trejo-Tellez and Gomez-Merino, 2012). Increasing water temperature decreases water viscosity, increasing nutrient uptake capacity by plant roots (Falah *et al.*, 2010). Research by Falah et al. on tomato plants cultivated in high water temperatures (up to 35ºC) in an NFT hydroponics system showed a short-term increase in water and nutrient uptake by plants; however, long-term effects ultimately resulted in growth depression and browning of roots due to decreased oxygen solubility. Table 2.6 depicts the inverse relationship between water temperature and oxygen solubility.

Table 2.6. Oxygen solubility in water as temperature is increased at 1 atm. Source: Trejo-Tellez and Gomez-Merino, 2012.

Temperature (°C)	**O_2 solubility (mg/L)**	**Temperature (°C)**	**O_2 solubility (mg/L)**
10	11.29	30	7.56
15	10.08	35	6.95
20	9.09	40	6.41
25	8.26	45	5.93

Nutrient solutions below 22ºC can provide sufficient oxygen for the roots of some plants without supplemental aeration (Trejo-Tellez and Gomez-Merino, 2012). However, the

oxygen requirement by plants also decreases because root respiration decreases, resulting in less vegetative growth. Temperatures above 22ºC increase oxygen diffusion so that oxygen demand cannot be covered by the nutrient solution alone (Trejo-Tellez and Gomez-Merino, 2012). DO levels below 3 – 4 mg/L inhibit root growth and increase browning, which can have a detrimental effect on plant yield (Gislerod and Adams, 1983) Nutrient Film Technique (NFT) is a type of hydroponics system used in hydroponics and aquaponics that provides particularly high oxygen transfer relatives to other systems because of the "film" of solution that passes through roots allowing for high oxygen transfer from the atmosphere (Bugbee, 2004; Somerville *et al.*, 2014). In addition to using an NFT system, supplemental aeration with pure O_2 can be implemented to increase DO in warmer water (Chun and Takakura, 1994). Aquaponics systems can particularly benefit from NFT and pure O_2 supplementation because of the high oxygen demand from fish and bacteria in addition to plant roots, as well as the warmer water required for optimal fish growth and bacterial performance (Somerville *et al.*, 2014).

2.6 Photosynthesis and Light-Emitting Diodes (LEDs) in Horticulture

2.6.1 Introduction to Photosynthesis and Light Intensity

Plants grow by assimilating carbon from CO_2 in the atmosphere to form sugars. Carbon assimilation is fueled by the absorption of light energy – photons – in a process called photosynthesis. Solar radiation from the sun is the predominant light source for agricultural crops, but only a fraction of this radiation is used by plants to drive their metabolism. Direct solar radiation ranges from 300 – 3,000 nm wavelengths, but "physiologically active radiation" that plants respond to ranges from 300 – 800 nm (Tazawa, 1999). Within this

range, the wavelengths of light that actually drive photosynthesis – "photosynthetically active radiation" (PAR) – range from 400 – 700 nm (Tazawa, 1999; Cope *et al.*, 2014).

The intensity of light energy absorbed by photosynthetic pigments and cells within plant tissue can be described by quantum yield – moles of CO_2 fixed per mole of photons absorbed (Cope *et al.*, 2014). Quantum yield can further be characterized as "photosynthetic photon flux density" (PPFD), which is an instantaneous measure of the moles of PAR photons (400 – 700 nm) received by a plant surface, in μmol/m^2-sec (Tazawa, 1999). The daily light integral (DLI) quantifies the total PPFD delivered to a plant in a 24-hr period (mol/m^2-day). Quantum sensors have been developed that selectively measure PPFD in the PAR range, reliably quantifying the amount of incident light being delivered to a plant surface in real-time (ref: Apogee Instruments). Fig. 2.4 illustrates two generations of Apogee Instruments quantum sensors as they relate to measuring PPFD within a spectral range of 389 – 692 nm ± 5 nm.

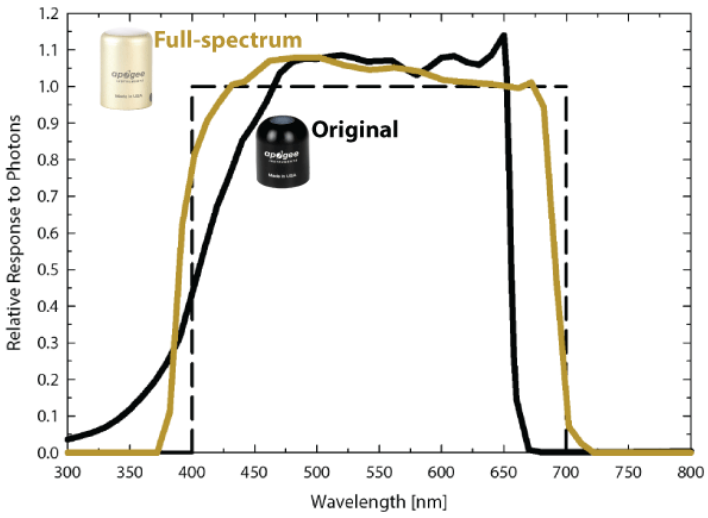


Figure 2.4. Two generations of Apogee Instruments quantum sensors as they relate to measuring PPFD within a spectral range of 389 – 692 nm ± 5 nm. Dotted line represents PAR, the 400 – 700 nm spectral range that drives photosynthesis in plants.

2.6.2 Light Quality, Chlorophyll, and Choosing the Best Lights

CEA greenhouses and indoor plant factories have incorporated artificial lighting to either supplement or completely replace solar radiation (respectively) as a consequence of desiring more environmental control. Artificial light sources for CEA facilities include high-pressure sodium (HPSL), fluorescent, incandescent and metal halide lamps (Wheeler, 2008), as well as the emergent light-emitting diode (LED). There are three components of artificial light that regulate plant growth: (1) light intensity, (2) light quality, and (3) photoperiod (Kang *et al.*, 2013). The plant's requirement of these components vary by variety, growth stage and its environmental conditions (Kang *et al.*, 2013). Light intensity was described previously as the amount of incident light upon a plant surface within 400 – 700 nm (PAR), measured as PPFD in μmol/m^2-sec. However, quantum sensors respond to a given photon of light equally, regardless of its wavelength (Tazawa, 1999). Light quality, then, describes the relative quantity of various wavelengths delivered by a particular light source. Fig. 2.5 depicts the light quality distribution of different artificial light sources expressed as relative energy percentage (Tazawa, 1999). As seen in the figures, all five lights provide very different quality of light to plant surfaces. This is important to consider for energy efficiency because different light types will supply more or less relevant PAR to plants with the same amount of electricity used.

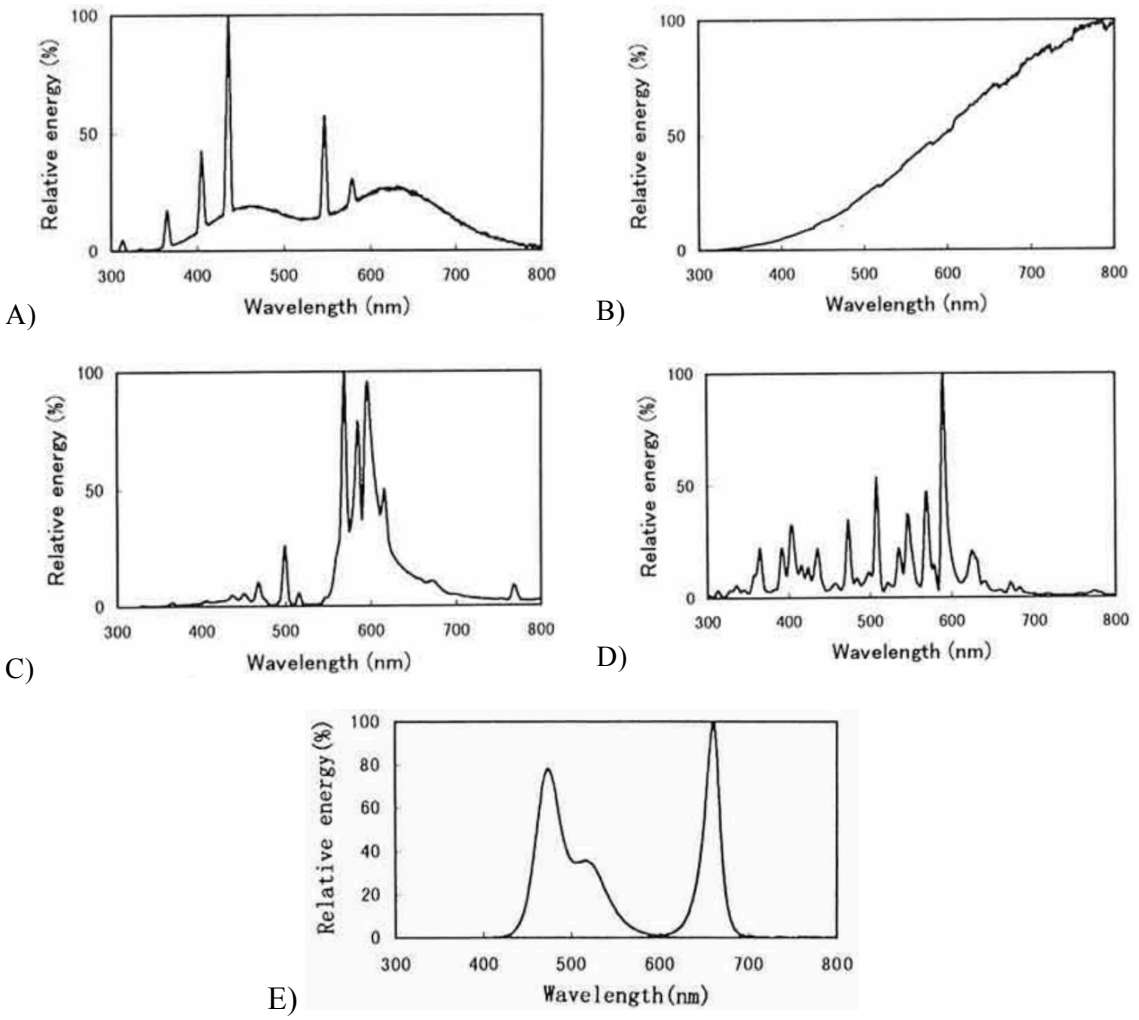


Figure 2.5. Spectral distributions of artificial lights used in CEA: A) Fluorescent lamp, B) Incandescent lamp, C) High-pressure sodium lamp, (HPSL), D) Metal halide lamp, E) R/G/B Light-emitting diode (LED) composite lighting. Source: Tazawa 1999.

The photosynthetic pigments in plants, "chlorophyll a" and "chlorophyll b", respond to relatively narrow wavelengths of light that roughly correspond to the colors red (663 – 642 nm) and blue (430 – 453 nm) on the visible spectrum (Hopkins, 1999). Carotenoids are another class of pigments that selectively respond to light; they protect chlorophyll from photodamage, shift non chlorophyll absorbing light energy to chlorophyll centers, as well as provide health benefits for consumers (Bian *et al.*, 2015). Fig. 2.6 illustrates the absorption peaks of these plant photopigments (Lichtenthaler, 1987). The resulting effect

is a non-uniform affinity for certain wavelengths of light (Fig. 2.7) (Tazawa, 1999). Considering only PAR supplied to plants for photosynthesis (400 – 700 nm), the optimal light choice can be determined via their spectral distributions.

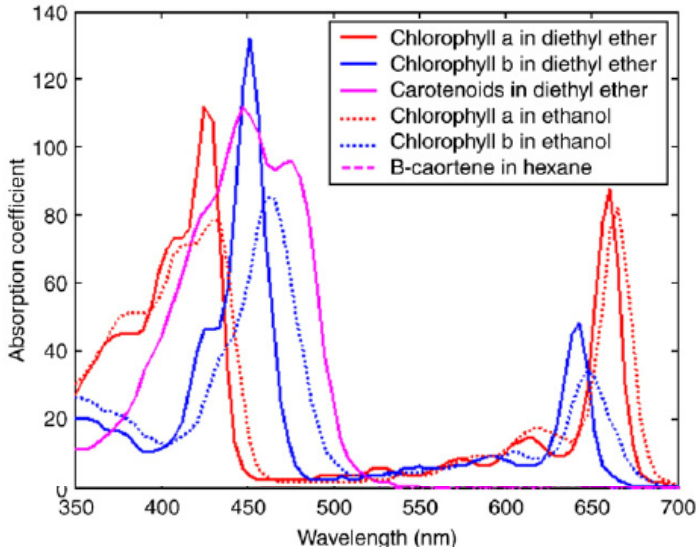


Figure 2.6. Absorption spectra of chlorophyll a, chlorophyll b, and carotenoids in diethyl ether and ethanol solutions. Source: Lichtenthaler 1987.

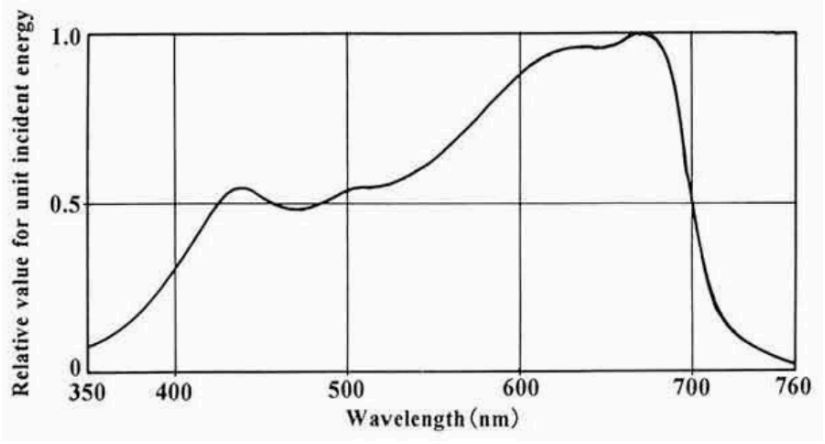


Figure 2.7. Average photosynthesis response action spectra for 61 different species of plants. Source: Tazawa 1999.

Light emitting diodes (LEDs) have the added benefit over conventional artificial lights because of their selective wavelength capabilities (Fig. 2.5.E). Both full-spectrum LEDs and selective combinations of LED lights have become increasingly common in

horticulture research because of their ability to match photosensitive ranges of chlorophylls a and b in plant tissue; full spectrum LEDs may have added benefits for plant photoreceptors not involved in photosynthesis, such as bloom signals and phototaxis (Chen *et al.*, 2014; Cope *et al.*, 2014; Dong *et al.*, 2014; Bian *et al.*, 2015; Kunoi *et al.*, 2017).

2.6.3 Overview of Light-emitting Diodes in Horticulture

CEA indoor facilities have the benefit of added control of environmental conditions for crop production; however, this comes at the expense of light energy supplied by the sun. Artificial lighting has been incorporated into greenhouses to supplement irradiance from the sun when weather and seasons impact light supply (Olle and Virsile, 2013), and artificial lighting is the sole light supply for completely enclosed indoor systems for urban agriculture and space systems (Bian et al., 2015). Conventional artificial light sources in CEA – fluorescents, incandescents, HPS and metal halides – are being challenged by an up and coming technology: the light-emitting diode (LED).

LEDs are solid-state electrical lights that are durable and lightweight, have high light-conversion efficiency and lower radiant heat output, and can provide selective spectra for plant growth experiments (Stutte *et al.*, 2009; Son and Oh, 2013). LEDs were invented in 1964, but were not applied to plant cultivation until NASA began suitability tests for space systems in the early 1990's (Monje *et al.*, 2003; Bian *et al.*, 2015). Since the 1990's, LED technology has made consistent significant advances for horticultural use in their output, electrical efficiency, cost, and selective wavelength availability (Stutte *et al.*, 2009; Stutte, 2015). These advancements follow a predictable, exponential curve; the Haitz model

describes LED light generation over a given area to be increasing 20-fold, coinciding with a 10-fold decrease in cost (Haitz and Tsao, 2011; Stutte, 2015). This is promising for LED's future in horticulture, as cost is currently the only main factor preventing their widespread implementation (Morrow, 2008). Research involving LEDs in horticulture has grown exponentially since its application to plant science in the 1990's because of advancements in technology and price (Fig. 2.8).

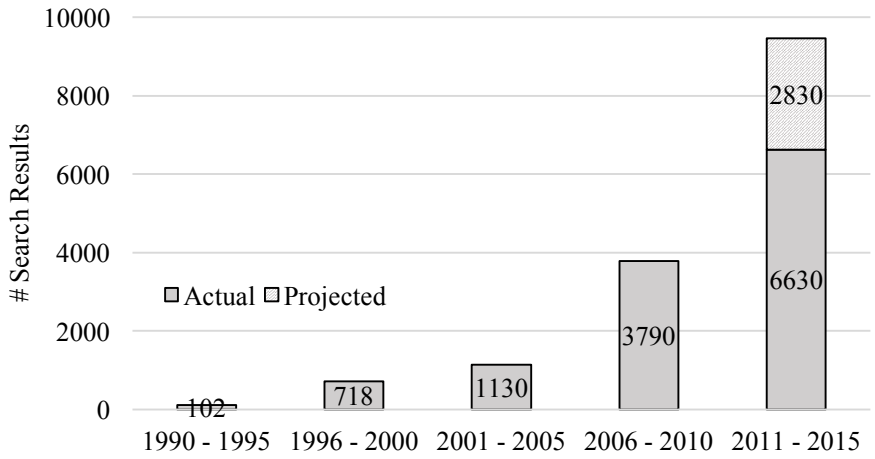


Figure 2.8. Number of scholarly articles (abstracts, peer-reviewed papers, theses, technical reports and books) with a keyword search matching "Horticulture" and "Light Emitting Diodes" since the 1990's. Source: Stutte 2015.

2.6.4 Advancements in Plant Science from LED Research

The adjustable light spectra feature of LEDs has resulted in significant advancements in plant science. Researchers have demonstrated that light quality follows a general trend across plant varieties, growth stage, and environmental conditions. Red (R) LEDs generally impact plant growth (e.g. fresh and dry weight, plant height and leaf area), while blue (B) LEDs generally impact photosynthesis (e.g. chlorophyll production, chloroplast development) and biomass indirectly (Wang *et al.*, 2009; Johkan *et al.*, 2010; Bian *et al.*, 2015). An experiment on LED light quality in red and green leaf lettuce (*L. sativa*) showed

that altering the R:B ratio at a fixed 171 ± 7 μmol/m^2-sec PPFD impacts plant growth, leaf shape and the accumulation of antioxidant phenols (Son and Oh, 2013).

The profound growth resulting from the narrow wavelength bands of R/B LEDs can be attributed to their considerable overlap with the sensitivity of photosynthetic pigments in plant cells (Lichtenthaler, 1987). The same rationale exists between R/B LEDs and full-spectrum LEDs as with conventional lamps; a higher supply of relevant PAR is delivered to plants with the same amount of electricity used. Despite positive results from R/B LED lights, it remains disputed in both research and industry sectors whether only providing R and B spectra is most beneficial for plant development. There have been reported benefits of including green (G) LEDs for plant growth and metabolic processes, as well as yellow (Y) LEDs for chlorophyll and carotenoid production (Cui *et al.*, 2009), suggesting that full-spectrum LEDs may be more beneficial for plant growth and a wider range of crops.

Photoperiod is the third component of artificial lighting that impacts plant growth. Solar radiation is limited by Earth's rotation, geographic location, weather and season. Enclosed systems supplied by artificial lighting are not subject to day length, location or weather; light cycles can be simulated indoors that elicit unique results that could not have been attained in the field. Research has been done with LEDs altering the daily light cycle – or "photoperiod" – to study the effect on plant growth. An experiment with lettuce (*L. sativa*) found that altering three photoperiods resulted in unique differences in plant growth: (1) a single-cycle, 18/6hr photoperiod (i.e. 18 hours with light, 6 hours without light) with 290 μmol/m^2-sec PPFD showed greatest root fresh weight, leaf dry weight, and longest roots,

(2) a two-cycle, 9/3hr photoperiod showed greatest plant height and fresh shoot weight, and (3) a three-cycle, 6/2hr photoperiod showed greatest leaf width, number of leaves, and root dry weight (Kang *et al.*, 2013). Photoperiod has also been coupled with altered light quality in lettuce; red (R) and blue (B) LEDs each delivered 120 μmol/m^2-sec PPFD at differing photoperiods and light ratios (e.g. RB 12/12hr dark vs. R 8/RB 4/B 8/4hr dark) (Kunoi *et al.*, 2017). The results indicated alternating R/B light produced better yields than simultaneous treatment with both lights (Kunoi *et al.*, 2017).

When light is absorbed by a photosynthetic pigment, the resulting energy is (1) used for photosynthesis, (2) dissipated as heat, or (3) re-emitted through chlorophyll fluorescence (van Iersel *et al.*, 2016). The latter, chlorophyll fluorescence, is the red light at 695nm that is re-emitted after it hits a plant surface and can be easily measured. It is a reliable estimator of electron transport rate (ETR) – which is associated with a plant's actual photosynthetic rate – and can likewise be used to quantify heat dissipation through deduction (Zhen and van Iersel, 2017). Because of thermal dissipation, only ~84% of delivered light (i.e. PPFD) is absorbed by a plant leaf and used for photosynthesis (van Iersel *et al.*, 2016):

$$PPFD_{absorbed} = 0.84\ x\ PPFD \qquad \text{(Eq. 2.3)}$$

Though it lowers photosynthetic efficiency, thermal dissipation is necessary and actually regulated by plants to prevent photons from damaging tissues from light saturation (van Iersel *et al.*, 2016). As such, the ETR from plants gradually decreases after repeated light exposure because photoinhibition is upregulated to prevent damage; more light energy is released as heat, and photosynthetic efficiency decreases (van Iersel *et al.*, 2016; van Iersel

and Gianino, 2017; Zhen and van Iersel, 2017). Researchers have exploited the benefits of LED lighting in its ability to be programmed to provide specific light outputs based on biofeedback from plants being delivered light (van Iersel *et al.*, 2016). Pulse-width modulation (PWM) adjusts the duty cycle produced by the LED, turning LEDs on and off at a high frequency (10,000's of a second) (Zhen and van Iersel, 2017) (Fig. 2.9).

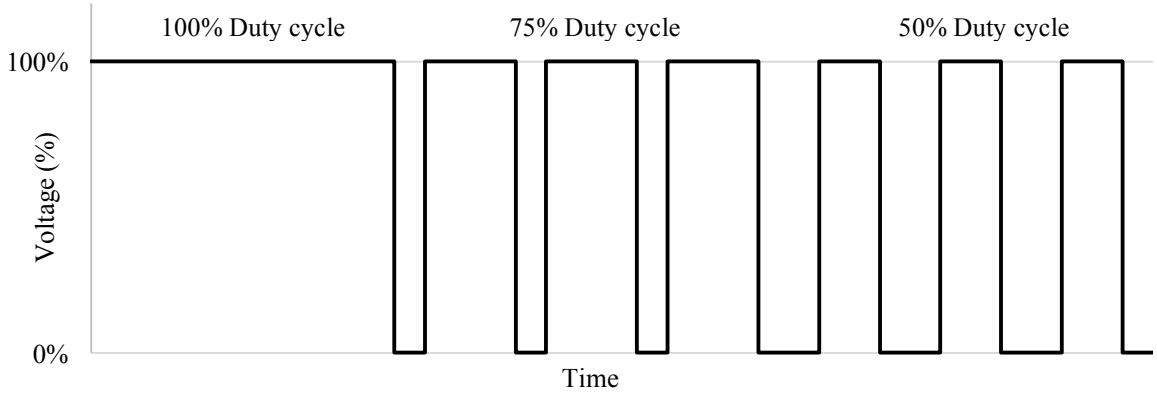


Figure 2.9. Simplified schematic with examples of duty cycles that can be programmed into LED lights with pulse-width modulation (PWM). Duty cycle is the percentage of time an LED is either "on" (producing its rated voltage) or "off" (producing no voltage).

Duty cycle is the percentage of time an LED is either "on" (producing its rated voltage) or "off" (producing zero voltage). In the 2016 study, ETR of the plants was measured through chlorophyll fluorescence, which determined when the LED duty cycle needed to be increased or decreased. These studies were novel in investigating selective control of LED light delivery based on plants' ability to efficiently use the light. Further investigating the impact of light/dark cycles on photosynthetic efficiency was an aim of this thesis research.

Light placement in enclosed systems also has an effect on crop productivity. LEDs are solid-state lights that have much lower heat transfer than fluorescent and HPS greenhouse lights (Massa *et al.*, 2008), allowing for LEDs to be brought much closer to plant surfaces

without causing light burning. Radiation energy received at a plant surface from the light source is related to the inverse square of the distance between the two points (Massa *et al.*, 2008). Eq. 2.4 displays this "Inverse Square Law," which states that brightness of the light source (B, in lumens/m^2) equals its luminosity (L, in lumens) divided by the squared distance between the light and plant, expressed as surface area of emitted light ($4\pi D^2$).

$$B = \frac{L}{4\pi D^2} \qquad \text{(Eq. 2.4)}$$

Plainly stated, lights that are closer to plants are able to provide more energy to them. This results in less energy needed to provide the same incident PPFD at the plant surface relative to a conventional lamp that would have to be placed at a farther distance to prevent burning.

Solid-state semiconductor technology gives LEDs longer operating lives, the ability to turn on/off instantly with no warm-up time, and allows for the integration of complex controls (Morrow, 2008). The many advantages of LEDs – namely its exponentially increasing efficiency and affordability, low heat transfer and high light output, and semiconductor technology – has resulted in innovations in lighting systems for plant production including: (1) side-lighting and (2) programmable lighting (Massa *et al.*, 2008), (3) plant factories for vertical farming (Kang *et al.*, 2013; Touliatos *et al.*, 2016), and (4) space systems providing fresh produce (Stutte, 2015).

CHAPTER 3: METHODS

3.1 System Design

The system was built in "Lab 4", a shop building in the BRAE department at Cal Poly. Space for the system was constrained to a 20 ft. x 20 ft. area in a section of Lab 4. Both components of the system – aquaculture and hydroponics – needed to be space-efficient.

A recirculating aquaculture system (RAS) was constructed for the "aquaculture" component because of the high stocking density of fish permitted in a small footprint, as well as added control relative to other aquaculture systems. A 300-gallon fish tank was joined to an AST Endurance nitrifying biofilter and solids separator via 2 in. Schedule 40 PVC pipe and fittings (Fig. 3.1), as well as to a Pondmaster 1200GPH pump that recirculated water. All pipe and fittings immediately downstream of the fish tank and biofilter were 2 in. diameter to minimize flow restriction due to sludge accumulation.

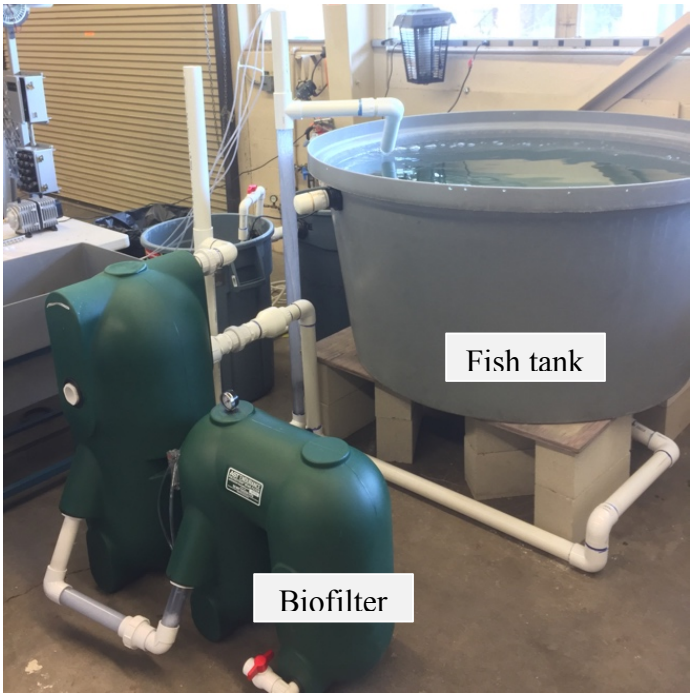


Figure 3.1. 300-gallon fish tank joined via 2 in. Sch. 40 PVC and fittings to a Pondmaster 1200GPH magnetic drive pump (not pictured) and biofilter/solids separator.

Fish were counted and weighed on 1/9/18 to determine the feed rate required for the experiment, as well as validate the size of the tank chosen for fish rearing. Three species of fish (bass, catfish, tilapia) totaled 59 kg biomass, 0.6 kg average weight per fish. Recommended feed rate for channel catfish at 21 – 24 ºC is roughly 1% of fish biomass in fish feed daily (Foltz, 1982). This would have been a feed rate of 590 g daily. However, the AST Endurance biofilter used was rated for 200 – 2000 gallons, with microbeads that provided a bacterial SSA of 0.75 ft^3 which could maintain TAN at or below 0.5 mg/L with a feed rate up to 454 g/day (ref: AST Endurance product manual). Because of the limitations of the biofilter, fish were only fed 400 grams daily of 41% protein "Purina Aquamax Sport Fish 500" to prevent excess nutrient load on the biofilter.

Split-flow was incorporated so partial flow was returned directly to fish tank, and remaining flow was diverted to plants before returning to the tank. Vertical farming technique was implemented for the "hydroponics" component of the system because it would allow the highest density of plants in the small space allotted in Lab 4 for the experiment. Nutrient Film Technique (NFT) was chosen as the hydroponic plant production method for being lightweight and affordable relative to other systems. A four-tiered shelving unit was acquired and installed, making it particularly suitable for creating multiple experimental factors related to plant production. The top three rows comprised the recirculating aquaponics system, and the bottom row the hydroponics system (Fig. 3.2).

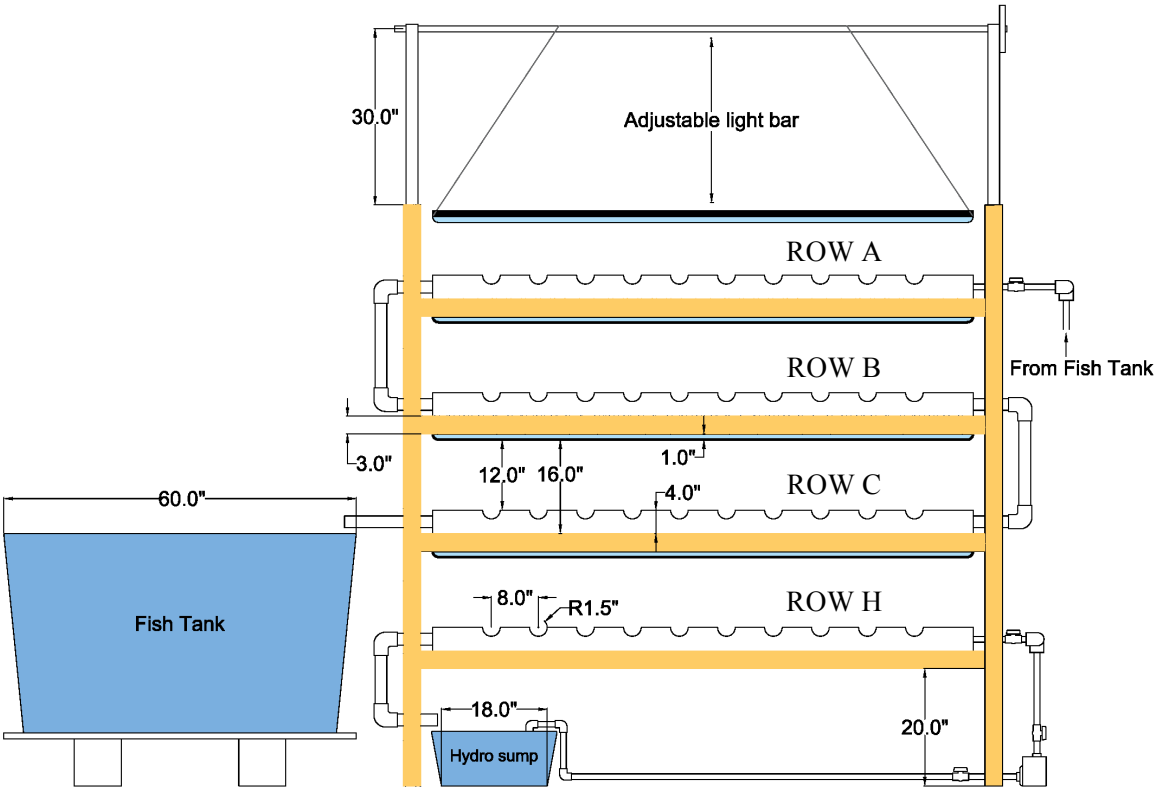


Figure 3.2. Front view of the system constructed for the experiment. The top three rows ("Rows A, B and C") received filtered water pumped from the fish tank; water gravity-flowed through all five columns of each row and back into the tank. The bottom row ("Row H") received water pumped from a separate sump and pump.

NFT columns were constructed using 4 in. PVC sewer drain pipe. This thin-walled pipe was chosen because it is far lighter and cheaper than Schedule 40 pipe. Thin-walls were not an issue because columns were designed to be gravity-fed rather than pressurized. A 4 in. diameter was determined sufficient to accommodate the relatively small root masses of leafy greens used in this experiment; however, a larger diameter (or larger plant spacing) would be needed for larger crops (e.g. tomato). Each of four rows of the shelving unit were equipped with five columns of 8 ft. lengths of PVC spaced 7 in. apart, totaling twenty NFT columns for all four rows. Ten 3 in. bores were drilled at 8 in. spacing in each column and staggered 4 in. between every column, resulting in an 8 x 7 in. plant spacing (Fig. 3.3).

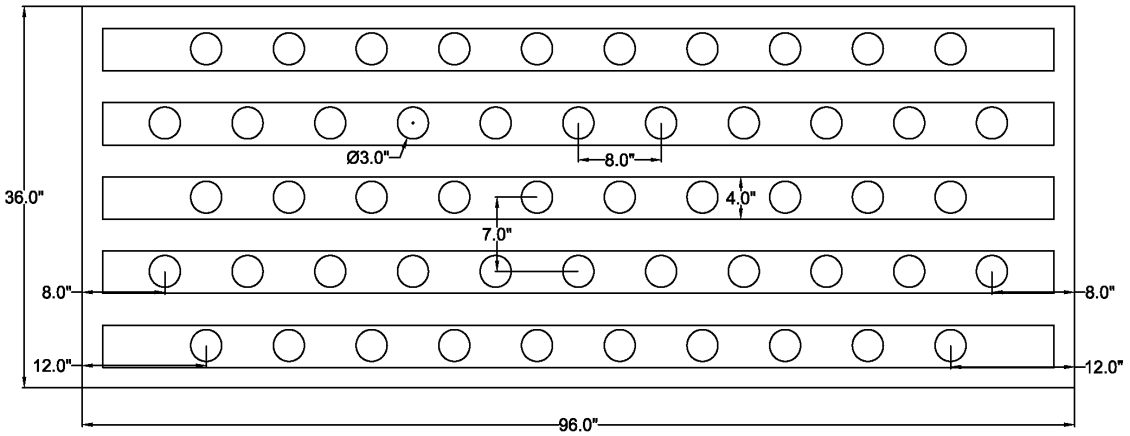


Figure 3.3. Top-down view of a row in the system constructed for the experiment. 8 ft. x 3 ft. shelving unit, five 4 in. diameter NFT columns per row, 92 in. NFT lengths. 3 in. holes to fit plant cups, 8 in. x 7 in. plant spacing along and between columns.

Weirs were made by lathing 2 in. holes through 4 in. PVC end caps, gluing a 2 in. adapter to the end caps, gluing the end caps to both sides of every NFT column, and applying a layer of silicone inside to seal the columns. This would create ~1 in. "film" of water within the columns that is desired for Nutrient "Film" Technique. Plant cups used to hold plants in their respective slots were 3 in. deep, allowing roots to reach the film of water in the 4 in. NFT columns. Each of five columns in the top three rows of the shelving unit were connected via 2 in. straight length of PVC pipe and elbows, and were joined by a union to make disassembly of NFT columns easier. A manifold joined five laterals with valves, unions, and fittings to connect to each of five NFT columns. The hydroponics system was a single shelf, and only needed 2 in. PVC pipe and elbows to drain water back into its sump. This construction process is further described in Appendix I.

A Pondmaster (PM) 1200GPH magnetic-drive utility pump was connected d/s of the 300-gallon fish tank, and u/s of the biofilter. Water was pumped up to the manifold of the top-most row and allowed to gravity-flow through the second and third rows before returning

to the fish tank. This pump was rated to provide ≥ 5 gpm for the aquaponics system (See section "3.3.6") with lifts higher than 10 ft (Fig. 3.4).

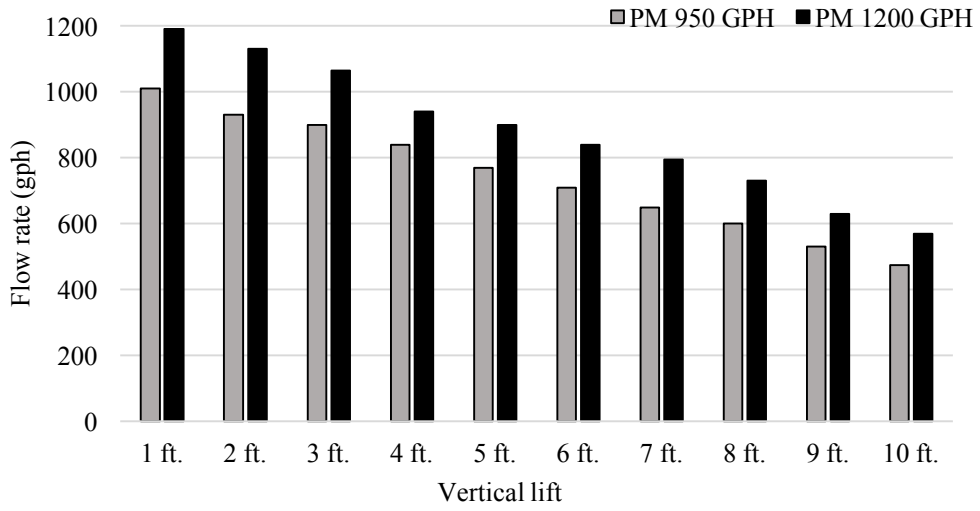


Figure 3.4. Performance chart of Pondmaster (PM) 950GPH and 1200GPH pumps used in hydroponics and aquaponics systems, respectively. Adapted from PM product manual.

Though the height between the water level of the fish tank and the upper manifold was only ~4 ft., there were losses to consider through the biofilter as well as all installed PVC valves and fittings, so the 1200GPH pump was conservatively chosen. The bottom-most hydroponic row was partitioned with its own 30-gallon water reservoir ("sump") and 950GPH pump – with the same columns, fittings and manifold as the aquaponics system – allowing water to return to the sump (Fig. 3.2). The hydroponic pump only needed to lift water 2 ft. and produce ≥ 5 gpm, and did not have any filter losses to consider. Though this pump was oversized (Fig. 3.4), it was chosen so the system had flexibility to be altered or expanded for future experiments. All nutrient and water additions were added to their respective reservoir (i.e. either to the fish tank or the hydroponic sump), and documented in separate files. The completed system can be seen in Fig. 3.5.

A)  B) 

Figure 3.5. A) Front view of fully assembled system: biofilter/solids separator (front), 300-gallon fish tank (back, left), and four-tiered shelving unit equipped with twenty LED light bars and NFT columns (back, right). B) Side view of shelving unit. Three rows of NFT columns were connected in series, allowing water to gravity flow back to fish tank.

3.2 Pilot Study

A pilot study was conducted by primarily freshmen in their course "BRAE 128: Careers in BioResource & Agricultural Engineering" during Fall 2017. Several plant varieties were grown over the course of 45 days on a 24-hr LED photoperiod – both aquaponic and hydroponic – in order to assess the suitability of certain leafy greens for this new system. This included romaine, butterhead, dwarf bok choy and dwarf Siberian kale. All four plant types grew well in both systems with bok choy appearing to have the strongest growth out of all four plant types, with little to no deformities. However, bok choy – even as a dwarf variety – outgrew the system after only 30 days (Fig. 3.6.A).

A)  B) 

C) 

Figure 3.6. A) Dwarf bok choy becoming crowded in the 8 in. x 7 in. spacing after 30 days into the 45-day pilot study. B) Butterhead lettuce on Day 30 without crowding issues. C) Romaine lettuce on Day 30 of pilot study showing signs of tipburn.

Bok choy grew over the other varieties, shading them and likely decreasing yield of the affected plants as a result. The 8 in. x 7 in. NFT plant spacing was more ideal for butterhead and romaine. Tipburn in both romaine and butterhead was evidenced in the last week of growth (Fig. 3.6.C), which could have been the result of poor airflow, nutrient deficiency

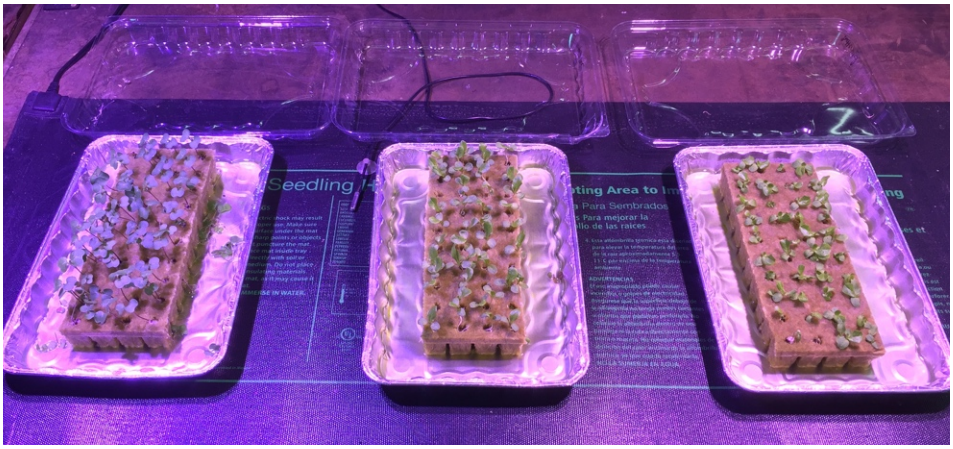
or excess light intensity (or all of these). For example, light intensity increases growth rate, increasing plant nutrient demand (particularly calcium). Poor airflow causes humidity to buildup, decreasing transpiration and likewise nutrient transport, resulting in tipburn.

3.3 Main Experiment

3.3.1 Plants: Germination

Heirloom, non-GMO organic seeds were purchased from Isla's Garden Seeds: (1) "Bronze Mignonette" butterhead lettuce (*L. sativa*), (2) red romaine lettuce (*L. sativa*), and (3) dwarf Siberian kale (*B. oleracea*). Butterhead, romaine and kale were chosen for the main experiment because of their successful growth during the pilot study. Seeds of all three plant varieties were planted in duplicates in 1 in. x 1 in. rockwool cubes. 40 rockwool cubes of each plant type were placed in a grow tray, totaling 240 seeds in 120 rockwool cubes in three separate trays (Fig. 3.7.A). Tap water was brought down to a pH of 5.6 with General Hydroponics "pH Down" phosphoric acid. Seeds were germinated with lids sealed for 48 hours on a grow mat heated to 28ºC. The lids were cracked to reduce humidity after the seedlings had sprouted. The lids were taken off completely two days after being cracked. Four 200W LED lights delivered an average of 150 μmol/m^2-sec to the seedlings on a 24hr light cycle for 10 days (Fig. 3.7.B). 0.1 g/L of "Jack's 20-20-20" fertilizer was supplemented for the final week of germination. The germination cycle totaled 14 days.

A)



B)

Figure 3.7. A) Three trays each contained 40 rockwool cubes, two seedlings per cube. A grow mat underneath maintained 28ºC temperature throughout the 14-day germination cycle. B) Day 14 of the germination cycle just prior to transplant. From left to right: dwarf Siberian kale, red romaine, "Bronze Mignonette" butterhead.

3.3.2 Plants: Transplanting to Aquaponics and Hydroponics Systems

Small and/or deformed seedlings were removed with tweezers from the rockwool cubes throughout germination. Each rockwool cube contained only one seedling at the time of transplant. Eight of the most robust plants of each plant variety were chosen to be transplanted into each of four rows of the NFT system. The plant breakdown in the system after transplant was three plant types, eight replicates of each plant type, 24 plants per row, and 96 plants total. Plants were transferred into 3 in. diameter plastic plant cups and secured

with Hydroton clay media (Fig. 3.8.A). Random plant placement assignments were made using Minitab software in order to minimize experimenter bias (Appendix J). Each plant within each treatment was given an identifying name (e.g. "A.4.3") describing the row/treatment (e.g. row/treatment "A" in "A.4.3"), the column number within the row/treatment (e.g. column "4" in "A.4.3"), and the slot number/location within the column (e.g. slot/location "3" in "A.4.3"). Plants were staggered between columns in each row, with one plant spaced in every other slot within an individual column (Fig. 3.8.B).

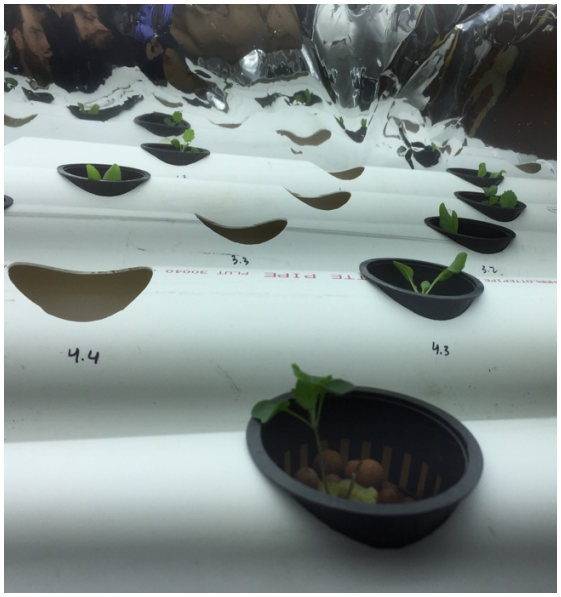
A)  B) 

Figure 3.8. A) Butterhead seedlings transferred into 3 in. diameter plastic plant cups with Hydroton media after the 14-day germination period. B) Seedlings randomly assigned within each row in staggered formation and in every other slot within each column.

This was done to minimize any anticipated shading that had been seen in the pilot study. All plants were grown for 31 days in the NFT system. In total, the plants were grown on a 45-day cycle from seed to harvest. At the end of the 45-day experiment, six of the eight plants of each plant variety within each treatment were chosen randomly using Minitab for collecting plant growth data (Appendix K). Six replicates were determined to be sufficient

for statistical analyses. The remaining plants (two of each variety per row) were designated for tissue analyses and potential losses throughout the experiment. Six replicates of each plant variety, three plant varieties, and four rows/treatments resulted in a total of 72 experimental units used for the experiment.

3.3.3 Aquaponics System: Water Quality Parameters

Four main parameters were measured daily to ensure fish, bacteria and plants remained healthy throughout the plant experiment: pH, dissolved oxygen (DO), temperature, and electrical conductivity (EC). The former two parameters, pH and DO, were especially important for fish and bacterial health. pH was measured with two Hach Pocket Pro pH meters (0.1 pH resolution, 0 – 14 range); probes were calibrated weekly. DO, temperature and EC were measured with a Hach HQ40D Portable Multi Meter (DO resolution of 0.01 mg/L with 0.01 – 20 mg/L range, temperature resolution of 0.1 ºC with 0 – 60 ºC range, EC accuracy of ± 0.5% from 1 µS/cm – 200 mS/cm). pH was maintained at 6.67 ± 0.13, DO at 7.41 ± 1.00 mg/L, temperature at 23 ± 1.3 ºC, and EC at 2.27 ± 0.18 mS/cm (Table 3.1). pH constantly decreased in the aquaponics system from fish and bacterial metabolism; carbonates were periodically added in the form of $KHCO_3$, K_2CO_3, and $CaCO_3$ whenever pH reached 6.6 or lower (Appendix A). DO was maintained with spherical air stones from three different sources: (1) compressed air tank in the BRAE sheds, (2) Eco-Plus 951 GPH air pump, and (3) Invacare Platinum XL oxygen concentrator (94% O_2, 4 LPM). Temperature was maintained using a 200W coiled water heater. EC increased throughout the experiment because of the consistent feed rate without a balanced amount of plants to match these additions. EC began at 1.89 mS/cm on Day 1 of the experiment, 1/14/18, and

ended at 2.55 mS/cm on the last day, 2/15/18 (Appendix C). This was not considered to be a major issue because of the increase in nutrient demand as plants grew larger. Periodic water exchanges were done to keep EC within a manageable range.

3.3.4 Hydroponics System: Water Quality Parameters

pH, dissolved oxygen (DO), temperature, and electrical conductivity (EC) were also measured daily in the hydroponics system throughout the experiment with the same instrumentation (Appendix B). pH was maintained at an average of 5.71 ± 0.18, DO at 8.65 ± 0.39 mg/L, temperature at 23 ± 1.5ºC, and EC at 1.82 ± 0.17 mS/cm (Table 3.1). Contrary to the aquaponics system that needed pH brought up, pH needed to be lowered in the hydroponics system whenever top-off water was added. General Hydroponics (GH) "pH Down" phosphoric acid was periodically added to target a pH of 5.7 (Appendix D). Carbonates were added to buffer the system and increase pH when it was below 5.6. DO was maintained using a single air stone from a 5W aquarium air pump. Temperature was maintained using a 200W coiled water heater. EC was controlled with synthetic hydroponic fertilizers; GH "FloraDuo" A&B 2-part nutrient solution was added to the 100L hydroponic sump in a 2:1 ratio of A:B to reach an initial EC of 1.47 mS/cm on 1/14/18, Day 1 of the experiment. The ratio was determined per the recommendations from GH; EC was chosen based on common ranges used for lettuce in hydroponics. EC was increased to 2.17 mS/cm by the last day, 2/15/18. EC was gradually increased to (1) provide more nutrients as plants grew larger, and (2) imitate what was happening in the aquaponics system from the fish feed rate.

Table 3.1. Averages, medians, and standard deviations of four water quality parameters measured daily in both aquaponics and hydroponics systems from 1/14/18 – 2/15/18.

	Aquaponics				Hydroponics			
	pH	**DO**	**Temp**	**EC**	**pH**	**DO**	**Temp**	**EC**
Avg.	6.67	7.41	22.9	2.27	5.71	8.65	23.3	1.82
Median	6.70	7.62	23.0	2.27	5.70	8.60	23.4	1.82
St. dev	0.13	1.00	1.30	0.18	0.18	0.39	1.54	0.17

3.3.5 Lights: Specifications and Experimental Treatments

Five 8 ft. long full-spectrum T8 LED light bars were installed in each row 12 in. directly above the base of each NFT column. "Row A" was an exception, whose light bars were mounted to the adjustable frame that was designed to keep LEDs 4 in. from the plant surface and move as they grew larger throughout the experiment. Wiring from the five light bars of each row were spliced together in series and sealed with silicone to prevent water damage. A detailed specs list of the LEDs can be found in Table 3.2.

Table 3.2. Specifications of the T8 LED light bars used in the experiment.

Model:	T8 Integrated V-Shaped LED, 8ft. length
Power/Voltage:	65W, AC85-265V
Lumens:	100 Lm/W
Frequency:	60Hz - 50Hz
Color temp:	"Cold white" 6000-6500K
Life:	50,000 hrs
Misc.:	270° Beam angle, >0.90 Power factor

A 16/8hr photoperiod was chosen to be the "standard" rather than a 24-hour photoperiod used in the pilot study to minimize plant defects from inadequate airflow. Plants from Row A were grown on a reduced 12/12hr photoperiod with PPFD of 289 ± 13 μmol/m^2-sec; plants from Row B were grown on an altered 2/1hr photoperiod with avg. PPFD of 268 ± 29 μmol/m^2-sec; Row C was the control, with a standard 16/8hr photoperiod and avg.

PPFD of 244 ± 38 μmol/m^2-sec. Row H's photoperiod was matched with Row C for the nutrient experiment (i.e. C vs. H) Row H's light intensity was roughly matched with Row C as well, with avg. PPFD of 246 ± 27 μmol/m^2-sec. Table 3.3 further illustrates the experimental treatments, PPFD, DLI, as well as experimental units used (i.e. plant types and number of plants used per treatment).

Table 3.3. Experimental treatments (nutrient solution, photoperiod, PPFD) and units (plants). Rows A-C had the same nutrients with varied photoperiod and light intensity. Row H vs. Row C had different nutrients with same light treatment. Six replicates of three plant varieties per treatment, totaling 18 plants/row and 72 experimental units total.

Row	Water source	Photo-period	PPFD (μmol/m^2-sec)	DLI (mol/m^2-day)	Plant types	plants/ treat.	plants/ row
A	aquaponic	12/12 hr	289 ± 13	12.5 ± 0.6	3	6	18
B	aquaponic	2/1 hr	268 ± 29	15.4 ± 1.7	3	6	18
C	aquaponic	16/8 hr	244 ± 38	14.1 ± 2.2	3	6	18
H	hydroponic	16/8 hr	246 ± 27	14.2 ± 1.6	3	6	18

The light treatment in Row A integrated adjustable lighting that kept the LEDs 3-6 in. above the plant surface throughout the duration of the experiment. The other rows had fixed lighting 12 in. above the base of each plant (not the plant surface, as this distance decreased throughout the growth cycle). The adjustable lighting in Row A created higher relative light intensity than the other treatments with the same instantaneous energy output (i.e. with five identical T8 LED light bars) because the distance between light and plant surface was decreased (Massa *et al.*, 2008). Row A's photoperiod was thus decreased to 12/12hr. If resulting plant growth was not negatively impacted, energy savings could be accomplished with this light treatment (i.e. 25% electricity savings with lights on 4 hours less per day). The light treatment in Row B was decided based on the findings from Kang et al. 2013 and van Iersel et al. 2016, 2017. In the 2013 study, the lowest photoperiod

interval used was a "three-cycle" (6/2hr); in this experiment, an "eight-cycle" interval (2/1hr) was chosen to study the effects of more frequent dark cycles on plant growth. Research from van Iersel et al. (2016, 2017) implemented pulse lighting on a much smaller scale (10,000 s of a second, rather than 2/1hr); however, a reduced photoperiod interval still investigated the theory that plants' photosynthetic efficiency can benefit from more frequent light/dark cycles. Row C was given a standard 16/8hr photoperiod with a PPFD that would benefit both leaf lettuce (*L. sativa*) and the more robust *Brassica* kale. Row H's photoperiod and PPFD were matched with Row C in order to compare plant growth differences from nutrient solution (i.e. aquaponics vs. hydroponics). LEDs from each of the four rows were plugged into four separate 15A-capacity 120V grow timers that were set to their respective photoperiod intervals.

3.3.6 Lights: Light Distribution Test

A light distribution test was done to determine the incident light that was being delivered to each plant in each treatment throughout the experiment. PPFD was measured at each plant location with an Apogee MQ-501 quantum sensor (180º field of view, 0 – 4000 μmol/m^2-sec PPFD range, 389 – 692 nm spectral range, ± 5% uncertainty) (Fig. 3.9.A). The LED light bars were installed 12 in. above the surface of the NFT columns, which is where the base of each plant was set. The Apogee sensor was ~2 in. tall, so all PPFD readings were standardized to a distance of 10 in. from the LED lights (Fig. 3.9.B). The exception was in Row A because of its adjustable lights; LED light bars were positioned 6 in. above the surface of the NFT columns for its light test. Detailed results of the PPFD at each plant location can be found in Appendix F.

A) 

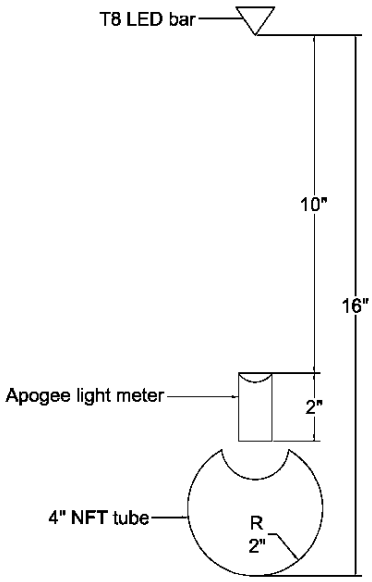
B) 

Figure 3.9. A) Apogee Instruments MQ-501 quantum sensor used to measure PPFD (µmol/m^2-sec) being delivered to each plant within the system. B) Side-view of system (Rows B, C, H); Apogee light meter measured PPFD delivered to each plant in system.

3.3.6 Additional Tests and Monitoring

A flow rate test was conducted after the light intensity test to ensure nutrients were adequately and similarly delivered in different nutrient treatments (i.e. aquaponic Row C vs. hydroponic Row H). This consisted of collecting water from each NFT column and measuring the volume of water collected over time (Fig. 3.10).

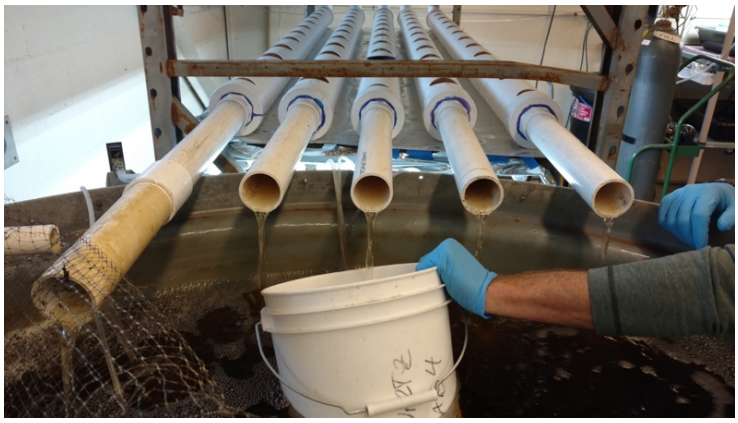


Figure 3.10. Flow rate test conducted just prior to transplanting plants. The aquaponics (pictured) and hydroponics systems were matched to produce 1 gpm per NFT column.

The targeted flow rate in the aquaponics system in part was dependent on the AST Endurance biofilter. A flow rate is recommended that will circulate the entire volume of water in the system every hour. The system was roughly 300 gallons; thus, the targeted flow rate was 5 gpm. The 1 in. valves connected at the upstream end of the NFT columns were adjusted so that each of five NFT columns in the aquaponics system produced 1 gpm of flow. The hydroponics system's flow rate through each NFT column was then matched with the aquaponics system (Appendix H). Flow rate was also important to prevent areas around the root zone from becoming anaerobic, and to provide an adequate nutrient replenishment for all plants along the lengths of the columns.

Two main environmental parameters were measured inside the system, as well as in the Lab 4 building Air temperature was measured in all four rows of the system and Lab 4 with "Onset HOBO Pendant" data loggers (-20 – 70 ºC range, 0.14 ºC resolution at 25 ºC). Relative humidity (RH) was also measured with an Elitech GSP-6 data logger (10 – 99%RH range, 0.1%RH resolution) in Row C and compared to Lab 4. Sensors of both HOBO and Elitech devices were placed in the direct center of each row to model the regions that experienced the highest air temperature and humidity. Sensors in Lab 4 were placed away from the system on a table with no nearby obstructions.

Water samples were collected from both aquaponics and hydroponics systems on Day 15, 25, 35 and 45 and sent to Fruit Grower's Laboratory (FGL) to be analyzed for their nutrient profiles. Alkalinity ($CaCO_3$), bicarbonate (HCO_3^-), boron (B), calcium (Ca^{2+}), carbonate (CO_3^{2-}), chloride (Cl^-), copper (Cu^{2+}), EC, iron (Fe^{2+}), magnesium (Mg^{2+}), manganese

(Mn), nitrate (NO_3^-, NO_3-N), pH, potassium (K^+), sodium (Na^+), sulfate (SO_4^{2-}), and zinc (Zn^{2+}) were measured. Original reports from FGL can be found in Appendix E. In addition to water sampling, plant tissue was also sampled on a subset of plants on the day of harvest (Day 45 from seed), which can be found in Appendix E. Last, growth pictures were taken periodically (Day 15, 25, 35, 45) of a random sampling of plants.

3.3.7 Response Variables

Multiple response variables were investigated to accurately describe plant growth. It was apparent that plant growth cannot be determined based on yield alone (i.e. dry weight of biomass) because of the many other factors involved in plant structure and health. The following response variables were measured to describe plant growth between treatments: (1) fresh weight of leaves, (2) dry weight of leaves, (3) dry weight of roots, (4) number of leaves per plant, number of deformed leaves per plant, (6) leaf length (L), (7) leaf width (W), (8) L:W ratio, and (9) stem length. The dry weights of leaves and roots were obtained by placing each individual sample in its own pre-weighed, labeled paper bag and dried in an oven at 103ºC for 72 hours before being weighed. Fresh weight of leaves (and stem) from each sample was recorded prior to being placed in the oven. Leaves were individually counted and measured with a ruler by length and width, and checked for any noticeable deformities (e.g. “burning”, “chlorosis”, “mottling”, “necrosis”, or “stunting”). Stem length was measured with a ruler.

3.8 Experimental Plan

The nutrient solution part of the experiment was a balanced, randomized factorial design. The independent variables (IV) were the nutrient source (i.e. aquaponic, hydroponic) and plant type (butterhead, romaine, kale); dependent variables (DV) were the mentioned response variables. The LED light variation part of the experiment was also a balanced, randomized factorial design, with IV's being light treatment (12/12hr w/ adjustable lighting, 2/1hr, 16/8hr) and plant type; DV's were also the mentioned response variables. Levene's statistical tests were done to assess equal variance among response variables. One-way Analyses of Variance (ANOVA) were used with either "Tukey" or "Dunnett" pairwise comparisons at 95% confidence to determine the means of each treatment, differences of means between treatments, confidence bounds of these differences, standard error of these differences, and associated p-values of each comparison. Tukey comparisons were used for nutrient solution treatments (i.e. "Row C" vs. "Row H") as well as PPFD results from the light tests, while Dunnett comparisons were used for the light treatment portion of the experiment (i.e. "Row A" and "Row B" vs. the control, "Row C"). Dunnett comparisons are slightly different than Tukey because they allow for a control treatment to be assigned ("Row C"). General Linear Models (GLM) were also fitted for the light treatments' response variables to determine if differences in PPFD had a significant effect on the results. Random assignments were always generated with MiniTab software.

CHAPTER 4: RESULTS

4.1 Water Quality (WQ) Parameters

Results of the four WQ parameters measured from 1/15/18 – 2/14/18 are graphed below.

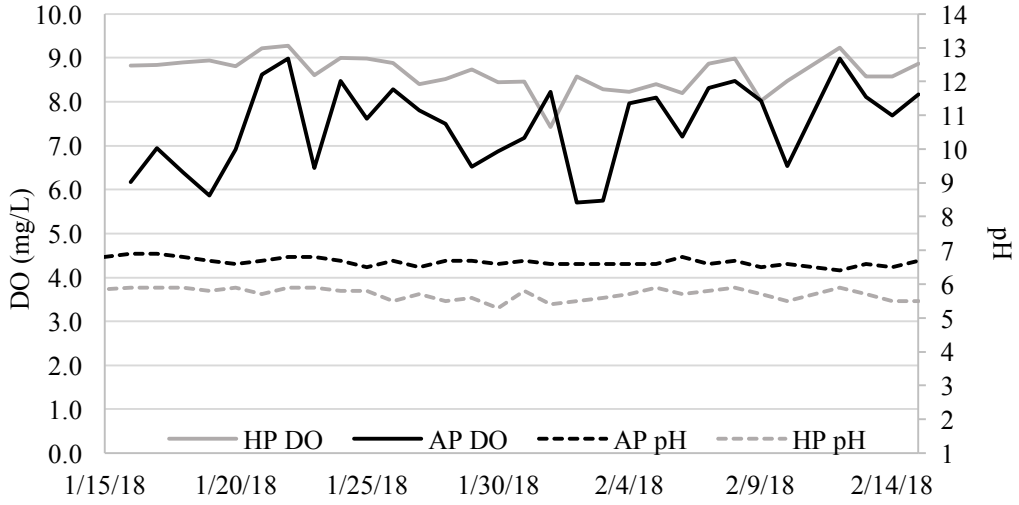


Figure 4.1. Daily measurements of pH and dissolved oxygen (DO) in both systems.

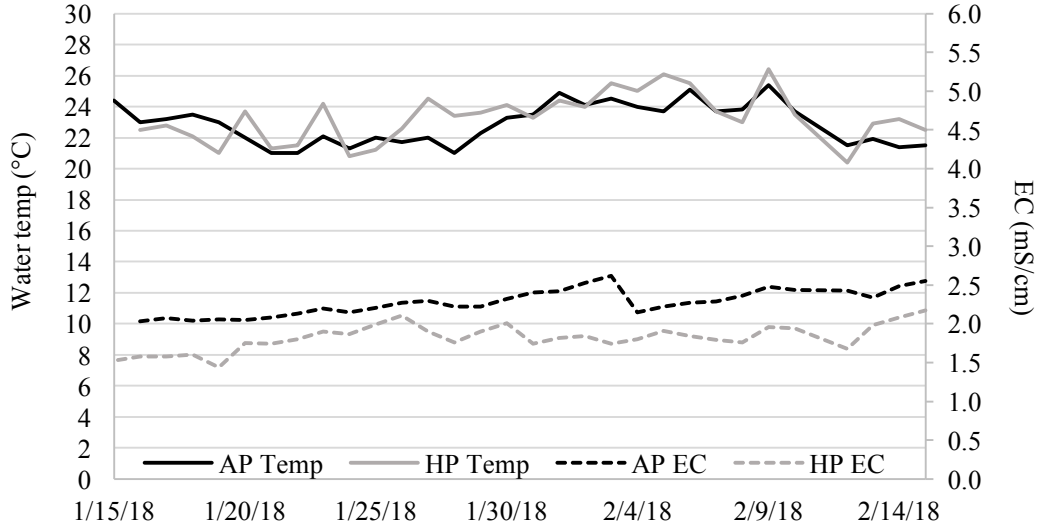


Figure 4.2. Daily measurements of water temp. (°C) and electrical conductivity (EC).

4.2 Light Test Results

Light tests modeled the actual light intensity delivered to each of six plant replicates within each treatment. This was meant to substantiate theoretical light intensities. Row A had a reduced photoperiod (12/12hr) relative to both Row C (16/8hr) and Row B (2/1hr, 16hrs

total light) because it was theorized that bringing the same number of lights closer to the plants would deliver a higher relative intensity. In a 24-hour period, Row A, in theory, would provide the same amount of light as the other treatments. Rows B, C and H were theorized to be the same, as they all had the same number of lights and plant spacing.

For butterhead, the only significant difference in PPFD delivery was between Row A and Row C light treatments (Levene's, p= 0.177; Tukey, p= 0.041) (Fig. 4.3). PPFD was higher in Row A than Row C by as much as 83.1 µmol/m^2-sec and as little as 1.6 µmol/m^2-sec. For romaine, the only significant difference in PPFD delivery was between Row A and Row C (Levene's p= 0.436; Tukey, p= 0.012) (Fig. 4.4). PPFD was higher in Row A than Row C by as much as 108.8 µmol/m^2-sec and as little as 13.6 µmol/m^2-sec. PPFD was not significantly different between kale replicates in any of the light treatments (Levene's, p= 0.188; ANOVA, p> 0.05) (Fig. 4.5). See Appendix G for statistics.

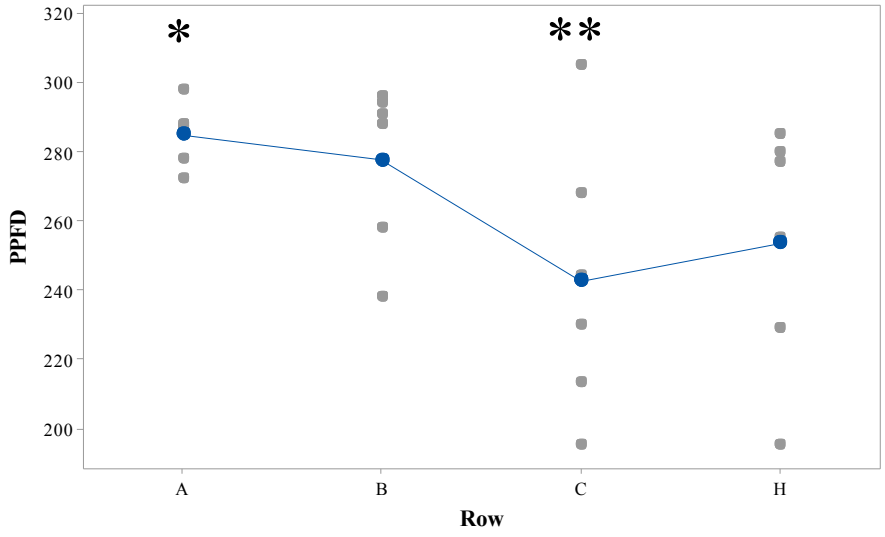


Figure 4.3. Butterhead Individual Value Plot of PPFD (µmol/m^2-sec), delivered in each treatment. There was only a significant difference between A-C light treatments (p= 0.041).

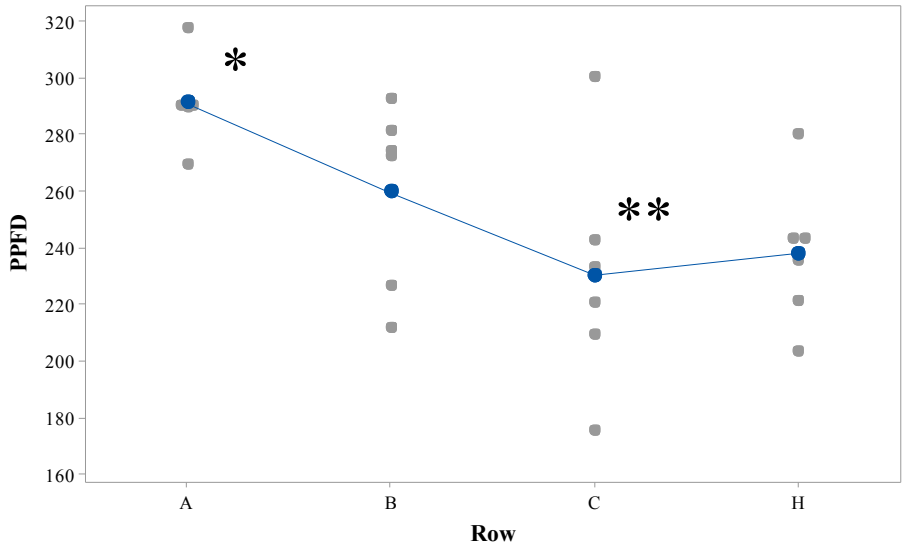


Figure 4.4. Romaine Individual Value Plot of PPFD (µmol/m^2-sec) delivered in each row. There was only a significant difference between A-C light treatments (p= 0.012).

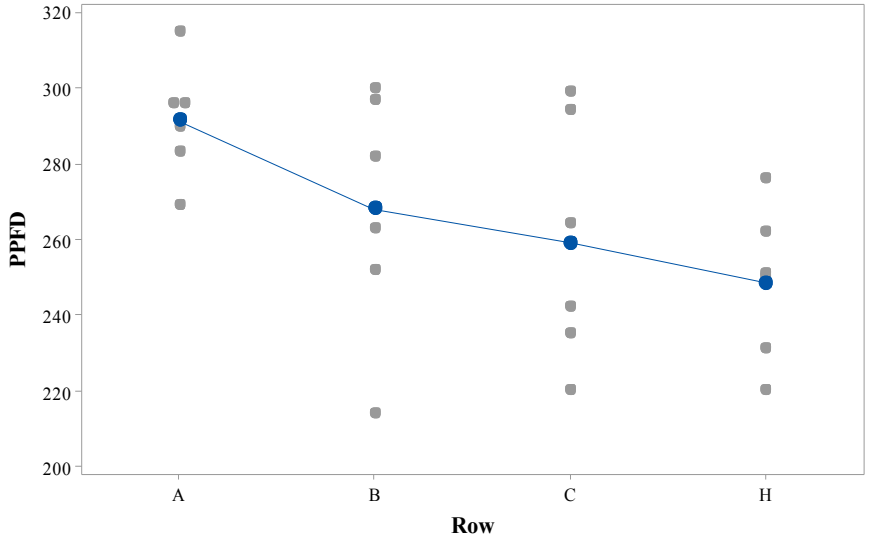


Figure 4.5. Kale Individual Value Plot of PPFD (µmol/m^2-sec) delivered in each row/treatment. There were no significant differences between any treatments (p> 0.05).

4.3 Environmental Conditions in System and Lab 4

Air temperature was measured from 1/22 – 2/15/18 in each row (Row A, B, C, H) as well as outside of the system in Lab 4. Relative humidity (RH) was measured the last 10 days of the experiment (2/5 – 2/15/18) in both Row C and Lab 4. See Table 1. Temp and RH measurements were taken every 15 minutes. Detailed figures can be found in Appendix L.

Table 4.1. Air temperature and relative humidity (RH) measurements taken throughout the experiment. Air temp. was recorded from 1/22 – 2/15/18, and RH from 2/5 – 2/15/18.

	Air Temp.	%RH
ROW A	24.0 ± 3.0 ºC	
ROW B	25.0 ± 2.8 ºC	
ROW C	24.8 ± 3.1 ºC	76.4 ± 7.17%
ROW H	24.5 ± 2.1 ºC	
LAB 4	20.8 ± 2.5 ºC	42.4 ± 6.3%

4.4 Response Variables

Response variables were measured in nutrient solution treatments and light treatments and statistically analyzed using MiniTab software. Fresh and dry weights indicated the rate of biomass production (i.e. the amount a plant grew), and were primary response variables in assessing plant growth. Supplementary response variables were also measured (root yield, # of leaves, # of deformed leaves, leaf length, leaf width, L:W ratio, stem length) to further profile plants grown in each treatment to better assess plant "quality." The following figures and statistics further describe the response variables in Appendix M: (1) Interval Plots describing the means and deviations of each plant type between treatments, (2) Interaction Plots determining whether responses to treatments were disproportional between plant types, (3) ANOVA Tukey/Dunnett statistics, and (4) GLMs.

4.4.1 Nutrient Solution Treatments: Plant yield

There was no significant interaction between nutrient solution treatment and plant type for either fresh or dry weights of leaves ($p >> 0.05$); plant yield responses were proportional between all plant types across nutrient treatments. As seen in Table 4.2, butterhead lettuce and kale both showed no significant differences in either fresh or dry yields from nutrient solution treatments (Tukey 95% CI, $p >> 0.05$). Romaine lettuce fresh and dry yields were

both greater in hydroponics "Row H" than aquaponics "Row C" by 18.4% and 27.0%, respectively (Tukey, p= 0.024 fresh, p= 0.027 dry).

4.4.2 Nutrient Solution Treatments: Plant quality

As seen in Table 4.2, all three plant types showed no significant differences in # of leaves, or # deformed leaves/plant from any of the nutrient solution treatments (Tukey, p> 0.05). Kale mean root yield was greater in aquaponics than hydroponics by 125% (Tukey, p= 0.008). Romaine mean leaf width was greater in hydroponics vs. aquaponics by 19.2% (Tukey, p<< 0.05). Kale mean leaf length was greater in aquaponics vs. hydroponics by 15.1% (Tukey, p=0.025). Romaine mean L:W ratio was greater in aquaponics vs. hydroponics 18.2% (Tukey, p<< 0.05). Butterhead mean stem length was greater in hydroponics vs. aquaponics 45.5% (Tukey, p= 0.041).

Table 4.2. Response variables from nutrient solution treatments by plant type (aquaponic "Row C" vs. hydroponic "Row H"). Treatments within a plant type that do not share the same letter are statistically different.

	Nutrient Solution Treatments					
	Butterhead		Romaine		Kale	
Response Variable	ROW C	ROW H	ROW C	ROW H	ROW C	ROW H
Fresh weight, leaves	a	a	a	b	a	a
Dry weight, leaves	a	a	a	b	a	a
Dry weight, roots	a	a	a	a	a	b
# leaves/plant	a	a	a	a	a	a
# deformed…/plant	a	a	a	a	a	a
Leaf length (L)	a	a	a	a	a	b
Leaf width (W)	a	a	a	b	a	a
L:W Ratio	a	a	a	b	a	a
Stem length	a	b	a	a	a	a

4.4.3 Light Treatments: Plant yield

There was a significant interaction between light treatment and plant type for both fresh and dry weights of leaves (p= 0.042 fresh, p= 0.013 dry); plant yield responses were disproportional from at least one plant type across treatments. As seen in Table 4.3, butterhead lettuce and romaine both showed no significant differences in fresh or dry yields between light treatments (Dunnett 95% CI, p>> 0.05). Kale fresh and dry yields were greater in the "Row C" control – with 16/8hr photoperiod and fixed lighting – compared to "Row A" with 12/12hr photoperiod and adjustable lighting – by 65.2% and 74.4%, respectively (Dunnett, p= 0.013 fresh, p= 0.009 dry).

4.4.4 Light Treatments: Plant quality

As seen in Table 4.3, all three plant types showed no significant differences in dry root yield, # of leaves, or # deformed leaves/plant from any of the light treatments (Dunnett, p> 0.05). Butterhead mean leaf length and width were both greater in Row A compared to Row C by 16.8% and 17.6%, respectively (Dunnett, p= 0.003 length, p=0.002 width). Romaine mean leaf length was greater in Row C vs. Row B by 15.6% (Dunnett, p= 0.001). Kale mean leaf length was greater in Row C vs. Row B 17.1% (Dunnett, p= 0.043). Butterhead mean L:W ratio was greater in Row C vs. Row A by 11.5% (Dunnett, p= 0.022), and also greater Row C vs. Row B by 14.5% (Dunnett, p= 0.005). Kale mean L:W ratio was greater in Row C vs. Row B by (Dunnett, p<< 0.05). Butterhead mean stem length was greater in Row B vs. Row C by 26.2% (Dunnett, p<< 0.05).

Table 4.3. Response variables from light treatments by plant type ("Row A" and "Row B" vs. "Row C" control). Treatments within a plant type that do not share the same letter are statistically different.

	Light Treatments								
	Butterhead			Romaine			Kale		
Response Variable	ROW A	ROW B	ROW C	ROW A	ROW B	ROW C	ROW A	ROW B	ROW C
Fresh weight, leaves	a	a	a	a	a	a	a	ab	b
Dry weight, leaves	a	a	a	a	a	a	a	ab	b
Dry weight, roots	a	a	a	a	a	a	a	a	a
# leaves/plant	a	a	a	a	a	a	a	a	a
# deformed…/plant	a	a	a	a	a	a	a	a	a
Leaf length (L)	a	ab	b	ab	a	b	ab	a	b
Leaf width (W)	a	ab	b	a	a	a	a	a	a
L:W Ratio	a	a	b	a	a	a	ab	a	b
Stem length	ab	a	b	a	a	a	a	a	a

4.6 Macro- and Micronutrient Profiles: Nutrient Solution, Leaf Tissue

Macro- and micronutrients were quantified in both the two different nutrient solutions as well as in leaf tissues at time of harvest. Water samples were sent from aquaponics and hydroponics systems to Fruit Grower's Lab (FGL) every 10 days until harvest (Day 15, 25, 35, 45). Macronutrient (Fig. 4.6) and micronutrient profiles (Fig. 4.7) in water were generated from FGL results (Appendix E). On Day 45, ten of the remaining plants that were not to be statistically analyzed were sent to FGL for tissue sampling. Macronutrient (Fig. 4.8) and micronutrient profiles (Fig. 4.9) in plant tissues were generated from FGL results. The aim of collecting both water and tissue samples was to be able to compare nutrients supplied with nutrients actually taken up into biomass.

4.6.1 Nutrient Solution: Macronutrients

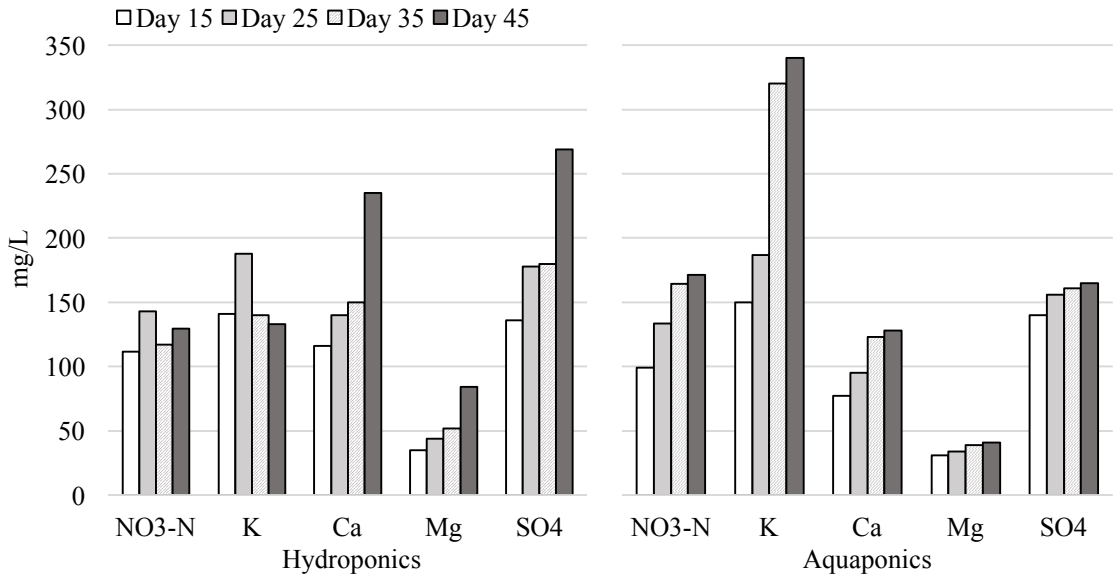


Figure 4.6. Macronutrient profile of both nutrient solutions sampled every 10 days in the system after transplanting (Day 15, 25, 35, 45). Courtesy of FGL.

4.6.2 Nutrient Solution: Micronutrients

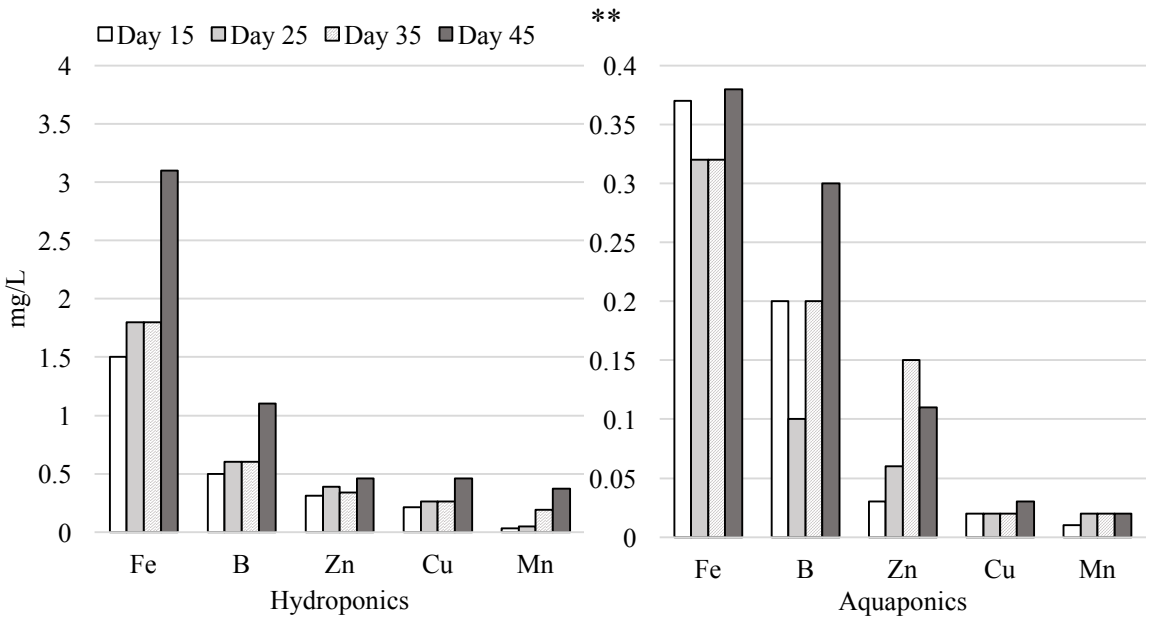


Figure 4.7. Micronutrient profile of both nutrient solutions sampled every 10 days in the system after transplanting (Day 15, 25, 35, 45). **Aquaponics scale 10:1. Courtesy of FGL.

4.6.3 Leaf Tissue: Macronutrients

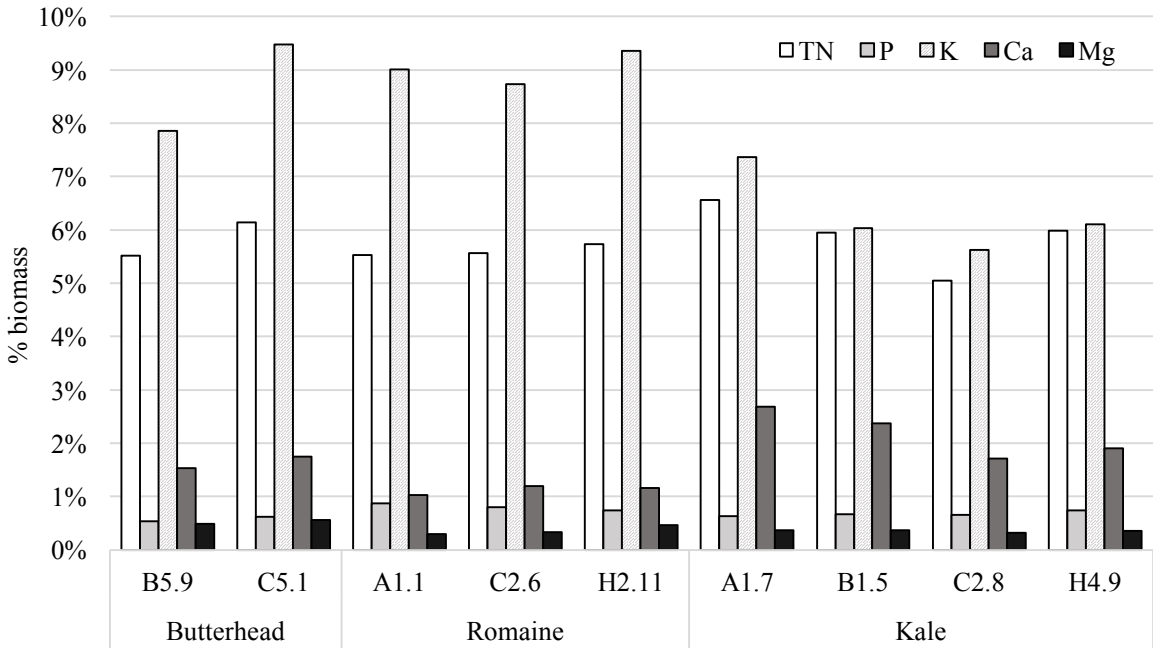


Figure 4.8. Leaf tissue macronutrient profile after harvest (Day 45). Courtesy of FGL.

4.6.4 Leaf Tissue: Micronutrients

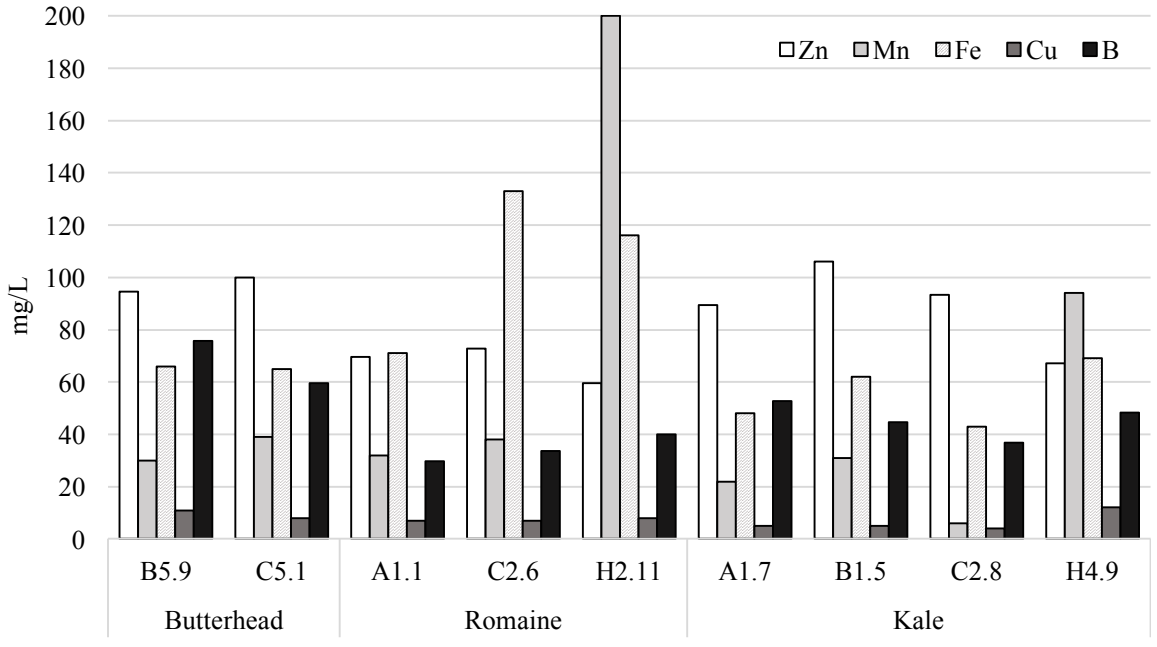


Figure 4.9. Leaf tissue micronutrient profile after harvest (Day 45). Courtesy of FGL.

CHAPTER 5: DISCUSSION

5.1 Discussion of Results

5.1.1 Water Quality Parameters (AP vs. HP)

As seen in Fig. 4.1, dissolved oxygen (DO) was more variable in aquaponics compared to hydroponics system (7.41 ± 1.0 mg/L vs. 8.65 ± 0.4 mg/L, respectively). This was likely due to fish respiration during feeding cycles; system DO substantially changes depending on the time of the measurement relative to time of feeding. Regardless, the DO was successfully maintained above 6.0 mg/L throughout the experiment, which were sufficient for fish, bacteria, as well as plants. Fig. 2 shows water temperature was more tightly correlated between aquaponics and hydroponics systems (22.9 ± 1.3 ºC vs. 23.3 ± 1.5 ºC, respectively). Both systems showed increases in water temperature at the end of January until roughly 2/10/18, which could be explained by the heat wave in San Luis Obispo that was recorded in air temp. measurements within Lab 4 (Fig. L.5, Appx. L).

pH was consistently higher in the aquaponics system compared to hydroponics because of the different conditions required by fish and bacteria relative to plants (Fig. 4.1). Fish and bacteria both prefer slightly basic conditions, but plant nutrients become less soluble as pH increases above neutral. A compromise was made in the aquaponics system, maintaining the pH slightly below neutral (pH 6.7 ± 0.13) to ensure nutrients were readily available to plant roots. The hydroponics system was maintained at an optimal level for plant nutrient uptake (pH 5.7 ± 0.18). Decreases in yield of aquaponic plants relative to hydroponics may be attributed to non-optimal pH.

EC was consistently higher in aquaponics than hydroponics (Fig. 4.2); however, unlike with pH, this was not intentional. The aquaponics system had a high density of fish relative to the amount of plants being grown for the experiment, resulting in an "unbalanced" system because of a higher nutrient load than plant uptake rate (Fig. 2.2). Two water exchanges – 10% exchange (~30 gallons) on 1/27/18 and 25% exchange (~100 gallons) on 2/2/18 – were done to bring EC down, which explain the drops in the EC curve seen in Fig. 4.2. Lettuce is considered "sensitive" to salinity, with a threshold EC of 1.5 mS/cm, while kale is "moderately sensitive" with a much higher threshold EC at 3.0 mS/cm (Table 2.6). As such, it may have been possible that butterhead and romaine yields were decreased in aquaponics relative to hydroponics because of EC reaching detrimental levels. In contrast, kale may have benefited from a higher EC in aquaponics relative to hydroponics because of a higher threshold, which could explain any increase in aquaponic kale yields. However, as non-optimal pH in aquaponics may have made less nutrients available to plants, a higher EC relative to hydroponics may have actually had a negligible effect on yield differences. Regardless, in future experiments it would be beneficial to either grow more plants or decrease the number of fish and feed rate to limit unbalanced variables.

5.1.2 Light Test Results

See Appendices F and G for test statistics and raw PPFD data. The light test results showed that PPFD had not been effectively matched either within or between treatments that were theoretically the same (i.e. same number of LEDs at same fixed distance with the same plant spacing). LEDs generally supplied more light to plants near the center of the rows than plants in outer columns and near the inlet/outlet. Row B with 2/1hr photoperiod was

intended to provide the same PPFD as the control, Row C, and only have altered photoperiod. Although the PPFD between Row B and C were not statistically different in any of the three plant types ($p > 0.05$), there was certainly a large variation within a given treatment. For example, a Row B butterhead sample ("B3.4") was supplied a PPFD of 296 μmol/m^2-sec, while a Row C butterhead ("C1.7") was provided 213 μmol/m^2-sec. The six butterhead replicates in Row B were supplied a mean PPFD of 278 ± 24 μmol/m^2-sec, while Row C were supplied a lower mean PPFD of 243 ± 40 μmol/m^2-sec. Similar trends were evident in romaine and kale as well. Row B did not result in statistically different plant yields relative to the control (Row C) in any of three plant types ($p > 0.05$); however, taking into consideration that Row B supplied more light energy to plants and still did not result in yield increases relative to Row C, it is likely that the lowered photoperiod interval of 2/1hr was not ideal compared to the standard 16/8hr photoperiod.

Row A was intended to supply a higher relative intensity to plants because of the decreased distance between LEDs and the plant surfaces, which justified decreasing the photoperiod to prevent this treatment from providing more light in a given day. However, with a 12/12hr photoperiod, Row A overall provided a lower "daily light integral" (DLI) than Rows B, C, and H (Table 3.3). In addition, the PPFD delivered by Row A was only statistically higher than the control (Row C) for butterhead and romaine, and not statistically higher than Row B in any of three plant types (Fig. 4.3, 4.4, 4.5). Kale ended up having statistically lower yields in Row A vs. Row C, but because PPFD was not statistically higher in Row A, this decrease in yield could have been due to light depravation rather than the intended treatment (i.e. decreased light distance and photoperiod). However, it is notable that even

with lower DLI that butterhead and romaine both did not result in lower yields than the control. Future experiments should match PPFD more effectively and further explore decreased LED-plant distance and photoperiods in lettuce.

5.1.3 Environmental Parameters (Air Temp., RH)

All four treatments in the system had similar air temperatures within 1 ºC of each other. However, the frequency of temperature changes varied greatly due to light treatment. For example, Row B had the most frequent variations because of its frequent on/off cycles from the 2/1hr photoperiod (Fig. L.3, Appx. L). There was also a general decrease in air temperature variation (i.e. smaller deviations from the mean) throughout the experiment. There was a heat wave from 1/29 – 2/10/18 that affected the air temperature within Lab 4 (Fig. L5), which decreased the difference in temperature between heat generated by LEDs and that of the building's ambient temperature. Increased air temperature late into the experiment was accompanied by high relative humidity generated by plants as they grew larger (76.4 ± 7.2% mean in Row C vs. 42.4% ± 6.3% mean in Lab 4, from 2/5 – 2/15/18) (Fig. L6). Humidity reached levels over 90%, which negatively impacts plant growth and increases disease susceptibility (Mashonjowa *et al.*, 2013). Fig. 5.1 shows a sample with fungal issues most likely due to high humidity coupled with poor air flow. Plants had been observed one week prior without evidence of disease or deformities, indicating that lack of environmental control may have had an impact. The plants were also at a harvestable size at this time, indicating in future experiments plants can be grown in as little as 38 days instead of a 45-day cycle from seed.

Figure 5.1. Butterhead sample at harvest (Day 45) showing fungal disease and bifurcation.

5.1.4 Response Variables: Plant yields

Among all response variables, plant yield was considered to be the most determining factor in assessing plant growth between treatments. The weight of the plant is overall the best physical assessor of growth, while the other variables chosen (e.g. root yield, stem length, leaf count and size) describe "quality" of growth. For example, a 10 g head of butterhead lettuce (dry weight) with a 4:1 L:W ratio vs. an 8 g butterhead with 2:1 L:W indicates that the larger head of lettuce also had much longer, slimmer leaves. Butterhead is a lettuce variety with broad leaves and a lower L:W ratio; the former treatment may have grown a larger head of lettuce, but it also resulted in unwanted characteristics (i.e. long, slim leaves).

Butterhead lettuce showed no differences in plant yields (fresh or dry weights) between light or nutrient solution treatments ($p > 0.05$). Out of the three plant types chosen, butterhead appeared to be the least sensitive to nutrient solution composition and to

changes in light quality, intensity, and photoperiod. Romaine lettuce yields did not differ due to any light treatments ($p > 0.05$), but yields did differ between nutrient solutions. Romaine plant yield, both dry and fresh weight, was greater in hydroponics than aquaponics ($p = 0.027$, $p = 0.027$). Though both lettuces belong to the same species (*L. sativa*), this variety appeared to prefer the conditions in the hydroponics system over aquaponics. Kale had the opposite yield response from treatments than romaine; yields differed due to light treatment but not nutrient solution treatment. Both kale fresh and dry yields were significantly lower in Row A with adjustable lighting and a shorter 12/12hr photoperiod interval than the control (Row C) with fixed lighting and a standard 16/8hr photoperiod ($p = 0.009$ dry weight, $p = 0.013$ fresh weight). Kale (*B. oleracea*) appears to have higher sensitivity to variation in light quality, intensity and photoperiod relative to *L. sativa*. However, the results of kale yields between Rows A and C should be taken with caution because PPFD was not statistically higher between these treatments.

5.1.5 Response Variables: Plant quality

Both lettuces (butterhead and romaine) did not show any significant differences between light or nutrient treatments for root yield ($p > 0.05$). Kale root yield did not differ due to light treatments ($p > 0.05$), but it was significantly lower in hydroponics compared to aquaponics ($p = 0.008$). Kale's response with root yield was opposite to that of plant yield; root yield varied based on nutrients, while plant yield varied based on light. This suggests that the size of roots for kale may be dependent on nutrients more-so than light, while the size of leaves is more dependent on light than nutrients. No leaf counts, deformed leaf count included, from any plant varieties significantly differed between any treatments ($p >$

0.05). Number of leaves, as well as severity of disease/deformity, is indicated to not differ based on nutrient or light source. However, this was accompanied by large amounts of variability within treatments. Increasing the sample size and/or designing a more effective way of quantifying deformities may reveal significance in future experiments.

Butterhead lettuce did not show any differences in leaf length, width, or L:W ratio between nutrient solutions ($p > 0.05$). Romaine showed both wider leaves in aquaponics compared to hydroponics ($p << 0.05$) and a greater L:W ratio in hydroponics vs. aquaponics ($p << 0.05$). Though both lettuce varieties, these results (as well as yield results) indicate that romaine is more sensitive than butterhead to nutrient solution treatment, and generally performed better in hydroponics than aquaponics. Butterhead may be the preferred variety for aquaponic vertical farms. Butterhead had both longer and wider leaves in Row A compared to the control (Row C), as well as a higher L:W ratio in Row C vs. Row A ($p << 0.05$); however, butterhead yields were not statistically different between these two treatments. This indicates that bringing LED lights closer to butterhead plants and shortening the photoperiod does not result in higher yields, but does result in longer and wider leaves relative to the control (i.e. alters morphology rather than biomass). Romaine also showed altered morphology due to LED light treatment; however, this was between Row B and the control. Decreasing the photoperiod interval from 16/8hr to 2/1hr resulted in shorter leaves in romaine ($p << 0.05$). Kale was sensitive to both nutrient solution and light treatments, with longer leaves in the aquaponic control compared to both Row H ($p = 0.025$) and Row B ($p = 0.043$). There was a considerable amount of variability in kale

results, which can be attributed to multiple experimenters doing leaf measurements as well as the difficulty in determining where "leaves" ended on each stalk.

Butterhead stem length was much longer in a reduced photoperiod of 2/1hr (Row B) compared to the control at 16/8hr (Row C) ($p= 0.00013$). Plant yield was not significantly different between B and C ($p >> 0.05$), so a longer stem cannot be attributed to a larger plant. Stem length 40 – 102 mm longer in Row B indicates this light treatment caused adverse effects on plant growth. Plants in this treatment had several instances of bifurcated stems with stunted leaves, as opposed to a healthy head of lettuce with uniform leaves emerging from a single stem. Longer stems are a symptom of stretching, a stressor that could be due to the frequent light/dark cycles relative to the control. Both romaine and kale did not have any statistically different stem lengths in either light or nutrient solution treatments ($p >> 0.05$).

5.1.6 Macro- and Micronutrients in Nutrient Solution and Leaf Tissue

The following table revisits recommended mineral nutrient concentrations for plants in standard hydroponics systems (Epstein and Bloom, 2005):

Macro-nutrient	**Concentration (mg/L)**	**Micro-nutrient**	**Concentration (mg/L)**
N, total	321 ± 130	Fe^{2+}	5.18 ± 1.79
PO_4^{3-}	36.9 ± 6.2	Cu^{2+}	0.042 ± 0.017
K^+	340 ± 101	Zn^{2+}	0.455 ± 0.374
Ca^{2+}	160 ± 10	Mn^{2+}	1.83 ± 0.96
Mg^{2+}	40.9 ± 3.3	$B(OH_4)^-$	0.573 ± 0.134
SO_4^{2-}	134 ± 53	MoO_4^{2-}	0.087 ± 0.037

According to the table and Fig. 4.6 and 4.7, both hydroponics and aquaponics systems provided several insufficient nutrients to plants. The hydroponic nutrient solution only provided sufficient sulfate (SO_4) (136 – 269 mg/L from Day 15 – 45), calcium (Ca) (116 – 235 mg/L), magnesium (Mg) (35 – 84 mg/L), boron (B) (0.5 – 1.1 mg/L) and zinc (Zn) (0.31 – 0.46 mg/L). The aquaponic nutrient solution only provided sufficient potassium (K) (150 – 340 mg/L), SO_4 (140 – 165 mg/L) and Mg (31 – 41 mg/L). Aside from K and nitrate nitrogen (NO_3-N), aquaponics provided fewer measured macro- and micronutrients than hydroponics. No aquaponic micronutrients were sufficient, not even iron (Fe) which was supplemented (Appx. C). Aquaponic micronutrients were plotted on a 10:1 scale because of how low the concentrations were relative to hydroponics (Fig. 4.7). EC in aquaponics was continuously higher than hydroponics throughout the experiment (Fig. 4.2); however, it is apparent that the ions comprising EC were not solely the essential mineral nutrients for plants. For example, sodium, chloride and bicarbonate ions in particular were much higher in aquaponics than hydroponic nutrient solutions (Appx. E), which may have contributed to the higher EC relative to hydroponics. Considering the aquaponics system provided less essential nutrients than hydroponics – and that plant yields in aquaponics were not significantly different than in hydroponics for butterhead and kale – this table of recommended nutrient concentrations is likely to be an overestimate. It is surprising, then, that aquaponics could provide similar yields to hydroponics (in butterhead and kale) with a non-optimal ratio of essential nutrients.

Two butterhead samples (B5.9, C5.1), three romaines (A1.1, C2.6, H2.11), and four kales (A1.7, B1.5, C2.8, H4.9) were sent to FGL for leaf tissue analysis. These were extra plants

grown in the system that had not been randomly chosen for response variable measurements. Twenty fresh leaves of each plant were required by the Lab for analyses, so fresh/dry yield could not be measured. However, possible differences in yields would not influence this data because macro- and micronutrients were measured as percentages of biomass and concentrations within tissue (respectively), as opposed to mass of nutrients in tissue. That being said, there are only single data points to represent experimental treatments, so any inferences drawn from the data cannot be backed by statistical evidence.

As seen in Fig. 4.8, total nitrogen (TN) and K were by far the highest expressed macronutrients in leaf tissue of all plant types across all treatments. TN and K are the highest supplied mineral nutrients in hydroponic fertilizers, which corresponds with the trend seen in leaf tissue. However, supplied K in nutrient solution was more than twice as high in aquaponics compared to hydroponics by Day 35 (Fig. 4.6), but this did not result in a corresponding trend in leaf tissue. In fact, two aquaponic samples for kale (B1.5, C2.8) had slightly lower %K in leaf biomass than in hydroponics (H). Aquaponic romaine (A1.1) also showed slightly lower %K in leaf tissue. Plant metabolic demand likely determined the nutrient uptake rate and ratio in plants, not the quantity or ratio of supplied nutrients between treatments. Nitrate nitrogen (NO_3-N) peaked at 171 mg/L in the aquaponics system by Day 45, which was ~40mg/L higher than hydroponics. %TN in leaf tissue did not deviate more than 1% between nutrient solution treatments within a given plant type.

Both NO_3-N and K appeared to have decreased in concentration by Day 45 in the hydroponic nutrient solution, indicating that these nutrients may have become limiting late

in the plant growth cycle because of their increasingly high demand as plants grew larger. Ca, Mg and SO_4 all began to accumulate by Day 45 – as well as the five micronutrients measured – indicating the proportion of mineral nutrients comprising EC was changing, despite EC being gradually brought up in the hydroponics system to account for growing plants. NO_3-N and K were decreasing in concentration, while the other nutrients were accumulating. In contrast, NO_3-N and K appeared to have accumulated in the aquaponics system by Day 45 – as well as the other macronutrients measured – indicating that the system was "unbalanced." The quantity and size of fish dictated the feed rate, which created a nutrient load greater than the nutrient demand by plants. Multiple water exchanges were necessary to bring down EC throughout the 31-days plants were in the aquaponics system (Appx. C) because of this unbalanced nutrient addition.

Micronutrients also showed non-proportional differences between supplied nutrients and leaf tissue uptake. Zn was supplied 4-6x higher in hydroponic nutrient solution compared to aquaponics by Day 45; however, [Zn] in leaf tissue was actually higher in aquaponics than hydroponics for both romaine and kale (Fig. 4.9). Fe was supplied more than 5x higher in hydroponic nutrients by Day 35 – and nearly 10x higher by Day 45; however, [Fe] was only slightly higher in hydroponic kale tissue, and actually higher in aquaponic romaine than hydroponic romaine. Copper (Cu) was more than 10x higher in hydroponic nutrient solution compared to aquaponics; however, [Cu] in leaf tissue was nearly identical for aquaponic vs. hydroponic romaine (7 mg/L vs. 8 mg/L, respectively). Boron (B) was more than 3x higher in hydroponic nutrient solution by Day 45, but was seen to be slightly higher in aquaponic kale tissue compared to hydroponic kale tissue (A1.7, H4.9). Manganese

(Mn) was a nutrient that was relatively proportional between concentration supplied in nutrient solution and concentration taken up into leaf tissue. [Mn] was over 6x higher in leaf tissue of hydroponic romaine (H2.11) compared to aquaponics (A1.1, C2.6), and also 3-15x higher in hydroponic vs. aquaponic kale. This was probably due to Mn being virtually non-detectable in aquaponic nutrient solution (0.01 – 0.02 mg/L).

Both hydroponic and aquaponic nutrient solutions appeared to have provided insufficient amounts of at least some mineral nutrients according to the literature (Epstein and Bloom, 2005). Aquaponics also supplied lower concentrations of most nutrients compared to hydroponics (K and NO_3 were exceptions), with a particularly large deficit of micronutrients. The hydroponics system was given a synthetic fertilizer solution with an ideal concentration of all essential macro- and micronutrients for leafy greens. In comparison, the aquaponics system relied on fish feed for mineral nutrients supplied to plants (in addition to added bicarbonates that supplied K and Ca). Alternative fish feeds designed for aquaponics rather than aquaculture can help supply more ideal concentrations of mineral nutrients for plants, which may have otherwise prevented more substantial growth in the aquaponic nutrient solution experiment.

5.2 Conclusions

5.2.1 Revisiting the Thesis Statement

The following conclusions were made based on the thesis statement made prior to executing the experiment:

"Thesis statement: (1) Aquaponics can provide more substantial nutrition for vertical farms compared to conventional hydroponics without decreasing plant yield or quality,"

With the given sample size and experimental methods, it was determined that both butterhead lettuce and kale plant yields – in leaf biomass – did not statistically differ between aquaponic and hydroponic nutrient solution. Because aquaponic yields were not lower than hydroponics for these two plant types, this portion of the thesis statement was achieved for butterhead and kale. Romaine may be less suited for aquaponic vertical farms based on the results. In terms of quality, there cannot be a definitive claim for or against aquaponics because of the limitations in quantifying this parameter. Future research will need to incorporate more effective variables to determine this.

"Thesis statement: (2) (a) decreasing LED photoperiod intervals from 16/8hr to 2/1hr will result in higher plant yields,"

Though plants have been implicated in benefitting from more frequent dark cycles (see Ch.2.6), a 2/1hr photoperiod did not result in larger plants. The light treatment with a decreased 2/1hr photoperiod interval (Row B) did not have higher yields in any plant types, nor did it have any higher measures of "quality" variables.

"Thesis statement: (b) decreasing the LED-plant surface distance by using adjustable lighting ~~will provide higher relative light intensity~~ than the other treatments with fixed

lighting, allowing for a lower photoperiod – and likewise less energy usage – relative to the control, and will not result in lower plant yields."

A strike-through in the thesis statement reflects a shortcoming of this experiment. It was theorized that decreasing the distance would provide higher intensity to plants relative to the other treatments; however, this was proven to only be true for butterhead and romaine plants in Row A vs. C. In addition, the 12/12hr photoperiod resulted in actually less light being delivered to plants within that treatment relative to other treatments. Any decreases in yield could have been attributed to less light being delivered to plants rather than the decreased LED-plant distance. However, even with less daily light being delivered, both butterhead and romaine had statistically similar yields between Row A and the control (Row C). These results suggest that butterhead and romaine can both be grown with 25% less energy than a standard 16/8hr photoperiod without seeing a decrease in yield.

5.2.2 Future Research and Closing Statements

Future research can overcome the shortcomings of this study in several ways. First, a larger sample size can be implemented to increase statistical power of the resulting data. There was generally a high standard error across variables for each treatment, which could have prevented significant differences between treatments from being seen. Focusing on a single plant type will also benefit research to limit the effects of interacting variables. Second, the next experiment should supply a lower stocking density of fish (or grow many more plants) to prevent the accumulation of nutrients (i.e. high EC) relative to the hydroponics system. Third, setting a growth cycle of 38 days rather than 45 days can potentially reduce

deformities in plants. For the most part, plants of all three plant types in every row appeared healthy and fully mature after 38 days; many deformities manifested in the final week. Fourth, the next experiment can more effectively match PPFD between treatments, as well as limit variation within treatments. If no other changes are made to the system, the treatment with adjustable lighting (Row A) can be set to a photoperiod of 14/10hr instead of 12/12hr to at least match the daily light output relative to the other treatments. A more substantial change can also be done to the system to limit variation within treatments: Rather than using five 8ft LED light bars that supply light for up to 50 plants per row – a single LED lamp per plant can be implemented with enclosures around each plant.

Despite its shortcomings, this thesis experiment was successful in demonstrating the potential place of aquaponics in future vertical farms in order to provide more substantial nutrition to consumers than current operations can provide. This experiment also attested to the unknowns in terms of the effect of light delivery on plant physiology, and suggests continued horticultural LED research in order to decrease overhead costs of vertical farms.

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Appendix A. Water Quality: Aquaponics

	pH	DO	Temp	EC
Avg.	6.67	7.41	22.9	2.27
Median	6.70	7.62	23.0	2.27
St. dev	0.13	1.00	1.30	0.18

DATE	TIME	pH	DO (mg/L)	Temp (°C)	EC (mS/cm)	Alk. (drops)	Alkalinity (mg/L CaCO3)	NH3-N (mg/L)	NO3-N (mg/L)
1/14/18	18:00	6.9	5.75	22	1.89		138	0	94
1/15/18	12:00	6.8		24.4				0.5	
1/16/18	10:30	6.9	6.17	23	2.03				
1/17/18	10:15	6.9	6.94	23.2	2.07				
1/18/18	11:00	6.8	6.39	23.5	2.04				
1/19/18	10:10	6.7	5.86	23	2.06				
1/20/18	13:00	6.6	6.91	22	2.05				
1/21/18	13:00	6.7	8.62	21	2.08				
1/22/18	10:00	6.8	8.99	21	2.13				
1/23/18	10:00	6.8	6.49	22.1	2.2				
1/24/18	10:00	6.7	8.48	21.3	2.15			0.25	138
1/25/18	10:00	6.5	7.62	22	2.21				
1/26/18	10:00	6.7	8.29	21.7	2.27				
1/27/18	10:00	6.5	7.8	22	2.3				
1/28/18	10:30	6.7	7.5	21	2.22				
1/29/18	10:00	6.7	6.52	22.3	2.22			0.25	137
1/30/18	10:00	6.6	6.87	23.3	2.32			102	
1/31/18	10:00	6.7	7.18	23.5	2.4				
2/1/18	10:00	6.6	8.22	24.9	2.42	4.5	76.95	0.5	
2/2/18	10:00	6.6	5.7	24.1	2.53				
2/3/18	10:00	6.6	5.75	24.5	2.62			0	110
2/4/18	10:30	6.6	7.97	24	2.15				
2/5/18	10:00	6.6	8.1	23.7	2.22				
2/6/18	10:00	6.8	7.21	25.1	2.27				
2/7/18	10:00	6.6	8.31	23.7	2.29				
2/8/18	9:30	6.7	8.47	23.8	2.36			0	164
2/9/18	10:00	6.5	8.02	25.4	2.48				
2/10/18	12:00	6.6	6.54	23.7	2.44				
2/11/18									
2/12/18	10:00	6.4	8.98	21.5	2.43				
2/13/18	10:00	6.6	8.11	21.9	2.34			0.25	194
2/14/18	10:00	6.5	7.68	21.4	2.49				
2/15/18	10:00	6.7	8.17	21.5	2.55				

Appendix B. Water Quality: Hydroponics

	pH	DO	Temp	EC
Avg.	5.71	8.65	23.3	1.82
Median	5.70	8.60	23.4	1.82
St. dev	0.18	0.39	1.54	0.17

DATE	TIME	pH -	DO (mg/L)	Temp (°C)	EC (mS/cm)
1/14/18	18:00	5.8	8.50	24.0	1.47
1/15/18					
1/16/18	10:30	5.9	8.83	22.5	1.58
1/17/18	10:15	5.9	8.84	22.8	1.58
1/18/18	11:00	5.9	8.90	22.1	1.60
1/19/18	10:10	5.8	8.94	21.0	1.44
1/20/18	13:00	5.9	8.81	23.7	1.75
1/21/18	13:00	5.7	9.22	21.3	1.74
1/22/18	10:00	5.9	9.28	21.5	1.80
1/23/18	10:00	5.9	8.60	24.2	1.90
1/24/18	10:00	5.8	9.00	20.8	1.87
1/25/18	10:00	5.8	8.99	21.2	1.99
1/26/18	10:00	5.5	8.88	22.6	2.11
1/27/18	10:00	5.7	8.40	24.5	1.90
1/28/18	10:30	5.5	8.52	23.4	1.76
1/29/18	10:00	5.6	8.74	23.6	1.90
1/30/18	10:00	5.3	8.45	24.1	2.01
1/31/18	10:00	5.8	8.46	23.3	1.74
2/1/18	10:00	5.4	7.43	24.4	1.82
2/2/18	10:00	5.5	8.57	24.0	1.84
2/3/18	10:00	5.6	8.29	25.5	1.74
2/4/18	10:30	5.7	8.23	25.0	1.80
2/5/18	10:00	5.9	8.40	26.1	1.91
2/6/18	10:00	5.7	8.20	25.5	1.84
2/7/18	10:00	5.8	8.86	23.7	1.79
2/8/18	9:30	5.9	8.99	23.0	1.76
2/9/18	10:00	5.7	8.02	26.4	1.96
2/10/18	12:00	5.5	8.48	23.5	1.94
2/11/18					
2/12/18	10:00	5.9	9.23	20.4	1.68
2/13/18	10:00	5.7	8.57	22.9	1.98
2/14/18	10:00	5.5	8.58	23.2	2.08
2/15/18	10:00	5.5	8.86	22.5	2.17

Appendix C. System Additions/Changes: Aquaponics

DATE	TIME	H3PO4 (mL)	KHCO3 (g)	K2CO3 (g)	CaCO3 (g)	EDDHA-Fe, 6% (g)	Fe, total (g)	Feed (g)	Tap water (gal)	Tap water (L)
1/13/18	15:00	55				8	0.48	600	300	1136
1/14/18	12:30	75						400		
1/15/18								400		
1/16/18								400		
1/17/18								400		
1/18/18								600		
1/19/18								600		
1/20/18	14:00			30	30			400		
1/21/18	13:30			30	30			400		
1/22/18								400	10	38
1/23/18								400		
1/24/18								400		
1/25/18	13:30			30	30			400		
1/26/18								400		
1/27/18	10:00			50	40			400	-30	-114
1/28/18	13:00		30		30			400	40	151
1/29/18								400		
1/30/18	18:00		90		50			400		
1/31/18	10:00							400		
2/1/18	10:00		50		40			400		
2/2/18	10:30		30		15			400	-70	-265
2/3/18	12:00					4	0.24	400	80	303
2/4/18	11:00		40		30			400		
2/5/18	12:00		50					400		
2/6/18	10:00			40	30			400	30	114
2/7/18	12:00		60		40			400		
2/8/18								400		
2/9/18	11:00			50	30			400	30	114
2/10/18								400		
2/11/18								0		
2/12/18	10:30		70		30			400	30	114
2/13/18	15:30		70		30			400		
2/14/18								400		
2/15/18										

	H3PO4 (mL)	KHCO3 (g)	K2CO3 (g)	CaCO3 (g)	Fe, total (g)	Feed (kg)	Tap water (L)
TOTAL (raw)	130.00	490.00	230.00	455.00	0.72	13.40	1589.70

Appendix D. System Additions/Changes: Hydroponics

DATE	TIME	H3PO4 (mL)	"A" 5-0-6 (mL)	"B" 1-5-4 (mL)	KHCO3 (g)	CaCO3 (g)	Tap water (gal)	Tap water (L)
1/13/18	16:20	75	200	100			32	120
1/14/18	12:00	60						
1/15/18								
1/16/18								
1/17/18								
1/18/18								
1/19/18	10:00	20	30	15				
1/20/18	10:00	10						
1/21/18	10:00	10	30	15			8	30
1/22/18								
1/23/18								
1/24/18								
1/25/18								
1/26/18	10:00	20	20	10				
1/27/18								
1/28/18	10:00						4	15
1/29/18								
1/30/18	10:00						4	15
1/31/18	10:00						4	15
2/1/18	10:00				5			
2/2/18	10:15		20	10			8	30
2/3/18	11:00				5.5			
2/4/18	11:00					5		
2/5/18	12:30	25	30	15			8	30
2/6/18								
2/7/18								
2/8/18	9:45	30	55	40			8	30
2/9/18								
2/10/18	12:00						4	15
2/11/18								
2/12/18	10:30	25	50	25			4	15
2/13/18								
2/14/18								
2/15/18								

	H3PO4 (mL)	"A" (mL)	"B" (mL)	KHCO3 (g)	CaCO3 (g)	Tap water (L)
TOTALS	275.00	435.00	230.00	10.50	5.00	317

Appendix E. FGL Lab Results

E.1 FGL Water Samples: Day 1 (Post-transplant)

E.1.1 Hydroponics System

ENVIRONMENTAL FGL AGRICULTURAL
Analytical Chemists

January 30, 2018
Cal Poly State University
HCS Department
1 Grand Avenue
San Luis Obispo, CA 93407-0861

Description : Hydroponics System 1
Project : CP BRAE Indoor Lettuce

Lab ID : CC 1880154-001
Customer ID : 8-30

Sampled On : January 16, 2018
Sampled By : Sean Foster
Received On : January 16, 2018
Matrix : Ground Water

Lettuce Irrigation Suitability Analysis

Test Description	Result				Graphical Results Presentation				
Cations	mg/L	Meq/L	% Meq	Lbs/AF	Good	Possible Problem	Moderate Problem	Increasing Problem	Severe Problem
Calcium	116	5.8	43	320	**				
Magnesium	35	2.9	22	95	**				
Potassium	141	3.6	27	380	**				
Sodium	24	1	8	65					
Anions									
Carbonate	< 10	0	0	0					
Bicarbonate	30	0.49	4	82	**				
Sulfate	136	2.8	23	370	**				
Chloride	26	0.73	6	71					
Nitrate	494	8	66	1300					
Fluoride	0.5	0.026	0	1					
Minor Elements									
Boron	0.50			1.4					
Copper	0.21			0.57					
Iron	1.5			4.1					
Manganese	0.030			0.082					
Zinc	0.31			0.84					
TDS by Summation	1000			2700					
Other									
pH	6.1			units					
E. C.	1.66			dS/m					
SAR	0.5								
Crop Suitability									
No Amendments	Poor								
With Amendments	Poor								
Amendments									
Gypsum Requirement	0.0			Tons/AF					
Sulfuric Acid (98%)	1.4			oz/1000Gal	Or 3.4 oz/1000Gal of urea Sulfuric Acid (15/49).				
Leaching Requirement	10			%					

Micro Irrigation System Plugging Hazard

Test Description	Result		Graphical Results Presentation		
Chemical			Slight	Moderate	Severe
Manganese	0.03	mg/L			
Iron	1.5	mg/L			
TDS by Summation	1000	mg/L			
No Amendments					
pH	6.1	units			
Alkalinity (As CaCO3)	20	mg/L			
Total Hardness	433	mg/L			
With Amendments					
Alkalinity (As CaCO3)	10	mg/L			
Total Hardness	4	mg/L			
pH	5.4 - 6.7	units			

Good Problem
Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

E.1.2 Aquaponics System

FGL ENVIRONMENTAL AGRICULTURAL
Analytical Chemists

January 30, 2018
Cal Poly State University
HCS Department
1 Grand Avenue
San Luis Obispo, CA 93407-0861

Description : Aquaponics System 1
Project : CP BRAE Indoor Lettuce

Lab ID : CC 1880154-002
Customer ID : 8-30

Sampled On : January 16, 2018
Sampled By : Sean Foster
Received On : January 16, 2018
Matrix : Ground Water

Lettuce Irrigation Suitability Analysis

Test Description	Result				Graphical Results Presentation				
Cations	mg/L	Meq/L	% Meq	Lbs/AF	Good	Possible Problem	Moderate Problem	Increasing Problem	Severe Problem
Calcium	77	3.8	18	210	**				
Magnesium	31	2.6	12	84	**				
Potassium	150	3.8	18	410	**				
Sodium	244	11	51	660					
Anions									
Carbonate	< 10	0	0	0					
Bicarbonate	100	1.6	9	270	**				
Sulfate	140	2.9	16	380	**				
Chloride	240	6.8	37	650					
Nitrate	440	7.1	39	1200					
Fluoride	0.2	0.011	0	0.5					
Minor Elements									
Boron	0.20			0.54					
Copper	0.020			0.054					
Iron	0.37			1.0					
Manganese	< 0.01			0.00					
Zinc	0.030			0.082					
TDS by Summation	1420			3900					
Other									
pH	6.9			units					
E. C.	2.15			dS/m					
SAR	5.9								
Crop Suitability									
No Amendments	Poor								
With Amendments	Poor								
Amendments									
Gypsum Requirement	1.1			Tons/AF					
Sulfuric Acid (98%)	5.6			oz/1000Gal	Or 14 oz/1000Gal of urea Sulfuric Acid (15/49).				
Leaching Requirement	14			%					

Micro Irrigation System Plugging Hazard

Test Description	Result		Graphical Results Presentation		
Chemical			Slight	Moderate	Severe
Manganese	< 0.01	mg/L			
Iron	0.37	mg/L			
TDS by Summation	1420	mg/L			
No Amendments					
pH	6.9	units			
Alkalinity (As CaCO3)	80	mg/L			
Total Hardness	320	mg/L			
With Amendments					
Alkalinity (As CaCO3)	16	mg/L			
Total Hardness	16	mg/L			
pH	5.4 - 6.7	units			

Good Problem
Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

E.2 FGL Water Samples: Day 10 (Post-transplant)

E.2.1 Hydroponics System

ENVIRONMENTAL FGL AGRICULTURAL
Analytical Chemists

February 6, 2018

Cal Poly State University
HCS Department
1 Grand Avenue
San Luis Obispo, CA 93407-0861

Description : Hydroponics System 2
Project : Ground Water Monitoring

Lab ID : CC 1880229-001
Customer ID : 8-30

Sampled On : January 24, 2018
Sampled By : Sean Foster
Received On : January 24, 2018
Matrix : Ground Water

Lettuce Irrigation Suitability Analysis

Test Description	Result				Graphical Results Presentation				
Cations	mg/L	Meq/L	% Meq	Lbs/AF	Good	Possible Problem	Moderate Problem	Increasing Problem	Severe Problem
Calcium	140	7	42	380	**				
Magnesium	44	3.6	22	120	**				
Potassium	188	4.8	29	510	**				
Sodium	32	1.4	8	87					
Anions									
Carbonate	< 10	0	0	0					
Bicarbonate	30	0.49	3	82	**				
Sulfate	178	3.7	24	480	**				
Chloride	35	0.99	6	95					
Nitrate	633	10	66	1700					
Fluoride	0.7	0.037	0	2					
Minor Elements									
Boron	0.60			1.6					
Copper	0.26			0.71					
Iron	1.8			5.0					
Manganese	0.050			0.14					
Zinc	0.39			1.1					
TDS by Summation	1280			3500					
Other									
pH	5.6			units					
E. C.	2.08			dS/m					
SAR	0.6								
Crop Suitability									
No Amendments	Poor								
With Amendments	Poor								
Amendments									
Gypsum Requirement	0.0			Tons/AF					
Sulfuric Acid (98%)	1.4			oz/1000Gal	Or 3.4 oz/1000Gal of urea Sulfuric Acid (15/49).				
Leaching Requirement	13			%					

Micro Irrigation System Plugging Hazard

Test Description	Result		Graphical Results Presentation		
Chemical			Slight	Moderate	Severe
Manganese	0.05	mg/L			
Iron	1.8	mg/L			
TDS by Summation	1280	mg/L			
No Amendments					
pH	5.6	units			
Alkalinity (As CaCO3)	20	mg/L			
Total Hardness	530	mg/L			
With Amendments					
Alkalinity (As CaCO3)	10	mg/L			
Total Hardness	4	mg/L			
pH	5.4 - 6.7	units			

Good Problem

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

E.2.2 Aquaponics System

FGL ENVIRONMENTAL AGRICULTURAL
Analytical Chemists

February 6, 2018
Cal Poly State University
HCS Department
1 Grand Avenue
San Luis Obispo, CA 93407-0861

Description : Aquaponics System 2
Project : Ground Water Monitoring

Lab ID : CC 1880229-002
Customer ID : 8-30

Sampled On : January 24, 2018
Sampled By : Sean Foster
Received On : January 24, 2018
Matrix : Ground Water

Lettuce Irrigation Suitability Analysis

Test Description	Result				Graphical Results Presentation				
Cations	mg/L	Meq/L	% Meq	Lbs/AF	Good	Possible Problem	Moderate Problem	Increasing Problem	Severe Problem
Calcium	95	4.7	22	260	**				
Magnesium	34	2.8	13	92	**				
Potassium	187	4.8	22	510	**				
Sodium	219	9.5	44	600					
Anions									
Carbonate	< 10	0	0	0					
Bicarbonate	60	0.98	5	160	**				
Sulfate	156	3.2	16	420	**				
Chloride	250	7.1	34	680					
Nitrate	591	9.5	46	1600					
Fluoride	0.1	0.0053	0	0.3					
Minor Elements									
Boron	0.10			0.27					
Copper	0.020			0.054					
Iron	0.32			0.87					
Manganese	0.020			0.054					
Zinc	0.060			0.16					
TDS by Summation	1590			4300					
Other									
pH	6.2			units					
E. C.	2.44			dS/m					
SAR	4.9								
Crop Suitability									
No Amendments	Poor								
With Amendments	Poor								
Amendments									
Gypsum Requirement	0.9			Tons/AF	Apply 0.113 Tons/AF if Sulfuric Acid amendment appli				
Sulfuric Acid (98%)	3.5			oz/1000Gal	Or 8.5 oz/1000Gal of urea Sulfuric Acid (15/49).				
Leaching Requirement	16			%					

Micro Irrigation System Plugging Hazard

Test Description	Result		Graphical Results Presentation		
Chemical			Slight	Moderate	Severe
Manganese	0.02	mg/L			
Iron	0.32	mg/L			
TDS by Summation	1590	mg/L			
No Amendments					
pH	6.2	units			
Alkalinity (As CaCO3)	50	mg/L			
Total Hardness	377	mg/L			
With Amendments					
Alkalinity (As CaCO3)	10	mg/L			
Total Hardness	10	mg/L			
pH	5.4 - 6.7	units			

Good Problem
Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

E.3 FGL Water Samples: Day 20 (Post-transplant)

E.3.1 Hydroponics System

March 5, 2018
Cal Poly State University
HCS Department
1 Grand Avenue
San Luis Obispo, CA 93407-0861

Description : Hydroponics System 3
Project : Ag Water Monitoring

Lab ID : CC 1880321-001
Customer ID : 8-30

Sampled On : February 3, 2018
Sampled By : Sean Foster
Received On : February 5, 2018
Matrix : Ag Water

Lettuce Irrigation Suitability Analysis

Test Description	Result				Graphical Results Presentation				
Cations	mg/L	Meq/L	% Meq	Lbs/AF	Good	Possible Problem	Moderate Problem	Increasing Problem	Severe Problem
Calcium	150	7.5	43	410	**				
Magnesium	52	4.3	25	140	**				
Potassium	140	3.6	21	380	**				
Sodium	44	1.9	11	120					
Anions									
Carbonate	< 10	0	0	0					
Bicarbonate	20	0.33	2	54	**				
Sulfate	180	3.7	29	490	**				
Chloride	23	0.65	5	63					
Nitrate	518	8.4	64	1400					
Fluoride	0.8	0.042	0	2					
Minor Elements									
Boron	0.60			1.6					
Copper	0.26			0.71					
Iron	1.8			5.0					
Manganese	0.19			0.52					
Zinc	0.34			0.92					
TDS by Summation	1130			3100					
Other									
pH	5.7			units					
E. C.	1.76			dS/m					
SAR	0.8								
Crop Suitability									
No Amendments	Poor								
With Amendments	Poor								
Amendments									
Gypsum Requirement	0.0			Tons/AF					
Sulfuric Acid (98%)	1.4			oz/1000Gal	Or 3.4 oz/1000Gal of urea Sulfuric Acid (15/49).				
Leaching Requirement	11			%					

Micro Irrigation System Plugging Hazard

Test Description	Result		Graphical Results Presentation		
Chemical			Slight	Moderate	Severe
Manganese	0.19	mg/L			
Iron	1.8	mg/L			
TDS by Summation	1130	mg/L			
No Amendments					
pH	5.7	units			
Alkalinity (As CaCO3)	20	mg/L			
Total Hardness	588	mg/L			
With Amendments					
Alkalinity (As CaCO3)	10	mg/L			
Total Hardness	4	mg/L			
pH	5.4 - 6.7	units			

Good Problem

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

E.3.2 Aquaponics System

FGL ENVIRONMENTAL AGRICULTURAL
Analytical Chemists

March 5, 2018
Cal Poly State University
HCS Department
1 Grand Avenue
San Luis Obispo, CA 93407-0861

Description : Aquaponics System 3
Project : Ag Water Monitoring

Lab ID : CC 1880321-002
Customer ID : 8-30

Sampled On : February 3, 2018
Sampled By : Sean Foster
Received On : February 5, 2018
Matrix : Ag Water

Lettuce Irrigation Suitability Analysis

Test Description	Result				Graphical Results Presentation				
Cations	mg/L	Meq/L	% Meq	Lbs/AF	Good	Possible Problem	Moderate Problem	Increasing Problem	Severe Problem
Calcium	123	6.1	22	330	**				
Magnesium	39	3.2	12	110	**				
Potassium	320	8.2	30	870	**				
Sodium	227	9.9	36	620					
Anions									
Carbonate	< 10	0	0	0					
Bicarbonate	60	0.98	4	160	**				
Sulfate	161	3.4	15	440	**				
Chloride	230	6.5	29	630					
Nitrate	727	12	52	2000					
Fluoride	< 0.1	0	0	0					
Minor Elements									
Boron	0.20			0.54					
Copper	0.020			0.054					
Iron	0.32			0.87					
Manganese	0.020			0.054					
Zinc	0.15			0.41					
TDS by Summation	1890			5100					
Other									
pH	6.6			units					
E. C.	2.79			dS/m					
SAR	4.6								
Crop Suitability									
No Amendments	Poor								
With Amendments	Poor								
Amendments									
Gypsum Requirement	1.1			Tons/AF	Apply 0.313 Tons/AF if Sulfuric Acid amendment appli				
Sulfuric Acid (98%)	3.5			oz/1000Gal	Or 8.5 oz/1000Gal of urea Sulfuric Acid (15/49).				
Leaching Requirement	18			%					

Micro Irrigation System Plugging Hazard

Test Description	Result		Graphical Results Presentation		
Chemical			Slight	Moderate	Severe
Manganese	0.02	mg/L			
Iron	0.32	mg/L			
TDS by Summation	1890	mg/L			
No Amendments					
pH	6.6	units			
Alkalinity (As CaCO3)	50	mg/L			
Total Hardness	467	mg/L			
With Amendments					
Alkalinity (As CaCO3)	10	mg/L			
Total Hardness	10	mg/L			
pH	5.4 - 6.7	units			

Good Problem

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

E.4 FGL Water Samples: Day 30 (Post-transplant)

E.4.1 Hydroponics System

FGL ENVIRONMENTAL AGRICULTURAL
Analytical Chemists

March 2, 2018
Cal Poly State University
BRAE Department
1 Grand Avenue
San Luis Obispo, CA 93407-0861

Lab ID : CC 1880434-001
Customer ID : 8-1469

Sampled On : February 13, 2018
Sampled By : Sean Foster
Received On : February 13, 2018
Matrix : Ground Water

Description : Hydroponics System #4
Project : Ground Water Monitoring

Lettuce Irrigation Suitability Analysis

Test Description	Result				Graphical Results Presentation				
Cations	mg/L	Meq/L	% Meq	Lbs/AF	Good	Possible Problem	Moderate Problem	Increasing Problem	Severe Problem
Calcium	235	12	47	640	**				
Magnesium	84	6.9	28	230	**				
Potassium	133	3.4	14	360	**				
Sodium	70	3	12	190					
Anions									
Carbonate	< 10	0	0	0					
Bicarbonate	30	0.49	3	82	**				
Sulfate	269	5.6	36	730	**				
Chloride	10	0.28	2	27					
Nitrate	574	9.3	59	1600					
Fluoride	1.5	0.079	1	4					
Minor Elements									
Boron	1.1			3.0					
Copper	0.46			1.3					
Iron	3.1			8.4					
Manganese	0.37			1.0					
Zinc	0.46			1.3					
TDS by Summation	1410			3800					
Other									
pH	5.5			units					
E. C.	2.10			dS/m					
SAR	1.0								
Crop Suitability									
No Amendments	Poor								
With Amendments	Poor								
Amendments									
Gypsum Requirement	0.0			Tons/AF					
Sulfuric Acid (98%)	2.1			oz/1000Gal	Or 5.1 oz/1000Gal of urea Sulfuric Acid (15/49).				
Leaching Requirement	13			%					

Micro Irrigation System Plugging Hazard

Test Description	Result		Graphical Results Presentation		
Chemical			Slight	Moderate	Severe
Manganese	0.37	mg/L			
Iron	3.1	mg/L			
TDS by Summation	1410	mg/L			
No Amendments					
pH	5.5	units			
Alkalinity (As CaCO3)	30	mg/L			
Total Hardness	932	mg/L			
With Amendments					
Alkalinity (As CaCO3)	10	mg/L			
Total Hardness	6	mg/L			
pH	5.4 - 6.7	units			

Good Problem
Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

E.4.2 Aquaponics System

FGL ENVIRONMENTAL AGRICULTURAL
Analytical Chemists

March 2, 2018
Cal Poly State University
BRAE Department
1 Grand Avenue
San Luis Obispo, CA 93407-0861

Description : Aquaponics System #4
Project : Ground Water Monitoring

Lab ID : CC 1880434-002
Customer ID : 8-1469

Sampled On : February 13, 2018
Sampled By : Sean Foster
Received On : February 13, 2018
Matrix : Ground Water

Lettuce Irrigation Suitability Analysis

Test Description	Result				Graphical Results Presentation				
Cations	mg/L	Meq/L	% Meq	Lbs/AF	Good	Possible Problem	Moderate Problem	Increasing Problem	Severe Problem
Calcium	128	6.4	24	350	**				
Magnesium	41	3.4	13	110	**				
Potassium	340	8.7	32	920	**				
Sodium	191	8.3	31	520					
Anions									
Carbonate	< 10	0	0	0					
Bicarbonate	50	0.82	4	140	**				
Sulfate	165	3.4	16	450	**				
Chloride	192	5.4	25	520					
Nitrate	759	12	56	2100					
Fluoride	0.1	0.0053	0	0.3					
Minor Elements									
Boron	0.30			0.82					
Copper	0.030			0.082					
Iron	0.38			1.0					
Manganese	0.020			0.054					
Zinc	0.11			0.30					
TDS by Summation	1870			5100					
Other									
pH	6.4			units					
E. C.	2.70			dS/m					
SAR	3.8								
Crop Suitability									
No Amendments	Poor								
With Amendments	Poor								
Amendments									
Gypsum Requirement	0.9			Tons/AF	Apply 0.244 Tons/AF if Sulfuric Acid amendment appl				
Sulfuric Acid (98%)	2.8			oz/1000Gal	Or 6.8 oz/1000Gal of urea Sulfuric Acid (15/49).				
Leaching Requirement	18			%					

Micro Irrigation System Plugging Hazard

Test Description	Result		Graphical Results Presentation		
			Slight	Moderate	Severe
Chemical					
Manganese	0.02	mg/L			
Iron	0.38	mg/L			
TDS by Summation	1870	mg/L			
No Amendments					
pH	6.4	units			
Alkalinity (As CaCO3)	40	mg/L			
Total Hardness	488	mg/L			
With Amendments					
Alkalinity (As CaCO3)	10	mg/L			
Total Hardness	8	mg/L			
pH	5.4 - 6.7	units			

Good Problem

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

E.5 FGL Leaf Tissue Samples: Day 45 (Total)

ENVIRONMENTAL FGL AGRICULTURAL
Analytical Chemists

Description : B5.9 Butterhead
Project : Cal Poly State University, BRAE Dept

BUTTERHEAD PLANT TISSUE ANALYSIS - 8TH LEAF

Test Description	Result	Units	Optimum Range	Graphical Results Presentation
				Deficient / Low / Ample / High / Excessive
Macro Nutrients				
Total Nitrogen (Leaf)	5.52	%	4.0 - 6.0	
Phosphorus (Leaf)	0.54	%	0.50 - 1.6	
Potassium (Leaf)	7.86	%	7.5 - 10	
Calcium (Leaf)	1.53	%	1.0 - 2.0	
Magnesium (Leaf)	0.49	%	0.50 - 0.80	
Micro Nutrients				
Zinc (Leaf)	94.6	ppm	25 - 500	
Manganese (Leaf)	30	ppm	15 - 500	
Iron (Leaf)	66	ppm	50 - 200	
Copper (Leaf)	11	ppm	8.0 - 45	
Boron (Leaf)	75.8	ppm	23 - 50	
Sodium (Leaf)	0.502	%	0.040 - 0.40	

Good — Problem

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

Description : C5.1 Butterhead
Project : Cal Poly State University, BRAE Dept

BUTTERHEAD PLANT TISSUE ANALYSIS - 8TH LEAF

Test Description	Result	Units	Optimum Range	Graphical Results Presentation
				Deficient / Low / Ample / High / Excessive
Macro Nutrients				
Total Nitrogen (Leaf)	6.14	%	4.0 - 6.0	
Phosphorus (Leaf)	0.62	%	0.50 - 1.6	
Potassium (Leaf)	9.48	%	7.5 - 10	
Calcium (Leaf)	1.75	%	1.0 - 2.0	
Magnesium (Leaf)	0.56	%	0.50 - 0.80	
Micro Nutrients				
Zinc (Leaf)	100	ppm	25 - 500	
Manganese (Leaf)	39	ppm	15 - 500	
Iron (Leaf)	65	ppm	50 - 200	
Copper (Leaf)	8	ppm	8.0 - 45	
Boron (Leaf)	59.6	ppm	23 - 50	
Sodium (Leaf)	0.808	%	0.040 - 0.40	

Good — Problem

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

Description : A1.1 Romaine
Project : Cal Poly State University, BRAE Dept

ROMAINE PLANT TISSUE ANALYSIS - 8TH LEAF

Test Description	Result	Units	Optimum Range	Graphical Results Presentation
				Deficient / Low / Ample / High / Excessive
Macro Nutrients				
Total Nitrogen (Leaf)	5.53	%	5.0 - 6.0	
Phosphorus (Leaf)	0.87	%	0.45 - 1.1	
Potassium (Leaf)	9.01	%	5.5 - 7.1	
Calcium (Leaf)	1.03	%	1.0 - 2.0	
Magnesium (Leaf)	0.30	%	0.60 - 0.80	
Micro Nutrients				
Zinc (Leaf)	69.5	ppm	20 - 400	
Manganese (Leaf)	32	ppm	10 - 400	
Iron (Leaf)	71	ppm	40 - 200	
Copper (Leaf)	7	ppm	5.0 - 50	
Boron (Leaf)	29.7	ppm	25 - 60	
Sodium (Leaf)	0.435	%	0.040 - 0.40	

Good — Problem

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

Description : C2.6 Romaine
Project : Cal Poly State University, BRAE Dept

ROMAINE PLANT TISSUE ANALYSIS - 8TH LEAF

Test Description	Result	Units	Optimum Range	Graphical Results Presentation
				Deficient / Low / Ample / High / Excessive
Macro Nutrients				
Total Nitrogen (Leaf)	5.57	%	5.0 - 6.0	
Phosphorus (Leaf)	0.80	%	0.45 - 1.1	
Potassium (Leaf)	8.73	%	5.5 - 7.1	
Calcium (Leaf)	1.20	%	1.0 - 2.0	
Magnesium (Leaf)	0.33	%	0.60 - 0.80	
Micro Nutrients				
Zinc (Leaf)	72.8	ppm	20 - 400	
Manganese (Leaf)	38	ppm	10 - 400	
Iron (Leaf)	133	ppm	40 - 200	
Copper (Leaf)	7	ppm	5.0 - 50	
Boron (Leaf)	33.7	ppm	25 - 60	
Sodium (Leaf)	0.583	%	0.040 - 0.40	

Good — Problem

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

Description : H2.11 Romaine
Project : Cal Poly State University, BRAE Dept

ROMAINE PLANT TISSUE ANALYSIS - 8TH LEAF

Test Description	Result	Units	Optimum Range	Graphical Results Presentation
				Deficient / Low / Ample / High / Excessive
Macro Nutrients				
Total Nitrogen (Leaf)	5.73	%	5.0 - 6.0	
Phosphorus (Leaf)	0.74	%	0.45 - 1.1	
Potassium (Leaf)	9.36	%	5.5 - 7.1	
Calcium (Leaf)	1.16	%	1.0 - 2.0	
Magnesium (Leaf)	0.46	%	0.60 - 0.80	
Micro Nutrients				
Zinc (Leaf)	59.5	ppm	20 - 400	
Manganese (Leaf)	200	ppm	10 - 400	
Iron (Leaf)	116	ppm	40 - 200	
Copper (Leaf)	8	ppm	5.0 - 50	
Boron (Leaf)	40.1	ppm	25 - 60	
Sodium (Leaf)	0.158	%	0.040 - 0.40	

Good — Problem

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

Description : A1.7 Kale
Project : Cal Poly State University, BRAE Dept

KALE PLANT TISSUE ANALYSIS

Test Description	Result	Units	Optimum Range	Graphical Results Presentation
				Deficient / Low / Ample / High / Excessive
Macro Nutrients				
Total Nitrogen (Leaf)	6.56	%	3.1 - 5.6	
Phosphorus (Leaf)	0.63	%	0.30 - 0.70	
Potassium (Leaf)	7.36	%	2.0 - 4.5	
Calcium (Leaf)	2.69	%	1.3 - 3.5	
Magnesium (Leaf)	0.37	%	0.25 - 0.75	
Micro Nutrients				
Zinc (Leaf)	89.5	ppm	30 - 350	
Manganese (Leaf)	22	ppm	30 - 350	
Iron (Leaf)	48	ppm	60 - 500	
Copper (Leaf)	5	ppm	4.0 - 100	
Boron (Leaf)	52.8	ppm	30 - 120	
Sodium (Leaf)	0.716	%	0.0 - 3.0	

Good — Problem

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

Description : B1.5 Kale
Project : Cal Poly State University, BRAE Dept

KALE PLANT TISSUE ANALYSIS

Test Description	Result	Units	Optimum Range	Graphical Results Presentation
				Deficient / Low / Ample / High / Excessive
Macro Nutrients				
Total Nitrogen (Leaf)	5.95	%	3.1 - 5.6	
Phosphorus (Leaf)	0.67	%	0.30 - 0.70	
Potassium (Leaf)	6.03	%	2.0 - 4.5	
Calcium (Leaf)	2.37	%	1.3 - 3.5	
Magnesium (Leaf)	0.37	%	0.25 - 0.75	
Micro Nutrients				
Zinc (Leaf)	106	ppm	30 - 350	
Manganese (Leaf)	31	ppm	30 - 350	
Iron (Leaf)	62	ppm	60 - 500	
Copper (Leaf)	5	ppm	4.0 - 100	
Boron (Leaf)	44.7	ppm	30 - 120	
Sodium (Leaf)	0.618	%	0.0 - 3.0	

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

Description : C2.8 Kale
Project : Cal Poly State University, BRAE Dept

KALE PLANT TISSUE ANALYSIS

Test Description	Result	Units	Optimum Range	Graphical Results Presentation
				Deficient / Low / Ample / High / Excessive
Macro Nutrients				
Total Nitrogen (Leaf)	5.05	%	3.1 - 5.6	
Phosphorus (Leaf)	0.66	%	0.30 - 0.70	
Potassium (Leaf)	5.62	%	2.0 - 4.5	
Calcium (Leaf)	1.71	%	1.3 - 3.5	
Magnesium (Leaf)	0.32	%	0.25 - 0.75	
Micro Nutrients				
Zinc (Leaf)	93.3	ppm	30 - 350	
Manganese (Leaf)	26	ppm	30 - 350	
Iron (Leaf)	43	ppm	60 - 500	
Copper (Leaf)	4	ppm	4.0 - 100	
Boron (Leaf)	36.7	ppm	30 - 120	
Sodium (Leaf)	0.603	%	0.0 - 3.0	

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

Description : H4.9 Kale
Project : Cal Poly State University, BRAE Dept

KALE PLANT TISSUE ANALYSIS

Test Description	Result	Units	Optimum Range	Graphical Results Presentation
				Deficient / Low / Ample / High / Excessive
Macro Nutrients				
Total Nitrogen (Leaf)	5.98	%	3.1 - 5.6	
Phosphorus (Leaf)	0.74	%	0.30 - 0.70	
Potassium (Leaf)	6.10	%	2.0 - 4.5	
Calcium (Leaf)	1.91	%	1.3 - 3.5	
Magnesium (Leaf)	0.35	%	0.25 - 0.75	
Micro Nutrients				
Zinc (Leaf)	67.2	ppm	30 - 350	
Manganese (Leaf)	94	ppm	30 - 350	
Iron (Leaf)	69	ppm	60 - 500	
Copper (Leaf)	12	ppm	4.0 - 100	
Boron (Leaf)	48.2	ppm	30 - 120	
Sodium (Leaf)	0.130	%	0.0 - 3.0	

Note: Color coded bar graphs have been used to provide you with 'AT-A-GLANCE' interpretations.

Appendix F. LED Light Distribution Test Data

* All values are measuring PPFD in μmol/m^2-sec

ROW A	
A1.5	315
A1.9	289
A2.4	290
A2.10	288
A3.2	278
A3.4	291
A3.6	298
A3.8	287
A3.10	272
A4.3	269
A4.5	290
A4.7	296
A4.9	283
A5.1	269
A5.3	286
A5.5	290
A5.7	317
A5.9	296
avg	289
median	290
st. dev	13

Butterhead	
A2.10	288
A3.2	278
A3.6	298
A3.8	287
A3.10	272
A5.3	286
avg	285
median	287
st. dev	9

Romaine	
A1.9	289
A3.4	291
A4.5	290
A5.1	269
A5.5	290
A5.7	317
avg	291
median	290
st. dev	15

Kale	
A1.5	315
A2.4	290
A4.3	269
A4.7	296
A4.9	283
A5.9	296
avg	292
median	293
st. dev	15

ROW B	
B1.1	211
B1.3	252
B1.7	258
B2.4	292
B2.6	297
B2.8	288
B2.10	238
B3.2	272
B3.4	296
B3.6	291
B3.10	226
B4.3	281
B4.5	300
B4.7	294
B4.9	274
B5.1	214
B5.3	263
B5.7	282
avg	268
median	278
st. dev	29

Butterhead	
B1.7	258
B2.8	288
B2.10	238
B3.4	296
B3.6	291
B4.7	294
avg	278
median	290
st. dev	24

Romaine	
B1.1	211
B2.4	292
B3.2	272
B3.10	226
B4.3	281
B4.9	274
avg	259
median	273
st. dev	33

Kale	
B1.3	252
B2.6	297
B4.5	300
B5.1	214
B5.3	263
B5.7	282
avg	268
median	273
st. dev	32

ROW C	
C1.1	175
C1.3	209
C1.5	220
C1.7	213
C1.9	195
C2.2	242
C2.10	235
C3.2	268
C3.4	299
C3.6	305
C3.10	233
C4.3	264
C4.5	294
C4.7	300
C5.3	230
C5.5	244
C5.7	242
C5.9	220
avg	244
median	239
st. dev	38

Butterhead	
C1.7	213
C1.9	195
C3.2	268
C3.6	305
C5.3	230
C5.5	244
avg	243
median	237
st. dev	40

Romaine	
C1.1	175
C1.3	209
C3.10	233
C4.7	300
C5.7	242
C5.9	220
avg	230
median	227
st. dev	42

Kale	
C1.5	220
C2.2	242
C2.10	235
C3.4	299
C4.3	264
C4.5	294
avg	259
median	253
st. dev	32

ROW H	
H1.3	203
H1.5	229
H1.7	231
H1.9	220
H2.2	221
H2.4	262
H2.6	277
H2.8	276
H3.2	243
H3.4	280
H3.8	285
H3.10	243
H4.3	255
H4.7	280
H5.1	195
H5.5	251
H5.7	250
H5.9	235
avg	246
median	247
st. dev	27

Butterhead	
H1.5	229
H2.6	277
H3.8	285
H4.3	255
H4.7	280
H5.1	195
avg	254
median	266
st. dev	35

Romaine	
H1.3	203
H2.2	221
H3.2	243
H3.4	280
H3.10	243
H5.9	235
avg	238
median	239
st. dev	26

Kale	
H1.7	231
H1.9	220
H2.4	262
H2.8	276
H5.5	251
H5.7	250
avg	248
median	251
st. dev	20

Appendix G. LED Light Distribution Test Statistics

G.1 Butterhead, Rows A – H

Method	Test Statistic	P-Value
Levene	1.82	0.177

One-way ANOVA: PPFD versus Row

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	$\alpha = 0.05$

Equal variances were assumed for the analysis.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Row	2	6142	3070.9	4.15	0.037
Error	15	11090	739.3		
Total	17	17232			

S	R-sq	R-sq(adj)	R-sq(pred)
27.1905	35.64%	27.06%	7.33%

Row	N	Mean	StDev	95% CI
A	6	284.83	8.95	(261.17, 308.49)
B	6	277.50	23.86	(253.84, 301.16)
C	6	242.5	39.6	(218.8, 266.2)

Pooled StDev = 27.1905

Tukey Pairwise Comparisons (95% Confidence)

Row	N	Mean	Grouping	
A	6	284.83	A	
B	6	277.50	A	B
C	6	242.5		B
H	6	253.5		B

Means that do not share a letter are significantly different.

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
B - A	-7.3	15.7	(-48.1, 33.4)	-0.47	0.888
C - A	-42.3	15.7	(-83.1, -1.6)	-2.70	0.041
C – B	-35.0	15.7	(-75.7, 5.7)	-2.23	0.098
H – C	11.0	21.7	(-37.3, 59.3)	0.51	0.623

Individual confidence level = 97.97%

G.2 Romaine, Rows A – H

Method	Test Statistic	P-Value
Levene	0.95	0.436

One-way ANOVA: PPFD versus Row

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Row	2	11229	5614	5.56	0.016
Error	15	15144	1010		
Total	17	26373			

S	R-sq	R-sq(adj)	R-sq(pred)
31.7744	42.58%	34.92%	17.31%

Row	N	Mean	StDev	95% CI
A	6	291.00	15.27	(263.35, 318.65)
B	6	259.3	32.7	(231.7, 287.0)
C	6	229.8	41.5	(202.2, 257.5)

Pooled StDev = 31.7744

Tukey Pairwise Comparisons (95% Confidence)

Row	N	Mean	Grouping	
A	6	291.00	A	
B	6	259.3	A	B
C	6	229.8		B
H	6	237.5		B

Means that do not share a letter are significantly different.

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
B - A	-31.7	18.3	(-79.3, 15.9)	-1.73	0.228
C - A	-61.2	18.3	(-108.8, -13.6)	-3.33	0.012
C – B	-29.5	18.3	(-77.1, 18.1)	-1.61	0.273
H - C	7.7	20.0	(-36.8, 52.1)	0.38	0.709

Individual confidence level = 97.97%

G.3 Kale, Rows A – H

Method	Test Statistic	P-Value
Levene	1.76	0.188

One-way ANOVA: PPFD versus Row

Null hypothesis	All means are equal
Alternative hypothesis	Not all means are equal
Significance level	α = 0.05

Equal variances were assumed for the analysis.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Row	2	3379	1689.5	2.17	0.148
Error	15	11668	777.8		
Total	17	15047			

S	R-sq	R-sq(adj)	R-sq(pred)
27.8897	22.46%	12.12%	0.00%

Row	N	Mean	StDev	95% CI
A	6	291.50	15.32	(267.23, 315.77)
B	6	268.0	32.4	(243.7, 292.3)
C	6	259.0	32.4	(234.7, 283.3)

Pooled StDev = 27.8897

Tukey Pairwise Comparisons (95% Confidence)

Row	N	Mean	Grouping
A	6	291.50	A
B	6	268.0	A
C	6	259.0	A
H	6	248.3	A

Means that do not share a letter are significantly different.

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
B - A	-23.5	16.1	(-65.3, 18.3)	-1.46	0.337
C - A	-32.5	16.1	(-74.3, 9.3)	-2.02	0.142
C - B	-9.0	16.1	(-50.8, 32.8)	-0.56	0.844
H - C	-10.7	15.6	(-45.4, 24.1)	-0.68	0.510

Individual confidence level = 97.97%

Appendix H. Flow Rate Test

* "AP_" = aquaponics NFT column; "HP_" = hydroponics NFT column.

	TEST 1			TEST 2			TEST 3		
#	Volume (mL)	Time (s)	*Flow rate (gpm)*	Volume (mL)	Time (s)	*Flow rate (gpm)*	Volume (mL)	Time (s)	*Flow rate (gpm)*
AP1	535	10	*0.85*	620	10	*0.98*	620	10	*0.98*
AP2	525	10	*0.83*	650	10	*1.03*	670	10	*1.06*
AP3	520	10	*0.82*	610	10	*0.97*	650	10	*1.03*
AP4	535	10	*0.85*	650	10	*1.03*	670	10	*1.06*
AP5	700	10	*1.11*	660	10	*1.05*	670	10	*1.06*
TOTAL FLOW:			*4.46*			*5.06*			***5.20***

NFT columns:		NFT columns:		NFT columns:	
avg. flow	0.89 gpm	avg. flow	1.01 gpm	avg. flow	**1.04 gpm**
st. dev.	0.12 gpm	st. dev.	0.03 gpm	st. dev.	**0.03 gpm**

	TEST 1			TEST 2		
#	Volume (mL)	Time (s)	*Flow rate (gpm)*	Volume (mL)	Time (s)	*Flow rate (gpm)*
HP1	675	10	*1.07*	680	10	*1.08*
HP2	670	10	*1.06*	685	10	*1.09*
HP3	665	10	*1.05*	670	10	*1.06*
HP4	710	10	*1.13*	685	10	*1.09*
HP5	685	10	*1.09*	695	10	*1.10*
TOTAL FLOW:			*5.40*			***5.41***

NFT columns:		NFT columns:	
avg. flow	1.08 gpm	avg. flow	**1.08 gpm**
st. dev.	0.03 gpm	st. dev.	**0.01 gpm**

Appendix I. NFT System Construction Process

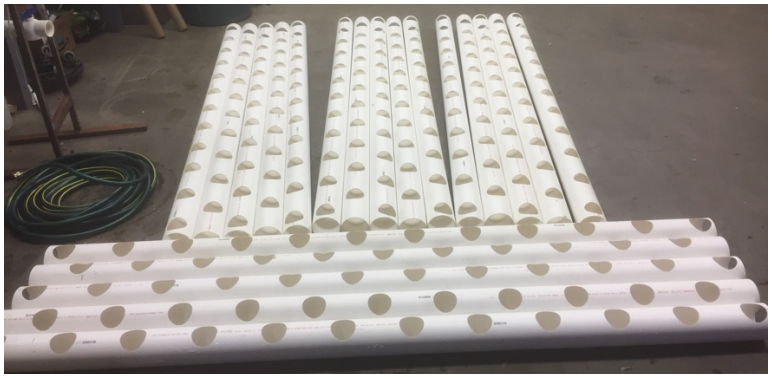


Figure I.1. Early stages of NFT column construction. Twenty lengths of 4 in. PVC were cut into 8 ft. sections with 3 in. bores drilled every 8 in. down the length of each pipe.

A)  B) 

Figure I.2. A) A lathe was used to drill holes in 4 in. end caps. B) 4 in. end caps after 2 in. fittings were glued with PVC primer/cement and sealed with silicone. 2 in. fittings were connected to 2 in. PVC which joined NFT columns between rows.

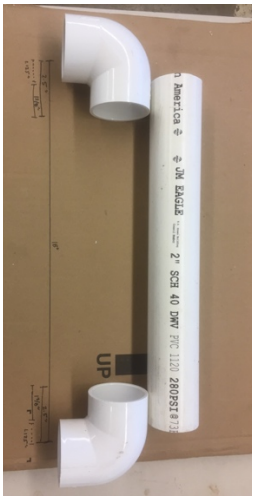
A)  B)  C) 

Figure I.3. A) 2 in. PVC pipe being cut to size with a bandsaw. B) 2 in. PVC pipe and fittings prior to assembly. C) Final assembly that joined NFT columns between rows.

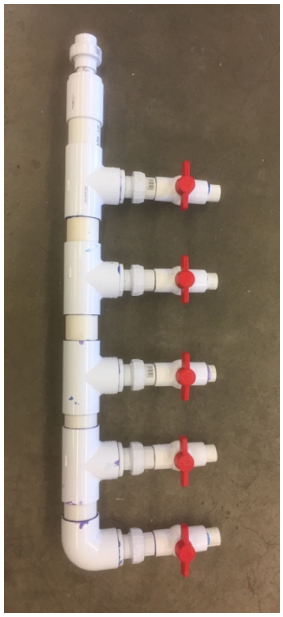
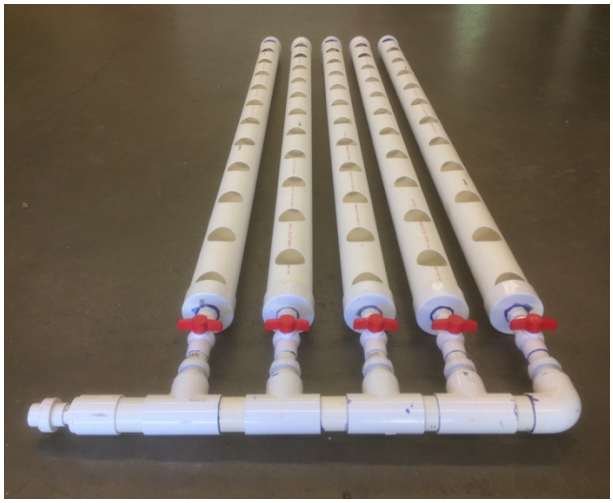
A)  B) 

Figure I.4. A) Assembled 2 in. PVC manifold with 1 in. unions and valves to connect to NFT columns. B) Manifold attached to all five 4 in. NFT columns.

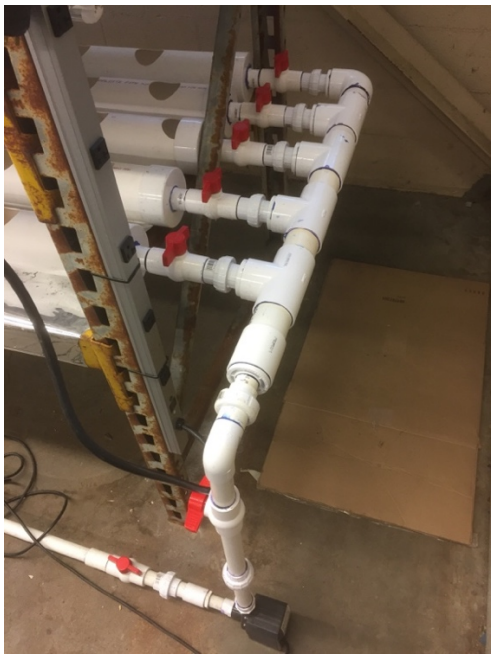


Figure I.5. Side view of hydroponics system with fully assembled valves, pump, manifold, unions, and NFT columns on the bottom row of shelving unit.

Appendix J. Randomized Plant Distributions

Row A (AP)	
A1.1	romaine
A1.3	kale
A1.5	kale
A1.7	kale
A1.9	romaine
A2.2	butterhead
A2.4	kale
A2.6	kale
A2.8	kale
A2.10	butterhead
A3.2	butterhead
A3.4	romaine
A3.6	butterhead
A3.8	butterhead
A3.10	butterhead
A4.3	kale
A4.5	romaine
A4.7	kale
A4.9	kale
A5.1	romaine
A5.3	butterhead
A5.5	romaine
A5.7	romaine
A5.9	kale

Row B (AP)	
B1.1	romaine
B1.3	kale
B1.5	kale
B1.7	butterhead
B1.9	butterhead
B2.2	kale
B2.4	romaine
B2.6	kale
B2.8	butterhead
B2.10	butterhead
B3.2	romaine
B3.4	butterhead
B3.6	butterhead
B3.8	butterhead
B3.10	romaine
B4.3	romaine
B4.5	kale
B4.7	butterhead
B4.9	romaine
B5.1	kale
B5.3	kale
B5.5	kale
B5.7	kale
B5.9	butterhead

Row C (AP)	
C1.1	romaine
C1.3	romaine
C1.5	kale
C1.7	butterhead
C1.9	butterhead
C2.2	kale
C2.4	romaine
C2.6	romaine
C2.8	kale
C2.10	kale
C3.2	butterhead
C3.4	kale
C3.6	butterhead
C3.8	kale
C3.10	romaine
C4.3	kale
C4.5	kale
C4.7	romaine
C4.9	butterhead
C5.1	butterhead
C5.3	butterhead
C5.5	butterhead
C5.7	romaine
C5.9	romaine

Row H (HP)	
H1.1	romaine
H1.3	romaine
H1.5	butterhead
H1.7	kale
H1.9	kale
H2.2	romaine
H2.4	kale
H2.6	butterhead
H2.8	kale
H2.10	romaine
H3.2	romaine
H3.4	romaine
H3.6	romaine
H3.8	butterhead
H3.10	romaine
H4.3	butterhead
H4.5	romaine
H4.7	butterhead
H4.9	kale
H5.1	butterhead
H5.3	butterhead
H5.5	kale
H5.7	kale
H5.9	romaine

Master			
1	butterhead	kale	romaine
2	butterhead	kale	romaine
3	butterhead	kale	romaine
4	butterhead	kale	romaine
5	butterhead	kale	romaine
6	butterhead	kale	romaine
7	butterhead	kale	romaine
8	butterhead	kale	romaine
9	butterhead	kale	romaine
10	butterhead	kale	romaine
11	butterhead	kale	romaine
12	butterhead	kale	romaine
13	butterhead	kale	romaine
14	butterhead	kale	romaine
15	butterhead	kale	romaine
16	butterhead	kale	romaine
17	butterhead	kale	romaine
18	butterhead	kale	romaine
19	butterhead	kale	romaine
20	butterhead	kale	romaine
21	butterhead	kale	romaine
22	butterhead	kale	romaine
23	butterhead	kale	romaine
24	butterhead	kale	romaine

Appendix K. Randomized Plant Harvest Order

ROW A		
Butterhead	**Romaine**	**Kale**
A5.3	A5.5	A5.9
A2.10	A5.1	A4.3
A3.8	A1.9	A4.9
A3.10	A5.7	A1.5
A3.6	A3.4	A2.4
A3.2	A4.5	A4.7

ROW B		
Butterhead	**Romaine**	**Kale**
B2.10	B1.1	B2.6
B3.4	B3.10	B5.7
B2.8	B3.2	B4.5
B4.7	B4.9	B5.3
B3.6	B2.4	B1.3
B1.7	B4.3	B5.1

ROW C		
Butterhead	**Romaine**	**Kale**
C3.2	C3.10	C2.2
C1.7	C1.1	C4.3
C3.6	C5.9	C4.5
C5.3	C4.7	C2.10
C5.5	C5.7	C1.5
C1.9	C1.3	C3.4

ROW H		
Butterhead	**Romaine**	**Kale**
H1.5	H2.2	H5.5
H4.3	H3.10	H1.7
H5.1	H3.4	H5.7
H3.8	H3.2	H1.9
H2.6	H5.9	H2.4
H4.7	H1.3	H2.8

#	ORDER
1	C4.5
2	C1.7
3	A3.4
4	H2.8
5	H2.6
6	B4.3
7	C1.5
8	B3.2
9	A5.9
10	H4.3
11	C4.3
12	B5.3
13	H5.9
14	B1.1
15	H5.1
16	A2.10
17	A3.8
18	A1.9
19	H3.10
20	H1.7
21	H3.4
22	H3.8
23	B3.10
24	C5.7
25	H2.2
26	B2.4
27	C3.4
28	H5.5
29	A3.6
30	B4.7
31	C1.3
32	H2.4
33	H5.7
34	H1.3
35	H3.2
36	C2.2

#	ORDER
37	B4.9
38	B3.4
39	A1.5
40	B3.6
41	A3.2
42	A4.7
43	B2.8
44	C3.6
45	B5.1
46	A5.1
47	C3.2
48	A4.3
49	C3.10
50	C5.5
51	A5.5
52	B5.7
53	A2.4
54	B2.10
55	C1.1
56	C2.10
57	B2.6
58	H1.5
59	A5.3
60	B1.3
61	H4.7
62	A5.7
63	A4.5
64	C4.7
65	C5.3
66	B1.7
67	A4.9
68	C5.9
69	H1.9
70	B4.5
71	C1.9
72	A3.10

Appendix L. Environmental Conditions in System and Lab 4

L.1 Air Temperature in Rows A – H, Lab 4

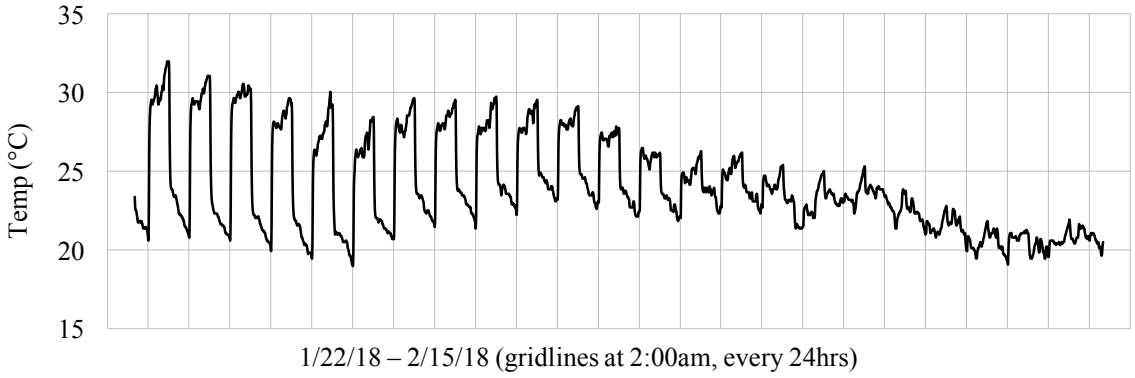


Figure L.1. Row A, 12/12hr photoperiod. Average temp.: 24.0 ± 3.0 ºC.

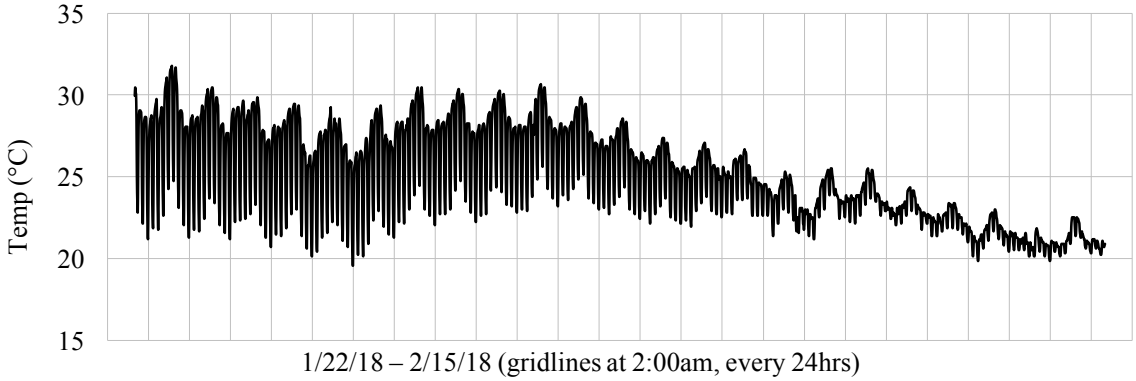


Figure L.2. Row B, 2/1hr photoperiod. Average temp.: 25.0 ± 2.8 ºC.

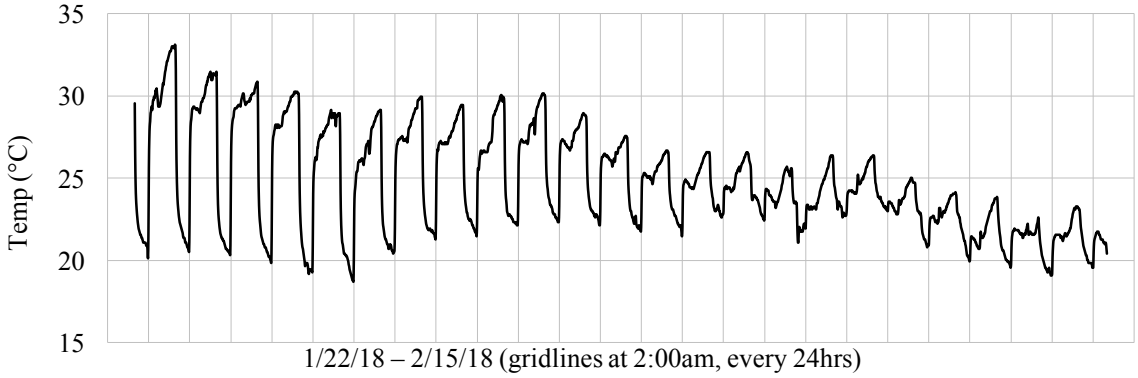


Figure L.3. Row C, 16/8hr photoperiod. Average temp.: 24.8 ± 3.1 ºC.

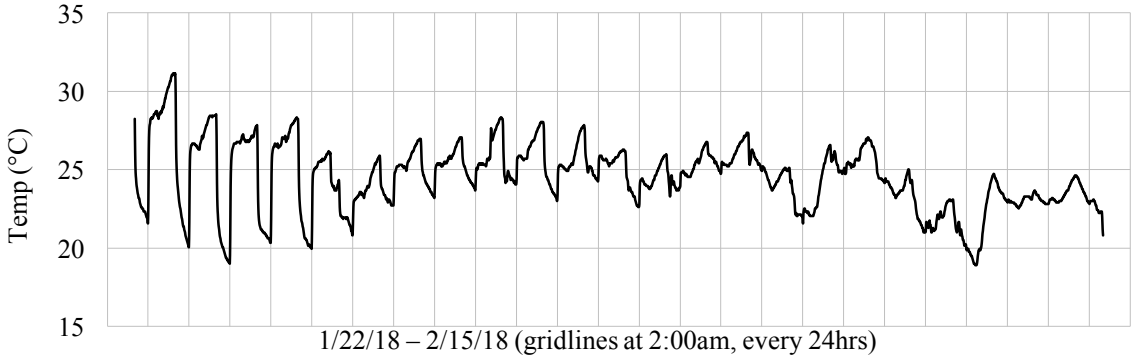


Figure L.4. Row H, 16/8hr photoperiod. Average temp.: 24.5 ± 2.1 ºC.

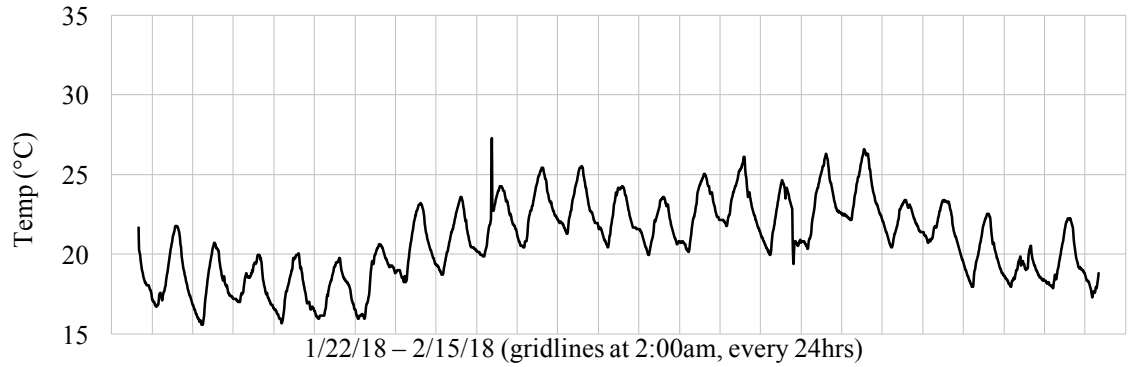


Figure L.5. Lab 4, outside of the system. Average temp.: 20.8 ± 2.5 ºC.

L.2 Relative Humidity (RH) in Row C, Lab 4

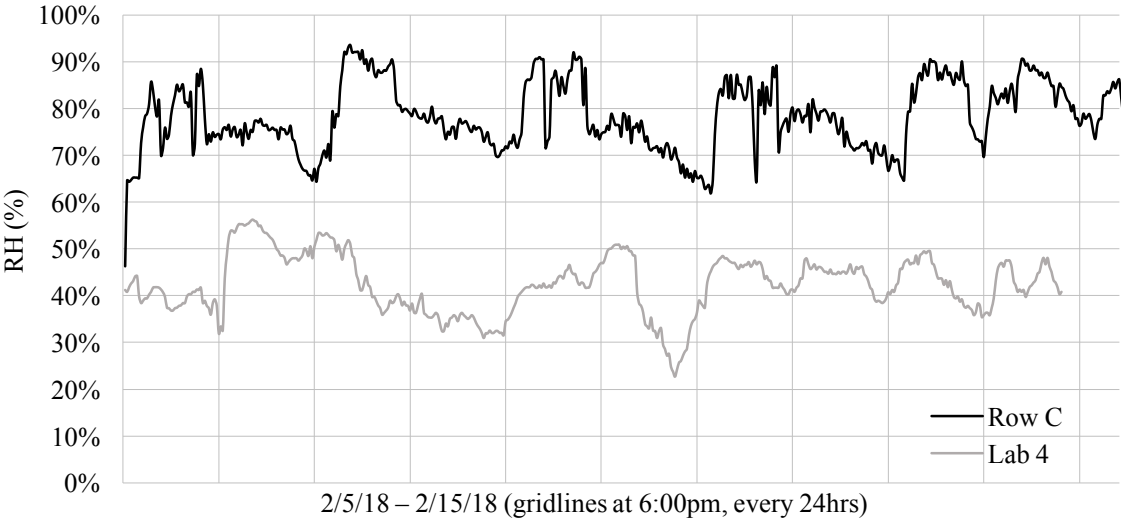


Figure L.6. Relative humidity (RH) in Row C and Lab 4 recorded every 15 minutes from 2/5/18 – 2/15/18. Row C Average RH: 76.4 ± 7.17%, Lab 4 Average RH: 42.4 ± 6.3%.

Appendix M. Plant Growth Statistical Analyses (MiniTab)

M.1 Response Variable: Plant yield (dry weight)

M.1.1 Descriptive Statistics

Plant type = butterhead

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Plant yield, dry weight (g)	A	6	7.91	3.13	5.28	7.43	13.90
	B	6	8.01	2.92	4.93	7.45	12.43
	C	6	6.75	2.32	4.21	5.88	9.91
	H	6	7.57	3.27	3.17	7.36	11.41

Plant type = kale

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Plant yield, dry weight (g)	A	6	12.13	2.46	9.03	11.88	15.72
	B	6	17.38	4.37	13.10	16.10	25.30
	C	6	21.28	6.65	12.73	20.26	33.25
	H	6	21.24	5.94	13.58	23.13	27.14

Plant type = romaine

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Plant yield, dry weight (g)	A	6	9.51	3.04	5.88	9.54	14.78
	B	6	10.76	2.39	8.36	10.43	14.07
	C	6	10.68	1.40	9.32	10.36	13.01
	H	6	13.56	2.34	11.01	12.93	16.94

M.1.2 General Linear Model (GLM): Light Treatments (Rows A, B, C)

Factor Information: Plant yield, dry weight

Factor	Type	Levels	Values
Treatment	Fixed	3	A, B, C
Plant type	Fixed	3	butterhead, romaine, kale

Analysis of Variance: Plant yield, dry weight

Source	DF	Adj SS	Adj MS	F-Value	P-Value
LIGHT INTENSITY (umol/m2-sec)	1	19.12	19.117	1.58	0.215
Plant type	2	798.70	399.351	33.08	0.000
Treatment	2	105.88	52.938	4.39	0.018
Treatment*Plant type	4	162.32	40.580	3.36	0.017
Error	44	531.16	12.072		
Lack-of-Fit	42	526.69	12.540	5.61	0.163
Pure Error	2	4.47	2.237		

Total	53	1650.11	

Model Summary: Plant yield, dry weight

S	R-sq	R-sq(adj)	R-sq(pred)
3.47447	67.81%	61.23%	50.68%

M.1.3 General Linear Model (GLM): Nutrient Solution Treatments (Rows C, H)

Factor Information: Plant yield, dry weight

Factor	Type	Levels	Values
Treatment	Fixed	2	C, H
Plant type	Fixed	3	butterhead, romaine, kale

Analysis of Variance: Plant yield, dry weight

Source	DF	Adj SS	Adj MS	F-Value	P-Value
LIGHT INTENSITY (umol/m2-sec)	1	29.20	29.201	1.74	0.197
Plant type	2	1171.77	585.887	34.97	0.000
Treatment	1	11.70	11.703	0.70	0.410
Treatment*Plant type	2	10.27	5.134	0.31	0.738
Error	29	485.91	16.755		
Lack-of-Fit	28	479.03	17.108	2.49	0.469
Pure Error	1	6.88	6.876		
Total	35	1770.21			

Model Summary: Plant yield, dry weight

S	R-sq	R-sq(adj)	R-sq(pred)
4.09335	72.55%	66.87%	56.85%

M.1.4 Dunnett and Tukey Multiple Comparisons (95% Confidence)

Plant type = butterhead; Factor Information: Plant yield, dry weight

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	1.16	1.62	(-2.80, 5.12)	0.72	0.702
B - C	1.26	1.62	(-2.70, 5.22)	0.78	0.663

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
C - H	-0.82	1.64	(-4.46, 2.83)	-0.50	0.628

Individual confidence level = 95.00%

Plant type = romaine; Factor Information: Plant yield, dry weight

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-1.17	1.37	(-4.51, 2.17)	-0.85	0.610
B - C	0.08	1.37	(-3.26, 3.42)	0.06	0.997

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
C - H	-2.88	1.11	(-5.36, -0.40)	-2.58	0.027

Individual confidence level = 95.00%

Plant type = kale; Factor Information: Plant yield, dry weight

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-9.15	2.78	(-15.93, -2.37)	-3.29	0.009
B - C	-3.90	2.78	(-10.67, 2.88)	-1.40	0.300

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
C - H	0.03	3.64	(-8.08, 8.15)	0.01	0.993

Individual confidence level = 95.00%

M.1.5 Figures

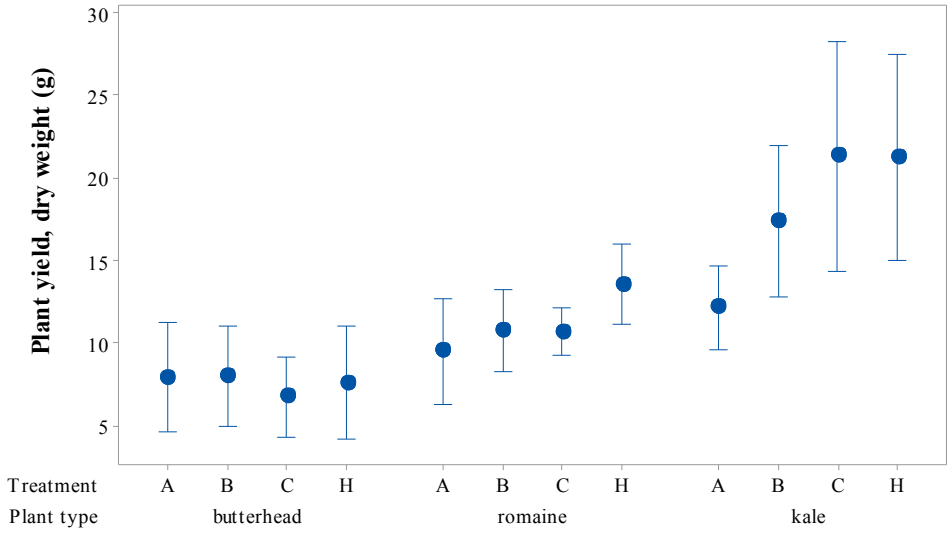


Figure M.1. Interval Plot of plant yield (dry weight) by plant types and treatment.

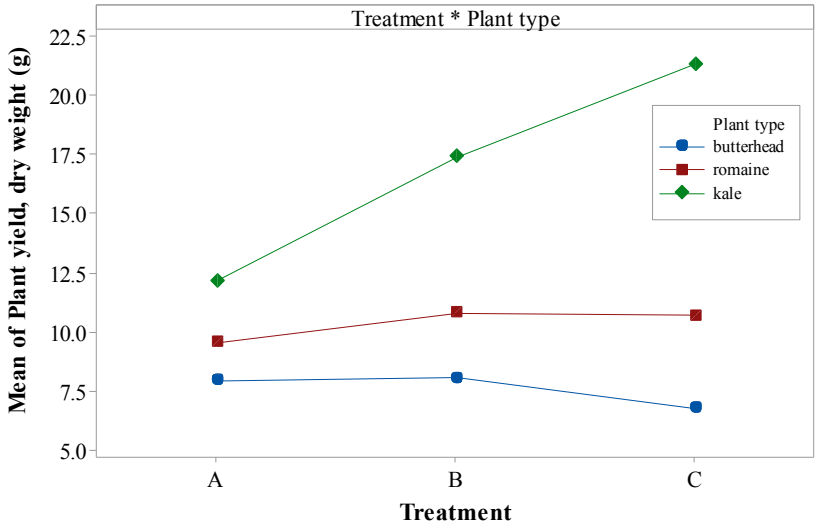


Figure M.2. Interaction plot of average plant yield (dry weight) for different plant types by light treatment. Significant interaction between treatment and plant type (p= 0.013).

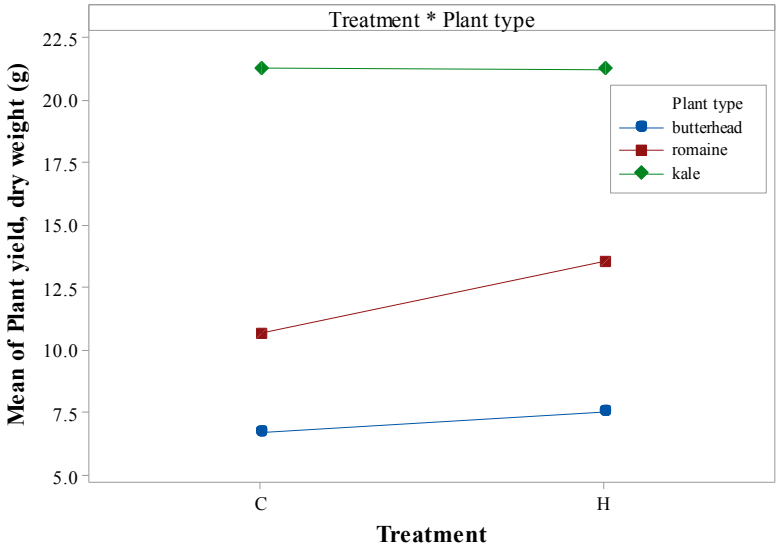


Figure M.3. Interaction plot of average plant yield (dry weight) for different plant types by nutrient treatment. No significant interaction between treatment and plant type (p= 0.679).

M.2 Response Variable: Plant yield (fresh weight)

M.2.1 Descriptive Statistics

Plant type = butterhead

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Plant yield, fresh weight (g)	A	6	178.4	32.5	148.7	172.1	236.5

	B	6	212.6	71.8	121.2	213.2	310.5
	C	6	180.5	34.6	145.0	173.2	233.2
	H	6	185.7	71.5	81.4	196.2	279.2

Plant type = romaine

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Plant yield, fresh weight (g)	A	6	278.7	53.3	210.5	285.6	358.8
	B	6	284.6	44.0	209.7	288.7	337.2
	C	6	300.8	30.9	270.1	290.8	360.1
	H	6	356.0	40.6	298.1	372.1	400.3

Plant type = kale

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Plant yield, fresh weight (g)	A	6	220.4	50.9	161.9	217.2	288.6
	B	6	319.1	69.4	212.2	310.3	420.6
	C	6	364.2	108.1	230.0	341.4	558.8
	H	6	371.3	123.9	241.7	351.8	511.3

M.2.2 Dunnett and Tukey Multiple Comparisons (95% Confidence)

Plant type = butterhead; Factor Information: Plant yield, fresh weight

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-2.2	28.7	(-72.1, 67.8)	-0.08	0.996
B - C	32.1	28.7	(-37.8, 102.0)	1.12	0.446

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
C - H	-5.1	32.4	(-77.4, 67.1)	-0.16	0.877

Individual confidence level = 95.00%

Plant type = romaine; Factor Information: Plant yield, fresh weight

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-22.0	25.2	(-83.6, 39.5)	-0.87	0.599
B - C	-16.1	25.2	(-77.7, 45.4)	-0.64	0.751

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value

C - H	-55.2	20.8	(-101.6, -8.8)	-2.65	0.024

Individual confidence level = 95.00%

Plant type = kale; Factor Information: Plant yield, fresh weight

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-143.8	46.1	(-256.2, -31.5)	-3.12	0.013
B - C	-45.2	46.1	(-157.5, 67.2)	-0.98	0.529

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
C - H	-7.1	67.1	(-156.7, 142.4)	-0.11	0.918

Individual confidence level = 95.00%

M.2.3 Figures

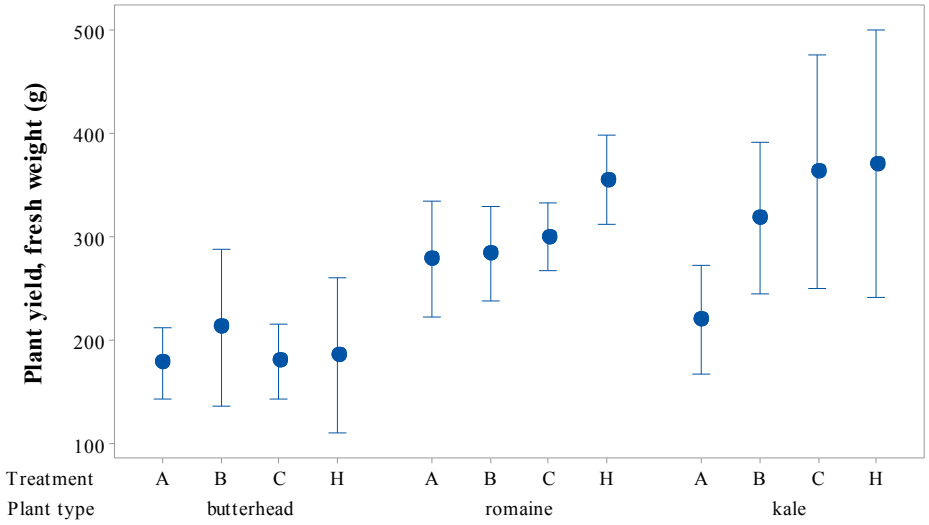


Figure M.4. Interval Plot of plant yield (fresh weight) by plant types and treatment.

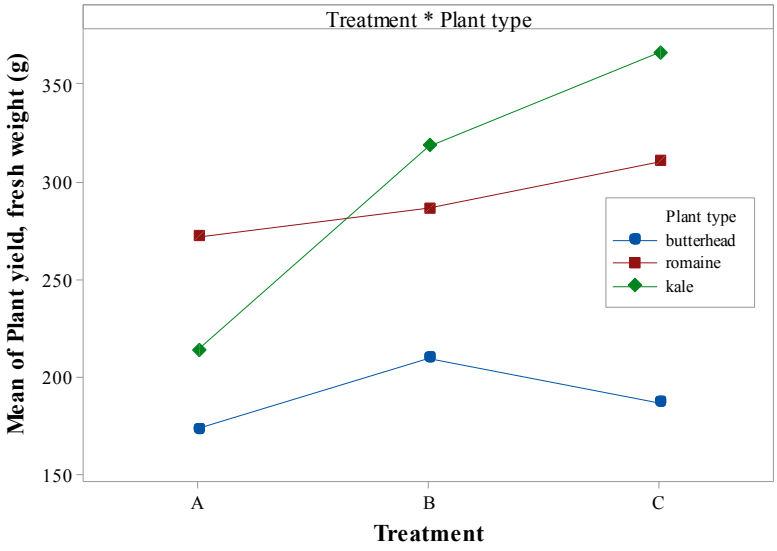


Figure M.5. Interaction plot of avg. plant yield (fresh weight) for different plant types by light treatment. Significant interaction between treatment and plant type (p= 0.042).

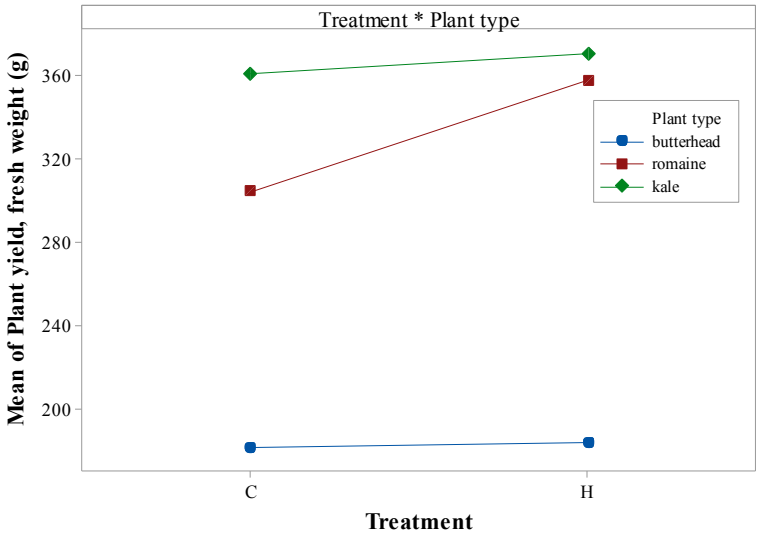


Figure M.6. Interaction plot of avg. plant yield (fresh weight) for different plant types by nutrient treatment. No significant interaction between treatment and plant type (p= 0.672).

M.3 Response Variable: Root yield (dry weight)

M.3.1 Descriptive Statistics

Plant type = butterhead

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum

Root yield, dry weight (g)	A	6	1.594	0.458	1.005	1.620	2.171
	B	6	1.768	0.790	0.868	1.550	3.004
	C	6	1.502	1.059	0.758	1.074	3.600
	H	6	1.467	1.058	0.381	1.270	3.382

Plant type = romaine

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Root yield, dry weight (g)	A	6	1.971	0.986	0.675	1.973	3.462
	B	6	2.69	3.22	1.06	1.50	9.25
	C	6	1.051	0.536	0.444	0.984	1.959
	H	6	0.9347	0.1991	0.6944	0.9291	1.1970

Plant type = kale

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Root yield, dry weight (g)	A	6	3.157	0.723	1.972	3.397	3.982
	B	6	3.829	1.588	2.358	3.547	6.110
	C	6	3.852	1.425	2.150	3.857	5.611
	H	6	1.705	0.696	0.816	1.720	2.811

M.3.2 Dunnett and Tukey Multiple Comparisons (95% Confidence)

Plant type = butterhead; Factor Information: Root yield, dry weight

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	0.092	0.466	(-1.045, 1.229)	0.20	0.972
B - C	0.266	0.466	(-0.871, 1.403)	0.57	0.794

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
C - H	0.035	0.611	(-1.327, 1.396)	0.06	0.956

Individual confidence level = 95.00%

Plant type = romaine; Factor Information: Root yield, dry weight

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	0.920	0.397	(-0.058, 1.898)	2.31	0.066
B - C	0.330	0.417	(-0.696, 1.356)	0.79	0.656

Individual confidence level = 97.25%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
C - H	0.117	0.233	(-0.403, 0.637)	0.50	0.628

Individual confidence level = 95.00%

Plant type = kale; Factor Information: Root yield, dry weight

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-0.695	0.751	(-2.527, 1.137)	-0.93	0.565
B - C	-0.023	0.751	(-1.855, 1.809)	-0.03	0.999

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
C - H	2.147	0.648	(0.704, 3.590)	3.32	0.008

Individual confidence level = 95.00%

M.3.3 Figures

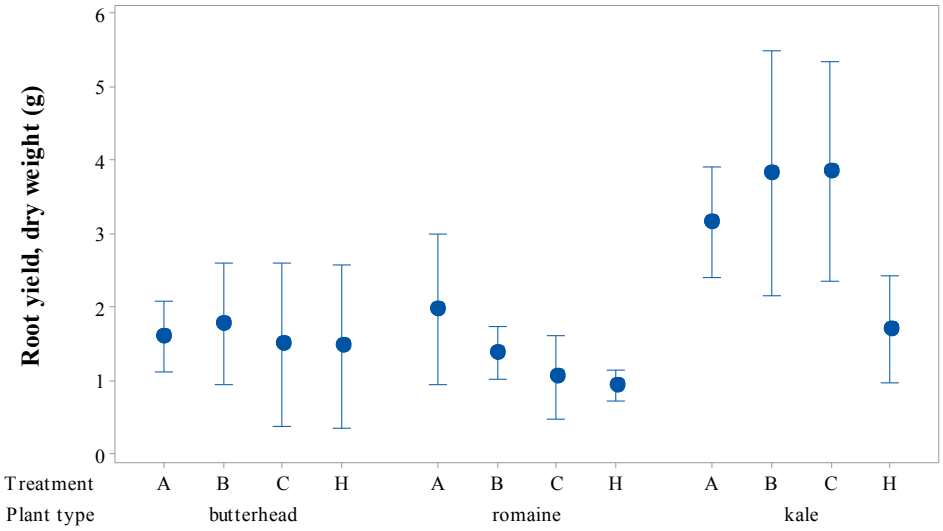


Figure M.7. Interval Plot of root yield (dry weight) by plant types and treatment.

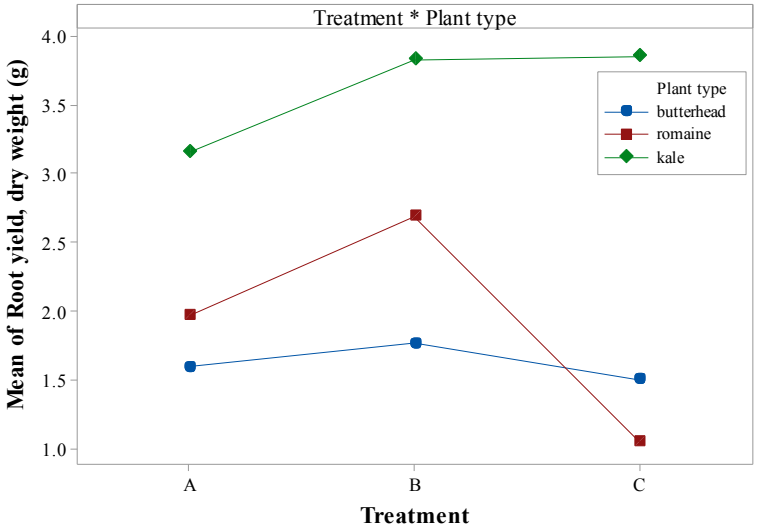


Figure M.8. Interaction plot of average root yield (dry weight) for different plant types by light treatment. No significant interaction between treatment and plant type (p= 0.570).

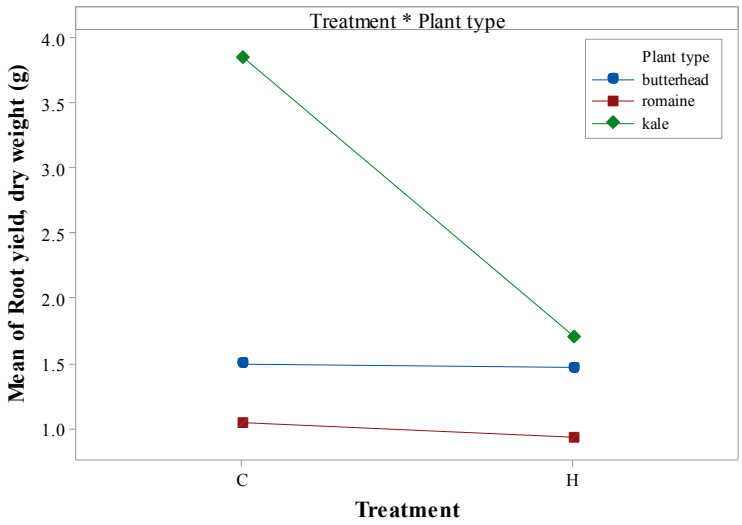


Figure M.9. Interaction plot of average root yield (dry weight) for different plant types by nutrient treatment. Significant interaction between treatment and plant type (p= 0.013).

M.4 Response Variable: Leaf Count

M.4.1 Descriptive Statistics

Plant type = butterhead

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Leaf Count	A	6	46.333	1.862	44.000	46.000	49.000

	B	6	66.67	22.07	40.00	63.50	107.00
	C	6	53.17	8.54	43.00	54.00	63.00
	H	6	53.17	12.06	32.00	55.50	65.00

Plant type = romaine

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Leaf Count	A	6	49.00	4.20	44.00	49.00	55.00
	B	6	58.33	10.58	45.00	59.50	72.00
	C	6	56.83	8.47	45.00	55.50	68.00
	H	6	52.67	9.42	41.00	52.00	68.00

Plant type = kale

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Leaf Count	A	6	14.17	2.79	11.00	13.50	18.00
	B	6	29.33	9.91	13.00	31.00	41.00
	C	6	25.33	11.24	15.00	22.00	46.00
	H	6	24.50	5.79	16.00	25.00	31.00

M.4.2 Dunnett and Tukey Comparisons (95% Confidence)

Plant type = butterhead; Factor Information: Leaf count
Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-6.83	7.91	(-26.13, 12.47)	-0.86	0.605
B - C	13.50	7.91	(-5.80, 32.80)	1.71	0.186

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	0.00	6.03	(-13.44, 13.44)	0.00	1.000

Individual confidence level = 95.00%

Plant type = romaine; Factor Information: Leaf count
Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-7.83	4.73	(-19.37, 3.70)	-1.66	0.202
B - C	1.50	4.73	(-10.03, 13.03)	0.32	0.930

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value

H - C	-4.17	5.17	(-15.69, 7.35)	-0.81	0.439

Individual confidence level = 95.00%

Plant type = kale; Factor Information: Leaf count

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-11.17	5.08	(-23.56, 1.23)	-2.20	0.079
B - C	4.00	5.08	(-8.39, 16.39)	0.79	0.655

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	-0.83	5.16	(-12.33, 10.66)	-0.16	0.875

Individual confidence level = 95.00%

M.4.3 Figures

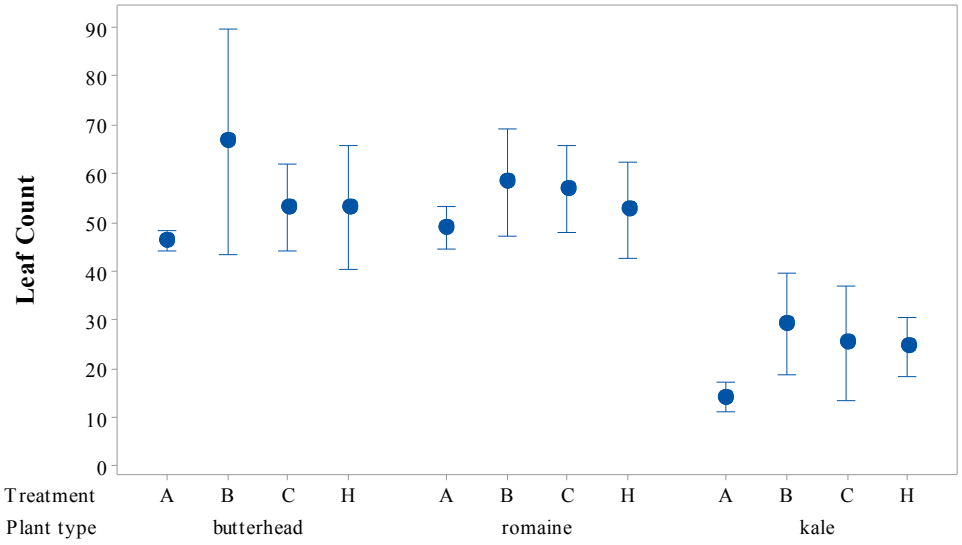


Figure M.10. Interval Plot of leaf count by plant types and treatment.

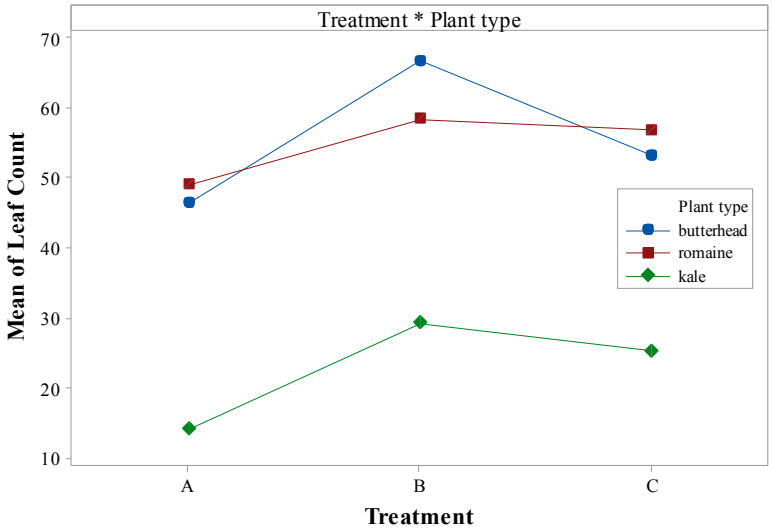


Figure M.11. Interaction plot of average leaf count for different plant types by light treatment. No significant interaction between treatment and plant type (p= 0.608).

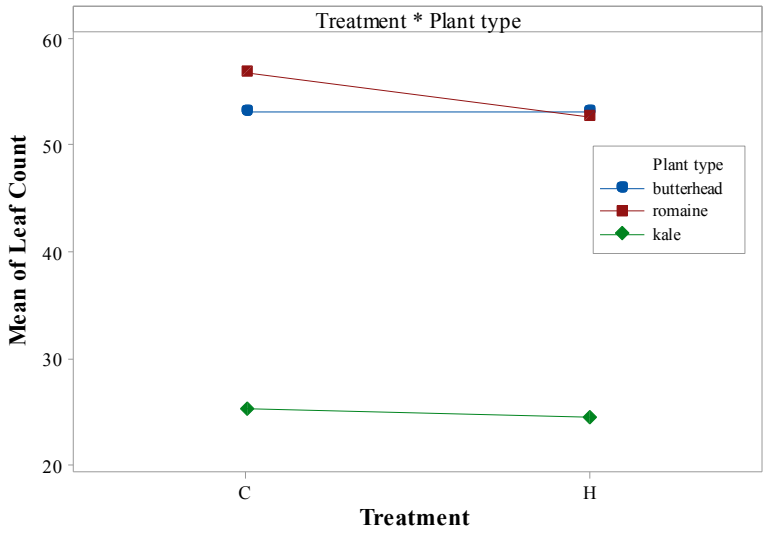


Figure M.12. Interaction plot of average leaf count for different plant types by nutrient treatment. No significant interaction between treatment and plant type (p= 0.851).

M.5 Response Variable: Leaf Length, Width, Ratio

M.5.1 Descriptive Statistics

Plant type = butterhead

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Leaf length (mm)	A	117	188.29	70.19	43.00	194.00	350.00

	B	107	165.87	53.59	65.00	160.00	293.00
	C	119	161.16	62.02	30.00	166.00	295.00
	H	153	167.18	57.35	30.00	172.00	355.00
Leaf width (mm)	A	117	115.19	41.97	29.00	126.00	190.00
	B	107	104.96	33.11	37.00	105.00	185.00
	C	119	97.91	47.37	22.00	95.00	201.00
	H	153	106.38	45.40	25.00	99.00	214.00
Ratio (L:W)	A	117	1.6606	0.2890	0.7716	1.6939	2.2800
	B	107	1.6168	0.4181	0.9118	1.6000	4.1667
	C	119	1.8519	0.8554	0.5882	1.5672	5.2000
	H	153	1.6948	0.5433	0.4483	1.5862	3.2500

Plant type = romaine

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Leaf length (mm)	A	159	217.32	90.64	41.00	227.00	390.00
	B	218	196.35	76.76	35.00	194.50	360.00
	C	138	227.02	77.71	25.00	240.50	375.00
	H	183	240.66	84.36	61.00	256.00	377.00
Leaf width (mm)	A	159	91.43	42.89	15.00	90.00	180.00
	B	218	84.74	42.75	10.00	76.50	198.00
	C	138	94.59	41.03	10.00	95.00	173.00
	H	183	112.72	38.40	19.00	120.00	188.00
Ratio (L:W)	A	159	2.5037	0.6461	1.3019	2.4211	4.6087
	B	218	2.5357	0.6845	1.4242	2.5200	5.6667
	C	138	2.5727	0.6039	1.3901	2.5827	4.1818
	H	183	2.1770	0.4437	1.1442	2.1958	4.1250

Plant type = kale

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Leaf length (mm)	A	39	309.3	138.2	73.0	330.0	526.0
	B	64	287.5	122.4	45.0	281.0	530.0
	C	90	336.7	133.1	50.0	344.5	585.0
	H	79	292.5	118.5	63.0	305.0	548.0
Leaf width (mm)	A	39	111.44	50.43	15.00	120.00	214.00
	B	64	115.88	54.12	11.00	111.50	242.00
	C	90	116.49	62.60	14.00	101.00	250.00
	H	79	109.29	66.82	13.00	95.00	284.00
Ratio (L:W)	A	39	2.921	0.932	1.878	2.541	5.147

B	64	2.6348	0.7674	1.5429	2.3741	4.5000
C	90	3.324	1.354	1.371	2.853	7.000
H	79	3.352	1.747	1.378	2.783	10.150

M.5.2 Dunnett and Tukey Multiple Comparisons (95% Confidence)

Plant type = butterhead; Factor Information: Leaf length
Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	27.13	8.14	(9.11, 45.16)	3.33	0.002
B - C	4.71	8.33	(-13.73, 23.15)	0.57	0.796

Individual confidence level = 97.25%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	6.02	7.26	(-8.28, 20.33)	0.83	0.407

Individual confidence level = 95.00%

Plant type = butterhead; Factor Information: Leaf width
Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	17.28	5.40	(5.32, 29.24)	3.20	0.003
B - C	7.06	5.53	(-5.18, 19.29)	1.28	0.338

Individual confidence level = 97.25%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	8.47	5.66	(-2.66, 19.61)	1.50	0.134

Individual confidence level = 95.00%

Plant type = romaine; Factor Information: Leaf length
Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-9.70	9.49	(-30.60, 11.20)	-1.02	0.476
B - C	-30.67	8.87	(-50.21, -11.13)	-3.46	0.001

Individual confidence level = 97.20%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value

H - C	13.64	9.20	(-4.45, 31.73)	1.48	0.138

Individual confidence level = 95.00%

Plant type = romaine; Factor Information: Leaf width
Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-3.17	4.93	(-14.02, 7.69)	-0.64	0.735
B - C	-9.85	4.61	(-20.00, 0.30)	-2.14	0.058

Individual confidence level = 97.20%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	18.12	4.46	(9.35, 26.89)	4.06	0.000

Individual confidence level = 95.00%

Plant type = kale; Factor Information: Leaf length
Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-27.4	25.1	(-83.6, 28.8)	-1.09	0.460
B - C	-49.2	21.4	(-97.2, -1.3)	-2.30	0.043

Individual confidence level = 97.39%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	-44.2	19.5	(-82.8, -5.7)	-2.27	0.025

Individual confidence level = 95.00%

Plant type = kale; Factor Information: Leaf width
Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-5.1	11.0	(-29.8, 19.7)	-0.46	0.868
B - C	-0.61	9.42	(-21.72, 20.50)	-0.07	0.997

Individual confidence level = 97.39%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	-7.20	9.96	(-26.86, 12.47)	-0.72	0.471

Individual confidence level = 95.00%

Plant type = butterhead; Factor Information: L:W Ratio

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-0.1912	0.0756	(-0.3586, -0.0239)	-2.53	0.022
B - C	-0.2351	0.0773	(-0.4063, -0.0639)	-3.04	0.005

Individual confidence level = 97.25%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	-0.1571	0.0852	(-0.3248, 0.0107)	-1.84	0.065

Individual confidence level = 95.00%

Plant type = romaine; Factor Information: L:W Ratio

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-0.0690	0.0758	(-0.2361, 0.0981)	-0.91	0.551
B - C	-0.0370	0.0709	(-0.1932, 0.1192)	-0.52	0.814

Individual confidence level = 97.20%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	-0.3957	0.0585	(-0.5107, -0.2807)	-6.77	0.000

Individual confidence level = 95.00%

Plant type = romaine; Factor Information: L:W Ratio

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-0.403	0.212	(-0.879, 0.073)	-1.90	0.111
B - C	-0.689	0.181	(-1.095, -0.283)	-3.80	0.000

Individual confidence level = 97.39%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	0.029	0.239	(-0.443, 0.500)	0.12	0.905

Individual confidence level = 95.00%

M.5.3 Figures

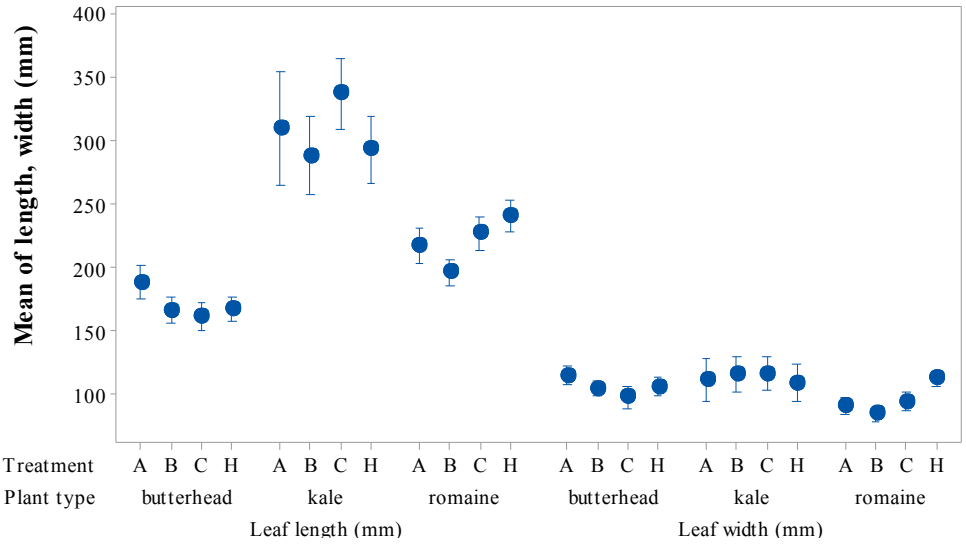


Figure M.13. Interval Plot of leaf length and width by plant type and treatment.

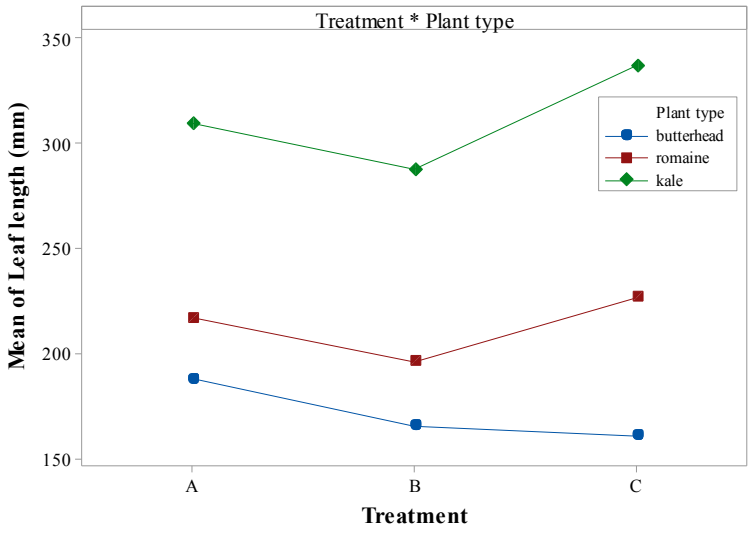


Figure M.14. Interaction plot of average leaf length for different plant types by LED light treatment. Significant interaction between treatment and plant type (p= 0.011).

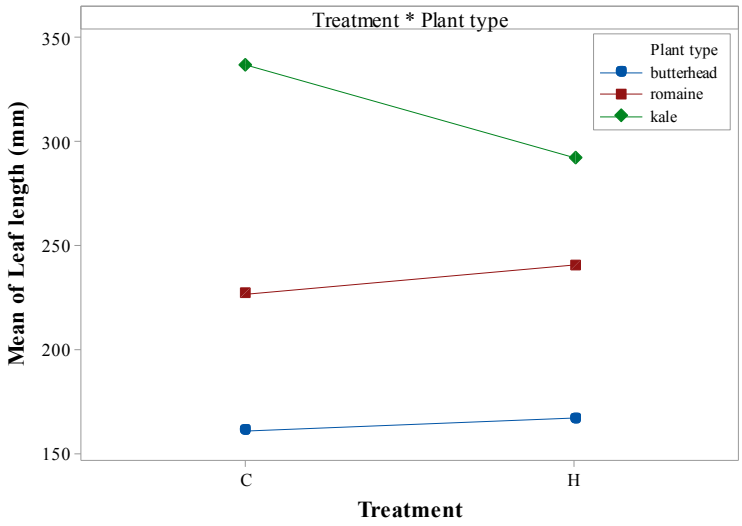


Figure M.15. Interaction plot of average leaf length for different plant types by nutrient treatment. Significant interaction between treatment and plant type (p= 0.002).

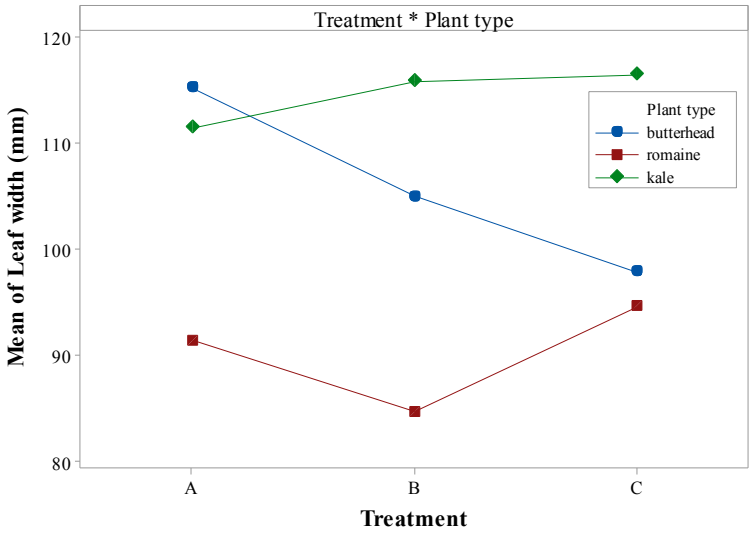


Figure M.16. Interaction plot of average leaf width for different plant types by LED light treatment. No significant interaction between treatments (p= 0.571).

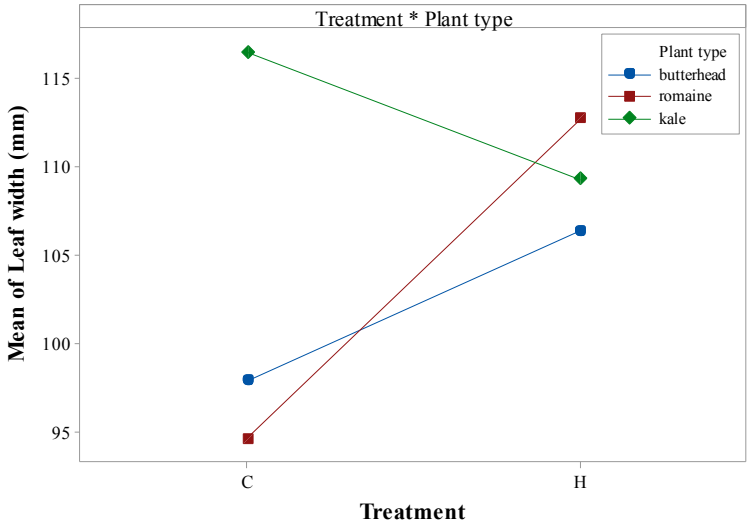


Figure M.17. Interaction plot of average leaf width for different plant types by nutrient treatment. No significant interaction between treatments (p= 0.078).

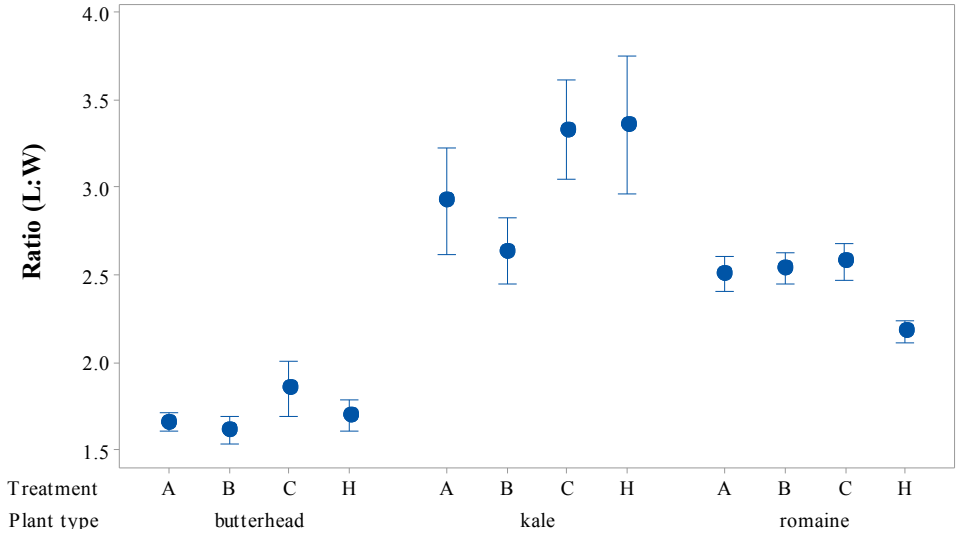


Figure M.18. Interval Plot of leaf length:width ratio (L:W) by plant type and treatment.

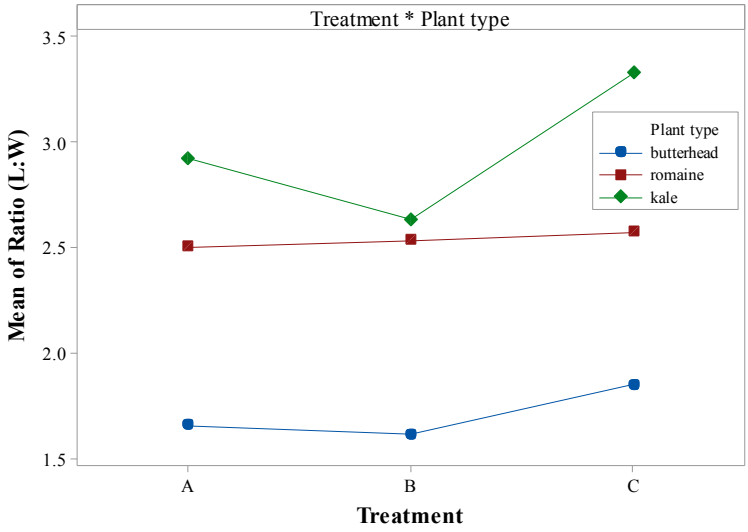


Figure M.19. Interaction plot of average L:W ratio for different plant types by LED light treatment. Significant interaction between treatments (p= 0.000).

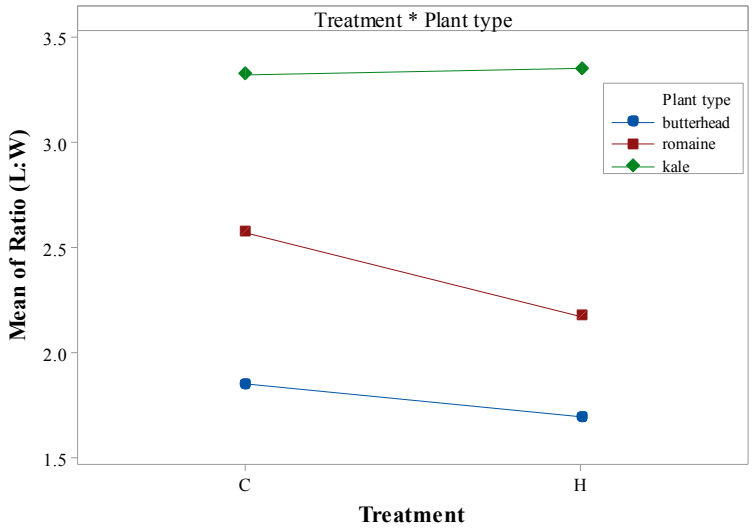


Figure M.20. Interaction plot of average L:W ratio for different plant types by nutrient treatment. Significant interaction between treatments (p= 0.011).

M.6 Response Variable: Stem Length

M.6.1 Descriptive Statistics

Plant type = butterhead

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Stem length (mm)	A	6	60.00	6.66	50.00	60.00	69.00

	B	6	153.5	35.1	110.0	153.0	200.0
	C	6	82.67	13.06	58.00	87.00	94.00
	H	6	120.3	37.2	70.0	117.5	175.0

Plant type = romaine

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Stem length (mm)	A	6	105.33	13.41	87.00	106.50	126.00
	B	6	122.00	22.12	87.00	131.00	140.00
	C	6	99.17	18.00	80.00	92.50	130.00
	H	6	118.2	41.6	63.0	115.0	188.0

Plant type = kale

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Stem length (mm)	A	6	64.7	35.5	35.0	50.0	125.0
	B	6	54.00	22.82	35.00	45.00	95.00
	C	6	66.7	28.8	30.0	69.5	106.0
	H	6	68.00	17.36	55.00	58.00	97.00

M.6.2 Dunnett and Tukey Multiple Comparisons (95% Confidence)

Plant type = butterhead; Factor Information: Stem length

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-22.7	12.7	(-53.6, 8.3)	-1.79	0.163
B - C	70.8	12.7	(39.9, 101.8)	5.58	0.000

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	37.7	16.1	(1.8, 73.5)	2.34	0.041

Individual confidence level = 95.00%

Plant type = romaine; Factor Information: Stem length

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	6.2	10.5	(-19.5, 31.8)	0.59	0.785
B - C	22.8	10.5	(-2.8, 48.5)	2.17	0.082

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value

H - C	19.0	18.5	(-22.2, 60.2)	1.03	0.328

Individual confidence level = 95.00%

Plant type = kale; Factor Information: Stem length

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-2.0	17.0	(-43.5, 39.5)	-0.12	0.990
B - C	-12.7	17.0	(-54.2, 28.9)	-0.74	0.684

Individual confidence level = 97.24%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	1.3	13.7	(-29.3, 31.9)	0.10	0.925

Individual confidence level = 95.00%

M.6.3 Figures

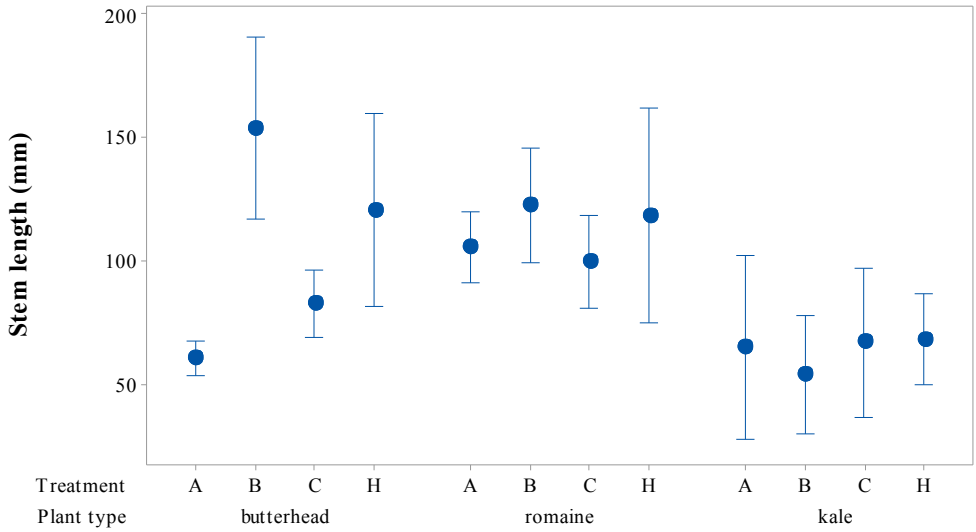


Figure M.21. Interval Plot of stem length by plant types and treatment.

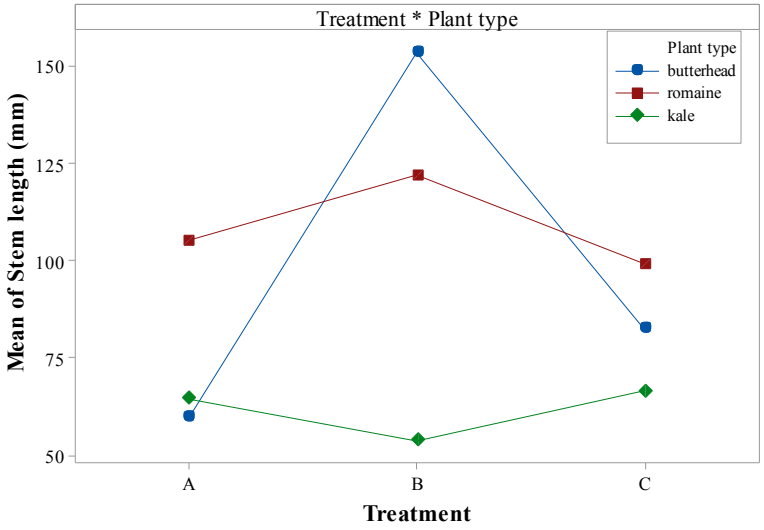


Figure M.22. Interaction plot of average stem length for different plant types by LED light treatment. Significant interaction between treatment and plant type (p= 0.00003).

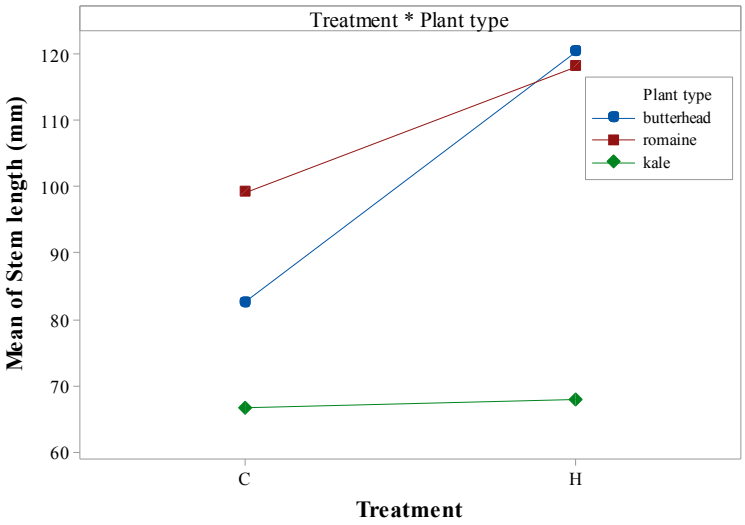


Figure M.23. Interaction plot of average leaf count for different plant types by nutrient treatment. No significant interaction between treatment and plant type (p= 0.300).

M.7 Response Variable: Deformities

M.7.1 Descriptive Statistics

Plant type = butterhead

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Deformities	A	3	9.00	2.65	7.00	8.00	12.00

	B	3	19.00	5.00	14.00	19.00	24.00
	C	3	19.00	5.57	13.00	20.00	24.00
	H	4	36.75	17.73	18.00	36.50	56.00

Plant type = romaine

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Deformities	A	4	24.50	9.26	17.00	21.50	38.00
	B	5	27.40	18.72	7.00	23.00	55.00
	C	3	18.33	3.21	16.00	17.00	22.00
	H	5	10.80	8.87	4.00	5.00	24.00

Plant type = kale

Variable	Treatment	N	Mean	StDev	Minimum	Median	Maximum
Deformities	A	3	2.00	3.46	0.00	0.00	6.00
	B	3	3.33	2.31	2.00	2.00	6.00
	C	4	6.50	3.00	3.00	7.00	9.00
	H	3	10.00	4.36	7.00	8.00	15.00

M.7.2 Dunnett and Tukey Multiple Comparisons (95% Confidence)

Plant type = butterhead; Factor Information: Deformities

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-10.00	3.74	(-20.71, 0.71)	-2.67	0.064
B - C	0.00	3.74	(-10.71, 10.71)	0.00	1.000

Individual confidence level = 97.13%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	17.8	10.8	(-10.1, 45.6)	1.64	0.162

Individual confidence level = 95.00%

Plant type = romaine; Factor Information: Deformities

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	6.2	10.4	(-20.9, 33.2)	0.59	0.773
B - C	9.07	9.97	(-16.79, 34.93)	0.91	0.568

Individual confidence level = 97.09%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	-7.53	5.46	(-20.90, 5.83)	-1.38	0.217

Individual confidence level = 95.00%

Plant type = kale; Factor Information: Deformities

Dunnett Multiple Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
A - C	-4.50	2.27	(-10.77, 1.77)	-1.99	0.152
B - C	-3.17	2.27	(-9.44, 3.10)	-1.40	0.337

Individual confidence level = 97.21%

Tukey Pairwise Comparisons (95% Confidence)

Difference of Levels	Difference of Means	SE of Difference	95% CI	T-Value	Adjusted P-Value
H - C	3.50	2.75	(-3.58, 10.58)	1.27	0.260

Individual confidence level = 95.00%

M.7.3 Figures

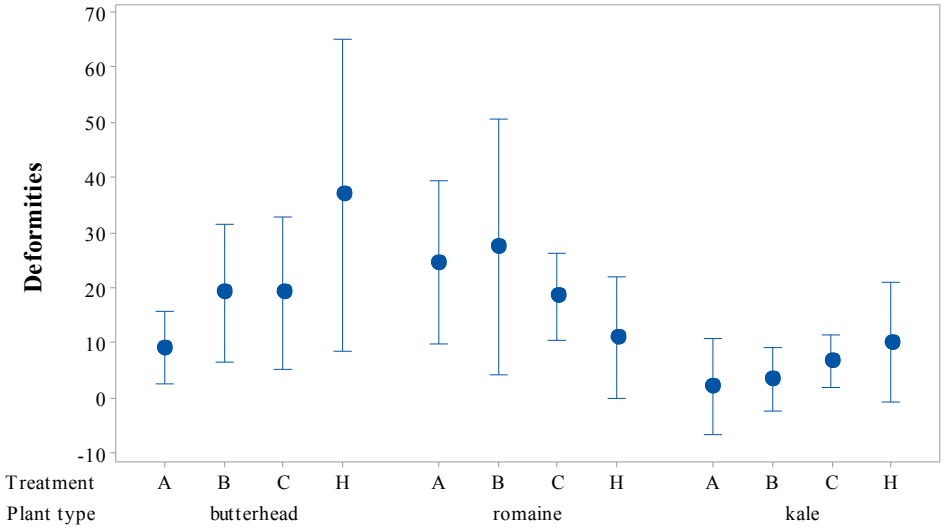


Figure M.24. Interval Plot of deformities by plant types and treatment.

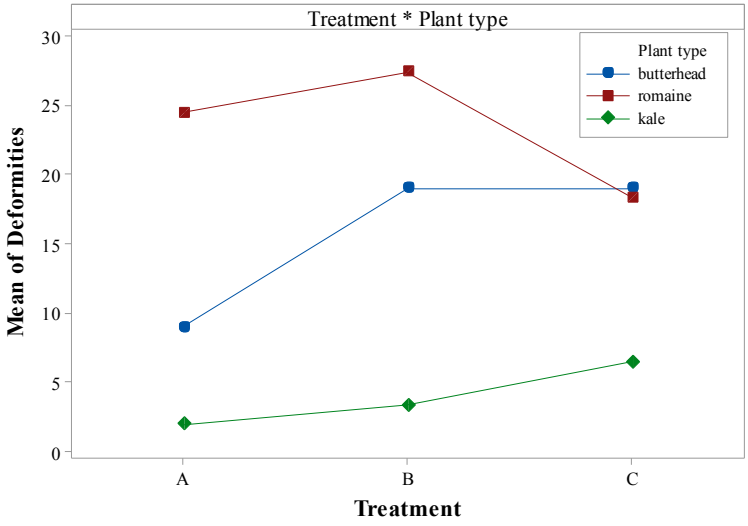


Figure M.25. Interaction plot of average # of deformities for different plant types by LED light treatment. No significant interaction between treatment and plant type (p= 0.527).

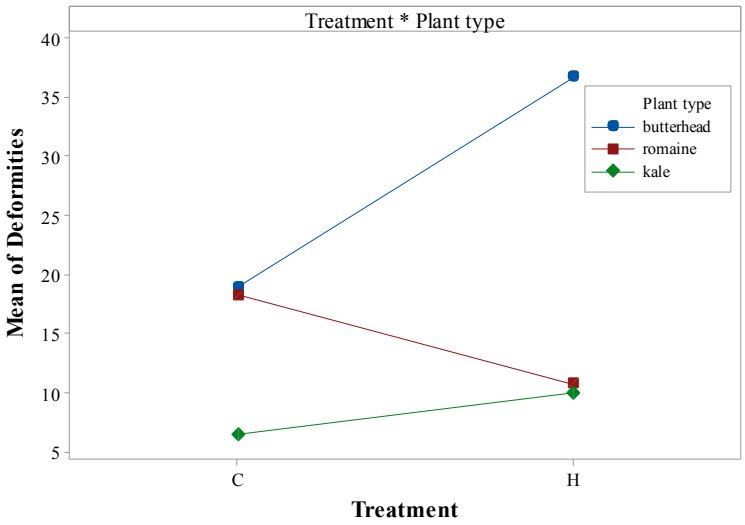


Figure M.26. Interaction plot of average # of deformities for different plant types by nutrient treatment. No significant interaction between treatment and plant type (p= 0.065).