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Energy Conservation By Intermittently Recirculating and Aerating an Aquaponics System with an Airlift

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ENERGY CONSERVATION BY INTERMITTENTLY RECIRCULATING AND AERATING AN AQUAPONICS SYSTEM WITH AN AIRLIFT

by

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A Thesis Submitted to the College of Engineering, Mechanical Engineering Department
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering

Embry-Riddle Aeronautical University
Daytona Beach, Florida
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ENERGY CONSERVATION BY INTERMITTENTLY RECIRCULATING AND AERATING AN AQUAPONICS SYSTEM WITH AN AIRLIFT

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This thesis was prepared under the direction of the candidate's Thesis Committee Chair, Dr. Peter B. Merkle, Professor, Daytona Beach Campus, and Thesis Committee Members Dr. Mark Fugler, Professor, Daytona Beach Campus, and Dr. Marc Compere, Professor, Daytona Beach Campus, and has been approved by the Thesis Committee. It was submitted to the Mechanical Engineering Department in partial fulfillment of the requirements for the degree ofMaster of Science in Mechanical Engineering

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Dedication

I dedicate my work to my loving parents, Lara Kristjansdottir and Thorsteinn Olafs.

All I have and will accomplish is only possible due to their endless love and support.

Ég elska ykkur.

Acknowledgements

I extend my warmest thanks to the following people for their inspiration, guidance, patience, and support. I am forever thankful for my family and their endless support. I would also like to thank Ms. Tammie Radikopf for her support and encouragement throughout my thesis research period.

I have truly enjoyed being a part of several extracurricular projects and I would like to thank Dr. Compere for welcoming me into his group of driven students. He has opened my eyes towards social responsibility and how I will be able to use my knowledge from my education to better lives and better the world.

I appreciate greatly Dr. Fugler and his advisement throughout the years. Thank you for always making me feel welcome and all of the intellectual and interesting conversations.

Lastly, I would like to thank Dr. Merkle for introducing me to aquaponics and the endless possibilities of improving current technologies. Thank you for accepting me as your first graduate thesis student, for your patience, and interest in seeing me succeed in my endeavors.

Abstract

Researcher: Bjorg Magnea Olafs

Title: Energy Conservation By Intermittently Recirculating and Aerating an Aquaponics System with an Airlift

Institution: Embry-Riddle Aeronautical University

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An airlift device providing aeration and circulation was designed to reduce electrical power requirements for aquaponics by eliminating the need for a water pump. The airlift performed better than predicted and achieved water flow rates of 10 L/min at 25 °C, in comparison to the theoretical design performance 2.65 L/min.

Koi (*Cyprinus carpio*) and sweet basil (*Ocimum basilicum*) were cultured for five weeks in two identical aquaponics systems. The system was located indoors and consisted of a fish tank, a sump tank, and a soil-free growth media bed under artificial lighting. The total water volume in each system was 230 liters.

Test conditions of intermittent vs. continuous aeration and recirculation were studied and growth rates of plants and fish were measured. Four week-long tests of intermittent aeration and circulation (50% on/50% off) showed net total bed growth rates per 1 KWh per day of 99.4%, while the continuous operated bed showed 50.3% growth per 1 KWh for the same period. The intermittently operated system showed 44.1% more growth for the same energy consumption. This suggests electrical power requirements for aquaponics aeration and recirculation may be reduced by as much as 75% with the use of an intermittent aeration and recirculation through an airlift. This suggests that intermittent

airlift technology may be useful for reducing energy costs, and increasing the feasibility of using renewable power in commercial aquaponics farms.

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Chapter I

Introduction

Significance of the Study

Aquaponics is an organic food production method that can help maintain food supply in the urban world (Ambekar, 2013). The goal of this project was to research energy conservation methods in an aquaponics system.

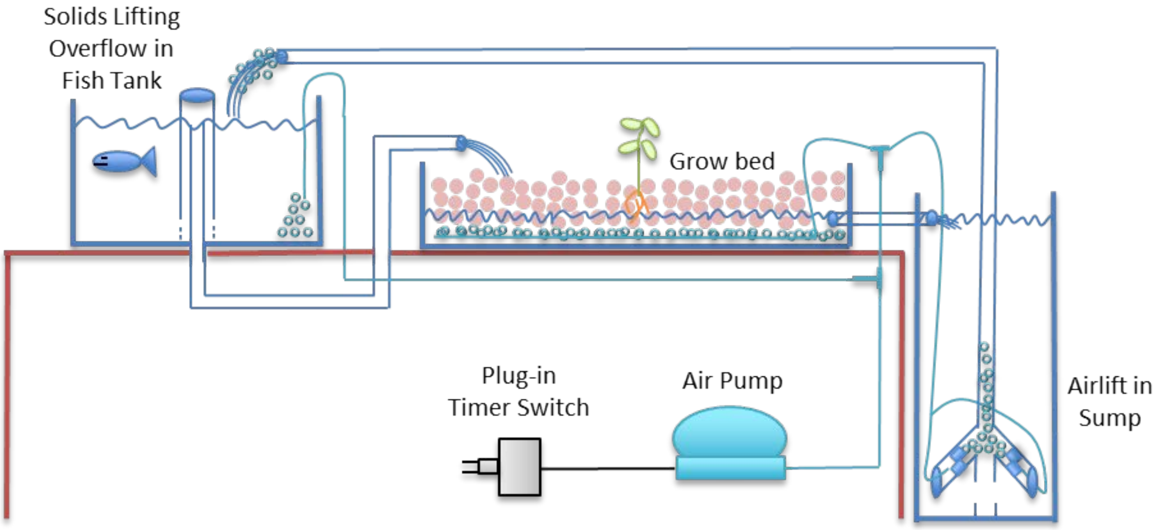

Figure 1: An explanatory schematic of the experimental apparatus operations.

This was accomplished by collecting data from an aquaponics experimental apparatus designed and built for this purpose (Figure 1). After literature review, the experimental unit was designed with an airlift device to provide water circulation instead of a water pump, reducing the electrical energy required. The unit uses two independent but identical aquaponic systems to study electricity conservation, and plant and fish growth under different aeration and recirculation conditions.

Airlift technology can reduce operational costs for aquaponics production and enable more feasible use of renewable energy. This report contains the apparatus design, data collection methods, and data analysis from the study.

Statement of the Problem

The study of aquaponics technology will be important in the near future for feeding the world's growing population. With this increasing population and scarcity of available agricultural soil, the production of genetically modified crops and other processed foods is increasing to meet food demand (Ambekar, 2013). Aquaponics can be used to mitigate the need for GMOs and processed foods, providing a solution to reduce this development, enabling production of natural foods in areas with limited land area.

Solar powered aquaponics systems have been successfully installed at several locations in the world, but the power requirements can be large and expensive (Connolly & Trebic, 2010). Nelson and Pade have put up a system in Haiti. With a less energy intensive system, renewable energy can become a more feasible option for powering such a system. Such a system can be constructed on roof tops in densely populated urban areas, reducing transportation costs and increasing local availability of organic produce. A solar powered aquaponics system can be a viable option of feeding people in the developing countries where access to electricity and agricultural soil is scarce. However, the energy requirements need to be reduced in order to make such a self-sustained system more economically feasible.

Purpose Statement

The purpose of this study is to make a technical contribution for the advancement and welfare of humanity through sustainable and healthy food production. Making aquaponics systems less energy intensive, aquaponics systems become more feasible wherever reliable electric utility service is unavailable and where ample renewable energy resources, such as solar and wind, may be used.

Limitations

This study is limited to a laboratory-scale soil-less media bed aquaponics systems with low fish density. Certain modifications and testing performed may be needed to apply these results to a different type of system, or similar system at larger scale.

Definitions of Terms

Airlift	Uses air to transfer water, removing the need for a water pump in the system and aerates the water at the same time.
Aquaponics	The combination of aquaculture and hydroponics. Beneficial bacteria are essential in the system to convert the ammonia from the fish waste to nitrites and nitrates, which the plants consume as nutrients.
Grow Bed	The hydroponic component of the system where the plants grow. This system utilizes a media grow bed, where the bacteria colonize the media. (Bacteria are also present on other surfaces and in the water phase). The solid waste is trapped in the media bed and the bacteria degrade it to nutrients for plant use.
Fish Tank	The aquaculture component of the system where the fish live.
Self-sustaining	Able to maintain itself by independent effort once commenced. (Merriam-Webster Dictionary)
Solids Lifting Overflow	A two-pipe drainage system, which enables bottom tank drainage through holes on a casing pipe and maintains constant water level by draining the water through an overflow pipe inside of the casing pipe.
Sump Tank	An optional component of aquaponics. In this system, it serves as a base addition tank and the airlift is located in this tank.

Sustainability	Involves methods that do not completely use up or destroy natural resources. Be able to last or continue for a long time. (Merriam-Webster Dictionary)

List of Acronyms

ERAU	Embry-Riddle Aeronautical University
FT	fish tank
GB	grow bed
GMOs	genetically modified crops
HVAC	heating, ventilation, and air conditioning
NREL	National Renewable Energy Laboratory
SLO	solids lifting overflow
SOTE	standard oxygen transfer rate (mass %)
WEC	wave energy converters

Chapter II

Review of the Relevant Literature

This review addresses subjects on energy conservation, efficient aquaponics designs, and selected renewable energy methods and resources available in the Central Florida climate.

Introduction

The world population is projected to increase to 9.2 billion by 2050, necessitating a 70% increase in food production in the near future (Ambekar, 2013). Therefore, sustainable use of natural resources in food production is of increasing importance.

A technology to address this concern, aquaponics, combines aquaculture and hydroponics. The system discussed here raises fish and plants together in a recirculating unit, in which nitrifying bacteria species convert the nutrient-rich water from the fish tanks to fertilizer for the plants through the sequential nitrification process described in equation 1 and equation 2.

$$2\ \mathrm{NH}_{4^+} + 3\ \mathrm{O}_2 \rightarrow 2\ \mathrm{NO}_{2^-} + 2\ \mathrm{H}_2\mathrm{O} + 4\ \mathrm{H}^+$$

(1)

$$2\ \mathrm{NO}_{2^-} + 1\ \mathrm{O}_2 \rightarrow 2\ \mathrm{NO}_{3^-}$$

(2)

Solid organic matter is also metabolized by heterotrophic bacteria to produce ammonia. In organic aquaponic practice, herbicides, to eliminate weeds, are replaced by biological pest control methods and physical barriers and isolation protocols to prevent pathogen and pest introduction. Aquaponics can reduce the need for long distance food transportation and can provide reliable and organic produce production year round. The system relies on natural mechanisms of nutrient cycles found in aquatic ecosystems, such as ponds and lakes.

The goal of this research is to minimize the energy requirements and make a system powered by renewable energy sources more feasible. In addition to greenhouse settings, an indoor system provides options to maintain the optimal air and temperature conditions for the living organisms in the system by taking advantage of the building's HVAC, waste heat, and cooling cycles.

Energy Efficiency Techniques in Aquaponics Design

Providing power to an air pump, water pump, water heater, and supplemental lighting is needed to operate most conventional aquaponics systems. An outdoor system can eliminate the need for supplemental lighting in sunny locations. The use of an airlift would decrease the energy input needed by eliminating the capital and energy costs of a water pump to recirculate the water.

Airlift for Water Transport

Most conventional aquaponics systems involve an air pump to provide aeration and a water pump to circulate the water through the system. However, savings in capital and operational costs can be obtained by combining the two pumps in one. The concept of an airlift is to use the air pump to both circulate the water and provide aeration to the system. A potential disadvantage of this method is the lift limitation, but one readily avoided by system design. The airlift performance depends on the amount of air injected, and the depth of the airlift pipe in the water as compared to the lift, called the submergence ratio. The submergence ratio is the most important factor in airlift pump performance, along with the air volumetric flow rate (Cho, Hwang, Lee, & Park, 2009).

Energy is needed for acceleration and overcoming friction only, therefore the airlift technique has very low energy requirements and can be more efficient than centrifugal or other pumps for low-head conditions. Airlifts work best with large bubbles and in small diameter pipes. One air pump can be used to provide air to the airlift, fish tanks, grow beds, and to other system components if needed (Nelson & Pade, 2008).

Optimum Conditions in Aquaponics Systems

The development and integration of the optimum conditions in an aquaponics system is important in order to maximize production, minimize water exchange and nutrient accumulation, and enhance cost and power savings. According to Dr. Rakocy, around 25-30% of fish feed is converted into usable energy (Rakocy, Bailey, & Hargreaves, 1993). In order to optimally size an aquaponics system, a balance must be found between the plant nutrients uptake and the fish waste, which is a combination of the quantity of fish and fish feed.

A well-balanced system will prevent nutrient accumulation and overfeeding, which includes cost and power savings, since fish food is an ongoing cost within the system and the fish are the main oxygen users in the system. Additionally, it is important to design the system with optimal oxygen levels and the best suitable hydraulic loading rate to maximize plant growth efficiencies, nutrient removal, and waste discharge, which is strongly dependent on the hydraulic flow rate (Endut A. , Jusoh, Ali, Wan Nik, & Hassan , 2009). Endut and his team performed a study to determine the optimum hydraulic loading rate, plant to fish ratio, and to find the mass balance of oxygen in a sustainable aquaponics system.

In order to minimize power consumption required for aeration, oxygen mass balance can be used to calculate the amount needed. According to Endut's findings, the overall oxygen mass balance for an aquaponics system is shown in equation 3.

$$24\ (Q + Qp)\ \Delta C = (k_{o/p}\ Wm + R_{BODT} + R_{NT})(1\text{-}WE) \tag{3}$$

Where: Q *= recycled water (*m^3*/day)*
Qp *= supplemental water (*m^3*/day)*
ΔC *= oxygen concentration differential (g/* m^3*)*
$k_{o/p}$ *= oxygen used (g/kg fodder/day)*
W *= daily feeding rate, percent from body mass*
m *= mass of reared fish (kg)*
R_{BODT} *= oxygen demand by heterotrophic organisms (g/* m^3*/day)*
R_{NT} *= oxygen demand of the autotrophic (nitrifying) microorganisms for ammonia oxidizing (g/* m^3*/day)*
WE *= water exchange in the system*
24 is the dimension uniformly constant (day/hour).

The oxygen mass balance equation describes the balance that must be met between the amount of oxygen that is present in the recycled and supplemental water, and the oxygen used by all organisms in the system, with the water exchange in the system taken into account.

The effects of different plant to fish ratios were analyzed in the same research. The water quality parameters percentage and the plant production increased with an increasing ratio up to the maximum of ratio of eight when the numbers started to slowly decrease. The limiting factor in this case is insufficient nitrogen in the media bed. The ratio of 8 is equivalent to a fish feeding rate of 15-42 g/m^2. Another experiment by Endut et al. concluded that nutrient removal was most efficient when the water flow rate was 1.6 L/min (Endut A. , Jusoh, Ali, Wan-Nik, & Hassan, 2009).

Intermittent Aeration and Recirculation

An additional option to conserve energy is to periodically turn off the air pump, which powers both the aeration and recirculation systems. When turning off the air pump, the system water will experience constantly decreasing dissolved oxygen level. However, it will increase rapidly when re-started. Experiments and data collection can be performed with an existing system to determine how long the living organisms can be without system power, and to evaluate if intermittency is feasible for energy savings.

Renewable Energy Methods Suitable for Daytona Beach, Florida

Homeowners in Florida experience one of the highest rates of home electricity use in the United States (Natural Resources Defense Council). The warm weather results in high demand for air conditioning. However, the state has huge potential for utilizing renewable energy, with sun power the most obvious candidate (Natural Resources Defense Council). Renewable energy is gaining interest globally due to the potential for the reduction of greenhouse gas emissions, long term cost-savings, and increased energy security.

Currently, Florida facilities generate energy from wind, biomass, biogas, and solar power. Data from 1991 to 2005, found in the National Renewable Energy Laboratory (NREL)'s national solar radiation data base, presents a yearly average of solar radiation of 4.86 kWh/m^2/day and the concentrated solar power resources have been recorded to reach 4.5-5.0 kWh/m^2/day in Daytona Beach.

Wind energy can be a viable choice for electricity generation, but only if the resources are available. As opposed to most other renewable energy technology, the land used for wind energy generation can simultaneously be used for agricultural purposes (Rosa, 2009, p. 799). According to the National Climatic Data Center, the annual average wind speed at sea level in central Florida is 3.79 m/s. Wind speeds less than 4 m/s are usually not feasible to utilize for energy generation.

There is also a potential for the development of near-shore tidal and wave-energy capture facilities (Natural Resources Defense Council). Wave energy converters (WECs) are designed to harvest the energy in waves, which are influenced by the winds on the ocean surface. Wave and tidal resource potential is typically given in TWh/yr. However, the amount of recoverable energy along the U.S. shelf is estimated to be 1,170 TWh/yr or 1/3 of the U.S. electricity usage per year. The total available wave energy along the East Coast is 237 Twh/yr and along the coast of Florida is 41 TWh/yr (Electric Power Research Institute, 2011).

While a self-sustained system can be easily operated and powered by solar power in the Daytona Beach area, wind energy is not sufficient and WECs still require further research. The main problem is to design a less energy intensive aquaponics system to make such a renewable energy powered aquaponics system more feasible.

Summary

Aquaponics systems are increasing in popularity and commercial greenhouse operations are growing rapidly (Kessler Jr., 2006). This shift to local year-round food production can lead to better food security in the future. It is important to design for maintaining optimal conditions in the system for all living organisms. This includes balancing plant nutrient uptake and fish waste production and maintaining optimal oxygen and pH levels. An energy efficient aquaponics system can be designed to be powered by renewable energy sources, with no electricity reliance on from a public utility grid. Having the system in a greenhouse or indoors can protect the fish and crops from biosecurity threats.

In an aquaponics system, using an airlift to pump the water a short vertical distance can eliminate the need for a water pump. The same air pump serves to move the water and provide aeration to the water, yielding energy and capital cost savings. Additionally, designing an intermittent on/off schedule for the air pump that ensures optimal living conditions for the fish and plants can reduce the energy requirements and thus reduce costs of energy supply. Further research on the effect of this on the plant growth in the system is required.

Daytona Beach and the surrounding areas in Central Florida have significant potential for utilizing renewable energy resources, especially solar. While wind energy is not a feasible option in the area due to low wind speeds. There is potential for capturing near-shore tidal, wave, or ocean, and river stream energy. However, this technology is still in the research and development stages. Daytona Beach was chosen as a place of interest to investigate, since it is the location of where this research is being conducted.

No academic or industrial publications on intermittent recirculation and aeration in an aquaponics system have been located at the time of this publication.

Hypothesis

The hypothesis of this research is to determine if energy consumption can be reduced by intermittently recirculating and aerating an aquaponics system with an airlift. Performance metrics used to test the hypothesis are pump energy consumption, dissolved oxygen levels, plant growth, fish growth, and intermittent pump operation. A control airlift operated aquaponics system will be used to compare with a second aquaponics system with an intermittent airlift operation.

Chapter III

Methodology

The objective of the experiment was to study if energy could be conserved by using an airlift to intermittently recirculate and aerate the aquaponics system. The plant growth effects were as measured. This experiment was performed by designing and constructing an aquaponics experimental apparatus, and by performing several tests on that apparatus. Data was collected and statistically analyzed. In this section, the experimental methods are described.

Research Approach

Intermittent aeration and recirculation through an airlift in an aquaponics system and the resultant effects on plant growth was researched by utilizing an aquaponics experimental unit, which included two independent, but identical, systems.

Design and Procedures

Tests were performed on the system over the 6 different periods, including a start-up and a control period. Data was collected in the beginning and end of all periods. Figure 2 on page 18 illustrates the six experiment periods with summary descriptions. Before each test week (excluding the start-up week), the following tasks were performed:

- Water in the sump tanks was replaced with de-chlorinated tap water to prevent nitrate and other chemical build up over time.
- 0.7 g. of chelated iron was added to the sump tank to prevent iron deficiencies.

- Water quality strips were used to measure the alkalinity, pH, nitrite, nitrate, and hardness.
- Pictures were taken to document growth.

The experimental periods are described below.

Period # 1 (Start-up week):

A biological active water from an existing aquaponics system was added to thesystem. The main objectives of the start-up week was to leak test the system, build up bacterial populations, and test the operation of the system.

Period # 2 (Week 1):

System #1 was operated with 15 minute intervals of running the air pump on/off, while system #2 operated constantly. Each system had approximately 150 g. of fish in its fish tank. The plants were weighed, and their length measured before and after the trial week.

Period # 3 (Week 2):

System #1 was operated with 15 minute intervals of running the air pump on/off, while system #2 operated constantly. Each system had approximately 150 g. of fish added to its fish tank, increasing the fish mass to approximately 300 g. in each system. The plants were weighed and their length measured before and after the trial week. Note: Possible tampering (removal of biomass) was observed on four plants in system #1. A statistically calculated curve was applied to these plants to estimate their growth during the week.

<u>Period # 4 – (Control, 4 days):</u>

After measuring the plants, the plants and fish were equally and randomly divided into the systems. Both system air pumps were continuously operated during this time and plants were measured at the end of the 4 day control period.

<u>Period # 5 (Week 3):</u>

All flowers and buds were removed from the plants, and each plant was trimmed. System #2 was then operated intermittently with 15 minute on/off intervals. All plants weighted before and after the week.

<u>Period # 6 (Week 4):</u>

System #2 was again operated intermittently with 15 minute on/off intervals and all plants were weighted at the beginning and end of the week.

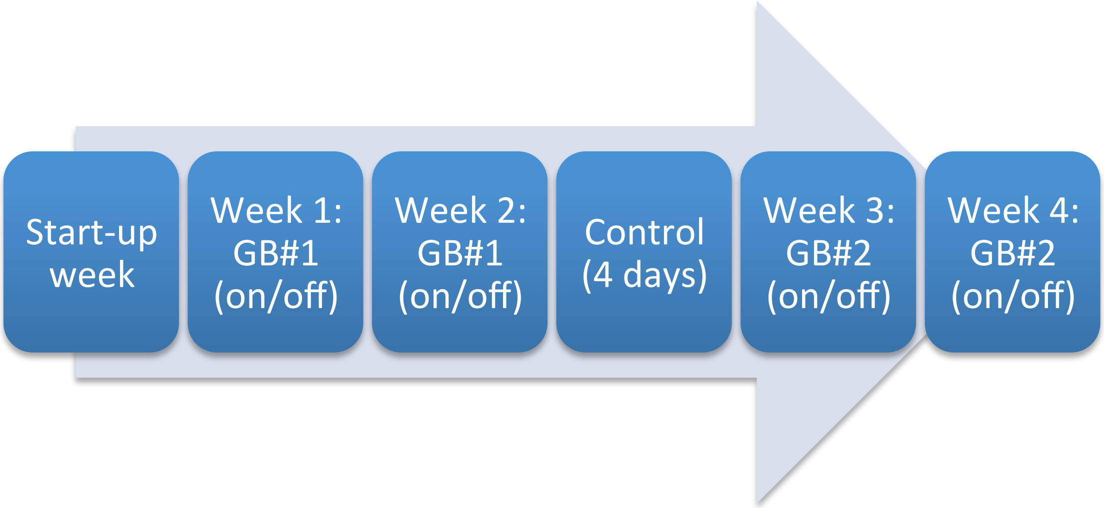

Figure 2: The experiment timeline. This figure summaries the operation of the systems during each period.

Apparatus and Materials

An aquaponics experimental unit, which includes two independent, but identical, media based aquaponics systems has been designed and built. This unit served as a tool to collect and analyze data on the systems' performances under different air pump operation configurations. The aquaponics system's main reservoirs are: a 75.7 liter (20 gallon) glass fish aquarium tank, a 151 liter (40 gallon) plastic media grow bed, and a 87 liter (23 gallon) plastic sump tank. The fish tank to media bed volume design ratio is 1:2. Figure 1 illustrates how these tanks interact.

Design calculations were carried out in order to achieve good flow through the piping (See section: Water and Air Pipe Flow). A solids lifting overflow (SLO) piping system was utilized to remove solids from the fish tank, and to simultaneously secure a constant water level. An airlift was designed to utilize compressed air to pump aerated water from the lowest to the highest water level in the system, eliminating the need for a water pump. An airlift with air pump not only reduces power consumption but simultaneously aerates the water, which promotes plant and fish growth. The piping system was sized by using head loss and frictional fluid flow equations. Other important design parameters were the fish feed to plant ratio and oxygen requirement calculations.

Solids Lifting Overflow

The water from the fish tank is designed to flow out of the bottom of the tank through a Solids Lifting Overflow (SLO). A SLO combines the benefits of an overflow and bottom tank drainage, by setting a constant water height and removing settle-able solids in the fish tank.

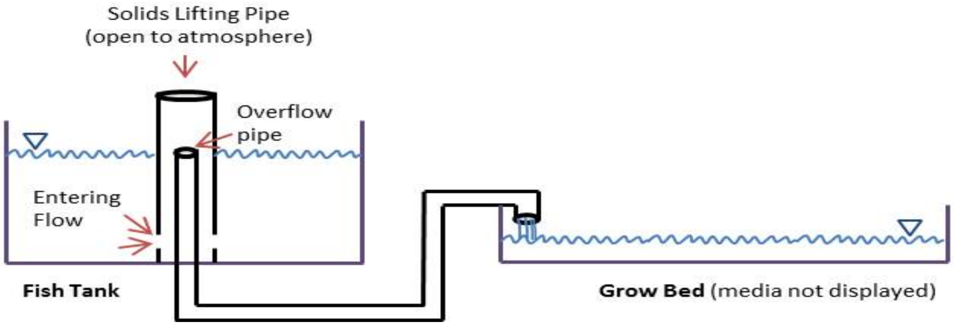

Figure 3: A SLO schematic. The SLO is located inside the fish tank and allows for bottom tank drainage through the solids lifting pipe. The solids lifting pipe has openings at the bottom to allow water to enter and is open to the atmosphere to avoid creating a siphon. The inner pipe has openings at the top of the pipe and maintains constant water level in the tank.

A SLO is a two-pipe system, with one drain/overflow pipe and casing/solids lifting pipe. The system is illustrated in Figure 3. The water enters the screened openings of the larger casing pipe and rises up until it reaches the top level of the drainage pipe which is located inside of the casing pipe. The water drains through the bottom of the fish tank into the media bed.

It is crucial to leave the top of the solids lifting pipe open to the atmosphere in order not to create a siphon, which could drain the fish tank, defeating the purpose of the pipe system (Dr. Storey, 2013). The solids lifting overflow piping system fits the needs of the system adequately and prevents the drainage of the fish tank when the airlift pump is turned off. The solids lifting pipe and overflow pipe for the system have 51mm and 25 mm diameters, respectively.

Airlift

The function of the airlift is to simultaneously aerate and pump water using compressed air. The water is pumped vertically from the sump tank to the fish tank. The ratio between the length of the submerged pipe and the required lift is called the submergence ratio and is an important airlift design parameter. The submergence ratio and air flow required to obtain a desirable water flow rate was calculated. A schematic of the airlift can be found in Figure 4 below. Complete design calculations can be found in appendix B, part b.

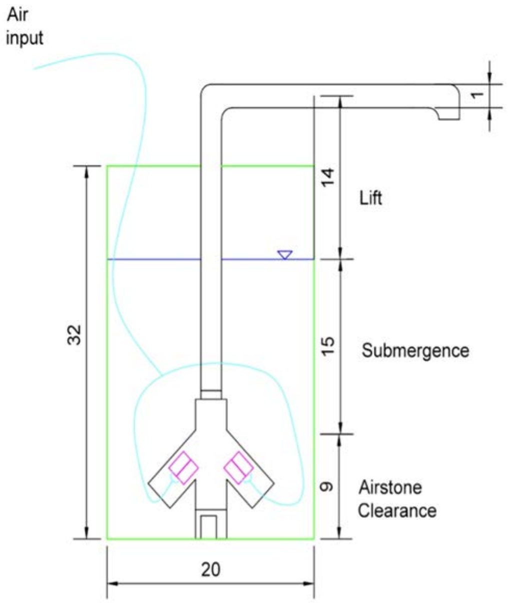

Figure 4: An airlift schematic. The schematic shows the dimensions of the submergance and lift which are used to determine the submergance ratio.

An airlift experiment was conducted with the objective to confirm the correlation between the theoretical performance calculations and actual performance. A full scale airlift was built and tested in the lab. It shall be noted that the airlift built for this experiment is larger than the airlift used in the final design.

The difference between using air stones and tubing only was investigated as well. The case with tubing only ended up being less efficient, having a ratio of water to air 1:1.85 as compared to 1:1.5 for the air stones. Therefore, for this particular design, it is more feasible to use the air stones instead of tubing only for air injection on the bottom of the airlift.

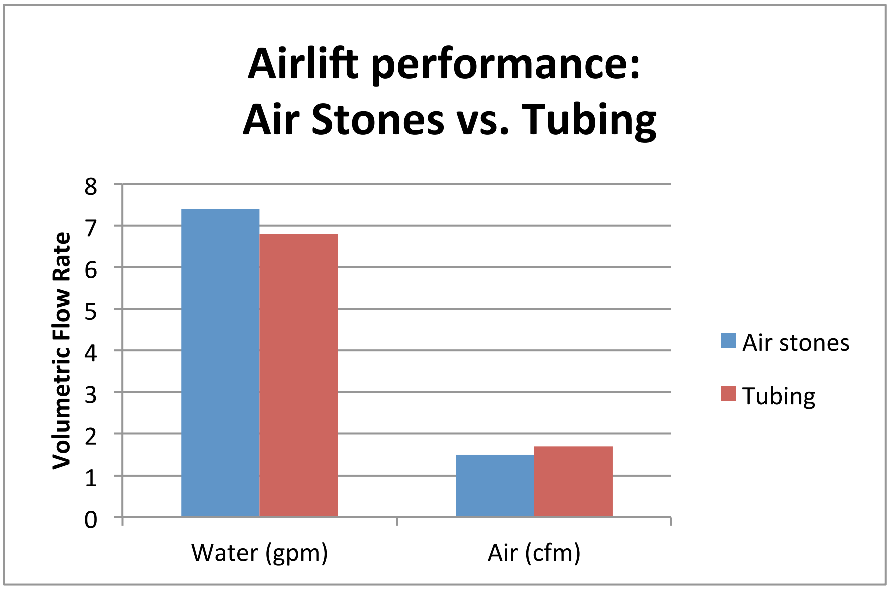

Figure 5: Airlift Performance: Air Stones vs. Tubing. The chart shows a comparison on the difference between using air stones and tubing for air insertion into the designed airlift.

The main conclusions from the airlift testing were that the designed airlift performed about 10% less than the calculated value. This difference could be a result of lack of precision in measurements, lack of temperature correlation, or inexact formulas or inputs. Variable water level in the test sump during operation was the most likely cause. See calculations and testing methods in appendix B, part a. The final airlift design that was used during the research had a higher actual water flow rate than the calculated value.

The desired water flow rate for the final design was 2.7 L/min, or a 30 min hydraulic retention time in the fish tank, and a 50% submergence ratio. The air flow rate required was calculated to be 11.3 L/min. However, the actual performance was 10 L/min water flow, 277% better performance. Possible reasons for this large increase can be several and include the possibility of higher air rate input than designed or inaccuracy in calculating the S-ratio input into equation B 1.

The S-ratio was provided in a table for pipes with diameter of 3 cm and 5 cm (La-Wniczak, Francois, Scrivener, Kastrinakis, & Nychas, 2010). The 3 cm value was used for design calculations even though a 2.54 cm diameter PVC pipe was used in the actual design. See calculations on the airlift final design in appendix B, part b.

Eliminating the use of a water pump in an aquaponics system could result in large energy savings. The power requirements for a water pump and an air pump in an approximately 1140 liter conventional raft-based aquaponics system were measured using a plug-in kilowatt meter. Both pumps drew about the same amount of power, with the water pump drawing approximately 3% more power. Therefore, by eliminating the water pump and using only an air pump to aerate and recirculate the water, at least 50% power savings can be achieved. More savings are feasible by intermittently operating the air pump.

Water and Air Pipe Flow

Water can flow due to gravity between two open reservoirs when the water levels are at different elevations. For a given water flow rate, pipe sizes can be determined by using modifications of the Bernoulli equation. The total head loss determines the minimum elevation difference required between the reservoirs to enable gravity flow. With increased pipe size, smaller elevation differences are needed.

Table 1: Water Piping. This table includes the water pipe sizes that were used in the design and built of the experimental unit.

Water Piping:	**PVC Pipe Size (cm)**	**Ball valve**
Airlift - Double wye	5.08	No
Airlift - pipe	2.54	No
SLO - casing	5.08	No
SLO - draining	2.54	No
FT to GB	2.54	Yes
GB to Sump	3.175	Yes

There are two types of losses in a pipe flow system that make the total head loss: major and minor. The major losses are due to the friction through the pipe length but the minor losses account for the friction through different types of fittings, such as valves, elbows, tees, entrances, exits, contractions, expansions etc. All pipe flow equations are located in appendix B, part c.

Table 2: Air piping. This table includes the air pipe and tubing sizes that were used in the design and built of the experimental unit.

Air Piping:	**Size:**	**Ball valve**
Pump to PVC	0.953 cm ID (tube)	No
All PVC	1.27 cm	Yes (3 ea. system)
PVC to air stones	0.476 cm ID (tube)	No

The total water volume in each system is approximately 227 liters. (See Table 3). The list of materials for the experimental apparatus are listed in appendix C, part a.

Table 3: The total water volume in each system.

Part	**Water Volume**
Fish Tank	70 liters
Grow Bed	81.4 liters
Sump Tank	73.7 liters
Piping	1.9 liters
Total:	**227 liters**

Conditions for Living Organisms

The fish species used were koi (*Cyprinus carpio*). Two types of commercial pellet feed from the same brand (Brand: Zeigler: 40% protein, 10% fat, 4% fiber, 1.12% phosphates) were given to the fish. A feed quantity of 1-3% of the total fish mass in the system was provided to the fish each day. A feeding log can be found in appendix C, part d.

Table 4: Optimal living conditions for koi. The table includes the tolerance levels for the some important water quality parameters that were monitored throughout the experiment (Nelson & Pade, 2008, p. 82).

Category	Tolerance Interval
Dissolved oxygen	4 mg/L – 10 mg/L
Temperature	18° - 24° C (65°-75° F)
pH	6 – 8
Nitrite	0 – 0.6 mg/L
Alkalinity	50 – 250 mg/L
Hardness	50 – 350 mg/L

Italian large leave basil, or sweet basil, (*Ocimum basilicum*) was chosen due to its rapid growth and mass volume of stem and leaves. Basil needs frequent air exchange around the leaves and good aeration in the root area. Basil does best in water in the temperature range of between 20° - 24° C (68°-75° F). The lighting for the plants was provided by fluorescent grow lights. The sides of the fish tanks were covered by a reflective material in order to keep the light away and to prevent undesired algae growth.

Table 5: The optimal temperature and pH range of the water for growing basil (Nelson & Pade, 2008, pp. 94, 126).

Category	Tolerance Level
Water temperature	20° - 24° C (68°-75° F)
pH (for nutrient uptake)	6.0 – 7.5

Average concentrations of plant nutrients in aquaponics have been developed by hydroponics and aquaponics growers. See recommended average concentrations of all other nutrients in table 6.

Table 6: A list of nutrients required by most plants to grow successfully and the recommended average concentration of each. Macro nutrients require higher concentration than micro nutrients. (*PPM = parts per million)
(Nelson & Pade, 2008, p. 127)

Macro Nutrients	Average Concentration	Micro Nutrients	Average Concentration
Nitrate (NO_3)	70 – 300 PPM*	Boron (B)	0.1 – 1.0 PPM
Ammonium (NH^{4+})	0 -31 PPM	Manganese (Mn)	0.1 – 1.0 PPM
Potassium (K)	200 – 400 PPM	Zinc (Zn)	0.02 – 0.2 PPM
Phosphorus (P)	30 – 90 PPM	Molybdenum	0.01 – 0.1 PPM
Calcium (Ca)	150 – 400 PPM	Copper (Cu)	0.02 – 0.2
Sulfur (S)	60 – 330 PPM		
Magnesium (Mg)	25 – 75 PPM		
Iron (Fe)	0.5 – 5.0 PPM		

The most common nutrient deficiencies are potassium, calcium, and iron (Nelson & Pade, 2008, p. 130). To prevent these deficiencies, potassium and calcium were added to the system in the form of potassium hydroxide (KOH) and calcium hydroxide ($Ca(OH)_2$), respectively. Both KOH and $Ca(OH)_2$ are concentrated bases, and will raise the pH in the system when added. KOH was primarily used to raise the pH in the system, since the tap water in Daytona Beach is relatively hard, containing large amounts of calcium and magnesium cations (Casiday & Frey). Since approximately 1/3 of the system water was replaced with de-chlorinated tap water each week, the water provided enough calcium for the plants. Furthermore, 0.7 grams of chelated iron was added to the system at the beginning of each test week to prevent iron deficiencies.

Table 7: This table includes the chemicals used in this experiment to prevent nutrient deficiencies of Calcium, Potassium, and Iron.

Chemical	**Source**	**Amount**
Calcium	De-chlorinated tap water (Ca^{2+})	The 73.7 liter sump water replacement in beginning of each test period.
Potassium	Concentrated base (KOH)	Approx. 3 ml added to each system to achieve 0.1 pH raise.
Iron	Chelated iron	0.7 g added to each system in the beginning of each test period.

The ideal pH for most systems is around 7.0. It is acceptable to maintain the pH range between 6.5 - 7.4. During the nitrification process, the *Nitrosomonas* bacteria release acid in the form of H+ when converting the ammonia (NH_4^+) into nitrite (NO_2^-). This lowers the pH of the water, and causes a constant need for adjustment. *Nitrobacter* bacteria convert the nitrite to nitrate (NO_3^-), which the plants pick up as nutrients. See chapter two for the nitrification process equations and figure 4 for a

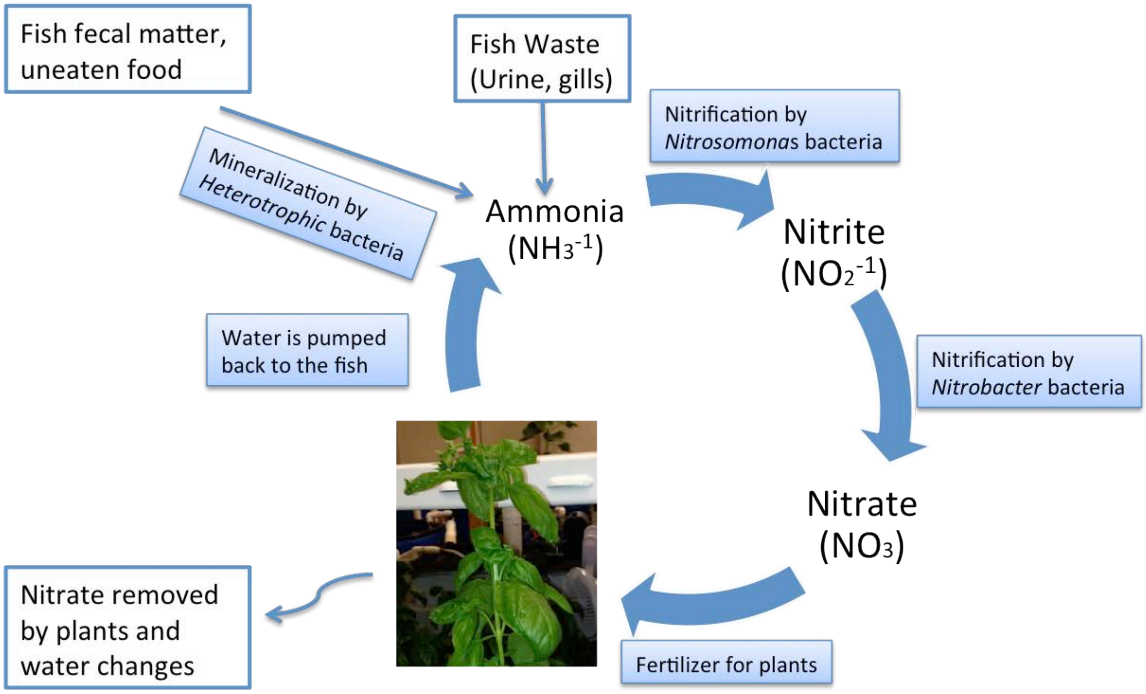

Figure 6: The nitrogen cycle in an aquaponics system.

schematic of the nitrogen cycle process in an aquaponics system.

The pH was monitored very closely throughout the experiment, the pH log can be found in appendix C, part c. The pH was measured manually with drops and a color comparison chart. The pH buffering capacity of water can be measured through alkalinity, which is expressed as a concentration (ppm) of calcium carbonate ($CaCO_3$). Figure 7 shows that the pH was maintained within optimal upper and level bounds.

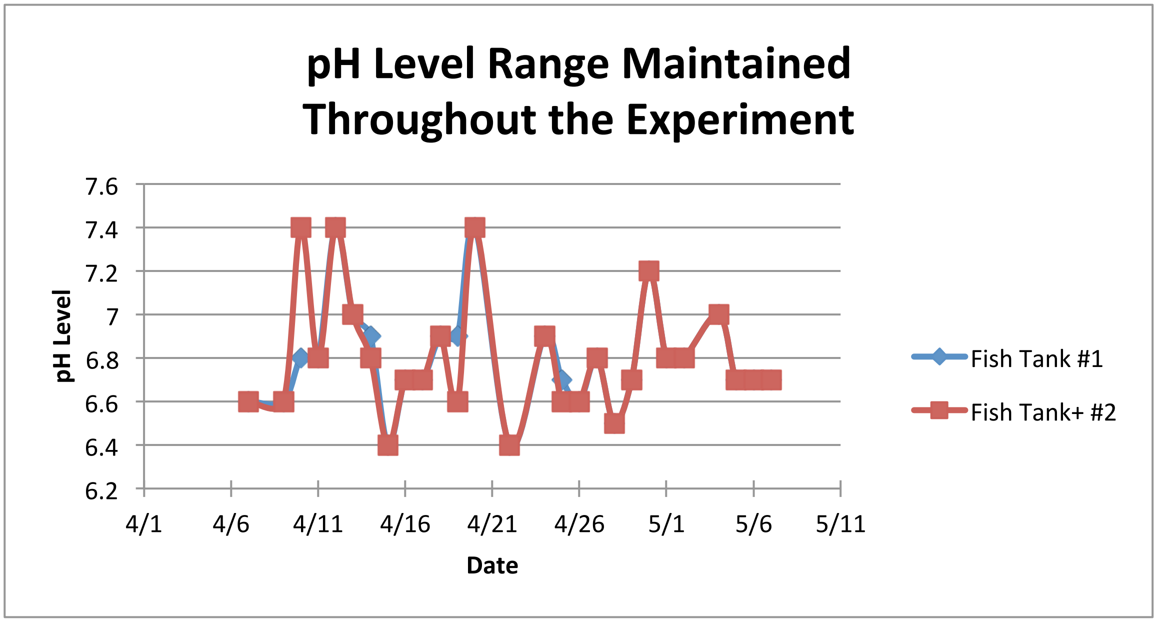

Figure 7: The pH level Measurements over the duration of the experiment. The pH in both fish tanks were maintained within acceptable upper and lower bounds. The pH level measurements ranged between 6.4-7.4.

Water quality strips were used to monitor the hardness, alkalinity, pH, nitrite and nitrate concentrations in the systems. The hardness stayed relatively high (200-240 ppm); the alkalinity was low but acceptable (30-60 ppm); the nitrite consistently measured 0 ppm; nitrate acceptable (50-180 ppm). The pH varied in the system, but was measured to be between 6.3-7.5 when the strips were used. All data and images can be found in appendix C, part b. and appendix D, part b, respectively

Optimal dissolved oxygen levels in an aquaponics system are 6-7 mg/L, although koi can survive at levels low as 4 mg/L. Oxygen and air pump sizing calculations can be found in appendix B, parts e and f, respectively.

The whole process of growing plants and fish through aquaponics requires beneficial bacteria. Three types of bacteria thrive on the media in the system and each serves a special purpose, as listed in table 8 and described in figure 4.

Table 8: List of all beneficial bacteria and its purpose in the system.

Bacteria	**Benefits**
Heterotrophic bacteria	Consumes fish waste, decaying plant matter, and uneaten food and converts to ammonia and other compounds.
Nitrifying bacteria – *Nitrosomonas*	Converts ammonia to nitrite (toxic to fish).
Nitrifying bacteria – *Nitrobacter*	Converts nitrite to nitrate (relatively nontoxic to fish)

The Experimental Setup in Pictures

The following images show the major components of the experimental apparatus.

Figure 10: A picture of the fish tank. Center: The SLO casing pipe. Top left: Airlift pumping aerated water into the tank.

Figure 9: A picture of the valve arrangement. It allows for easy access to adjust the air flow.

Figure 8: A picture of the airlift piping system. It is located in the sump tank. Top right: the overflow pipe (w/ ball valve) from GB to sump.

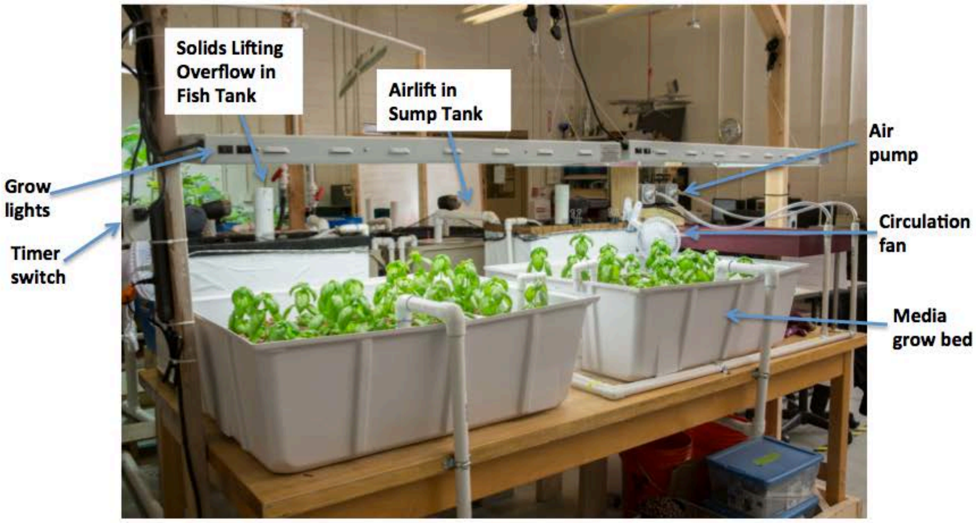

Figure 11: A picture of the experimental setup. Each system has one media based grow bed, fish tank, sump tank, fluorescent grow light, circulation fan, aquarium heater and an air pump. The system on the right is labeled as system #1 and the one to the left is system #2.

Sample Sizes and Data Sources

Each grow bed had 20 basil plants, providing each system with 20 samples of basil to monitor. The average weight of the 20 plants from both systems were used for the comparison.

Before and after each test week, the plant roots were individually dried and weight and stem length of the whole plants were measured. Both the stem length (total length excluding the roots) and the weight were measured. They were then carefully inserted back into the grow media.

Data Collection Device

The stem lengths were measured with a measuring tape. The plant weight was measured with a scale, which provided resolution of 0.1 grams.

Instrument Reliability

A repetitive study was performed to analyze the reliability of the drying method utilized in this study. One small basil plant and one large basil plant from the system were dried and measured 30 times. Then the averages were statistically analyzed and 95% confidence levels were calculated by utilizing the t-distribution. The raw data and calculations from the repetitive study on root drying can be found in appendix B, part d. The 95% confidence interval of the mean for the small and the large plant were 3.8923-3.9077 g. for an average of 3.90 g. and 11.6425-11.6575 g. for an average of 11.65 g., respectively.

Instrument Validity

This quantitative research on energy conservation is designed to be generalized for all types of aquaponics systems. However, each system is different and other types of fish and plants than used in this experiment can have different needs. It is critical that the cultural conditions of all living organisms in the system are taken into a consideration.

Chapter IV

Experimental Results

Data Tables and Graphs

In figure 9 and table 9, the plant growth rate per grow bed per period throughout the experiment is presented. During week 1, the intermittent system (GB #1) experienced a growth increase of 179%, while the constant system grew by 154%, which is a 25% difference. However, during week 2, the constant system (GB #2) performed 28.4% better than the intermittent system. The reason for these differences can be that the plants were in different stages of their growth during the two weeks. By looking at the two weeks together, a growth difference of 3.4% more in the constant system (GB #2) is observed.

Furthermore, the plant growth rates during the 4 day control period after week 2

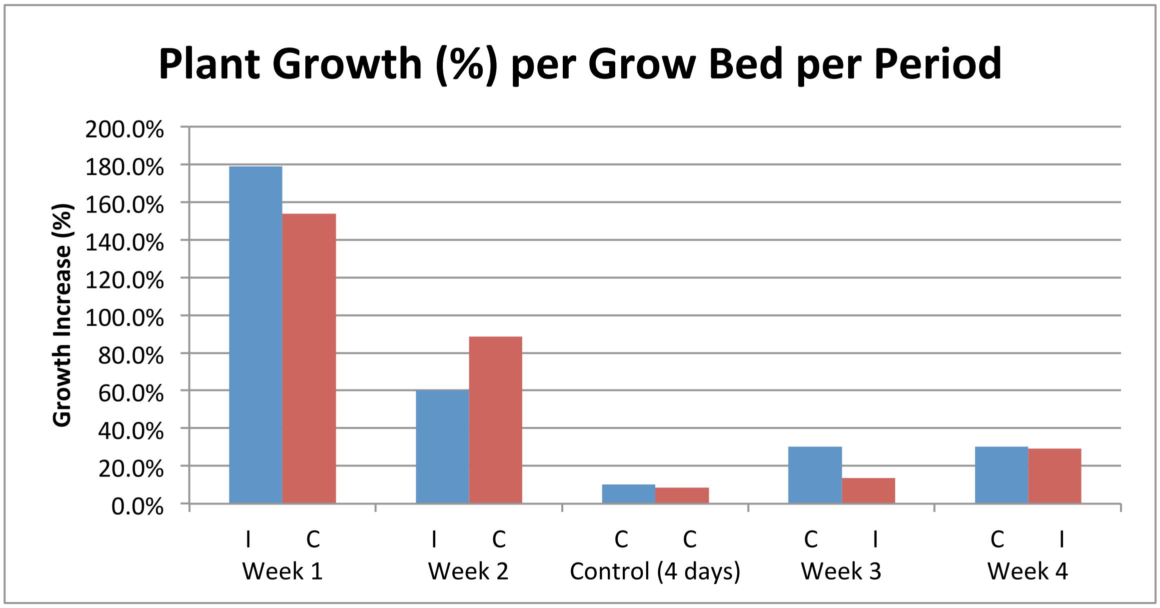

Figure 12: Plant Growth (%) per Grow Bed per Period. The chart shows the plant growth per grow bed per period in percent increase. Note: I = Intermittent, C = Constant.

in GB #1 and GB #2 were 10.4% and 8.5%, respectively. This demonstrates a 1.9% better performance in GB #2, which serves as the constant operating system during week 1 and 2.

Table 9: Bed Growth (%) per Period. The growth rate is presented in percentage growth during each period.

Bed Growth (%) per Period		
Period:	**GB #1 (I):**	**GB #2 (C):**
Week 1	179.0%	154.0%
Week 2	60.3%	88.7%
	GB #1 (C):	**GB #2 (C):**
Control	10.4%	8.5%
	GB #1 (C):	**GB #2 (I):**
Week 3	30.0%	13.7%
Week 4	30.4%	29.4%

A kilowatt-meter was used to measure the real energy consumption of both the constant and intermittently operating air pump. Table 10 shows the total KWh/day for each air pump. 50% less energy is consumed by the intermittently operated air pump.

Table 10: The energy consumption (KWh) of both the intermittently and constantly operated air pumps.

	Air pump (KWh)	
	Constant	Intermittent
KWh per day	0.86	0.43

Figure 10 and table 11 present the average plant growth per 1 KWh/day. Equation 4 was used to obtain the values:

$$\% \text{ Growth in GB per 1 KWh} = \frac{\% \, \boldsymbol{growth\ per\ day}}{\boldsymbol{Total\ KWh\ consumption\ per\ air\ pump\ per\ day}} \qquad \textbf{(4)}$$

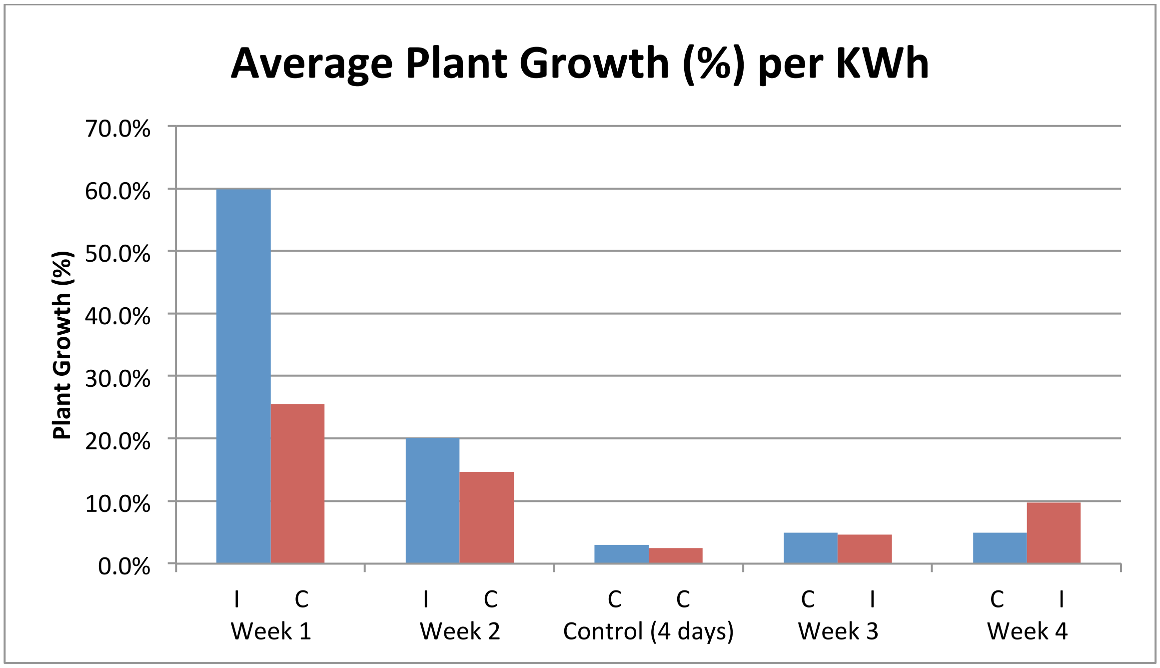

Figure 13: Average Plant Growth (%) per KWh. The chart presents the average plant growth rate per 1 KWh per day in the systems.

By comparing the values for both grow beds for average growth rate per 1 KWh/day in the grow beds, a difference of 34.3 % better performance by the intermittent system (GB #1) during week one and only a 5.5% better performance by the constant system (GB #2) during week two was observed. By looking at both weeks, the intermittent system performs 28.8% better than the constant system, when measured based on energy usage. During the control period, GB #1, the intermittently operated media bed, performed 0.5% better, based on energy usage.

Table 11: The table presents the average bed growth rate per 1 KWh per day.

Avg. Bed Growth (%) per 1 KWh per Day		
Period:	**GB #1 (I):**	**GB #2 (C):**
Week 1	59.9%	25.6%
Week 2	20.2%	14.7%
	GB #1 (C):	**GB #2 (C):**
Control	3.0%	2.5%
	GB #1 (C):	**GB #2 (I):**
Week 3	5.0%	4.6%
Week 4	5.0%	9.8%

Lastly, the fish mass was also monitored at the beginning and at the end of the experiment. Fish were gradually added to the system over the first two weeks for safety reasons. Only one fish death was observed. The fish was 5 grams and sick when it was added to the system in the beginning of week 2 and died two days later. Due to its minimal weight, the loss was negligible, and the same amount of feed to both systems was continued. In table 12, the fish mass was documented to show the overall increase in fish mass over the 5 experimental periods. After week 2, 150 g of fish was exchanged between the systems. Total fish mass in the end of the experiment was 1044 grams, showing a 73% increase in both systems combined.

Table 12: Fish Mass Growth during Experiment. The fish mass was monitored in the beginning and end of the experiment. *Dead fish mass (5 g. subtracted).

	Fish mass (grams)		
	FT #1	**FT #2**	**Both FTs**
Week 1: Fish Added	146	147	293
Week 2: Fish Added	157	152*	309
Total fish mass added	303	299	602
Total mass after randomization	302	300	602
Total fish mass end of experiment	550	494	1044
Growth increase (%)	82%	65%	73%

Power Saving Estimates: Water Pump vs. Air pump

The power consumption of a water pump and an air pump in a larger (300+ gal.), conventional raft-based aquaponics system was measured. A kilowatt-meter was used to obtain the real energy consumption. The water pump required slightly more energy than the air pump to run continuously for 24 hours. Energy savings of approximately 51% can be accomplished by eliminating the water pump and using air pump only to both aerate and pump the water.

Table 13: Energy consumption of a water pump and an air pump in a 300+ gallon raft based aquaponics system.

	Air pump	**Water pump**
KWh per day	1.77	1.82

Equation 5 shows the total percentage decrease in energy consumption that can be achieved by eliminating the water pump in an aquaponics system.

$$Energy\ consumption\ decrease\ (\%) = \frac{1.82}{(1.77 + 1.82)} * 100 = 51\% \quad \textbf{(5)}$$

Conclusion

An airlift was successfully designed to simultaneously aerate and pump the water in an aquaponics system. A pumping energy savings of 51% was observed in an aquaponics system by eliminating the water pump. Additionally, 50% energy savings were observed by intermittently operate the air pump with 15 minute on/off intervals. A total of 75% circulation energy savings from a conventional aquaponics system, which has constant operation of a water and air pump, can be obtained by running an intermittent airlift aquaponics system. Also, with the 75% circulation energy savings, a 44.1% better growth production performance per 1 KWh in the intermittent system was observed during the experiment.

Chapter V

Discussion, Conclusions, and Recommendations

This chapter includes a discussion on observations and findings during the experiment, followed by the conclusions. The chapter closes with recommendations for design and implementation.

Discussions

An airlift design was successfully operated to obtain adequate aeration and water circulation in an aquaponics system, and did not reduce the system yield. Considerable circulation energy savings were achieved by using an intermittent airlift to aerate and circulate the water in the system. No considerable plant growth rate reduction was experienced.

Airlift Design

The airlift produced higher water flow rate in practice than theoretical prediction. The airlift provided an average water flow rate of 10 L/min, compared to calculated flow rate value of 2.65 L/min. There could be multiple reasons for the water flow rate increase, including higher air flow rate input. The air flow rate was not measured with a flow meter, prohibiting exact air flow rate monitoring through the air piping. Another reason is that a smaller diameter pipe was used than calculated for. The calculations expected a 3 cm diameter pipe but a 2.54 cm pipe was used.

Plant Growth Stages

The plants grew most rapidly during the first week. The growth rate decreased over time. Initially, when the plants were put into the system, their weight ranged from 2.2 – 16.3 grams, which supports the conclusion that the growth rate peak could have occurred at different times for different plants. To compensate for this, the growth rates in the media beds during first and last two-week periods were analyzed together.

Fish Growth

Initially, the fish mass was measured and equally added to both systems. The fish mass was not monitored throughout the experimental period, but was measured in the beginning and end. The same amount of feed was provided to the fish tanks each day. An assumption was made that the same fish feed would provide the same amount of fish waste to the system.

Fish tank #1 and fish tank #2 experienced 82% and 65% mass increase, respectively. The reasons for the 19% mass increase difference can be several and include the fact that the sample size was small, which is likely to experience larger errors than larger samples. Another factor, known as hormesis, could also be one of the reasons for this mass difference. Hormesis is a term that is used to describe how stressors of different intensities, durations, and frequencies can affect various response patterns at the organismic level in living organism, including fish. It has been proven that the physical fitness of fish can be improved by exposing it to low levels of stress for certain duration and level of intensity (Schreck, 2010).

The intermittent operation during the experiment possibly exposes the fish to low levels of stress and could be a beneficial factor for fish growth. However, since the fish mass was not measured in the end of each week, it will not be possible to confirm if hormesis effected the fish growth. Hormesis is a phenomenon worth researching during further research on the subject.

Conclusions

An intermittent airlift was successfully operated to obtain adequate aeration and water circulation in an aquaponics system. From this experiment, it can be concluded that up to 75% energy savings in the recirculating and aerating processes in an aquaponics system can be accomplished by providing aeration and circulation through the use of an intermittently operated airlift instead of a constantly operated water pump and air pump. The intermittent airlift operation did not appear to reduce the plant yield of the system when growth increase was measured based on energy input. For the same amount of energy consumed, the intermittently operated system showed 44.1% more growth.

Airlift

The airlift was successfully designed and built to provide aeration and recirculation to the system. The airlift's water flow rate was higher than anticipated. It provided adequate amount of aeration and recirculation to the systems. Aerating and circulating the water through an airlift provided acceptable cultural conditions for both fish and plants, resulting in 971% total plant growth and 73% total fish mass growth over the duration of experiment, including the start-up period, in both systems combined. Additional benefits of an airlift include fewer system components to purchase and maintain and less heat energy is needed since the air pump blows warm air into the water. Furthermore, less evaporation was experienced by intermittently operating the airlift.

Intermittent Aeration and Recirculation

The plant growth was slightly affected by the intermittent operations of the air pump. By looking at the first two weeks and last two weeks, the intermittent system had a difference of 3.4% and 17.7% less growth, respectively. During the control period, only 1.9% plant growth difference was measured. However, when the plant growth was measured based on energy consumption the intermittently operated system performed better. The growth percentage differences per 1 KWh in the intermittent system during the first and last two weeks were 39.7%, and 4.4%, respectively. An intermittently airlift operating system showed total of 44.1% more growth increase per same energy input throughout the experimental period. These numbers support the conclusion that an aquaponics system can successfully operate and grow produce by turning the aeration and recirculation on and off in 15 minute intervals.

Energy Savings

It can be concluded that significant circulation energy savings can be achieved by using an intermittently operating airlift in an aquaponics system. By analyzing a conventional aquaponics system, which uses an air pump for aeration and water pump for recirculation, 51% energy savings can be achieved by replacing the water pump with an airlift. Additional 50% energy savings, a 75% energy savings in circulation from the conventional system, can be attained by intermittently operate the airlift. The intermittent operation was not shown to considerably affect the plant growth rate.

Recommendations

The following recommendations are offered for aquaponics farmers, researchers, or other practitioners in the field of aquaponics.

Recommendations for Practitioners

These are the recommendations on how the design, operation and maintenance could have been done differently:

1. Use a wider sump tank: Wider tank, with larger water volume, could minimize the need for occasional water addition. Water addition was needed when the water level got lower and started to affect the airlift pumping performance.
2. Add a base addition tank: Concentrated base was added to the system several times a week. A small base addition tank or a dripping system could save system maintenance time.
3. Add a pH meter: The water pH was measured several times a week by using drops and a color table. A pH handheld meter could save system maintenance time.
4. Add an automatic feeder: Both systems got the same amount of feed each day. The fish was fed twice daily. An accurate automatic feeder could save system maintenance time.

Recommendations for Improving this Study

There are several recommendations on what could be done differently when performing this study:

1. Plant from seed: Start the experiment with similar sized seedling. By having similar sized plants initially and throughout the experiment, the growth differences could be better observed visually. Also, it could lessen the risk of plant growth booming at different times.
2. Integrate an air flow meter to monitor the air flow through the piping.
3. Further research on the on/off intervals could be beneficial. Smaller on/off timing, such as 1 minute on/off, could result in smaller oxygen level fluctuations in the fish tank, while still only operating the pump 50% of the time. Factors, such as mechanical reliability, would need to be taken into consideration.

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APPENDIX B

Formulas and Calculations

a. Airlift Experiment

An airlift experiment was conducted with the objective to confirm the correlation between the theoretical performance calculations and actual performance. Note: The airlift calculations and experiment where performed on a larger airlift than used in the final design.

Design and Procedures

The design parameters were as follows:

Table B 1: The design parameters for the experimental airlift are listed in this table.

Design Parameter	Value
Submergence	22”
Air stone clearance	9”
Lift required	10”
Submergence ratio	$\frac{22}{22+10}$= 0.69
D_{pipe}	2”
$Q_{water\ required}$	4.4 gpm

The air flow rate required to maintain water flow of 4.4 gpm can be calculated by using the equation B 1 (La-Wniczak, Francois, Scrivener, Kastrinakis, & Nychas, 1999). The formula requires SI units but answers have been converted back to English units.

$$Qa = \frac{\mathrm{Qw}(p\mathrm{w} - p\mathrm{w} * \mathrm{as})}{\mathrm{F}(p\mathrm{w} * \mathrm{as} - p\mathrm{a})} + Qa, \mathrm{min} \tag{B 1}$$

Where:

Q_a = air flow rate (m^3/min)

Q_w = water flow rate (0.0165 m^3/min)

p_w = density of water (1000 kg/m^3)

F = dimensionless coefficient assuming negligible losses (1)

p_a = density of air (1.2 kg/m^3)

a_s = submergence ratio

$Q_{a,min}$ = minimum air rate to obtain water lift at chosen pipe diameter and submergence ratio.

(1.351 m^3/hr for ratio=0.7, from Table 1 (La-Wniczak))

Gives:

$$Qa = \frac{0.0165\frac{m3}{min}*\frac{60\ min}{1\ hr}(1000\frac{kg}{m3}-1000\frac{kg}{m3}*0.69)}{1(1000\frac{kg}{m3}*0.69-1.2\frac{kg}{m3})} + 1.351\ \frac{m3}{hr} = 1.36\ m^3/hr * \frac{0.59\ cfm}{1\ m3/hr} = \mathbf{0.8\ cfm}$$

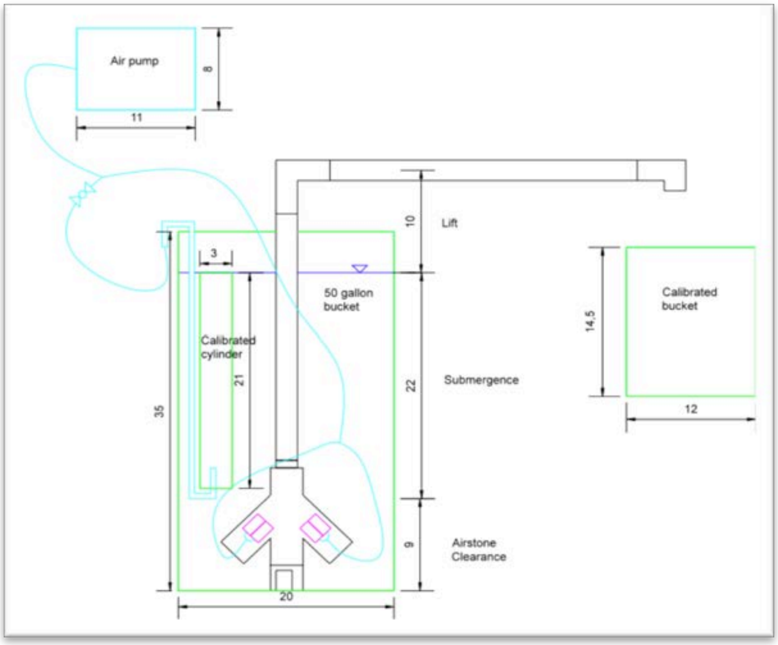

Figure B 1: Schematic of the airlift testing apparatus.

In order to verify that the calculations provided accurate answers, an experiment was setup that demonstrated the full scale airlift. The water was pumped through the airlift into a 5 gallon bucket for 30 seconds and the water volume measured. This provided us with the exit water flow rate.

Additionally, the air flow exiting the air stones/tubing was measured utilizing a 2L calibrated cylinder. The cylinder was filled with water and placed upside-down in the water reservoir, leaving no air. The air was turned on for 2 seconds and readings taken off the cylinder, enabling the air flow rate to be measured. See a schematic of the airlift testing apparatus in figure B 1.

Figure B 2: A picture of the airlift experiment setup.

Apparatus and Materials

The following is the complete list of parts and tools needed for the airlift experiment:

- 1 x Air pump
- (Pentair model: SL44B. cfm approx. 2.5 @1 psi)
- 1 x large drum (50 gallon)
- 1 x small bucket (5 gallon)
- Stopwatch
- PVC pipe, 3” (4 in. needed)
- PVC pipe, 2” (5 ft. needed)
- PVC pipe, ½” (6 ft. needed)
- Tubing, ½” (20 ft. needed)
- Tubing, 1/4” ID (1 foot needed)
- 1 x PVC elbow, 2”
- 1 x PVC 45°, 2”
- 1 x PVC Charlotte 3-way wye fitting, 3”
- 1 x PVC reducer, 3”x2”
- 4 x PVC elbow, ½”
- 4 x Sweetwater Generation II diffusers, 2 in.
- 4 x Threaded male to barb adapter, 1/8”
- 3 x Barbed T, 1/4”
- 1 x ¼” barb to 3/8” threaded female
- 1 x Threaded coupling, ½”
- 1 x Flat/Threaded coupling, ½”
- 1 x PVC threaded reducer, ½”x3/8”
- 2 x PVC threaded male to barb, ½”
- 1 x 2000 ml calibrated cylinder
- 2 x Barbed T, ½”
- 3x Threaded male to barb adapter, ½”
- 1 x Ball valve, ½”

Experimental Results and Analysis

During the airlift experiments, data was collected and analyzed. Four separate testing were carried out. Both the case with air stones and tubing only for air injection were inspected for water and air flow rates. The water to air ratio was utilized to determine which injection method performed better.

Water and Air Flow Rates Using Air Stone Injection

The water flow rate was close to the same throughout the testing with average of 28.2 L/min (7.4 gpm). The numbers from the air flow data through the air stones had the average of 42.9 L/min (1.5 cfm). These numbers result in water to air ratio of 1:1.5 for the airlift using air stones.

Table B 2: Water flow rate leaving the airlift through the air stones.

Water Flowrate with Air Stones	
Trial #	**Airlift Q_{water} (L/min)**
1.1	28
1.2	28.8
1.3	27.8
Average:	**28.2 (7.4 gpm)**

Table B 3: Air flow rate entering the airlift pipe through the air stones.

Air Flowrate from Air Stones	
Trial #	**Cylinder Q_{air} (L/min)**
2.1	40.8
2.2	42
2.3	48
2.4	47.7
2.5	36
Average:	**42.9 (1.5 cfm)**

Assuming linearity, the estimated water flow through the airlift injected with 0.8 cfm of air injection can be calculated (See equation B 2) by comparing it to the experimental data.

$$\frac{1.5\ cfm}{0.8\ cfm} = \frac{7.4\ gpm}{x} \rightarrow \text{x = 3.95 gpm} \tag{B 2}$$

3.95 gpm is approximately 10% less than the 4.4 gpm that the pre-experimental calculations required. This difference can be a result of lack of precision in measurements, lack of temperature correlation, or inexact formulas or inputs.

Water and Air Flow Rate Using Tubing Injection

The performance difference between using air stones and tubing only for air injection was tested. The air bubbles coming straight from the tube are larger and provide less surface area between the air bubbles and water. That results in less aeration through the airlift. However, the objective was to observe the difference in water flow rate, not the aeration efficiency.

The water flow rate leaving the airlift had the average of 26.1 L/min (6.8 gpm), which was lower water flow rate than when air stones were used. Logically, the air flow rate entering the airlift from the tube was higher than the air stones due to less resistance. The average air flow rate was 48.6 L/min (1.7 cfm). The lower water flow rate and higher air flow rate resulted in a water to air ratio of approximately 1:1.85. See table B 4 and B 5

Table B 4: The water flow rate entering the airlift pipe, using tubing only.

Water Flow rate with Tube Only	
Trial #	**Airlift Q_{water} (L/min)**
3.1	26.4
3.2	25.2
3.3	26.8
Average:	**26.1 (6.8 gpm)**

Table B 5: The air flow rate entering the airlift straight from the tube.

Air Flow rate from Tube	
Trial #	**Cylinder Q_{air} (L/min)**
4.1	48
4.2	48.6
4.3	49.2
Average**:**	**48.6 (1.7 cfm)**

Experiment Conclusion

The designed airlift performed close to expectations that were based on the pre-experiment calculations. By using air injection of 1.5 cfm through air stones, the water flow rate required was beyond reached. According to the calculations, the designed airlift should reach 4.4 gpm of water with an 8 cfm air injection. However, the experiment data was used to estimate the water flow rate that would occur at the designed air flow rate of 8 cfm. The airlift performed 10% less than expected. This difference can be a result of lack of precision in measurements, lack of temperature correlation, or inexact formulas or inputs. According to the experiment data, an air flow rate of 0.9 cfm should deliver 4.4 gpm through the designed airlift, using air stones, and 69% submergence ratio.

The difference between using air stones and tubing was inspected during the experiment. The case with tubing only ended up being less efficient, having a ratio of water to air to be 1:1.85 instead of 1:1 ½. Therefore, for this particular design, it is more feasible to use the air stones instead of tubing only.

The results also show that the tubing only, which provides larger bubbles than the air stones, was less efficient. These results were unexpected. These results open questions for if the performance degrades when there is excessive air injection or if bubbles are too large.

b. Airlift – Final Design

Design parameters

The design parameters for the final airlift design are listed in table B 6:

Table B 6: A list of the design parameters for the final airlift design.

Design Parameter	Value
Submerged air stone clearance	9”
Submergence of pipe	24” – 9” = 15”
Lift required	14”
Submergence ratio	15/15+14 = 0.517 ≈ 50%
D_{pipe}	1”
$Q_{water\ required}$	0.7 gpm (0.00265 m^3/min)

The required air flow rate input to maintain a water flow rate of 0.7 gpm can be calculated by using the following formula. The formula requires SI units but answers have been converted back to English units. This is the same formula as equation B 1 that was used for designing the airlift in appendix B, part a.

$$Qa = \frac{\mathrm{Qw}(pw - pw * \mathrm{as})}{\mathrm{F}(pw * \mathrm{as} - pa)} + Qa, \mathrm{min}$$

Where:

Q_a = air flow rate (m^3/min)

Q_w = water flow rate (0.00265 m^3/min)

p_w = density of water (1000 kg/m^3)

p_a = density of air (1.2 kg/m^3)

a_s = submergence ratio

$Q_{a,min}$ = minimum air rate to obtain water lift at chosen pipe diameter and submergence ratio. (0.465 m^3/hr for: submergence ratio=0.5, S-ratio[1] of 3, and diameter of riser tube=1 to 1-1/4 in. (≈3cm) from Table 1 (La-Wniczak))

F = dimensionless coefficient assuming negligible losses (1)

Gives:

$$Qa = \frac{0.00265\,\frac{m3}{min} * \frac{60\ min}{1\ hr}(1000\frac{kg}{m3} - 1000\frac{kg}{m3} * 0.5)}{1(1000\frac{kg}{m3} * 0.5 - 1.2\frac{kg}{m3})} + 0.465\ \frac{m3}{hr} = 0.62\ \mathrm{m}^3/\mathrm{hr} * \frac{0.59\ \mathrm{cfm}}{1\ m3/hr} \approx \mathbf{0.4\ cfm}$$

Result: The air volumetric flow rate required to be inserted into the airlift to achieve the required water flow rate of 0.7 gpm is approximately 0.4 cfm.

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[1] The S-ratio is the ratio between the cross sectional area of the air injector (S_a) and the horizontal cross sectional area of the cone (where water is flowing) at the level of the injector exit, minus the cross section of the injector (S_w). $S = S_w / S_a$

c. Pipe Flow Equations

An excel spreadsheet was developed to easily calculate the total head loss. The head loss was obtained by inserting values for the diameter and length of the PVC pipe and all PVC fittings. The equations are listed below:

Head Loss Equations (Cimbala & Cengel, 2013, Equation 6.10):

Major head loss: $h_f = \frac{8*f*L*Q^2}{\pi^2*g*d^5}$

(B 3)

Minor head loss: $h_m = K * \frac{v^2}{2*g} = K * \left(\frac{Q}{\pi*r^2}\right)^2 * \frac{1}{2*g}$

(B 4)

Where, $v = Q/A = \frac{Q}{\pi*r^2}$

(B 5)

Total head loss: $h_L = h_f + h_m$

(B 6)

Friction Factor Equations (Cimbala & Cengel, 2013, Equation 6.49):

Reynolds number (duct): $Re = \frac{p*d*v}{\mu} = \frac{p*d*(\frac{Q}{r2*\pi})}{\mu}$

(B 7)

Frictional factor (Haaland equation): $\frac{1}{\sqrt{f}} = -1.8 * \log\left(\left(\frac{\frac{\epsilon}{D}}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right)$

(B 8)

Where:

f = Darcy-Weisbach frictional factor for full-flowing circular pipe

L = length of pipe (m)

Q = water flow rate (m3/s)

g = gravitational force (9.81 m2/s2)

d = diameter (m)

K = resistance coefficient

v = velocity (m/s)

p = density of liquid (kg/m3)=997 kg/m3 for water at 25°C

μ = viscosity (N*s/m2)=0.000901 N*s/m2 for water at 25°C

ϵ = Roughness value=0.0000015 mm for PVC pipe

ϵ/D = relative roughness.

d. Repetitive Study on Root Drying Method

Two plants, one small and one large, were dipped in water and dried 30 times each. The weights were recorded in table B 7 in order to statistically analyze the accuracy of this method.

- The small plant had 3” long roots and had 3.5” long stem.
- The large plant had 3.25” long roots and had 7” long stem.
- Normal distribution was assumed.

Table B 7: Raw data of the weight of the plants.

	Weight (g)	
Trial #	**Small plant**	**Large plant**
1	4.1	11.7
2	4.2	11.7
3	3.8	11.7
4	4.1	11.7
5	4	11.9
6	4	11.6
7	4	11.9
8	4	11.8
9	3.9	11.6
10	3.9	11.6
11	3.9	11.6
12	3.8	11.7
13	3.9	11.6
14	3.9	11.4
15	3.9	11.7
16	3.9	11.7
17	3.7	11.6
18	3.8	11.8
19	3.8	11.6
20	3.9	11.7

21	4	11.6
22	3.9	11.6
23	3.9	11.5
24	3.9	11.6
25	3.9	11.5
26	3.9	11.7
27	3.8	11.7
28	3.7	11.5
29	3.8	11.6
30	3.8	11.7
Sample mean ($\bar{x}$):	**3.90**	**11.65**

Equations B 9, B 10, and B 11 are statistical analysis equations that were used to calculate the variance, standard deviation, and confidence interval of the means, respectively, for a sample with $n \geq 30$. The sample size and sample means were known.

Known variables

Sample size: $n = 30$

Sample means:

$\bar{x}_{\text{small}} = 3.90$ g

$\bar{x}_{\text{large}} = 11.65$ g

Equations

$$\text{Variance: } s^2 = \frac{1}{n}\sum_{i=1}^{n}(X_i - \bar{x})^2$$

(B 9)

$$\text{Standard Deviation: } s = \sqrt{s^2}$$

(B 10)

$$\text{Confidence Interval: } \bar{x} \pm (Z_{\alpha/2}) * \frac{s}{\sqrt{n}}$$

(B 11)

Table B 8: The squared deviations from the mean are calculated and used to find the variance and the standard deviation of the sample.

Squared deviations from the mean		
	Small plant	**Large plant**
Trial #	$(X_i - \bar{x})^2$	$(X_i - \bar{x})^2$
1	0.040	0.002
2	0.090	0.002
3	0.010	0.002
4	0.040	0.002
5	0.010	0.063
6	0.010	0.003
7	0.010	0.063
8	0.010	0.023
9	0.000	0.003
10	0.000	0.003
11	0.000	0.003
12	0.010	0.002
13	0.000	0.003
14	0.000	0.063
15	0.000	0.002
16	0.000	0.002
17	0.040	0.003
18	0.010	0.023
19	0.010	0.003
20	0.000	0.002
21	0.010	0.003
22	0.000	0.003
23	0.000	0.023
24	0.000	0.003
25	0.000	0.023
26	0.000	0.002
27	0.010	0.002
28	0.040	0.023
29	0.010	0.003

30	0.010	0.002
$\sum_{i=1}^{n}(X_i - \bar{x})^2$:	**0.0123333**	**0.01183**

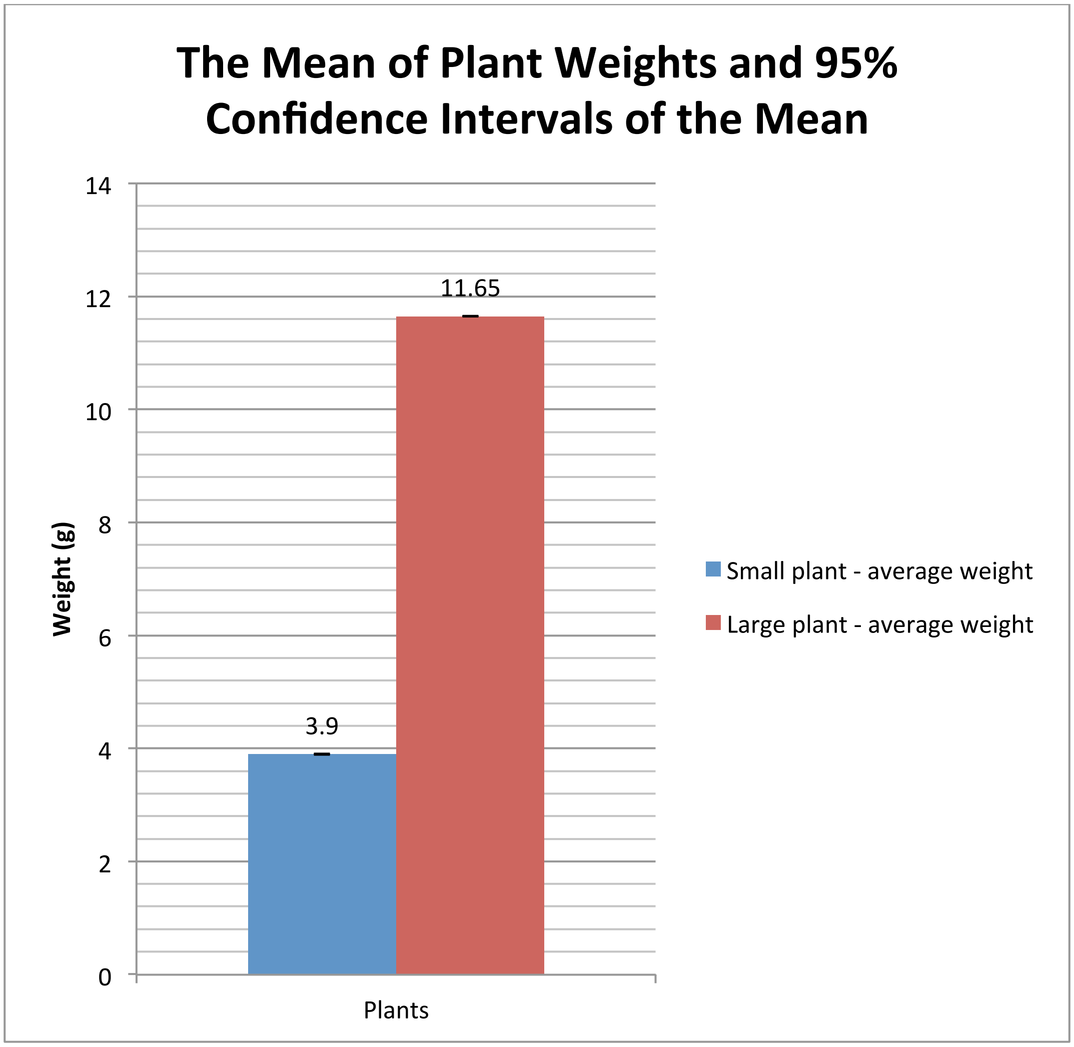


Figure B 3: This chart presents the means and the 95% confidence interval of the mean of both the plants. Error bars have been incorporated to represent the confidence interval but it can be observed that the interval is very minimal.

Table B 9: This table includes the values for the variance, standard deviation, and also the 95% confidence interval around the mean of the plant weights.

	Small plant	Large plant
Variance	0.000425287	0.000408046
Standard deviation	0.020622496	0.020200148
95% confidence interval	3.8923 g. – 3.9077 g.	11.6425 g. – 11.6575 g.

e. Oxygen Calculations

The following is the calculation on how much aeration is required for the fish, plants, and bacteria. The author of Recirculating Aquaculture states: "In a pure recirculating aquaculture system, the ratio of 1.0 kg of oxygen per 1 kg of feed fed is the safe recommended design value". This amount of oxygen is sufficient for the nitrifying bacteria, heterotrophic bacteria, plants, and fish. By using the suggested feed rate ratio of 16 grams of feed per m^2 of grow bed area per day (Lennard Ph.D., 2012) the daily amount of fish feed and oxygen was calculated:

1. Feed rate ratio: 16 g of fish feed/m^2 of grow bed area per day (A_{GB}=0.7 m^2)

2. Daily amount of fish feed into the system = $\frac{16\ g}{m2*d}$ * 0.7 m^2 = 11.2 g fish feed/day

   Note: If fish is fed 1%, 2%, or 3% of their body weight 1120 g., 560 g., and 374g. of fish is required, respectively.

3. Amount of oxygen needed, using 1:1 ratio = 11.2 g O_2/day * $\frac{0.0022\ lb}{1\ g}$ * $\frac{1\ day}{24\ hr}$ =

   0.00103 lbs. O_2/hr

4. The oxygen injected by one 2” air stone can be calculated using equation B 12.

$$\text{Oxygen injection} = Q_s * W_{air} * W_{oxygen\ in\ air} * SOTE * L * FTE \tag{B 12}$$

Where:

Q_s = suggested flowrate through diffuser

(Aquatic Eco-Systems, 2013)

W_{air} = 0.075 lbs of air in ft^3

$W_{oxygen\ in\ air}$ = By weight, 23% of air is oxygen

(20.9% volume of moles)

Standard Oxygen Transfer Efficiency (SOTE) = 0.01 lbs/ft for

medium pore diffuser

L = depth of diffuser

Full-Time Efficiency (FTE) = 0.51 with T_{water} = 68° F and D.O.

level = 4 mg/L (Aquatic Eco-Systems, 2013)

Gives:

$$Q_{oxygen} = 0.2\,\frac{ft3}{min} * 0.075\,\frac{lbs}{ft3} * 0.23 * \left(0.01\,\frac{lbs}{ft} * 1\text{ ft}\right) * 0.51 * \frac{60\ min}{1\ hr} = 0.001035\text{ lbs. } O_2\text{/hr}$$

Number of 2” air stones needed to fulfill system oxygen demand = 0.00103/0.001035 = 0.99 = 1 air stone.

Result: The total air flow needed to fulfill the oxygen demand in system is 2 cfm. The airlift requires 4 cfm through two air stones to successfully pump the water. A lot of aeration goes through the airlift and therefore the air stone in the fish tank is not required. However, an air stone in the fish tank was incorporated into the design to be used when periodically turning of the airlift due to repairs or for any other reason.

f. Air Pump Sizing

The air pump was chosen based on the air needs for the aeration and recirculation of the system. See table 9 for a compiled list of air volumetric flow rate requirements in the system.

Table B 10: The air volumetric flowrate required in order to provide air to all three major components. The fish tank air stone is optional since the airlift will provide enough aeration for the fish.

Part	Amount	Notes
Airlift	4 cfm	two 2” air stones
Fish Tank	(2 cfm)	one 2” air stone (to be used when airlift is not in use)
Grow Bed	2 cfm	PVC air distribution grid
Max Total Volumetric Flow Rate	**6 cfm**	

The main pressure drop in the system is due to water and diffuser pressures. In a small system such as this one, pressure drop through pipes, fittings and due to elevation differences are negligible. The diffusers have a maximum of 0.25 psi pressure drop (Aquatic Eco-Systems) and the max pressure drop due to water occurs in the sump tank on a depth of 24”.

Diffuser pressure ≤ 0.25 psi each

Water pressure = $P = \frac{Ls*Sg}{2.31} = \frac{24\text{ in }*1}{2.31} * \frac{1\text{ ft}}{12\text{ in}} = 0.87\text{ psi}$

Where:
L_s = Maximum submerged depth (24”)
S_g = Specific gravity of liquid ($S_{g,water}$=1)

Total maximum pressure = (2 x 0.25 psi) + 0.87 psi = 1.37 psi

Therefore, the air pump is required to provide 6 cfm of air at 1.37 psi pressure. The air pump performance can be determined by looking at its performance curve (See figure 4). The curve shows the air volumetric flow rate at certain pressures. Note that the chart provides pressure in MPa and air volumetric flowrate in m^3/min.

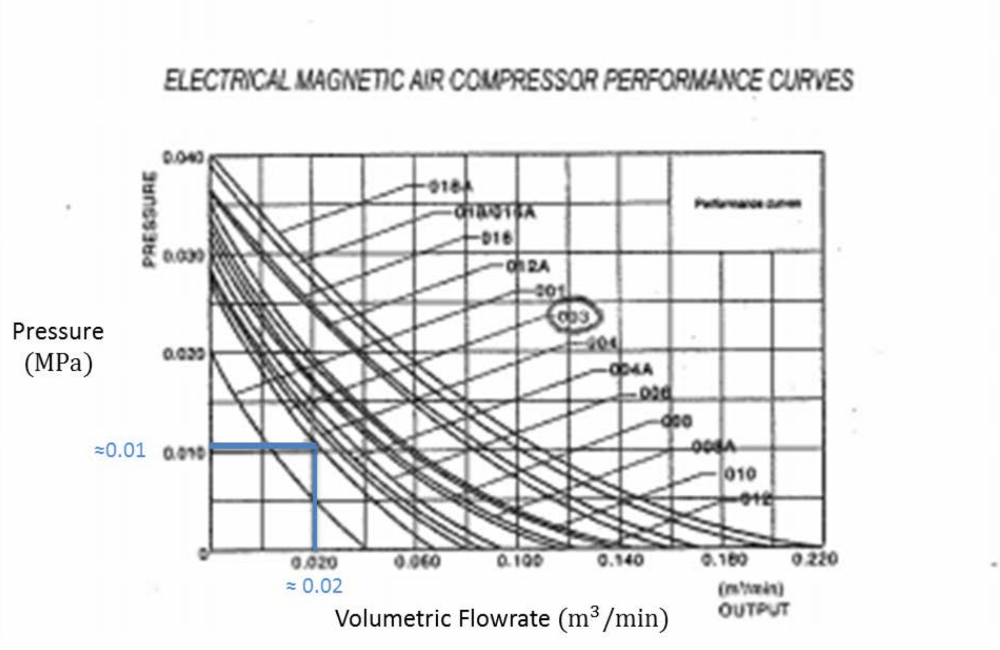


Figure B 4: The performance curve for Eco air Commercial 3 air pump, which was chosen for the system. The air pump provides the required air flow rate under given pressure. (1.37 psi ≈ 0.01 MPa; 0.6 cfm ≈ 0.02 m^3/min)

APPENDIX C

Tables

a. List of Materials for the Experimental Apparatus

The following table includes all major parts required to build the aquaponics experimental apparatus. Included is the quantity and function of each part.

C 1: List of Materials and their functions for the experimental apparatus.

PARTS LIST

Part	**Quantity**	**Function**
SUPPORT STRUCTURE:		
Table (49"x95"x32")	1	To carry system
Lumber 2X4, 10'	1	To hold lights
Lumber 2X4, 96"	3	To hold lights
11 in UV Black Cable ties	1	To fasten cords
FISH TANK		
Aquarium tank (20 gal, glass)	2	To accommodate fish
Black & White Poly-Per Foot	3	To prevent algae growth
Fish net	1	To cover tanks
Paper Clips	12	To secure netting
Elastic String	1	To secure netting
Automatic Fish Feeder	2	To feed fish (automatic)
1" Bulkhead fitting	2	To seal drainage piping
Fish (Koi and goldfish)	40	To provide waste to bacteria
Fish Hand Net	1	To catch fish
Coralife Thermometer Digital	2	To monitor water temperature
Aqueon Submersible Aquarium Heater (L=13", 150W)	2	To regulate water temperature
GROW BED:		
40 gal Botanicare plastic reservoir (Grow Bed)	2	To hold media
Clay hydro pebbles (45 L bags)	6	To serve as media
Basil Plants	16	To utilize and clean system of nitrates
6" Circulating fan	2	To provide air circulation
Gutter Guard	1	To prevent media clogging overflow pipe
SUMP:		
23 gal Waste can	2	To serve as a sump tank
Polycarbonate Sheet 0.093"x12"x24"	1	To secure airlift
LIGHTS, AIR, AND POWER:		
Fluorescent Grow Lights	2	To provide lighting for plants
Rope Ratchet Light Hanger Pair	2	To hold lights
Eco Air Commercial Air Pump 3	2	To provide air to the system
15 min analog timer (double outlet)	2	To regulate air pump and light ON/OFF times

Hose Clamps (1/4" x 5/8")	6	To secure tubing
1/2" OD x 3/8" ID Vinyl Tube	1	To transport air
15' Extension Cord	1	To provide electricity
6 Outlet Black Surge, 8' Cord	2	To provide electricity
Sweetwater Air diffusers (2")	6	To produce little air bubbles
PIPING:		
1/2' x 1/4' PVC Bush MXF	2	To transport air
1/2" PVC Adapter SXF	6	To transport air
3/8" ID Hose Barb Straight Adapter	2	To transport air
3/16" ID Hose Barb Straight Adapter	2	To transport air
1/4" ID Vinyl Tube Braided	5	To transport air
1/4" OD Vinyl Tube 1/8" ID	2	To transport air
1/2 x 1/4 PVC 40 Bush MXF	2	To transport air
1/2" PVC 40 Adapter SXF	6	To transport air
3/8ID Hose Barb X1/2MIP Straight Adapter	2	To transport air
3/16 ID Hose Barb X1/4MIP Straight Adapter	2	To transport air
1/4 ID Vinyl Tube Braided (sold by foot)	5	To transport air
1/4" OD Vinyl Tube 1/8 ID (sold by foot)	2	To transport air
PVC pipes (1/2")	4	To transport air
PVC cap slip (1/2")	4	To transport air
PVC elbow - 10 pack (1/2")	3	To transport air
PVC ball valve, slip to slip (1/2")	6	To transport air
PVC Tee (1/2")	6	To transport air
PVC Pipes (1/2")	2	To transport air
PVC Cap Slip (1/2")	6	To transport air
PVC Tee (1/2")	2	To transport air
Conduit Clamp (1/2")	1	To fasten air pipe
PVC Double Wye fitting (2")	2	To transport water
PVC bushing (2" - 1")	2	To transport water
PVC ball valve (1")	2	To transport water
PVC Tee (1")	2	To transport water
PVC 45D (1")	2	To transport water
PVC Threaded female to slip (1")	2	To transport water
PVC pipes (1") - 10' long	3	To transport water
PVC elbow (1")	10	To transport water
1"x3/4" PVC Bushing	4	To transport water
3/4"x1/2" PVC Bushing	4	To transport water
PVC pipes (1-1/4") - 2' long piece	2	To transport water
Bulkhead fitting (1-1/4")	4	To transport water
Male adapter (1-1/4")	4	To transport water
PVC Ball Valve (1-1/4")	2	To transport water
1" PVC Conduit Strap (4 pack)	1	To fasten water pipe
PTFE pipe seal tape	2	To seal threaded fittings

PVC Primer and Cement	1	To glue pipes and fittings
PVC Union Slip to Slip (1")	4	To allow for pipe cleaning

b. Water Quality Strips – Values

C 2: Water quality strip results from week 1-2 and the control period. The desired range for each parameter is listed.

	Desired	Pre-Week 1		Pre-Week 2		Pre-Control	
	Range (ppm)	System #1	System #2	System #1	System #2	System #1	System #2
Hardness	50 - 350	200	200	240	200	220	220
Alkalinity	50 - 250	60	60	40	30	40	40
pH	6.3 - 7.3	7.5	7	6.8	6.8	6.5	6.3
NO2	0 - 0.6	0	0	0	0	0	0
NO3	70 - 300	180	180	160	160	75	75

C 3: Water quality strip results from week 3-4 and at the end of the experiment. The desired range for each parameter is listed.

	Desired	Pre-Week 3		Pre-Week 4		End-Week 4	
	Range (ppm)	System #1	System #2	System #1	System #2	System #1	System #2
Hardness	50 - 350	220	220	200	200	200	200
Alkalinity	50 - 250	60	60	60	70	40	40
pH	6.3 - 7.3	6.5	6.5	7.0	7.2	6.6	6.5
NO2	0 - 0.6	0	0	0	0	0	0
NO3	70 - 300	80	80	50	50	50	50

c. pH log

C 4: The pH base addition log. It records the amount of base required to keep the pH within an optimal range.

pH Base Addition Log

Date:	Day:	pH #1	pH #2	Addition GB#1 (ml)	Addition GB#2 (ml)	KOH/ CaOH	Notes:
4/7/2014	Mon	6.6	6.6	21	21	KOH	
4/8/2014	Tue	NC*	NC				*NC = Not Checked
4/9/2014	Wed	6.6	6.6	12 + 11	12 + 11	KOH	
4/10/2014	Th	6.8	7.4	12	0	KOH	
4/11/2014	Fri	6.8	6.8	6	6	KOH	
4/12/2014	Sat	7.4	7.4			CaOH2	Water change (iron added)
4/13/2014	Sun	7	7			CaOH2	Water Addition
4/14/2014	Mon	6.9	6.8				
4/15/2014	Tue	6.4	6.4	21+12	21+12	KOH	
4/16/2014	Wed	6.7	6.7	20	20	KOH	
4/17/2014	Th	6.7	6.7	21	21	KOH	
4/18/2014	Fri	6.9	6.9			CaOH2	Water Addition
4/19/2014	Sat	6.9	6.6			CaOH2	Water change (iron added)
4/20/2014	Sun	7.4	7.4				
4/21/2014	Mon	NC	NC				
4/22/2014	Tue	6.4	6.4	22	22	KOH	
4/23/2014	Wed	NC	NC			CaOH2	Water change (iron added)
4/24/2014	Th	6.9	6.9				
4/25/2014	Fri	6.7	6.6	20	23	KOH	
4/26/2014	Sat	6.6	6.6	21	21	KOH	
4/27/2014	Sun	6.8	6.8	15	15	KOH	
4/28/2014	Mon	6.5	6.5	24	24	KOH	
4/29/2014	Tue	6.7	6.7	20	20	KOH	
4/30/2014	Wed	7.2	7.2				Water change (iron added)
5/1/2014	Th	6.8	6.8	18	18	KOH	
5/2/2014	Fri	6.8	6.8	15	15	KOH	
5/3/2014	Sat	6.5	6.5	24	24	KOH	
5/4/2014	Sun	6.8	6.8	15	15	KOH	
5/5/2014	Mon	NC	NC				
5/6/2014	Tue	7.0	7.0	10	10	KOH	
5/7/2014	Wed	6.7	6.7	20	20	KOH	
5/8/2014	Th	6.7	6.7	20	20	KOH	
5/9/2014	Fri	6.7	6.7	20	20	KOH	
5/10/2014	Sat	6.8	6.8	15	15	KOH	
5/11/2014	Sun	NC	NC				

5/12/2014	Mon	7.0	7.0	10	10	KOH
5/13/2014	Tue	6.7	6.7	20	20	KOH
5/14/2014	Wed	6.7	6.7	20	20	KOH
5/15/2014	Th	6.7	6.7	20	20	KOH
5/16/2014	Fri	6.8	6.8	15	15	KOH
5/17/2014	Sat	NC	NC			
5/18/2014	Sun	7.0	7.0	10	10	KOH

d. System Fish Mass and Feeding Log

C 5: System fish mass. Total fish mass added to the systems and their growth increase throughout the experiment.

	Fish mass (grams)		
	FT #1	FT #2	Both FTs
Week 1: Fish Added	146	147	293
Week 2: Fish Added	157	157	314
Total fish mass added	**303**	**304**	**607**
Total mass after randomization	302	305	607
Total fish mass end of experiment	550	494	1044
Growth increase (%)	82%	65%	73%

C 6: Fish feeding log. It lists the amount of pellet feed that was given to the fish daily.

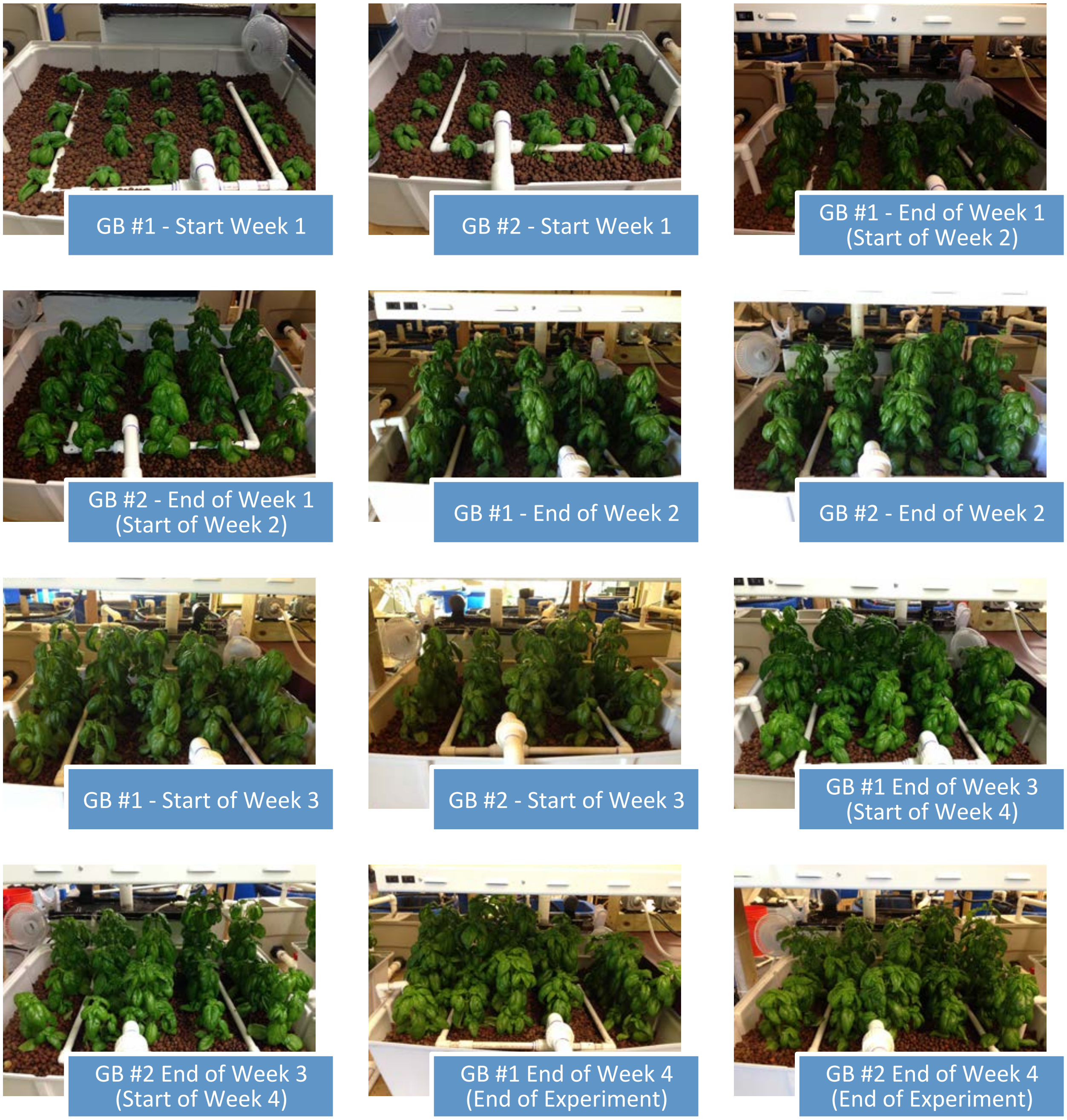
Feeding log

Date:	Day:	1st	2nd	Total feed:	Pellets: Dark/Light
4/5/2014	Sat	1.7	1.7	3.4	D
4/6/2014	Sun	1.7	1.7	3.4	L
4/7/2014	Mon	1.7	2	3.7	D
4/8/2014	Tue	1.8	0	1.8	L
4/9/2014	Wed	1.7	1.7	3.4	D
4/10/2014	Th	1.7	1.9	3.6	L
4/11/2014	Fri	1.8	1.7	3.5	D
4/12/2014	Sat	1.8	2.5	4.3	L
4/13/2014	Sun	4.2	4.8	9	D
4/14/2014	Mon	4.0	4	8	L
4/15/2014	Tue	4.0	4	8	D
4/16/2014	Wed	4.1	4	8.1	L
4/17/2014	Th	4.0	5.3	9.3	D
4/18/2014	Fri	4.0	4	8	L
4/19/2014	Sat	4.0	4	8	D
4/20/2014	Sun	4.0	4	8	L
4/21/2014	Mon	4.1	4	8.1	D
4/22/2014	Tue	4.0	4	8	L
4/23/2014	Wed	4.1	4.1	8.2	D
4/24/2014	Th	4.2	4.1	8.3	L
4/25/2014	Fri	4.2	4.5	8.7	D

4/26/2014	Sat	4.3	4.2	8.5	L
4/27/2014	Sun	4.1	4.3	8.4	D
4/28/2014	Mon	4.0	4.6	8.6	L
4/29/2014	Tue	4.5	4.3	8.8	D
4/30/2014	Wed	4.6	4.5	9.1	L
5/1/2014	Th	4.6	4.5	9.1	D
5/2/2014	Fri	4.5	4.5	9.0	L
5/3/2014	Sat	4.5	4.6	9.1	D
5/4/2014	Sun	4.7	4.5	9.2	L
5/5/2014	Mon	4.6	4.9	9.5	D
5/6/2014	Tue	4.6	4.7	9.3	L
5/7/2014	Wed	4.7	4.7	9.4	D
5/8/2014	Th	4.0	4.6	8.6	L
5/9/2014	Fri	4.5	4.3	8.8	D
5/10/2014	Sat	4.6	4.5	9.1	L
5/11/2014	Sun	4.6	4.5	9.1	D
5/12/2014	Mon	4.5	4.5	9.0	L
5/13/2014	Tue	4.5	4.6	9.1	D
5/14/2014	Wed	4.7	4.5	9.2	L
5/15/2014	Th	4.6	4.9	9.5	D
5/16/2014	Fri	4.6	4.7	9.3	L
5/17/2014	Sat	4.7	4.7	9.4	D
5/18/2014	Sun	4.0	4.6	8.6	L

APPENDIX D

Figures


GB #1 - Start Week 1

GB #2 - Start Week 1

GB #1 - End of Week 1 (Start of Week 2)

GB #2 - End of Week 1 (Start of Week 2)

GB #1 - End of Week 2

GB #2 - End of Week 2

GB #1 - Start of Week 3

GB #2 - Start of Week 3

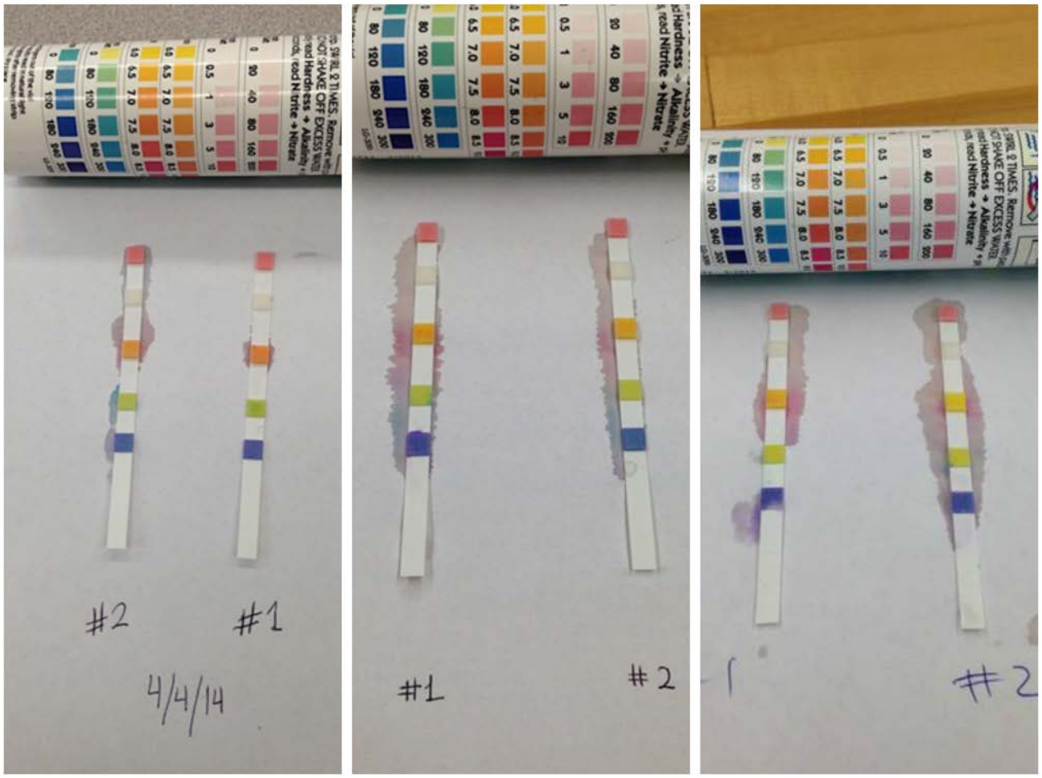
GB #1 End of Week 3 (Start of Week 4)

GB #2 End of Week 3 (Start of Week 4)

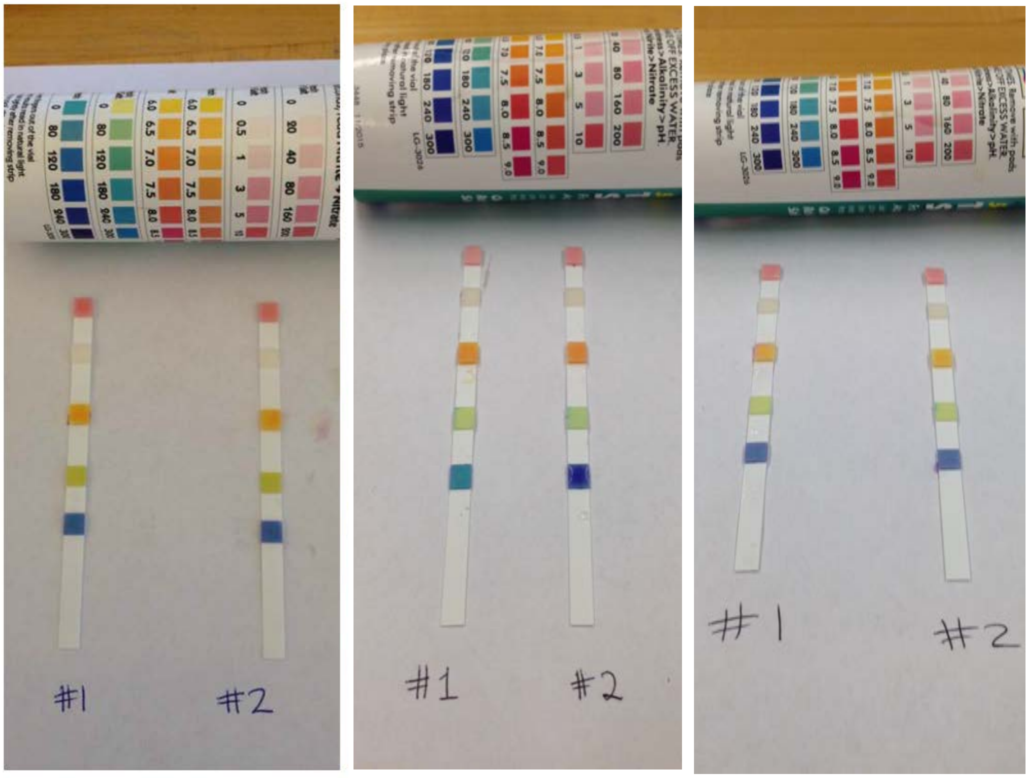
GB #1 End of Week 4 (End of Experiment)

GB #2 End of Week 4 (End of Experiment)

D 1: Pictures of the plants in both grow beds throughout the experiment.



D 3: Water quality strips representing the water quality in the systems in the beginning of week 1, week 2, and control period, respectively.



D 2: Water quality strips representing the water quality in the systems in the beginning of week 3, week 4, and at the end of experiment, respectively.