The Effect of Irrigation Timing and Duration on Yield and Quality of Aeroponically Grown Lettuce (*Lactuca sativa L.*)

A Thesis

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Master of Professional Studies

Concentration in Controlled Environment Agriculture and Astrobotany

by

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ABSTRACT

As astronauts venture further from Earth for longer durations, as seen with NASA’s return of astronauts to the Lunar surface, the demand for food grown in situ (spacecraft, space habitats, etc.) is likely to increase. Due to the water scarcity related to human spaceflight missions, crop production systems and methods with minimal water consumption and volumes must be utilized, which is why NASA and other spaceflight entities are developing aeroponic systems for the microgravity environment.

This master’s thesis examines a modular aeroponic system and evaluates its performance against a deep water culture control. Results showed no difference in shoot fresh weight and dry weight between the deep water culture control and aeroponic treatments, which are encouraging results for aeroponics, both commercially on Earth as well as space applications.

BIOGRAPHICAL SKETCH

Skylar J. Laham is from Santa Monica, California, where he enjoyed his youth as a resident of the windward side of the Santa Monica Mountains National Recreation Area. His backyard was also home for families of deer, coyotes, birds, mountain lions, and other species native to the chaparral ecosystem; which is where he found his passion for the environment and ecology.

Elevated 1,200 feet above the city and unperturbed by light pollution, Skylar spent most of his nights bivouacked under the stars and fell in love with all things space. Along with his interests of nature and science, Skylar was also inclined towards athletics. His father taught him how to box at an early age, and by his late teens and early twenties Skylar trained as a boxer with the goal of competing in the Olympics. Though on track with that goal, he felt an escalating urge to return to academia. After his transition from the ring to the academic arena, Skylar worked at NASA and DOD research laboratories for approximately half a decade, where he developed astronaut life support systems.

Cornell University

ACKNOWLEDGMENTS

I would like to thank my family for their support up to this point. My mother for sharing her kindness with nature and her Native American roots with me as a child. My sister for her sweetness and for bringing her gorgeous children into the world. My brother for his sheer intellect, our strong brotherly bond, and for being a joy to be around. An especially big thankyou to my father for his generosity, both intellectually as well as financially during graduate school, and for introducing me to backyard bivouacking as a child.

Thank you to the Mattson lab for enabling me to engineer and construct a modular aeroponic system from the ground up by ordering its vast assemblage of components. Additionally, thank you for your aid with the master's experiment. Even while faced with the COVID pandemic and its challenges, you helped me feel at home during my time at Cornell. As for my advisor Neil, I could not have gotten a better advisor or a better friend than you. You are what every academic should strive to be, and to say that you were well deserved of full professorship is an immense understatement. Thank you so much, and congratulations on your recent achievement!

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
APH	Advanced Plant Habitat
CEA	Controlled Environment Agriculture
DLI	Daily Light Integral
DWC	Deep Water Culture
GPH	Gallons Per Hour
HPS	High Pressure Sodium
ISS	International Space Station

INTRODUCTION

Launching and growing plants in space is a longstanding feature of United States space exploration that spans from before the formation of the National Aeronautics and Space Administration (NASA), where in the mid to late 1940's varieties of maize, rye, and cotton seeds were flown in space (Burgess, 2017). More recently in the mid to late 2010's, growing crops in space transitioned away from purely experimental. Use of space crops for astronaut consumption has been emphasized, as seen with the Advanced Plant Habitat (APH) aboard the International Space Station (ISS). The APH already supplied a variety of crops including cabbage, lettuce, mizuna, and more to astronauts (NASA, 2019). The harvested crops are more than fresh alternatives to freeze-dried foods and sources of essential nutrients, they are also beneficial to astronaut mental health, wellbeing, and job performance (NASA, 2010).

Now as NASA returns astronauts to the Moon to establish a permanent presence on the lunar surface with the Artemis mission, large scale plant cultivation off Earth befits the US' space exploration agenda. Along with the aforementioned benefits associated with small controlled environment agriculture (CEA) systems such as the APH, larger growth chambers yield substantial advantages to astronaut life support systems and habitats. These advantages include enhancing air purification, CO_2 scrubbing, and resource recycling capabilities, while decreasing the reliance on less sustainable physical chemical life support systems, lowering long-term mission costs, and increasing life support system robustness (NASA, 2017).

The advantages of cultivating crops in space have not gone unnoticed by other spacefaring nations however, as in 2019 China landed a miniature biosphere on the Moon (Figure 1). The Chang’e-4 lander contains potatoes, thale-cress (*Arabidopsis*), cotton seeds which sprouted on the lunar surface, as well as other organisms (Castelvecchi, 2019).

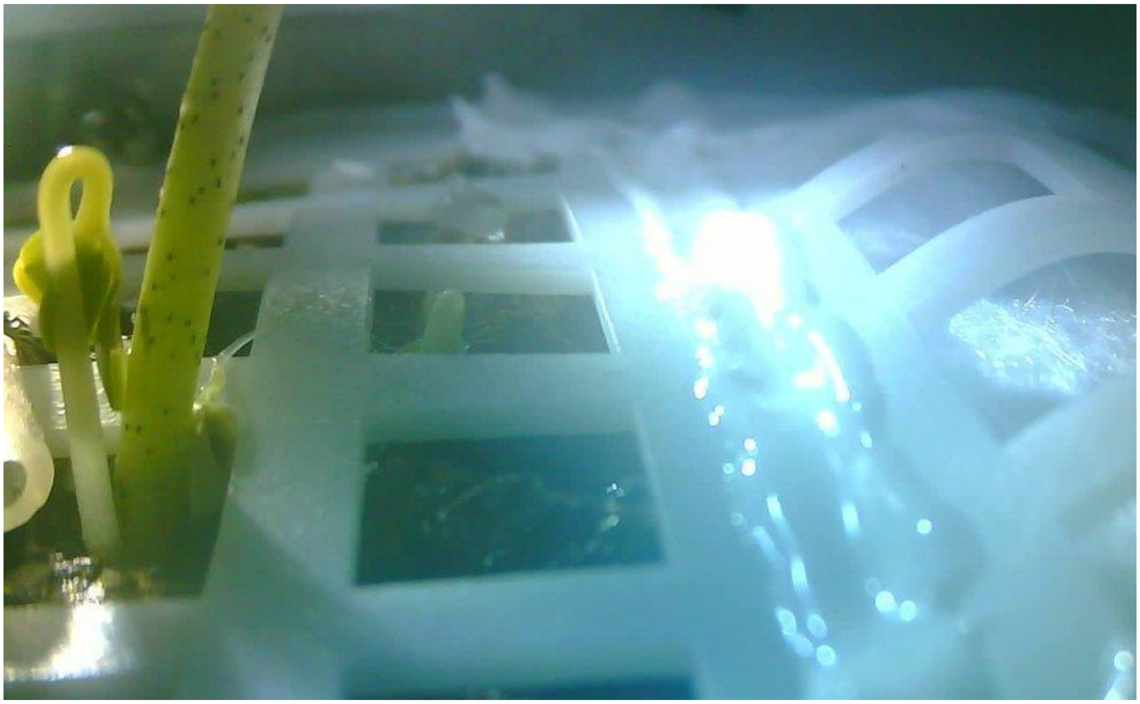

Figure 1. Seeds sprouted on the Lunar surface in the Chinese Chang’e-4 lander. From “China's moon Lander sprouted a plant, but now it's dead”, Kooser (2019).

The CEA systems currently flown by NASA aboard the ISS are hydroponic, with various autonomous and manual irrigation methods. Manual irrigation is performed by astronauts, whereby water is injected via syringe into an injection port which feeds into small rooting packets called “plant pillows” (Massa et al., 2017). The autonomous active water delivery method is the same, except water is pumped into plant pillows, with irrigation timing determined by an array of sensors. The autonomous capability to regulate irrigation and other environmental controls is in large part due to the vast array of sensors embedded into the growth chamber. These sensors amount to over 180 in number and relay real time information within the growth chamber to measure temperature, oxygen and carbon dioxide content, as well as moisture levels in the air, leaves, stem, and roots (Manje et al., 2020).

Even with abundance of sensors and automation, irrigating plants in space is inherently challenging due to the physical properties and behavior of water, as surface tension and capillary action dominate in microgravity (Figure 2). Thus, providing plants with adequate aeration in microgravity poses a serious challenge. As a result, some NASA researchers have proposed to grow plants in space aeroponically, where aeration is inherently sufficient at the roots (NASA Spinoff, 2006). Clawson et al., (2000) describes aeroponics as “the process of growing plants in an air/mist environment without the use of soil or an aggregate media. Aeroponics has contributed to advances in several areas of study including root morphology, nutrient uptake, drought and flood stress, and responses to variations in oxygen and/or carbon dioxide root zone concentrations.” Furthermore, aeroponic systems reduce water volume and usage requirements by up to 98%, as well as fertilizer usage by 60% (NASA Spinoff, 2008). Thus, from a sustainable resource utilization perspective, aeroponics appears to be more suitable than the plant pillow method for microgravity spaceflight applications, as well as on the Lunar and Martian surfaces where access to water is extremely scarce.

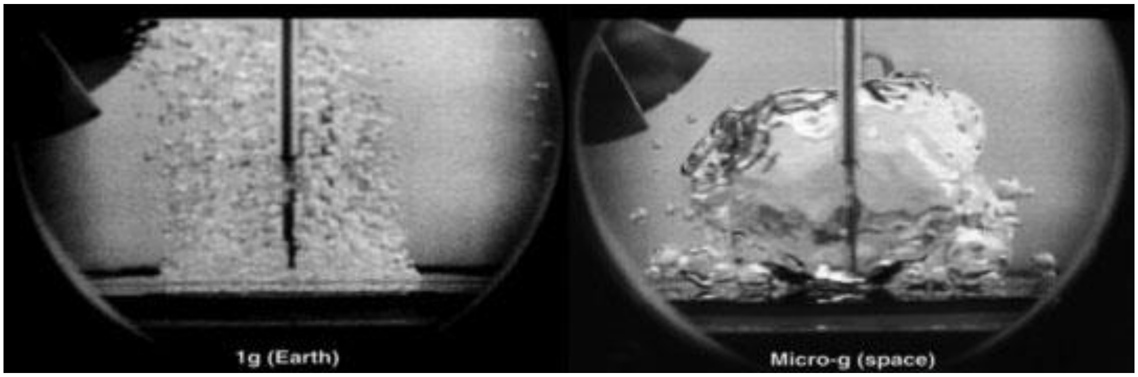

Figure 2. Behavior of water and air under the Earth's gravity (left) and microgravity (right) conditions. Note that independent of the condition, air has lower mass than water. However, in microgravity the air bubbles do not rise (are not displaced) above the water. Thus, the air bubbles coalesce at the source of aeration (in this case, around a water heating element). From "Zero gravity: The lighter side of science", APS Physics (2007).

While aeroponics may be a viable option for space crop production, it also has a place on Earth. Due to the small water volume requirements and infrequent pump usage associated with aeroponic systems, aeroponics lends itself well among commercial growers looking to decrease their electricity costs from frequent water pump usage, as well as those who have limited access to water sources. At the point of submitting this master's thesis, there has been a substantial amount of aeroponic research published in scientific journals, particularly relating to potatoes, tomatoes, as well as ornamentals such as chrysanthemums.

The aim of this master's thesis is the optimization and identification of irrigation intervals (time off) and durations (time on) in aeroponics, to increase plant yield and quality while decreasing electricity consumption and water usage. In preparation for this research, a literature review was conducted and a table containing the irrigation intervals, durations, and crops used in the studies was compiled.

With aeroponic systems, water and nutrients are delivered to the roots in the form of small droplets. These droplets are typically generated via spray nozzles or ultrasonic foggers. Jamshidi et al. (2019) compared the irrigation intervals and ultrasound frequencies of ultrasonic foggers with regards to vertical aeroponic systems for tomato production. Jamshidi et al. reported that a 15-minute irrigation interval outperformed 10 and 20 minute intervals with respect to plant yield. Furthermore, Jamshidi et al. found that a 50 KHz ultrasound frequency significantly outperformed 107 KHz and 2.1 MHz in terms of plant height, root length, root dry weight, and yield. Additionally, Jamshidi et al. noted that growing aeroponically may reduce water consumption by 99% and nutrient usage by 50% compared to conventional cultures.

Tshisola (2014) identified aeroponic systems as environmentally friendly and sustainable options well suited for the future of horticulture. Tshisola also compared multiple irrigation intervals and durations with potatoes and found that 20 minutes off and 30 seconds on resulted in the largest fresh and dry tuber weight, as well as the lowest tuber nutrient concentration. Conversely, 50 minutes off and 30 seconds on resulted in the lowest fresh and dry tuber weight, as well as the highest tuber nutrient concentration. Ritter et al. (2001) also grew potatoes and found that tuber yield was approximately 70% higher with aeroponics than with hydroponics. Though the aeroponically grown tubers weighed roughly 33% less than their hydroponically grown counterparts, the number of tubers produced was over 2.5-fold more than that of hydroponics.

Similar to Ritter et al. (2001), Khalil (2020) reported that growing potatoes aeroponically maximized the number of minitubers. Unlike Ritter et al. (2001), Khalil found that minituber yields were very similar between most aeroponic and hydroponic grown potato cultivars. Farran (2006) observed no difference in tuber yield or number between aeroponic and hydroponic treatments. Farran also indicated that aeroponics would be an appropriate system for potato production.

Unlike many of the other papers identified, Molitor (1999) worked with ornamentals (chrysanthemums). Molitor found that with a 30-minute irrigation interval, an irrigation duration of 120 seconds performed best during the summer, whereas 30 seconds performed better during the winter. The literature review by Buckseth et al. (2016) combed through approximately 100 aeroponic papers and concluded that aeroponic systems appear to be the best in many respects. These include rapid seed production, increased rates of survival and growth for young plants, as well as air circulation. The irrigation timing from the following papers were examined and used to inform as well as select the irrigation intervals and duration seen in this master's thesis (Table 1).

Table 1. List of aeroponic literature reviewed with pertinence to irrigation intervals and durations, as well as spray methodologies.

Irrigation Off (Interval)	Irrigation On (Duration)	Crop	Notes	Source
30 minutes	~30 seconds	Chrysanthemum	Conducted in winter	Molitor, 1999
30 minutes	~120 seconds	Chrysanthemum	Conducted in summer	
None provided	15 minutes	Tomato	Ultrasonic foggers used in place of nozzles	Jamshidi et al., 2019
20 minutes	30 seconds	Potato	Highest fresh and dry weights, lowest nutrient concentrations	Tshisola, 2014
50 minutes	30 seconds	Potato	Lowest fresh and dry weights, highest nutrient concentrations	

10 minutes	3 seconds	Potato	4 liter / hour nozzle	Ritter et al., 2001
5 minutes	30 seconds	Potato		Khalil, 2020
20 minutes	10 seconds	Potato		Farran, 2006
10 to 30 minutes	10 to 30 seconds	Potato		Buckseth et al., 2016

METHODS AND MATERIALS

Aeroponic System

An aeroponic system was designed and comprised of 24 five-gallon white buckets. White pigmented buckets were selected as they reflect a large amount of radiation, maintaining an adequate root temperature and inhibiting algal growth inside the buckets (Li et al., 2020). Three net pots were inlayed on the lid of each bucket to held one plant per net pot. The lid design (along with the entire aeroponic system) was developed to be modular and can fit as many as 10 medium sized net pots per bucket. Each treatment (including the control) was comprised of six buckets arranged in two columns by three rows, totaling 18 plants per treatment (Figure 3).

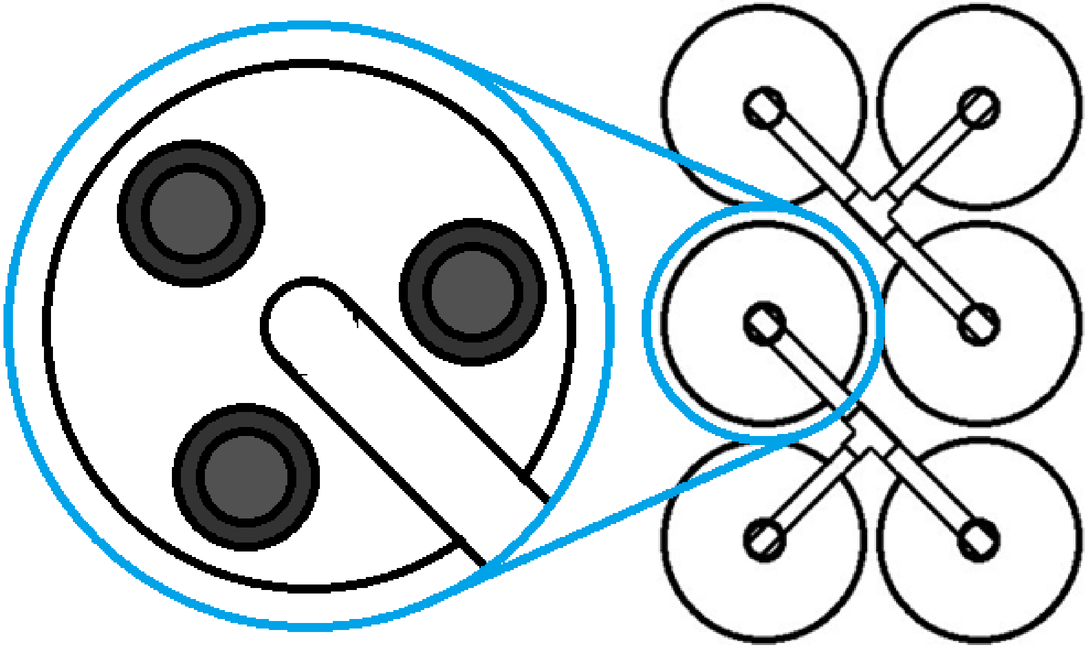

Figure 3. Arrangement of buckets per treatment, and orientation of net pots integrated into bucket lids.

The water inlet was plumbed through the lid and sprays through six nozzles mounted perpendicularly on a vertically oriented PVC pipe inside each bucket, which provided approximately 6.6 gallons per hour (gph) of irrigation per bucket. The water drained through a bulkhead at the base of each bucket, which collected in a 17-gallon reservoir (Figure 4). A deep water culture (DWC) system of the same plant spacing (3 plants per bucket) was used as a control treatment. To keep the roots of the DWC control submerged in water, the drains were raised to the base of the net pots via PVC pipe, elevating the water level. The six buckets shared a common reservoir and each reservoir was dedicated to a single treatment. Thus, four reservoirs were used in total.

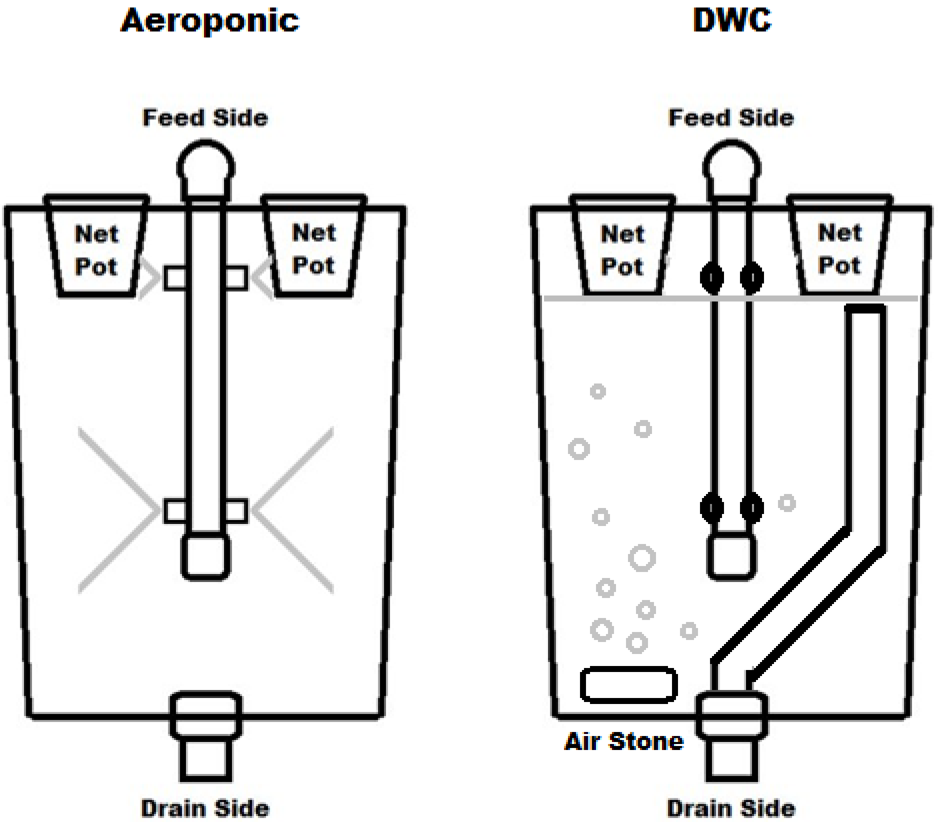

Figure 4. Schematic of aeroponic and DWC internal bucket design. Aeroponic system (left), DWC (right).

Each treatment comprised six buckets, each with 3 plants which drained into its own designated reservoir. Furthermore, both aeroponic and DWC treatments drained into their own 17-gallon reservoir. Three treatments used aeroponics (as above) and one treatment was the DWC control. All treatments were plumbed identically, except for the DWC control where nozzles were not attached to the vertical irrigation pipes (Figure 5). Without the nozzles acting as bottlenecks on flowrate, circulation within the DWC buckets increased. Increased flow rate and circulation in DWC is essential for providing adequate dissolved oxygen to roots (Yang, 2020). Because the DWC control required continuous pump operation, and as the high-pressure water pumps used in the aeroponic treatments were not designed to operate continuously, a submersible pump was used with DWC instead. Three large air pumps aerated all reservoirs, with two air stones per reservoir. Furthermore, one air stone ran into each of the DWC buckets to enhance aeration.

Figure 5. Complete aeroponic system. Plumbed from reservoir (beneath buckets), to pump (in orange), to filters (in blue) to buckets (through red hose and mated to PVC).

Crop Cultivar, Germination, and Transplanting

Lettuce (*Lactuca sativa L.*) cultivar 'Rex' is considered a standard for hydroponic butterhead lettuce, and seeds from Johnny's Selected Seeds (Winslow, Maine) were used in the experiment (Johnny's Selected Seeds, 2021). 'Rex' seeds were placed in 1 in^3 rockwool cubes which were presoaked in nutrient solution for 15 minutes. The seeded cubes were then covered in a growing tray with drainage holes and left to germinate in a partially shaded area of a greenhouse for 14 days. The plants were then transplanted into net pots embedded into the aeroponic and DWC treatments and the experimental treatments (described below) began.

Experimental Treatments, and Irrigation Intervals and Durations

The DWC was used as the control for the experiment as it is a coninuously running hydroponic system, and therfore does not have irrigation interval and duration. Additionally, DWC was selected as it is often considered to produce the heighest plant quality and yield among hydroponic systems (Verdoliva et al., 2021). Irrigation intervals and durations were informed by the literature review. Each aeroponic treatment was controlled via timers, programable to one second intervals. The aeroponic treatments selected for the experiment included: 5 minute (Aero-5), 10 minute (Aero-10), and 20 minute (Aero-20) off irrigation intervals. All three aeroponic treatments had a 30 second on irrigation duration. Note that the on duration was increased several seconds to account for the time it took water to be pumped from the reservoir to the nozzles, thus allowing for 30 seconds where the roots were actually sprayed with water.

Nozzle Selection

Spray nozzles with approximately 60 micron droplet size emission and a 110° spray angle at approximately 1.1 gph flow rate were selected. A wide spray angle is considered ideal for maximum droplet coverage within buckets and also reduces the potential harm to roots from high pressure spray associated with narrow spray angle nozzles. Droplet sizes around 50 microns were typical in other research papers, as that is the droplet size between fog and mist, where fog droplet sizes are <50 microns, and mist droplet sizes are >50 microns (Oliver, 2008).

Lighting

Four high pressure sodium (HPS) light fixtures were mounted on greenhouse trusses approximately five feet above the aeroponic system, providing supplemental light from 0500 (5:00 AM) to 2100 (9:00 PM), corresponding with an 16 hour on / 8 hour off photoperiod. Additionally, truss-mounted HPS light fixtures located parallel to both sides of the aeroponic system ran on the same timing cycle as the light fixtures directly overhead. The average supplemental light intensity measured across the entire system was ~212 µmol·m^{-2}·s^{-1}, with the highest measured light intensity at ~9% above the average, and the lowest measured light intensity at ~22% below the average (Figure 6). Light intensities were measured on three separate nights to ensure consistency. On top of ambient light, the daily light integral (DLI) provided by supplemental lighting which was on for approximately 16 hours a day equated to roughly 12.21 mol·m^{-2}·d^{-1}.

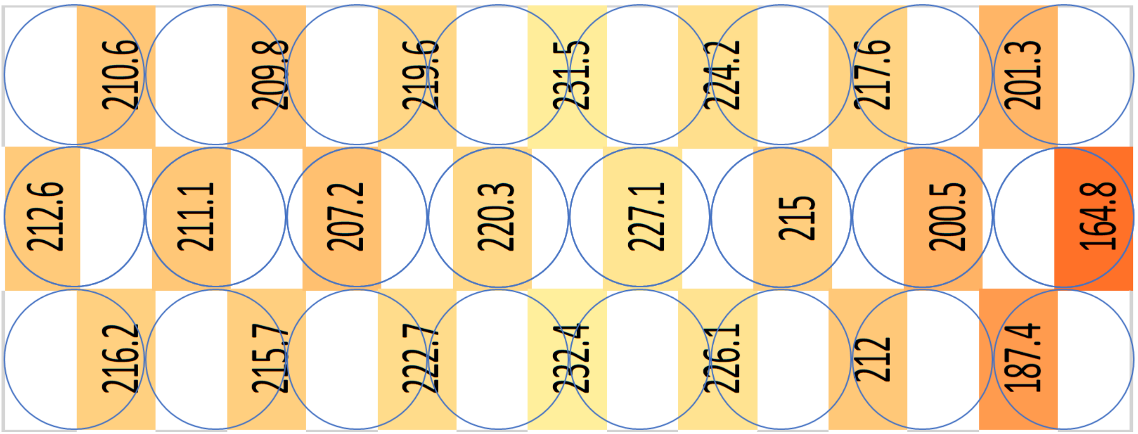

Figure 6. Light intensity map. Bucket location outlined in blue. Units in µmol·m^{-2}·s^{-1}.

Water Quality, Maintenance, Filtration, and Fertilizer

Figure 7. Aeroponic reservoir system. Water is drained from beneath the aeroponic buckets then pumped back up where it is recirculated.

Each of the four reservoirs were filled with tap water from Ithaca New York, which is a high quality water source (Electrical conductivity of 0.30 dS/m and alkalinity of ca. 115 ppm $CaCO_3$) relative to other municipalities (CIWS, 2021). With each treatment a 50 micron cartridge filter was plumbed inline after the reservoir and pump, and before the buckets and nozzles (Figure 7). Plumbing the filter after the pump reduces the risk of pump failure in the event that the pump isn't primed, as it doesn't have to overcome the additional pressure on the inlet side generated by the cartridge filter. Jack's Hydroponic nutrient solution was used at a 1:100 dilution providing 150 ppm nitrogen with a complement of other nutrients (Mattson, 2014). The EC and pH of each reservoir was measured every third day. Water was adjusted to maintain an EC of 1.5 to 2.7 mS/cm, and a pH between 5.5 to 6.

Data Collection

As rockwool cubes were not completely uniform, plant height was instead measured from the rim of the net pots. The rim was approximately 0.3 inches above the top surface of the rockwool. Three measurements were made for plant volume: the diameter of the widest horizontal point of the plant (x), the diameter horizontally perpendicular to the widest point (y), and plant height (z). The equation $V = h * \pi * r^2$ was used to calculate cylindrival volume. Where “V” is volume, “h” is plant height, and “r” is the plant width (averaged from the two plant width measurements). Chlorophyll index was measured with a Chlorophyll Meter SPAD-502 (Konica Minolta Inc., Tokyo, Japan), and three measurements were made per plant and later averaged. At harvests, plants were removed from the system and their root length measured (length of the longest root from the base of the rockwool cube to the tip of the root). Then roots and shoots were separated, weighed, and placed in a drying oven. After drying, the root and shoot dry weight was measured.

RESULTS

Plant Height

Treatments were compared weekly, and though there appeared to be visual differences among treatments (crops from the DWC treatment appeared taller and larger than those of the aeroponic treatments), the differences were statistically insignificant (Figure 8). Thus, lettuce height was the same among all treatments at each of the three weekly harvests.

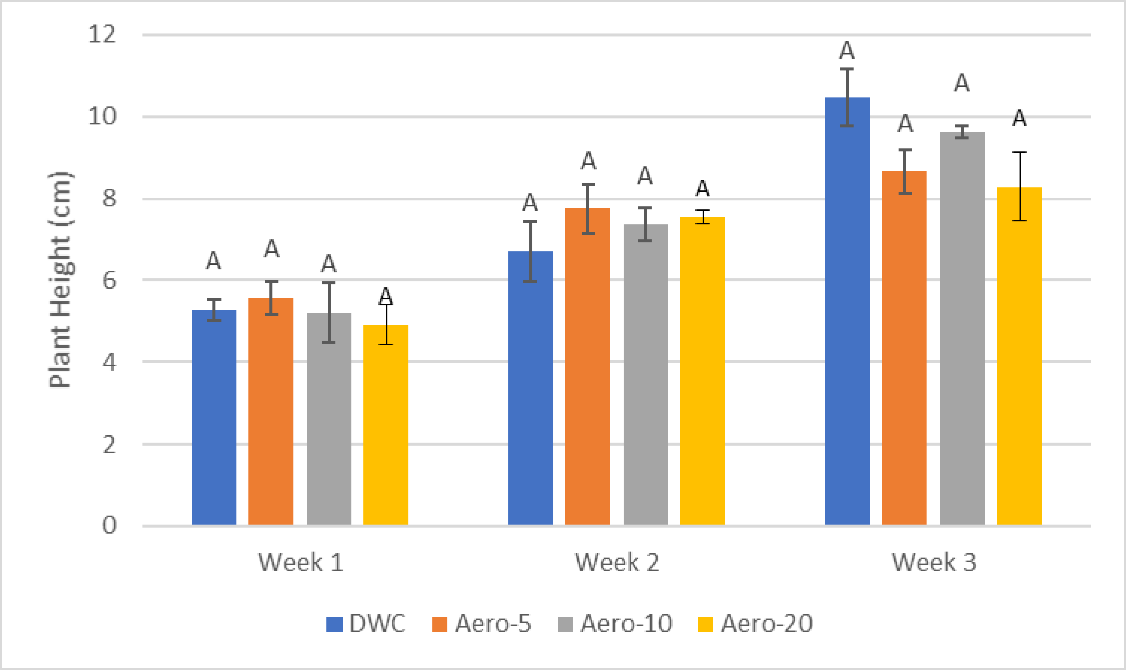

Figure 8. Comparison of weekly plant height among treatments. Letters represent mean separation comparison across aeroponic duration or DWC within each week using Tukey’s HSD (alpha=0.05). Error bars represent standard error.

Plant Volume

There were no statistically significant differences found in plant volume among treatments harvested at weeks one and two (Figure 9). However, by week three the DWC control had greater volume than Aero-5 and Aero-20. Worth mentioning is the large variability (standard error) seen at the final week among DWC and Aero-20.

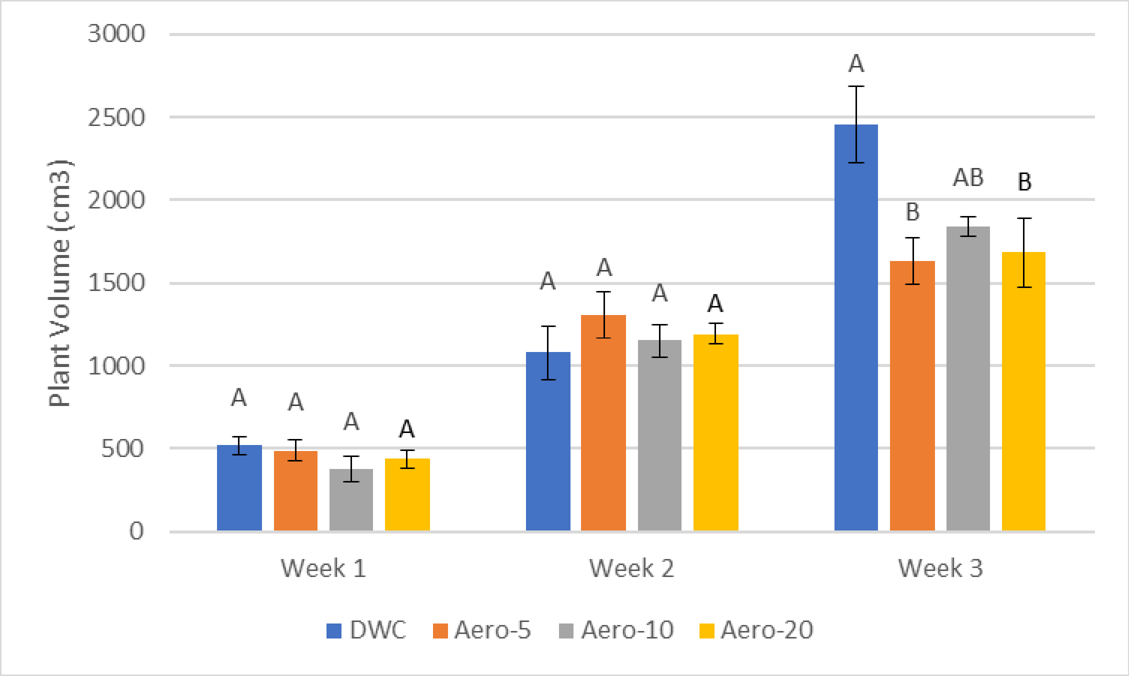

Figure 9. Comparison of weekly plant volume among treatments. Letters represent mean separation comparison across aeroponic duration or DWC within each week using Tukey’s HSD (alpha=0.05). Error bars represent standard error.

Chlorophyll Index

At the first harvest, the DWC control, Aero-5, and Aero-20 had a higher chlorophyll index than Aero-10 (Figure 10). By the second week Aero-10 has caught up with Aero-5 and Aero-20 and the only significant difference was that DWC (control) has lower chlorophyll index than Aero-20. However, by the final harvest DWC caught up and all treatments exhibited the same chlorophyll index.

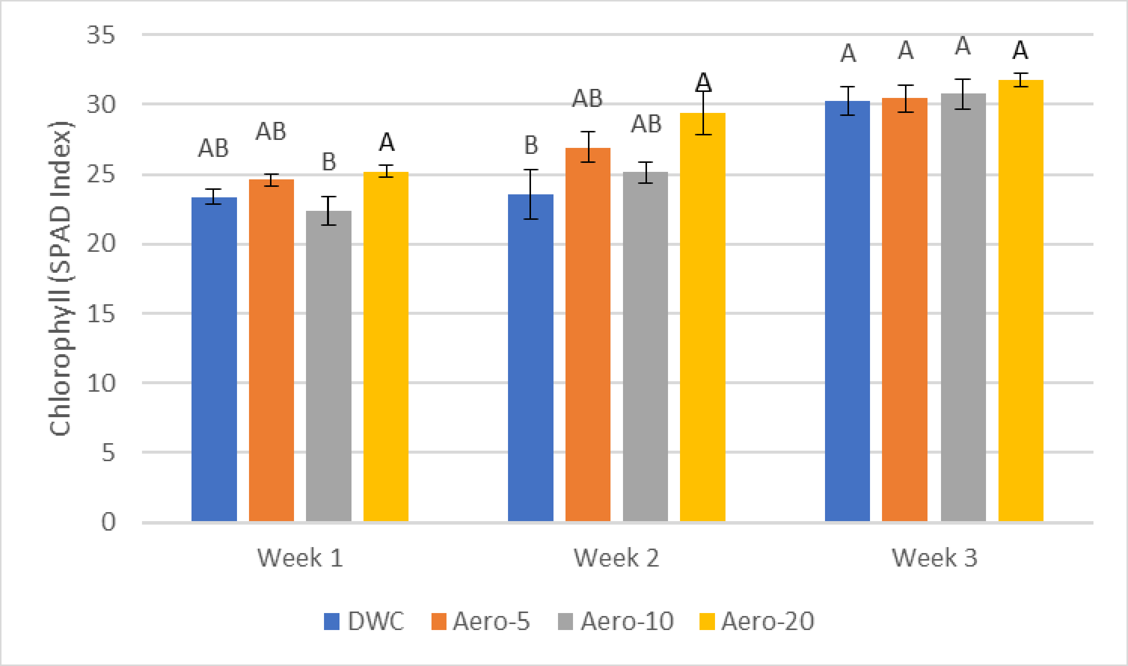

Figure 10. Comparison of weekly plant chlorophyll index among treatments. Letters represent mean separation comparison across aeroponic duration or DWC within each week using Tukey’s HSD (alpha=0.05). Error bars represent standard error.

Shoot Fresh Weight

For each of the three weekly harvests there were no different in shoot fresh weight based on aeroponic/DWC treatment (Figure 11). Worth mentioning is the large standard error for DWC at the final harvest. Though not statistically significant, the shoots and foliage of DWC did appear visually fuller than the aeroponic treatments.

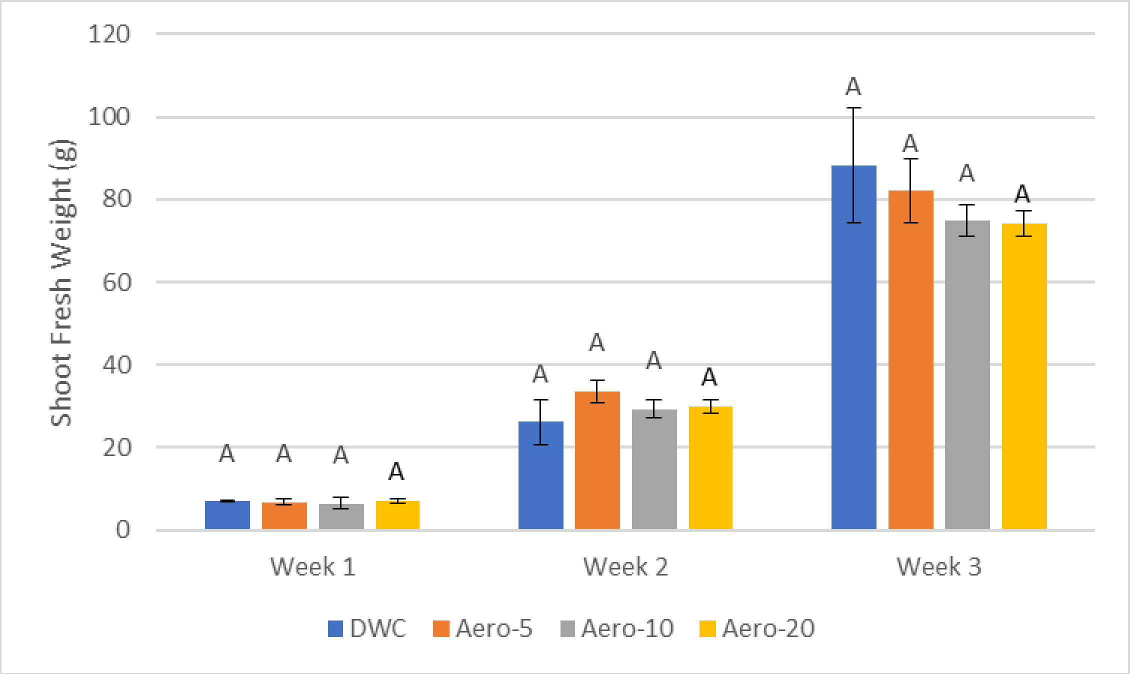

Figure 11. Comparison of weekly shoot fresh weight among treatments. Letters represent mean separation comparison across aeroponic duration or DWC within each week using Tukey's HSD (alpha=0.05). Error bars represent standard error.

Shoot Dry Weight

Similar to shoot fresh weight, there were no significant differences between aeroponic and DWC treatment for any of the three weekly harvests (Figure 12). Note the large standard error seen with DWC and Aero-5 at week three.

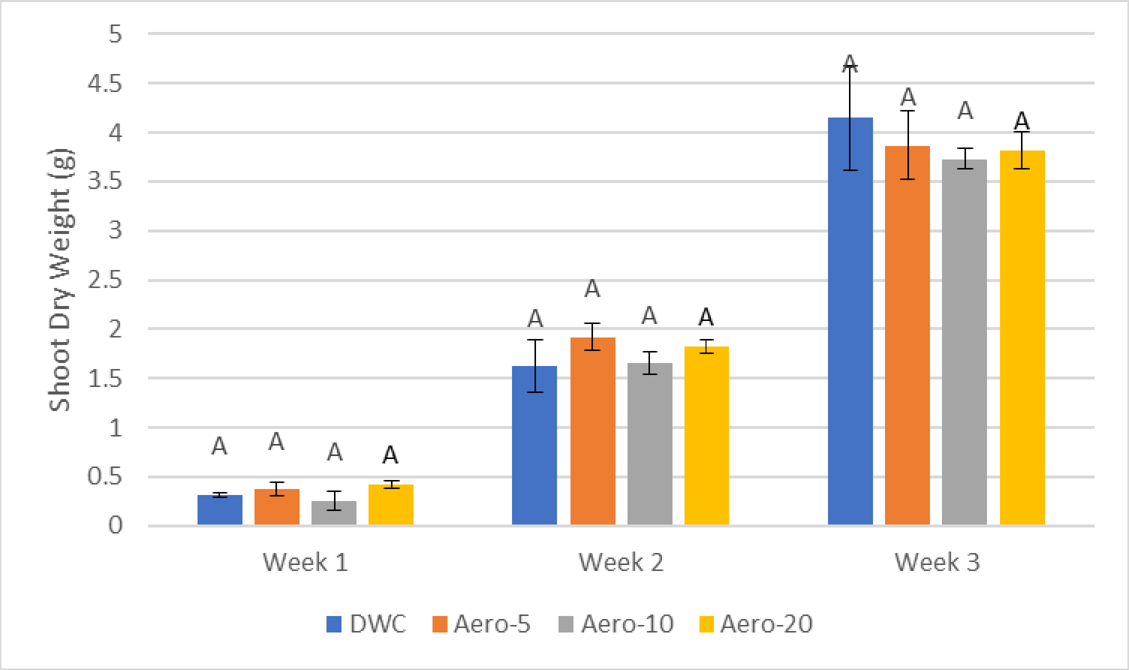

Figure 12. Comparison of weekly shoot dry weight among treatments. Letters represent mean separation comparison across aeroponic duration or DWC within each week using Tukey's HSD (alpha=0.05). Error bars represent standard error.

Root Fresh Weight

Root fresh weight did not differ significantly by treatment at any of the three weekly harvests (Figure 13). Note that one DWC crop from week was three was an outlier and excluded from statistical analysis.

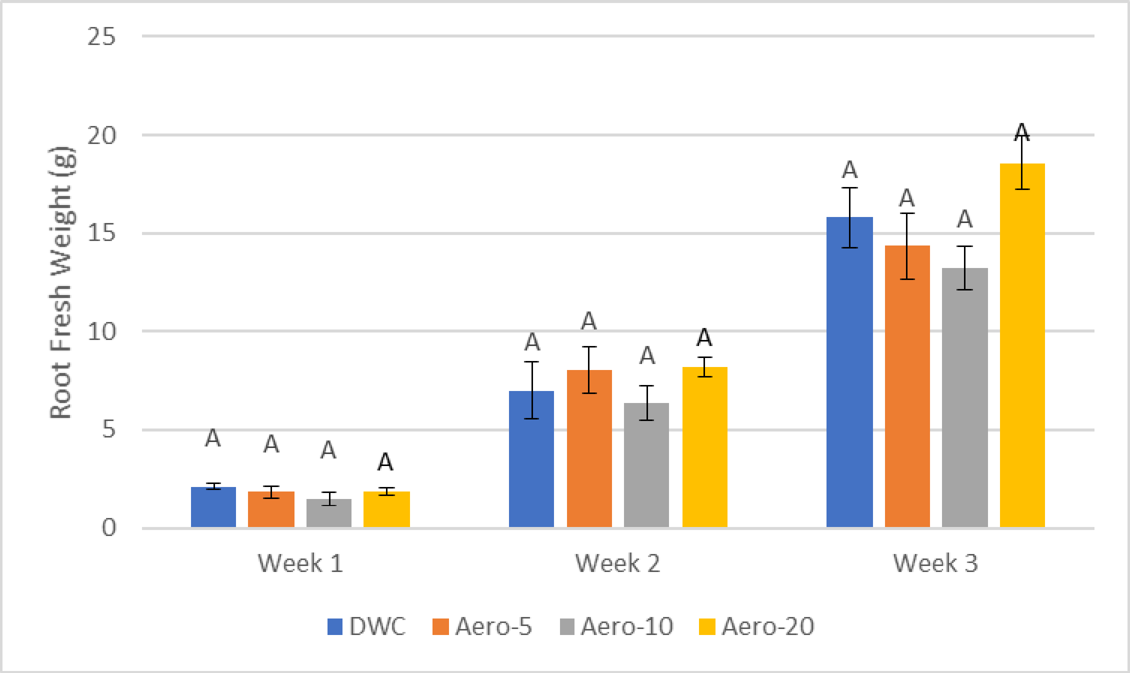

Figure 13. Comparison of root fresh weight among treatments. Letters represent mean separation comparison across aeroponic duration or DWC within each week using Tukey's HSD (alpha=0.05). Error bars represent standard error.

Root Dry Weight

From the first harvest, Aero-5 and Aero-10 root dry weight was too small to measure and was not plotted on the graph. However, as the roots grow into the second week all dry weights were statistically the same among treatments. By the third harvest, Aero-20 developed the greatest root dry weight which was significantly greater than Aero-5 and Aero-10 (Figure 14).

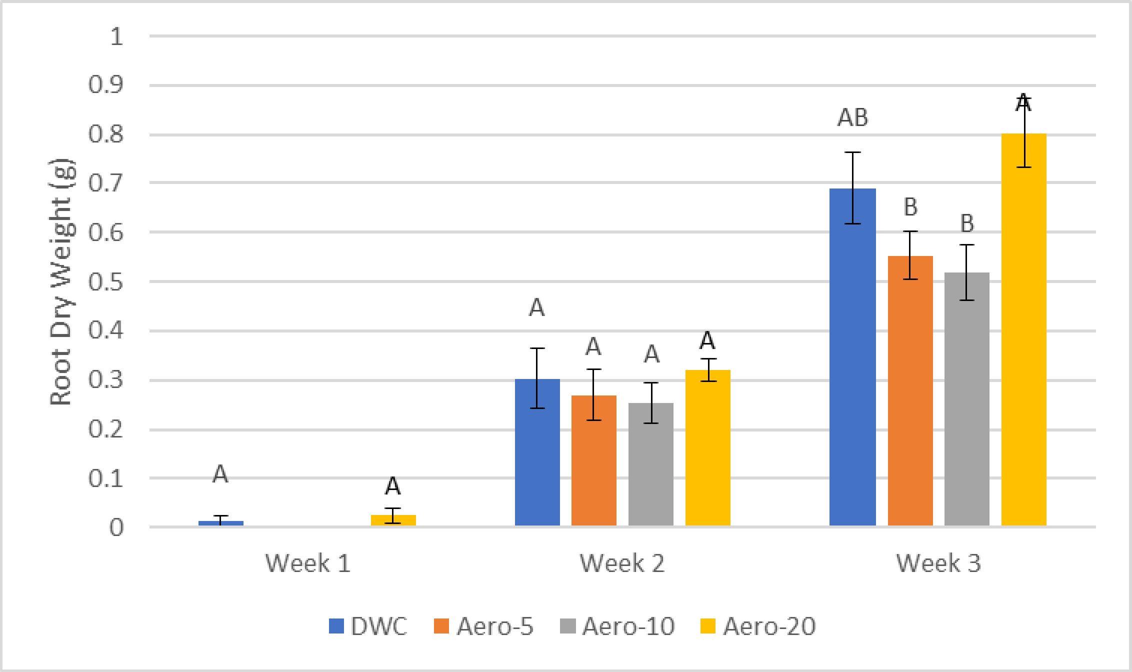

Figure 14. Comparison of weekly root dry weight among treatments. Letters represent mean separation comparison across aeroponic duration or DWC within each week using Tukey’s HSD (alpha=0.05). Error bars represent standard error.

Root Length

At the first harvest, the DWC control had the longest root length, with Aero-10 having the smallest (Figure 15). By the second harvest, root length among all treatments were the same. Interestingly, though DWC had the longest root length at week one, by week three it had the shortest roots. Conversely, the aeroponics treatments resulted in the longest root length, and were statistically the same among each other.

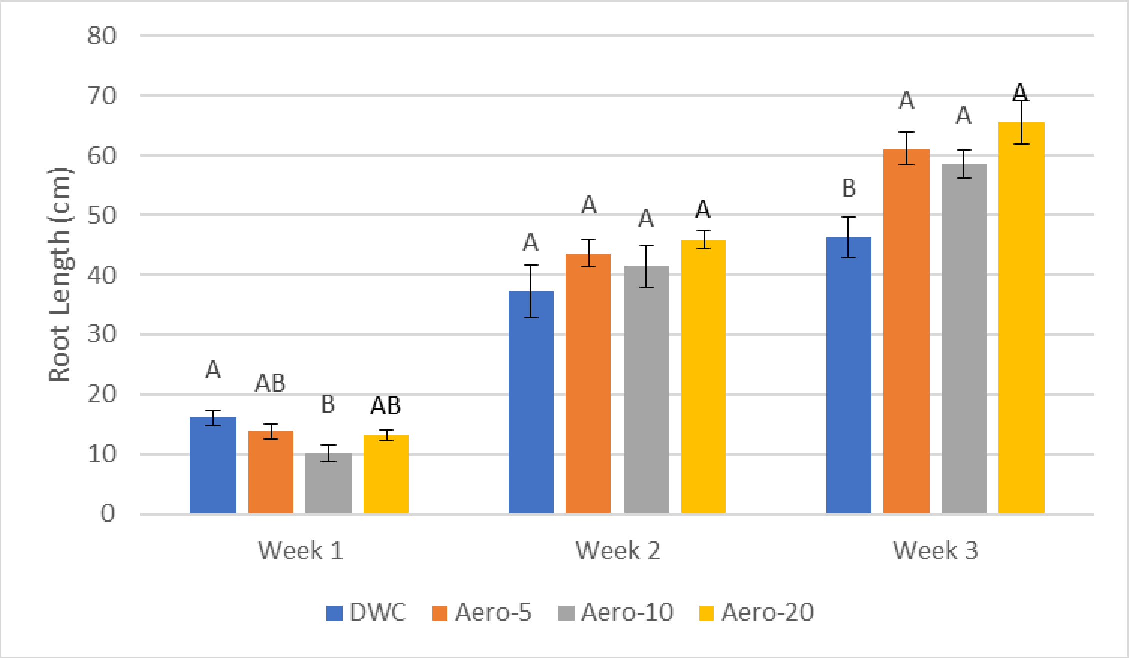

Figure 15. Comparison of weekly root length among treatments. Letters represent mean separation comparison across aeroponic duration or DWC within each week using Tukey’s HSD (alpha=0.05). Error bars represent standard error.

DISCUSSION

Aeroponic lettuce grew very similar to its DWC counterpart in overall biomass parameters such as shoot fresh weight and dry weight, though there were some key differences between the DWC control and aeroponic treatments. Both DWC and Aero-20 treatments showed the highest root dry weight among treatments. As all aeroponic treatments were shown to have significantly longer roots than DWC by week 3, it appears that the roots of the DWC control were thicker and broader in structure compared to roots grown aeroponically. In terms of plant volume, DWC and the Aero-10 treatment both outperformed the other aeroponic treatments. Whereas Aero-5 and Aero-20 treatments resulted in the smallest plant volume.

The results of shoot fresh weight do not match what Ritter (2001) reported, which was a 70% increase in yield with aeroponics over hydroponics (perlite substrate with drip irrigation). Furthermore, unlike the results reported by Ritter (2001), plant height observed with the aeroponic treatment was not significantly higher than the hydroponic treatment. However, similar to Ritter's findings, root length was greater with aeroponics than hydroponics. The differences observed here vs. Ritter (2001) may be due to crop (potato vs. lettuce) as well as specific hydroponic comparison (deep water culture control vs. perlite with drip irrigation). With regards to shoot dry weight, the results of the present study were somewhat similar to what Khalil (2020) reported, where shoot dry weight was highest with the hydroponic treatment. Though DWC crops visually appeared larger than aeroponic crops, this was not reflected in the findings. Thus, in contrast to Khalil (2020), no differences in shoot dry weight were identified among treatments. Perhaps if the experiment were repeated with a larger sample size, the subsequent results may match Khalil’s observations. Interestingly, like Khalil’s findings there were no differences in yield (shoot fresh wight) between aeroponic and hydroponic treatments.

These results are very promising in terms of aeroponic biomass matching deep water culture hydroponic biomass, and if they can be replicated with larger sample sizes, they may make aeroponics a much more alluring and economic irrigation option among the horticulture community. This would mean that aeroponics which uses a much smaller volume of water could be successfully used in commercial lettuce production and may be adaptable to space, pending its performance in microgravity / partial gravity. For commercial applications on Earth, Aero-10 appears to be a viable option for commercial growers looking to decrease electricity consumption and water volume requirements while maintaining crop productivity. In contrast, the greater foliage density observed in Aero-20 (same shoot fresh weight as DWC and smaller plant volume) is an ideal fit for space crop production. As volume is one of the primary limiting factors of space growth chambers, higher density crops make it possible to fit more plants inside small chambers, be grown to maturity, and harvested.

Though Aero-5 was irrigated the most frequently, it showed the smallest plant volume and root dry weight among treatments. Aero-5 may have underperformed due to inadequate aeration at the roots, where the high irrigation frequency prevented adequate drainage. In contrast, water on the roots of Aero-20 would have had four times longer to drain than Aero-5, which may have resulted in the in the significantly larger root dry weight observed with Aero-20 (Blok et al., 2017).

Worth noting is that if sample sizes had been larger, more of the trends visually observed in the master's thesis might have been statistically significant, which would differ from the findings presented in this master's thesis. This may be particularly applicable with the DWC control, as it showed the most variability among all treatments. Furthermore, environmental factors (lighting, plant location in the aeroponic system and greenhouse, air and water temperatures, air flow, etc.) may have had some influence on crop performance among treatments. Thus, running the experiment multiple times would be a logical next step.

A follow up experiment examining irrigation off durations at 30 seconds, 1 minute, and 2 minutes was conducted, however the experiment suffered several setbacks. One challenge faced was salt buildup around the net pots and foliage due to nutrient rich water from the aeroponic nozzles escaping through the large openings of the net pots. This wouldn't have been an issue at low to moderate EC (<2.5 mS/cm), however, at times the nutrient solution in the reservoirs during the second experiment reached as high as 2.9 mS/cm.

Furthermore, between experiments one and two, the aeroponic system was cleaned with bleach. It appears that some residual bleach was trapped inside of the system even after multiple rinses with tap water. Subsequently the second batch of crops used in the follow up experiment sustained damage to their roots and grew slower than their counterparts from the initial experiment. Due to these circumstances the results of the second experiment have not been presented. However, the follow up experiment was very informative in terms of system design and lessons learned. Future work with this type of aeroponic system should consider having a barrier at the top of the net pots between the root systems and the shoots to reduce spray leakage and nutrient buildup on shoots. Additionally, the system would benefit from more automation, such as integrated sensors (EC, pH, water level, etc.) and a monitor / alert system.

CONCLUSION

This study was an informative proof of concept for a modular aeroponic system which may perform equally well as DWC (in terms of shoot fresh weight and dry weight) and shows encouraging results for aeroponics, both with commercial as well as space applications. While follow up studies are recommended to validate these findings, it appears that aeroponics can be implemented by growers to reduce electricity consumption and water volume requirements without compromising on plant yield. In general, the aeroponic treatments performed as well as the DWC control in terms of shoot fresh weight and dry weight. However, some aeroponic treatments resulted in smaller plant volume (Aero-5 and Aero-20) and root dry weight (Aero-5 and Aero-10). Based on this study, aeroponic systems with a 10 minute off interval can be tentatively recommended for commercial growers in place of other hydroponic systems, and aeroponic systems with a 20 minute off interval is recommended for space crop production.

Though the results are promising, repeating the experiment and increasing the sample size would be the next step to confirm the findings. Furthermore, additional experiments should be conducted to identify ideal irrigation timing and droplet sizes.

REFERENCES

1. Burgess, C., & Dubbs, C. (2007). *Animals in space: From research rockets to the space shuttle*. Springer Science & Business Media.
2. *Growing plants in space*. (2019, April 9). NASA. https://www.nasa.gov/content/growing-plants-in-space
3. *Growing plants and vegetables in a space garden*. (2010, June 15). NASA. https://www.nasa.gov/mission_pages/station/research/10-074.html
4. *Lunar, Martian greenhouses designed to mimic those on earth*. (2017, April 21). NASA. https://www.nasa.gov/feature/lunar-martian-greenhouses-designed-to-mimic-those-on-earth
5. Castelvecchi, D., & Tatalović, M. (2019, January 15). Plant sprouts on the Moon for first time ever. *Nature*. https://doi.org/10.1038/d41586-019-00159-0
6. Kooser, A. (2019, January 15). *China's moon Lander sprouted a plant, but now it's dead*. CNET. https://www.cnet.com/news/chinas-moon-lander-sprouted-a-plant-but-now-its-dead/
7. *Zero gravity: The lighter side of science*. (2007). APS Physics | APS Home. https://www.aps.org/publications/apsnews/200703/zero-gravity.cfm
8. Massa, G. D., Newsham, G., Hummerick, M. E., Morrow, R. C., & Wheeler, R. M. (2017). Plant pillow preparation for the veggie plant growth system on the international space station. *Gravitational and Space Research*, *5*(1), 24-34. https://doi.org/10.2478/gsr-2017-0002
9. Monje, O., Richards, J. T., Carver, J. A., Dimapilis, D. I., Levine, H. G., Dufour, N. F., & Onate, B. G. (2020). Hardware validation of the advanced plant

habitat on ISS: Canopy photosynthesis in reduced gravity. *Frontiers in Plant Science*, *11*. https://doi.org/10.3389/fpls.2020.00673

10. *Progressive plant growing has business blooming | NASA spinoff*. (2006). NASA Spinoff. https://spinoff.nasa.gov/Spinoff2006/er_2.html
11. Clawson, J., Hoehn, A., Stodieck, L., Todd, P., & Stoner, R. (2000). Re-examining Aeroponics for Spaceflight plant growth. *SAE Technical Paper Series*. https://doi.org/10.4271/2000-01-2507
12. *Experiments advance gardening at home and in space | NASA spinoff*. (2008). NASA Spinoff. https://spinoff.nasa.gov/Spinoff2008/ch_3.html
13. Molitor, H., & Fischer, M. (1999). Effect of several parameters on the growth of chrysanthemum stock plants in aeroponics. *Acta Horticulturae*, (481), 179-186. https://doi.org/10.17660/actahortic.1999.481.18
14. Jamshidi, A., Moghaddam, A., & Ommani, A. (2019). Effect of Ultrasonic Atomizer on the Yield and Yield Components of Tomato Grown in a Vertical Aeroponic Planting System. *International Journal of Horticultural Science and Technology*, *6*(2), 237-246. https://doi.org/10.22059/ijhst.2019.278366.284
15. Tshisola, S. (2014). Improved potato (Solanum tuberosum L.) seed production through aeroponics. https://core.ac.uk/download/pdf/37421161.pdf
16. Ritter, E., Angulo, B., Riga, P., Herrán, C., Relloso, J., & San Jose, M. (2001). Comparison of hydroponic and aeroponic cultivation systems for the production of potato minitubers. *Potato Research*, *44*(2), 127-135. https://doi.org/10.1007/bf02410099

17. Khalil, M. M., & Hamed, A. H. (2020). Pre-basic seed potato production in aeroponic cultures. *Menoufia Journal of Plant Production*, *5*(9), 253-263. https://doi.org/10.21608/mjppf.2020.117356
18. Farran, I., & Mingo-Castel, A. M. (2006). Potato minituber production using aeroponics: Effect of plant density and harvesting intervals. *American Journal of Potato Research*, *83*(1), 47-53. https://doi.org/10.1007/bf02869609
19. Buckseth, T., Sharma, A., Pandey, K., Singh, B., & Muthuraj, R. (2016). Methods of pre-basic seed potato production with special reference to aeroponics—A review. *Scientia Horticulturae*, *204,* 79-87. https://doi.org/10.1016/j.scienta.2016.03.041
20. Li, X., Peoples, J., Huang, Z., Zhao, Z., Qiu, J., & Ruan, X. (2020). Full daytime sub-ambient radiative cooling in commercial-like paints with high figure of merit. *Cell Reports Physical Science*, *1*(10), 100221. https://doi.org/10.1016/j.xcrp.2020.100221
21. Yang, T., & Kim, H. (2020). Effects of hydraulic loading rate on spatial and temporal water quality characteristics and crop growth and yield in Aquaponic systems. *Horticulturae*, *6*(1), 9. https://doi.org/10.3390/horticulturae6010009
22. *Rex - Pelleted lettuce seed*. (2021). Johnny's Selected Seeds. https://www.johnnyseeds.com/vegetables/lettuce/butterhead-lettuce-boston/rex-pelleted-lettuce-seed-2967JP.html#q=rex&lang=en_US&start=1
23. Verdoliva, S. G., Gwyn-Jones, D., Detheridge, A., & Robson, P. (2021). Controlled comparisons between soil and hydroponic systems reveal increased water use efficiency and higher lycopene and β-carotene contents in hydroponically grown

tomatoes. *Scientia Horticulturae*, *279*, 109896. https://doi.org/10.1016/j.scienta.2021.109896

24. Oliver, J. E. (2008). *Encyclopedia of world climatology*. Springer Science & Business Media.
25. (2021). DLI Calculator. https://dli.suntrackertech.com
26. CIWS. (2021). *2021 Annual drinking water quality report*. https://www.cityofithaca.org/DocumentCenter/View/13030/2020-Annual-Water-Quality-Report-
27. Mattson, N., & Peters, C. (2014). InsideGrower. https://www.greenhouse.cornell.edu/crops/factsheets/hydroponic-recipes.pdf
28. Blok, C., Jackson, B. E., Guo, X., De Visser, P. H., & Marcelis, L. F. (2017). Maximum plant uptakes for water, nutrients, and oxygen are not always met by irrigation rate and distribution in water-based cultivation systems. *Frontiers in Plant Science*, *8*. https://doi.org/10.3389/fpls.2017.00562