PLANT THE MOON – FINAL EXPERIMENT REPORT

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INTRODUCTION

Our team is participating on behalf of South Dakota State University's College of Engineering. Being that our group includes four senior level mechanical engineering students, we wanted to go above the required project scope. The scope of the Plant the Moon Challenge was to grow the best crops using a lunar regolith simulant. With that said, our experiment consisted of two different main experiments. The first being, to compare different mix ratios of lunar regolith simulant mixed with different additives to determine which mixture provides superior growth. The second experiment dug into efficiency, after extensive research, our team decided to make a fully autonomous aeroponics growth system to compare the results to a more standard drip irrigation system. Our main goals for this challenge were to not only find the best mixture using as much lunar regolith as possible, but to also take as much workload of the astronauts by making an autonomous system to grow their food. With these two experiments running in parallel, our group intends to demonstrate that, while the lunar regolith mixtures are well equipped for starting the plants as seedlings, the advantages of aeroponics for the plant's later stages are too great to be overlooked.

DEVELOPMENT OF THEORY

This section will break into two parts, one covering the theory of HPA (High Pressure Aeroponics) and the other covering the additives chosen for the experiment.

High Pressure Aeroponics

Aeroponics is the theory of growing plants without a solid medium for root growth, instead the plants are suspended in the air and watered periodically. There are two variants to this system which involve water pressure, a high-pressure variant (pressures exceed 100psi) known as HPA, and a low-pressure variant (pressures below 100psi) known as LPA. In a HPA system, the water is pressurized to be sprayed through misting nozzles, where a very fine mist then coats the roots of the plants. LPA systems typically do not produce very fine mists instead these systems slowly drip or regularly run water over the roots.

For HPA, the group found experiments that indicated growth rates that could be as much as three times greater than that of traditional growing techniques [4]. These results were the inspirational foundation for this experiment. Upon further investigation, the group found that the roots are sensitive to the droplet sizes, favoring the ranges of under 100 microns in droplet size [4]. Information availability on aeroponics is scarcer than for some other, more common, techniques. With that being the case, nutrient recommendations were based off the demands in comparable hydroponics systems.

Additives

Soil structure and texture are two qualities that describe a medium for growing. Soil structure is the specific geometry of the soil, a good soil characterized by large amounts of empty space between particles. This space can be filled with air and water, allowing plant roots to grow into these pockets [2]. Texture is the average proportions of particles sizes, namely clay (0–2 microns), silt (2-50 microns), sand (50-2000 microns), and gravel (2000 microns and above). These soil qualities impact several of its properties, such as soil drainage, nutrient storage, and workability [2]. A loam denotes a mix of the various particle sizes and is generally considered a good texture. A graphic showing the various mixtures and the designations is shown in figure 1.

Lunar highlands regolith is a fine substance with a mean particle size of 94 microns and a range of particle sizes from 0-1 mm [1]. This gives pure regolith a texture of sandy loam according to figure 1, this is a relatively good texture as it has a balance of particle sizes [3]. However, it has a soil structure that is very dense and compact. This poses challenges for breathability and drainage when growing plants in this medium.

Because of the above challenges with regolith the team decided that the soil structure must be improved. To improve the structure of the regolith, four additives were chosen: two non-organics and two organics. Vermiculite and perlite were the non-organic additives. These minerals are baked causing them to expand and become porous. This is meant to improve the amount of air pockets and water retention. Miracle Grow potting soil and coconut coir were chosen as the organic additives. Potting soil is manufactured to be an all-purpose growing medium for plants and as such it was used as the control. It was also chosen to be mixed with the regolith and used to improve the soil structure of the regolith. Coconut coir or coconut shavings are porous and stranded providing air pockets, nutrients, and water retention.

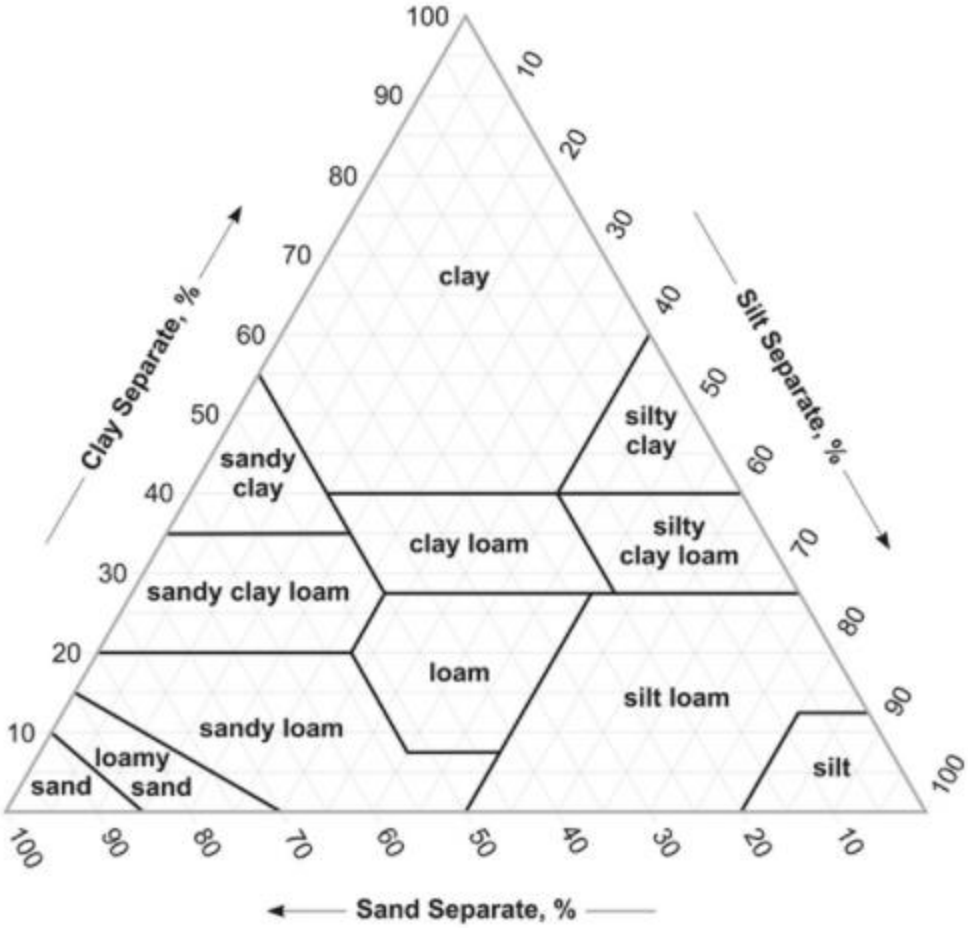

Figure 1: Graphical Soil Texture Chart

Experimental Apparatus

To eliminate sources of human induced error with the experimental results the greenhouse was heavily automated. This automation includes lighting control, temperature monitor and control, water nutrient monitor and control, and watering control. The greenhouse was built inside of a diamond-patterned mylar wrapped enclosure, isolating it from the thermal fluctuations of the lab housing the enclosure. The greenhouse features two growing system: a HPA system and a drip irrigation system for the soil/regolith-based plants. Both growing systems feed off the same central water supply which is monitored by the subsystem detailed below in the water quality subsection. The lighting that was chosen used red-blue dominant LED grow lights that were automatically run on a timing schedule. Temperature was controlled by an electronically controlled vent. The vent worked by toggling between either circulating air within the enclosure or taking in air from the surrounding shop, depending on ambient conditions. A 3D CAD model is shown in figure 2 without the mylar providing a clear view of the major components.

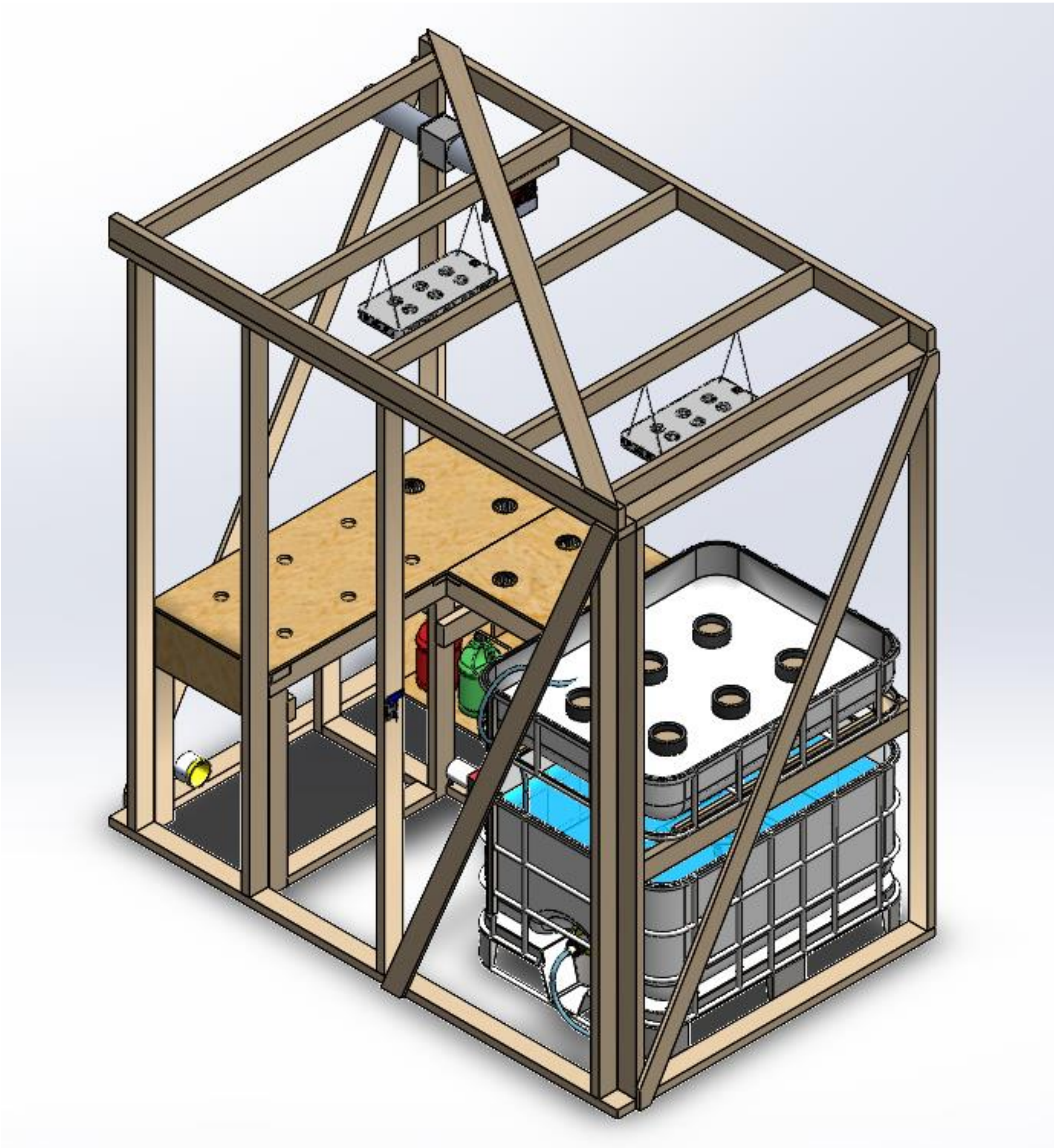

Figure 2: 3D CAD Model of the test apparatus

The automation system monitors and controls electrical conductivity (EC - a measure of particles present in the water supply, in this case the amount of nutrients), pH level, temperature, and light cycle. The greenhouse automated nutrient and pH adjustment system with temperature compensation. This system uses parallel peristaltic pumps to add General Hydroponics (GH) Flora series of nutrients and GH pH up/down to the water supply of the greenhouse. The system is controlled by a central Arduino unit taking in reading from a Gravity Analog EC meter V2, and a Gravity analog pH meter pro V2. The temperature measurement is accomplished by a

DS18B20 waterproof thermistor, which is inserted into the main water supply. A block diagram showing the inputs and outputs of this subsystem is shown in figure 3. The nutrients are added in ratios as recommended by GH as shown in their supplied feed chart shown in figure 5.

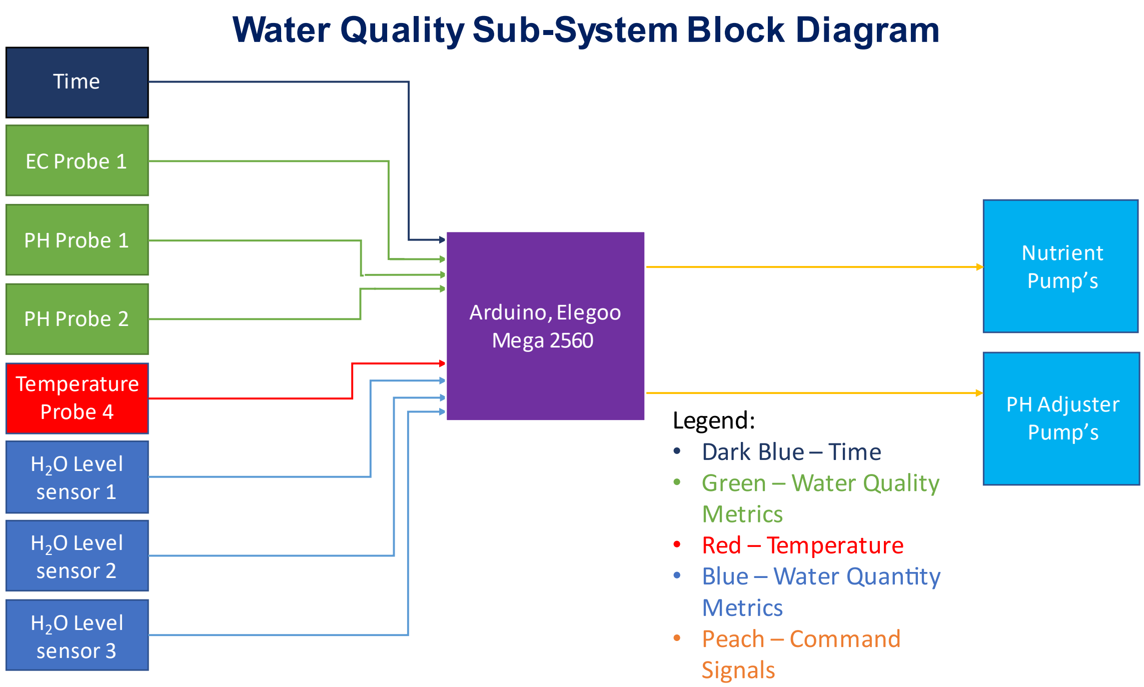

Figure 3: Water Quality Sub-System Block Diagram

	MEDIUM FEED	GROW (18H PHOTOPERIOD)				BLOOM (12H PHOTOPERIOD)								
	Week	1	2	3	4	1	2	3	4	5	6	7	8	9
	Growth stage	Seedling/ Clone	Early Growth	Early Growth	Late Growth	Early Bloom	Early Bloom	Mid Bloom	Mid Bloom	Mid Bloom	Late Bloom	Late Bloom	Ripen	Flush
	Total Nitrogen (ppm)	50	110	145	170	145	145	130	130	130	90	90	70	
	EC range (mS/cm)	0.5-0.6	1.0-1.2	1.3-1.6	1.6-2.0	1.6-1.9	1.6-1.9	1.6-1.9	1.6-1.9	1.6-1.9	1.0-1.3	1.0-1.3	0.7-0.9	
	PPM range (500 scale)	250-350	500-650	650-850	800-1000	800-100	800-100	800-1000	800-1000	800-1000	500-650	500-650	350-450	
BASE NUTRIENTS	FloraMicro (ml/gal)	2.0	4.2	5.6	6.8	6.1	6.1	5.3	5.3	5.3	3.8	3.8	2.3	
	FloraGro (ml/gal)	2.0	3.8	5.2	6.4	5.3	5.3	5.3	5.3	5.3	3.8	3.8	2.3	
	FloraBloom (ml/gal)	2.0	3.0	3.8	4.8	6.8	6.8	7.6	7.6	7.6	4.5	4.6	3.6	

Figure 4: General Hydroponics Recommended Feed Schedule [5]

Measurement Methods

Plant Mass

Mass of the plant breaks down into two parts. There is the green vegetative mass, and root mass. During the growth period measuring these independently is hard without destructive methods. Thus, at the end of the growth period the plant will be cut at the base of the vegetative section, creating two separate masses to be measured. The vegetative mass of all experiments and the root mass of HPA experiments can be measured directly at the end of the experiment.

For the regolith/soil-based experiments the root mass is hard to extract without damaging the root system corrupting the results. To remedy this the full mass of the planter, regolith, and root mass, are going to be weighed. At the beginning of the experiment before transplantation the full will be saturated with water and weighed. At the end of the experiment after the separation of the vegetative growth and root system the regolith will again be saturated with water, eliminating water variability.

$$m_{root} = m_{total} - m_{planter} - m_{regolith} \tag{1}$$

Height

Height is a relatively simple variable to measure as it can be done during the experiment period with non-destructive methods. The height of the tomato plants will be measured from the base of the vegetative growth to the tip of its thickest vine. The height of the beans will be measured from the base of the vegetative growth to the tip of its main shoot. This will be measured on a weekly basis and plotted at the end of the experiment period.

Diameter

This variable is going to be defined slightly differently for the tomatoes and legumes. Tomatoes will have three separate random vines marked with a piece of string. The length of this vine will be measured from the main stem to the tip of the vine, giving a radius. In the absence of large enough vines, the radius will be 0. This variable will then be averaged per tomato plant and compared. Because the legume chosen is a thick stalked bush with no large stem off-shoots, the diameter is defined as tip-to-tip distance of its leaves when viewed from above and, the leaves are held perpendicular to the main stalk.

Fruit Mass

If the plants grow sufficiently to start fruiting during the experimental period, the fruits will be harvested. Then the masses of the fruits from each plant will be weighed and compared on a bar graph.

Germination Rates

Germination rates are defined by whether the plant is alive by the transplantation date of March 17th. Regardless of any health characteristics or the variables defined above. This data is recorded below in results section.

RESULTS AND ANALYSIS

Shortly after the experiment began, the experimental apparatus suffered severe and repeated major system failures. Because of this, no data for plant growth outside of the germination phase was recorded as it is either non-existent or thoroughly corrupted and omitted.

Germination Rates

In Table 1 the type of plant, unique plant number, amount of regolith mixed with additive, and the status on March 17th. On the transplantation date the data in Table 2 was calculated according to the germination rate section above. The data is segregated based off the additive used, and the plant in the medium. Tomatoes fared the best in all the trials, several times having a 100% germination rate. The tomatoes had the highest germination rates in the miracle grow potting soil and the coconut coir pucks. In all other additive categories, the tomatoes germinated at equal rates. Although the sample size is small this gives the best evidence for tomatoes being the better choice for food production. The legumes fared the worst, having a 0% germination rate in approx. 60% of all experiment categories. They also failed in all the organic additives and controls, only germinating in the coconut coir pucks and non-organic additives.

Table 1: Individual Germination Results

Perlite			
plant	plant #	regolith mix	status
T	1	50	Germinated
L	2	50	Germinated
T	7	75	Dead
L	8	75	Dead
Vermiculite			
plant	plant #	mix	status
T	3	50	Germinated
L	4	50	Germinated
T	9	75	Dead
L	10	75	Dead
Coconut coir			
plant	plant #	mix	status
T	5	50	Germinated
L	6	50	Dead
T	11	75	Dead
L	12	75	Dead
Potting soil			
plant	plant #	mix	status
T	13	50	Dead
L	14	50	Dead
T	15	75	Germinated
L	16	75	Dead
Control			
plant	plant #	mix	status
T	19	0	Germinated
L	20	0	Dead
T	21	0	Germinated
L	22	0	Dead

Coconut coir pucks			
plant	plant #	mix	status
T	23	0	Germinated
L	24	0	Germinated
T	25	0	Germinated
L	26	0	Dead
T	27	0	Germinated
L	28	0	Germinated
T	29	0	Germinated
L	30	0	Germinated
Pure regolith			
plant	plant #	mix	status
T	17	100	Dead
L	18	100	Dead
T	31	100	Germinated
L	32	100	Dead
T	33	100	Germinated
L	34	100	Dead
T	35	100	Dead
L	36	100	Dead

Table 2: Overall Germination Rates

Additive	Overall germination rate (%)	Tomato rate (%)	Legume rate (%)
Perlite	50	50	50
Vermiculite	50	50	50
Coconut coir	25	50	0
Soil	25	50	0
Control	50	100	0
Coconut coir puck	88	100	75
Pure regolith	25	50	0

Experimental Apparatus Failures

Approximately one week after transplantation on March 22nd, the HPA system suffered a catastrophic pump failure for a still yet unknown reason. The team decided the pump failure was a result from a factory defect or induced during shipping thus failing far earlier than expected. The second pump was installed on March 24th and less than 20 hours later, the second pump also failed. This initiated an intense and long troubleshooting period on the high-pressure pump system.

The failure of the second pump caused the team to suspect the design had an issue causing premature pump failure. The first pump was taken apart and examined. The pump and motor were undamaged as the pump components had no major visible failures. The team applied power to this disassembled pump motor assembly and the motor worked fine. The primary suspect became the included pressure switch on the pump assembly. The pressure switch for both pump assemblies had completely failed.

The team decided to build a replacement pressure switch to control the pump assembly. The team designed a new pressure switch using a low side high power MOSFET transistor to control the pump motor. An Autex pressure transducer was added to read the pressure from the HPA assembly. During initial testing of this new design the MOSFET failed after roughly two on/off cycles. Replacing the MOSFET resulted in a similar failure, indicating that the transistors were experiencing a reverse (fly back) voltage spike from the motor assembly.

Typically, in motor designs, a reverse biased diode is installed in parallel to protect the sensitive electronics from reverse voltage spikes. The pump assembly did not have a reverse biased diode installed which was causing the failures. The pump assembly is typically used in automotive applications and did not include this diode protection where it is not required. Our design includes power from a standard PC power supply adding to the issue. The power supply most likely has a response time on the order of nanoseconds whereas an automotive battery likely has a response on the order of microseconds. This causes a greater release of energy within the switching time of the included pressure switch, causing sparking and premature failure.

The team installed a reverse biased diode in parallel to the motor to block the reverse voltage spike damaging the switch and transistors. A parallel troubleshooting process also included the installation of a DC-to-DC converter, typically known as a buck-converter. The addition of the buck-converter allowed the team to precisely control the voltage and amperage to the motor assembly. Once both items were integrated into the design of the pump assembly, the system failures have been halted and resolved. The pump became fully operational on Tuesday April 13th the final week of the experiment period. This unfortunately caused no reliable data to be collected and analyzed outside of initial germination before transplantation.

CONCLUSIONS

The germination rates for tomatoes were reliably the highest within the dataset, while the legumes failed in most of the experiments. This shows that out of these two choices tomatoes would likely fare better in a lunar environment.

While the results that have begun to present themselves in the past week appear to be the start of something interesting, they are far from experimental standards. Due to the complexity of the system, the troubleshooting process ultimately proved to be far more costly, timewise, than had been accounted for.

APPENDIX A

References

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[5] "Flora Series Feedcharts," *General Hydroponics*, 02-Apr-2021. [Online]. Available: https://generalhydroponics.com/resources/floraseries-feedcharts/. [Accessed: 30-Apr-2021].

List of Abbreviations

HPA – High Pressure Aeroponics
LPA – Low Pressure Aeroponics
LED – Light Emitting Diode
CAD – Computer Aided Drafting
EC – Electrical Conductivity
GH – General Hydroponics