Sustainable Backyard Gardening: An Investigation into the Feasibility of Implementing a Small-Scale Aquaponic System for Household Consumption.

By
Mack Johnson
University of Colorado at Boulder

A thesis submitted to the
University of Colorado at Boulder
in partial fulfillment
of the requirements to receive
Honors designation in
Environmental Studies
December 2016

Thesis Advisors:

Paul Lander, Geography Department, Committee Chair
Dale Miller, Environmental Studies Program
Pete Newton, Environmental Studies Program

Table of Contents

Contents

Abstract

Aquaponic food systems have been gaining popularity over the last decade for their ability to simultaneously produce fish and vegetables within the confines of a single standalone system. Throughout the United States and Australia, organizations have implemented aquaponics on a large-scale for community food gardens. Most studies in this field focus on input requirements, productivity, and economic benefit of commercially-sized aquaponic systems. Little has been done on the opposite end of the spectrum, the personal, home-sized system and its potential to supply a family with low-cost food. This thesis investigates the feasibility of implementing a small-scale aquaponic system of <200 gallons for household consumption. Feasibility was assessed on cost, construction process including tools and materials, productivity, and maintenance requirements. It is hypothesized that small-scale aquaponics systems can be easily constructed and maintained to augment household food supply, and that the use of recycled materials can reduce the startup costs and increase the rate of return for the aquaponics implementer. Research included the construction of two common aquaponic systems, the first with plastic 55-gallon barrels using a design plan devised by Travis W. Hughey called barrel-ponics. The second, used an Intermediate Bulk Container (IBC) which acts as a grow bed and fish tank. Within both systems, tomatoes, bell peppers, jalapeno peppers, shishito peppers, kale, squash, and eggplant were grown. The fish species used to stock both tanks was Nile Tilapia (*Oreochromis niloticus)* with 20 in the IBC system and 5 in the barrel-ponic system. Over a three month grow period data was collected for productivity which included measurements of inputs, plant/fish growth and amount of produce harvested. Other factors that were analyzed included the construction process, cost to build and maintain each system, and the cost benefit of grown produce versus store bought produce. It was found that the IBC system was significantly easier to construct and maintain due it its simple design. The barrel-ponic system was cheaper and materials were somewhat more common although, there were many issues associated with its flood/drain system. At the observed level of productivity, both systems operating year-round would take several years to generate a positive return on investment. However, production trends were observed after the three-month period to continue to increase suggesting that a high output rate could be achieved and thus increase the rate of return. Small-scale aquaponic system such as these can be constructed relatively easily and maintained so long as there is access to informational documents, construction materials, reliable electrical grid, operational equipment, and adequate climate to support a yearlong grow season. Further research must be conducted on long term productivity levels for aquaponic systems at this scale as well as prices of materials to better determine the economic feasibility for household use.

Acknowledgements

I would like to thank my committee chair member Paul Lander for meeting with me regularly to discuss ideas and concepts for my project. I would also like to thank Pete Newton and Dale Miller for encouraging me to succeed and being available when I needed help. I could not have even started this thesis without the help from my Aunt and Uncle, Lynette and Phil, who so graciously allowed me to build these aquaponic systems in their backyard. Their curiosity and support for this project has enabled me to continue with more aquaponic experiments in the years to come. Lastly, I would like to thank my mother, father, and girlfriend Heather for their support throughout this whole endeavor.

Introduction

Sustainable agriculture has been defined as an environmentally safe way of producing food based off of three components: "plant and animal productivity, environmental quality and ecological soundness, and socioeconomic viability" (Neher, 1992). Food production is the basis upon which all other human needs are structured. Current food production methods must keep up with rising demands from population growth and in turn have steered away from the classic family farm and into large scale commercial operations. While these operations can produce enormous amounts of food, there are still households that experience some level of food insecurity. This occurs when a household is unable to acquire nutritionally adequate and safe foods (USDA).

Over the last thirty years, a food production method called aquaponics has been gaining popularity for its ability to sustainably produce fish and vegetables almost entirely in a closed loop system. Aquaponics utilizes the nitrification process of bacteria to provide a healthy growing environment for plants and fish within the same system, with inputs consisting of electricity, water, and fish feed. Throughout the United States and Australia, organizations have implemented aquaponics on a large-scale for economic purposes or community gardens. Most studies in this field focus on input requirements, productivity, and economic benefit of commercially sized aquaponic systems. Current research defines small-scale aquaponic systems as having a tank size of 1,000 liters and growing space of $3m^2$ (FAO, 2015). Little research has been done to understand the potential for small-scale systems with tank capacities of less than 1,000 liters to produce enough food to be considered economically viable.

This thesis project investigates the feasibility of implementing a small-scale aquaponic system defined for the remainder of this thesis as <1,000-liter tank capacity for household food production. Research for this project included the construction of two common aquaponic configurations; one size was 55-gallons with a 4.5 sq./ft. grow bed area and the other 150-gallons with 9 sq./ft. of grow bed area. Each system was stocked with Nile Tilapia (*Oreochromis niloticus)* and grew tomatoes, bell peppers, jalapeno peppers, shishito peppers, squash, kale, and eggplant. The systems were operated from June 5, 2016 to August 5, 2016 to represent a standard growing period. Both systems were monitored daily and data collected consisted of water quality, plant and fish growth, quantity of produce harvested by weight, and maintenance required. Other factors, such as access to materials and tools, cost of supplies, and level of difficulty of construction and maintenance, were also examined.

I hypothesize that small-scale aquaponics systems can be easily constructed and maintained to augment household food supply. It is also believed that the use of recycled materials can reduce the startup costs and increase the rate of return for the user. This study aims to expand the knowledge of small-scale aquaponic system construction and implementation for their potential benefit to food insecure households. The range of use for this study encompasses fellow college students, households of various economic status, professionals in any field regarding agricultural and sustainability practices, as well as any individual who is interested in sustainable food production methods.

Background

Aquaponics is a unique system that mimics the symbiotic relationship between plants and fish found in natural ecosystems. It is a combination of aquaculture, raising fish in tanks, and hydroponics, the production of plants in a solution of nutrient rich water. Wastewater from the fish tank is cycled through bio-filters, plant grow beds and then back to the fish tank. The bio-filter is the first stop for the water as it removes any solid waste particles. Next, media in the grow bed housing nitrifying bacteria converts the dissolved wastes from ammonia to nitrate and then nitrate, a more accessible nutrient for plants (FAO, 2015). As the water moves through the grow bed, plants uptake key nutrients and the water is returned back to the fish tank with reduced concentrations of ammonia and nitrite. Since the system operates as a closed loop, the enriched water from excess nutrients does not need to be exchanged for fresh water, as would be done in tradition aquaculture systems. This greatly increases the efficiency, allowing for less than 2% of daily water exchange and a sustainable repurpose of wastewater (Rakocy, 2012). It is this cycling process that allows fish, plants, and bacteria to simultaneously live in a healthy environment.

This concept has been around for thousands of years with some of the first examples found in southeast Asia where rice was grown in wet fields that contained fish (Turcious and Papenbrock, 2014). It was not until the 1970s-1980s that aquaponic research began to move forward. Eventually, in the late 1980s Dr. Mark McMurtry created the first closed-loop aquaponic system called the aqua-vegeculture system (Al-Hafedh et al., 2008; Love et al. 2014). Since then James Rakocy has been the most notable pioneer for modern aquaponic research and development with his team at the University of Virgin Islands (Ako, 2014).

Aquaponics is most commonly used, and may be most useful, in areas of water scarcity, nutrient deficient soils, and where growing space is limited. Current applications of aquaponic systems range from micro-sized systems to full-scale commercial systems. There has also been an increase in the educational use of small and large aquaponic systems. The hands-on nature of aquaponic construction and maintenance provide a unique learning experience for elementary schools, high schools, universities, and continuing education classes. These classes are aimed at connecting general populations to sustainable agricultural practices and empowering them to producing their own food. Humanitarian aid projects have begun to adopt aquaponics as a way to improve food security in urban settings. The Food and Agriculture Organization of the United Nations (FAO) implemented a pilot program in Israel's Gaza Strip and West Bank in response to food security crises seen in that area (FAO Aquaculture Newsletter 50, 2012).

Literature Review

Aquaponic System Structure

There are several variations for an aquaponic system to be constructed, each with their own strengths and weaknesses. While there are no specific guidelines on how to build a system, the concept can be broken down to five types which include: Nutrient Film Technique (NFT), Vertical system, Media based system, Deep Water Culture (DWC), and Wicking bed system (Datta, 2014). For this review, only the NFT, DWC, and media based systems will be analyzed, as they are the most widely used commercially.

The NFT technique is one in which plant roots are partially submerged in a V-shaped gutter with a thin layer of running water moving through. This system requires little effort to maintain, less initial startup costs, as well as significantly less water than the other two systems. However, the decreased amount of water lowers the plant yield and can cause the system to be less stable (Goddek et al.,2015). The DWC is where rafts with special pockets for the plants are placed on the surface of the water, allowing for the roots to become suspended in the water flow. This makes it easy to maintain, provides a constant flow of water, and a large amount of root surface area is exposed to the nutrient flow. Disadvantages are the large amount of water, increased infrastructure, and limit on types of plants able to have roots submerged (Danaher et al., 2013; Datta, 2014). The media base model is where a grow bed is filled with porous gravel and periodically flooded and drained. This system is commonly used for backyard aquaponics as opposed to commercial use because of its inefficiency to distribute nutrients equally in a large bed (Goddeck et al., 2015). The use of Deep Water Culture (DWC) and Nutrient Film Techniques (NFT) seem to be the most adaptable for large-scale production systems.

A wide range of vegetable types can be grown using recycling aquaculture techniques and a decent variation of fish depending on where the system is located (Rakocy, 2012). The most common type of fish production is tilapia, catfish, and ornamental fish such as Koi or goldfish. They are adaptable and can handle greater variation in temperature and pH level than most other fish. As for vegetable produce, the list is extensive with the most common including: lettuce and other leafy greens, tomatoes, herbs, peppers, and beans (Rakocy, 2012).

Productivity and Efficiency

Aquaponic systems use far less water when producing 1 kilogram of meat than traditional methods of farming, recycling up to 98% of the initial water. With aquaculture being the fastest growing sector of animal production, the incorporation of aquaponics into this sector can help to alleviate increasing water demands and environmental degradation (Klinger & Naylor, 2012). Aquaponic productivity is dependent on several factors including the size of operation, finding the optimal growing environment for fish, plants, and bacteria, and the correct ratio of fish to plants. Balancing these factors will ensure a productive yield from the system (Tyson et al., 2011).

An efficient aquaponic system must be sized correctly so that the nutrient production from fish is balanced with the amount of nutrient uptake by plants (Buzby & Shin Lin, 2014). Too much nutrients and the plants will be unable to successfully filter all of the waste, not enough nutrients and the plants will not have the correct amount for healthy growth. Optimal ratios have been reported to be based off of fish feed ratio per day to square meter of plant grow bed area (Goddek et al., 2015). This can vary from system to system based on the type of fish, plant type and age, and frequency of feeding. A rate of 50-100g per square meter has been accepted by several studies, although specific rates are difficult to quantify (Rakocy, 2012).

Several plants have been shown to have high nutrient uptake capabilities such as water spinach, tomatoes, and eggplant. These plants require larger systems than herbs and leafy green plants, but can reduce levels of ammonia, nitrogen, and nitrite 78.32-85.48% and 82.93-92.22% (Enduta et al., 2011; Gabber & Junge, 2009). Alternatively, for increased productivity of fish culture, rye, barley, and oat can be grown and subsequently used as fish feed. These grains produce favorable levels of proteins and carbohydrates necessary for fish growth. The addition of fats and minerals is needed in order to have a productive fish feed. This combination can be set up to increase fish yield, while still maintaining the closed system (Ghaly et al., 2005).

A key factor for an aquaponic system to function properly is healthy nitrifying bacteria. Otherwise known as biofiltration, these microbes perform optimally at temperatures of 25-30C and a pH range of 6.0-9.0(Lam et al., 2015; Lennard & Leonard, 2004; Rakocy, 2012). In climates where temperature is not constant, aquaponic systems must be contained indoors so that temperature can be controlled. Nitrification is an acid producing process so an alkaline base must be added to keep pH levels safe for bacteria and fish.

Large Scale System Studies

A case study in New South Wales, Australia used the effluent from Barramundi aquaculture to fertilize lettuce production. The current aquaculture system was able to produce 40,000 kilograms of Barramundi and integrated a 550 square meter lettuce grow bed able to produce 220,000 lettuce plants annually. The incorporation of hydroponic lettuce was able to reduce the cost of effluent disposal and provide a secondary means of income (Rupasinghe & Kennedy, 2010). Analysis of the net present value of returns showed it to be a profitable system. However, the rate of return was highly sensitive to the price of lettuce and Barramundi. When Barramundi market prices rose or fell 20% the net present value increased 123% or dropped 123%. This sensitivity must be considered when scaling up aquaponic systems for commercial use (Rupasinghe & Kennedy, 2010).

Another case study from the University of Hawaii investigated three local aquaponic farms and found them to all be profitable. The labeling of organic or aquaponic grown food was able to increase the price of goods. Of course, as with the previous study, there were variables that could reduce profit and or complicate the system. The farms required high operational cost such as labor and electricity. More importantly was the risk of total crop failure due to pests or disease, but the study concluded that aquaponic systems were commercially feasible in local markets (Ako et al., 2013).

The most famous commercial-scale aquaponic unit was developed at the University of the Virgin Islands. Red tilapia and leafy greens were efficiently produced at a commercial level. Larger operations were shown to have high returns and less risk of complications when compared to the smaller units (Rakocy, 2000). There is a necessity for more comprehensive research on large-scale commercial aquaponic systems, mainly on systems that are not in tropical regions. If commercial aquaponics is going to evolve into more markets, studies must be done to assess the viability of using aquaponics in different regions.

Small Scale System Studies

The Food and Agriculture Organization of the United Nations released a technical paper in 2015 that extensively summarizes the various components of small-scale aquaponic systems. It is focused as a resource paper so that it may describe and discuss major concepts in aquaponics to a wide range of individuals and organizations (FAO, 2015). It also provides supplemental appendices that cover more in-depth topics such as fish and plant diseases with potential remedies, calculating stocking density and ammonia production, and building guidelines for the three main types of aquaponic systems NFT, DWC, and media bed (FAO, 2015). This technical paper has become a very useful resource for my system maintenance, water quality parameters, and general monitoring of plant/fish health. The paper only briefly discusses cost benefit analysis of a small-scale system with a tank volume of 1500L and is based off of a mature system functioning for 12 months at maximum capacity. It also defines the term “small-scale” for aquaponics as a system with a 1,000L or more fish tank volume. Whereas the scale for this project is defined as being 500L or less for fish tank volume.

Methods

Research for this thesis included the construction, maintenance, and data collection of two different small-scale aquaponics systems. The media bed technique using a flood drain system was chosen because of its simplicity and built in bio filter. The first was a 50-gallon fish tank with a 4.5 Sq./ft. grow bed area, the second was a 150-gallon fish tank with a 9.5 Sq./ft. grow bed area. Both systems were stocked with Nile Tilapia (*Oreochromis niloticus*) and produced tomatoes, squash, eggplant, green bell peppers, jalapeno peppers, shishito peppers, and kale. Data collection for each system consisted of both quantitative and qualitative techniques.

System Construction

Below is a brief overview of each systems construction process and related components. More detailed information on the construction process and photographs can be found in appendix 3 and 4, as well as the links provided in those sections.

IBC system

The use of Intermediate Bulk Containers (IBC's) for aquaponics has become one of the most common ways in which a system is constructed. They are relatively cheap, structurally strong, readily available worldwide, and have numerous blue prints online for various system designs. For this thesis, I have chosen to use one food grade 275-gallon tote for both the grow bed and fish tank. This configuration allows for the grow bed to sit above the fish tank, allowing for the spatial footprint to be reduced and to harness the force of gravity for drainage into the fish tank. The media bed is constructed by cutting the top third of the tote off and placing it in the base support so that it can sit above the remaining tote and metal frame (Appendix 3).

The water flow for this system uses a bell siphon which is composed of three pipes, increasing in size from 1" to 2" and then 4". The first pipe is called the stand pipe and this is the part where water flows into from the grow bed. The length of this pipe determines the max water level for the grow bed. The second pipe, called the bell, sits over the stand pipe with a cap on the top to form an air tight seal at that end. Slits are cut on the bottom to allow for water to fill the inside of the bell pipe and into the stand pipe. The third piece of piping is called the media guard and it's positioned around the two smaller pipes to prevent any media debris from clogging the siphon.

The siphon works by utilizing pressure differences exerted on water in the grow bed. As the water level rises to begin draining into the stand pipe, air pressure outside of the siphon pushes down on the water forcing air out of the stand pipe and creating a vacuum. Once the vacuum is created the pressure difference quickly sucks the water up the bell pipe and into the stand pipe where it drains into the tank below. As the water drains to the level of the slits on the bell pipe air is able to enter the siphon, breaking the vacuum seal and stopping the flow of water. This whole flood/drain cycle in completed 6-10 times an hour, 24 hours a day.

Barrel-ponics system

For this aquaponic system I chose to use a method devised by Travis W. Hughey who appropriately named it “Barrel-ponics”. The system is comprised of three plastic 55-gallon barrels which are used as the fish tank, grow beds, and reservoir tank. These barrels are just as common, if not more so, than the IBC totes and can be purchased for much less. Since this system does not have the modular properties of the IBC, a wooden support frame was built to house each barrel component. The barrels were halved to form the grow beds and a single barrel was placed on its side and buried into the ground about half way to help reduce the amount of temperature fluctuation. An opening was made on its unburied side for access to fish, pumps, and monitoring components (Appendix 1&2).

This system also used gravity to initiate the flood/drain cycle, but used a reservoir barrel to fill and then completely drain into both grow beds. A barrel was cut in half and mounted on the wooden frame roughly 6” above the grow beds. A standard toilet valve was mounted to a counter weight that would begin to fill once the water in the reservoir reached a certain level. The counter weight was made out of a plastic bottle and had a small drainage hold in the bottom where the cap was. This weight would slowly drain as the reservoir drained and when emptied would close the seal initiating another flood cycle.

The grow bed drainage for this system did not use a bell siphon, but instead a simple drainage pipe which lay beneath the grow bed media. This pipe was 1/3 the length of the grow bed and was covered by a media guard so that debris would not clog the system. The total amount of water in the reservoir estimated to be 20-25-gallons was enough to fill both beds 1-2” below the top layer of clay media so long as the counter weight drained properly and the seal was re-established within the reservoir. From the grow beds the water is drained back into the fish tank using several elbow attachments (Appendix 4).

System Set Up

After construction, both systems were filled with water and grow bed media so that the cycling process could begin. This involved running the system without any inputs for one week so that any plumbing issues could be resolved. Next, 100% ammonia was added to the fish tank and cycled for another week. Naturally, the ammonia would take several weeks to be broken down by the nitrifying bacteria colony growing in the media. Instead, live bacteria culture was purchased from a fish store to speed up this process. Once ammonia and nitrate dropped to below 1ppm and the pH was at a range between 7-8 plants were added to the system. Plant seedlings were acquired from Sunbeam Farms in Boulder County and a local hardware store. The roots were washed of dirt and then transplanted 6" apart in the grow beds. The next day tilapia was added to the system. Due to time constraints the tilapia used in this study were juvenile to intermediate with sizes ranging from 3-5". They were sourced through aquaponic practitioners through craigslist and aquaponic discussion boards.

For this research, the media bed technique was used as it is common among aquaponic enthusiasts and beginners alike for its simplicity and low cost. The design consists of a grow bed filled with light expanded clay aggregate (hydroton) or any porous rock. The media plays two important roles for the aquaponic system; by supporting root structures and providing a surface for nitrifying bacteria to grow as well as acting a bio-filter for the water to become purified. Water is pumped from the fish tank and into the grow bed on a flood drain cycle. The use of a bell siphon allows for this cycle to function without timers or multiple pumps.

System Maintenance

Maintenance and monitoring were split into daily, weekly, and monthly tasks based on their level of importance. Daily tasks required feeding the fish once in the morning and once in the evening. For the IBC system the fish were given 20 grams of feed each time and the barrel-ponic system was given 8 grams. Other tasks included checking the function of heaters, submersible pumps, aeration pumps, and removing unwanted debris in the grow bed and fish tank. During the first month, water quality tests were taken on a daily basis to monitor the nitrification cycling process. These tests measured pH levels, ammonia, nitrite, and nitrate in parts per million (PPM). Once nitrite and ammonia levels became more stable around 0 ppm water quality tests were then taken once per week.

Other weekly tasks included the addition of water to the fish tank which was lost due to evaporation and transpiration, averaging 5 gallons per week for the IBC system and 5 gallons every two weeks for the barrel-ponic system. Fish tanks and plumbing systems were cleared of debris and excess effluent build up to ensure the desired flow rate was maintained. This is especially important for the barrel-ponic system because roots are able to move into the drain outlet pipe and cause blockages. Plant growth was recorded every two weeks and any harvestable produce was collected then weighed. Water quality measurements were taken once a week after the first month as listed above.

Monthly tasks consisted of thoroughly cleaning out the submersible pumps and for the IBC system, checking that the flow rate still initiated the bell siphon. Harvestable fish were taken out and processed. Lastly, plants that were finished with their harvestable stage were removed and a new plant was transplanted.

Data Collection

Qualitative data collection for this project consisted of daily observations of each system using field notes and photographs to record changing characteristics of plants, fish, water, and other miscellaneous phenomena throughout the three month grow period. Plant and fish observations detailed color, physical response to their environment, behavioral characteristics, and quality of produce yield.

Quantitative data that was recorded for this project included weekly measurements of plant growth, fish growth, weight of harvested produce and water quality tests. The water quality tests were taken in ppm for ammonia, nitrite, nitrate, and pH levels. During the cycling stage and first month of fish introduction these tests were conducted on a daily basis to record the change that occurs as nitrifying bacteria begin to colonize an aquaponic system. After ammonia and nitrite levels dropped to a safe concentration the tests were done twice a week till the end of the grow period as the system was stabilizing and did not need the constant monitoring. Costs associated with maintenance and materials were also recorded for analysis.

Results

Research results for this project consisted of plant and fish growth totals measured in centimeters for plants and estimated in inches for fish. Produce harvested for each system was recorded by weight in grams providing amounts for single harvests and overall totals for the three month grow period. Cost for each system was calculated using construction materials, operational equipment, and electrical costs.

Plant Growth

The graphics below document plant growth for both systems over a three month grow period. Tomatoes, squash, and bell peppers grew the fastest for both systems, while shishito peppers, jalapenos, and eggplant grew the slowest for the barrel system. Tomatoes quickly overtook space in both systems and had to be attached to bamboo stakes after the first month. The quick growth of tomato plants in the barrel system could be a reason for the lack of comparable growth for other plants. Tank size also is believed to be a limiting factor for plant growth observed with the barrel system. The optimal grow bed area to water volume of 1:1 was more successfully achieved in the IBC container than with the barrel system, which had a ratio closer to 2:1 (Bernstein, 2011).

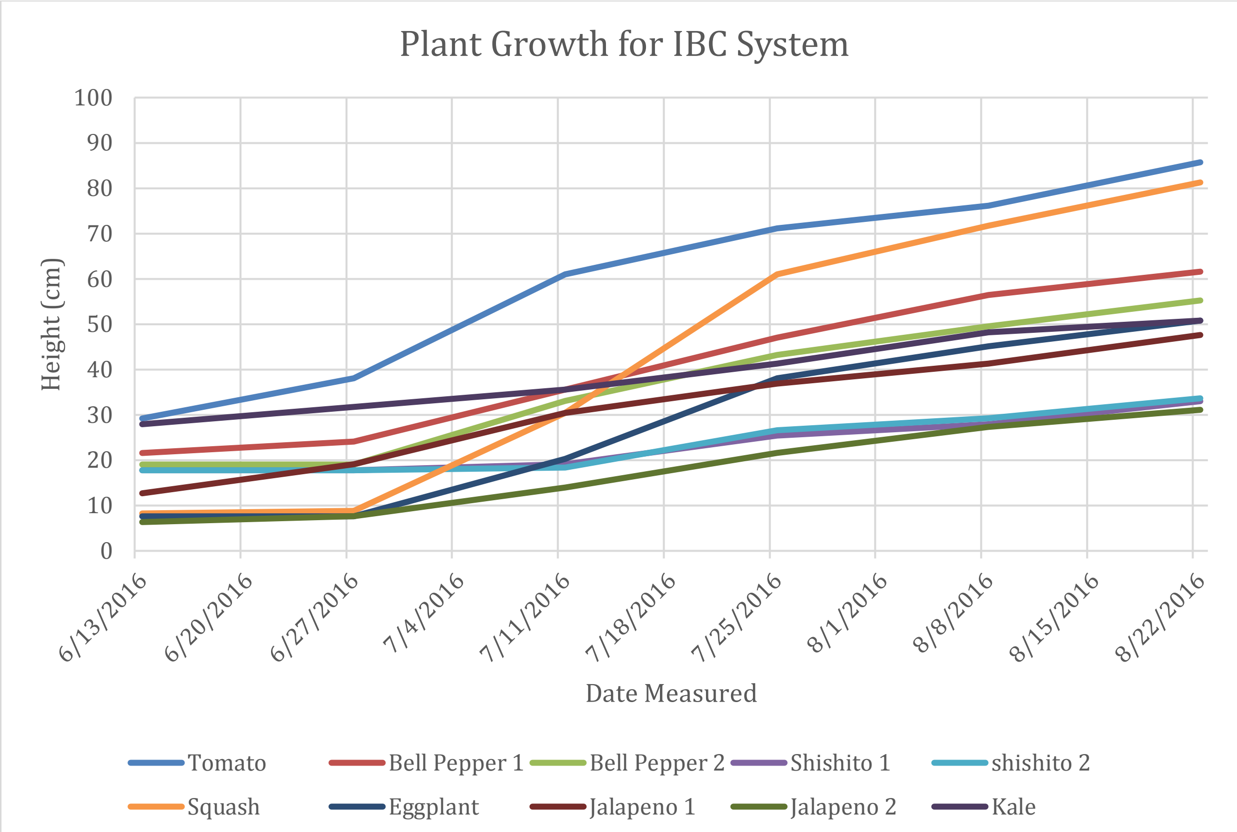

Figure 1. Displays the growth of plants over the three month grow period for the IBC system.

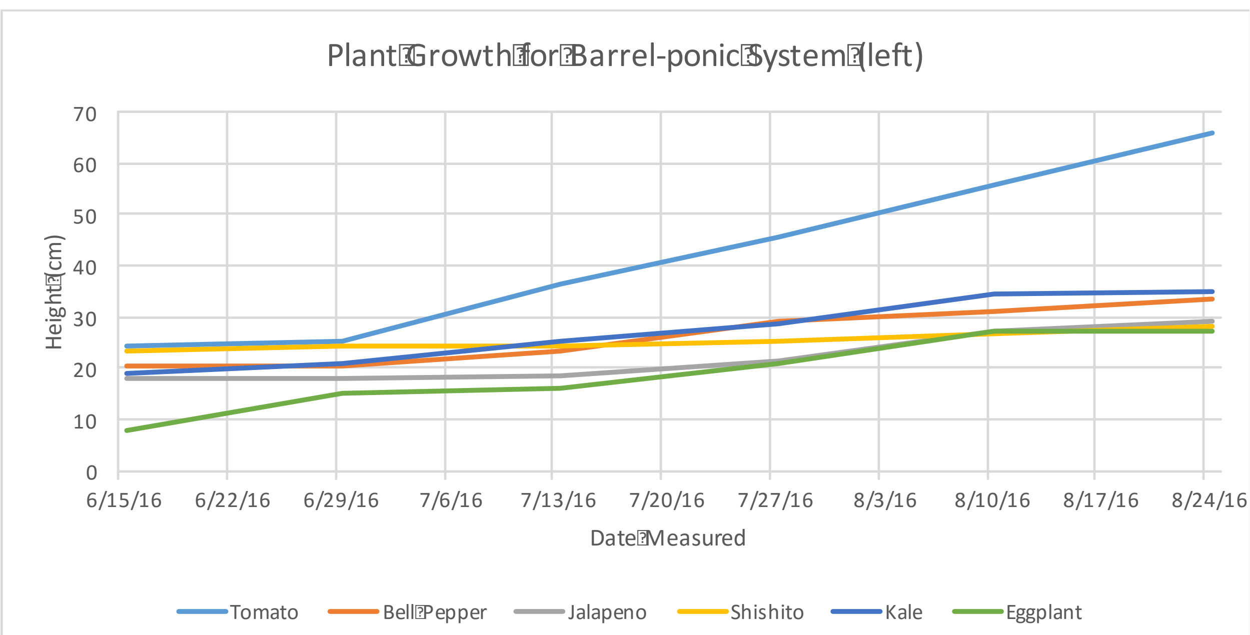

Figure 2. Displays the growth of plants in the left barrel grow bed over the three month grow period for the Barrel-ponic system.

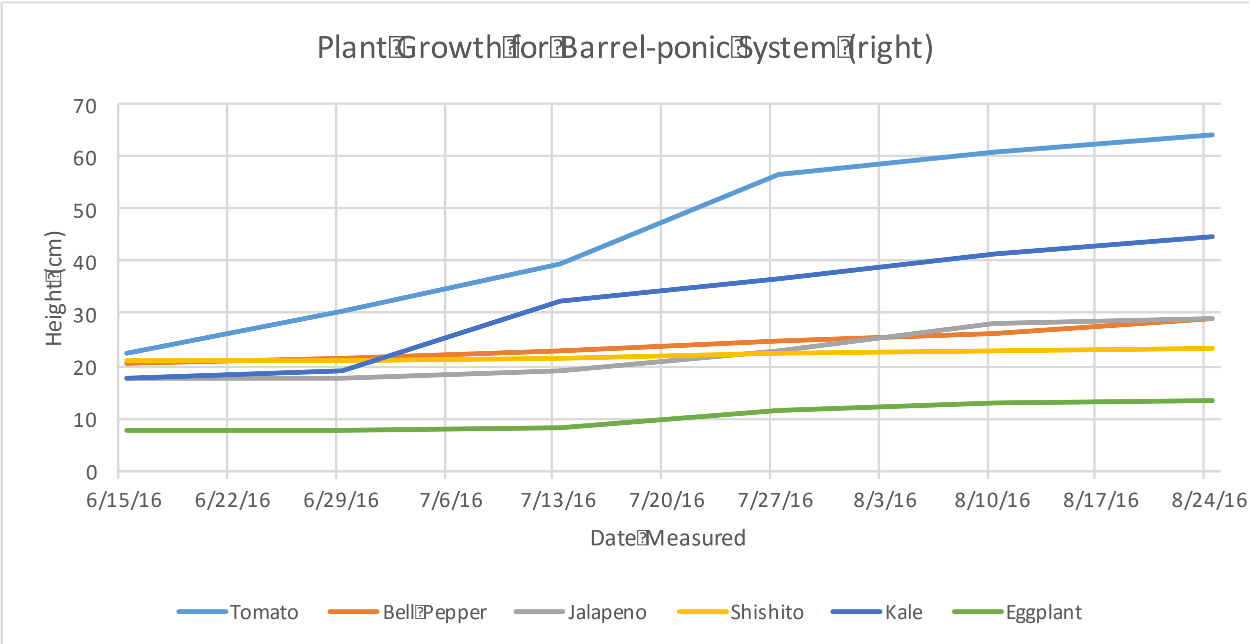

Figure 3. Displays the growth of plants in the right barrel grow bed over the three month grow period for the barrel-ponic system.

Fish Growth

Because of the scope of this research project as a feasibility report in addition to time and tool constraints, growth was not able to be successfully measured for each fish. The barrel-ponic system was easier to catch and monitor fish so average growth was able to be calculated for each fish. For the IBC system several fish were identified based on color and size (e.g. more pink/red, significantly smaller, more pronounced fins than others) were chosen as fish to be measured. From these specimens a rough average was able to be made. The fish were measured to grow between 2-3.5" in the IBC tank and .5-1" in the barrel system; accounting for roughly half their body length.

System Costs

The cost for each system was broken down into two categories, 1) the materials needed for construction, and 2) the tools required for monitoring and maintenance of the systems. Cost of tools needed for construction was not factored into the cost analysis because it is assumed that many of the basic hand tools are commonly found in households (e.g. screwdrivers, scissors, measuring instruments). As for power tools, it is recommended that individuals look into ways to rent/borrow the more expensive tools required for these builds. The frame materials for the barrel-ponic system are acknowledged; however, this component can be constructed in various ways from relatively easy and inexpensive to complex and costly.

Electricity consumption from the heater, submersible pump, and aeration pump was estimated using the price paid at the site location of 14.3 cents per kilowatt-hour. It is hard to obtain an exact figure for the cost of electricity consumed by each system. The heaters operate by turning on when water temperature falls below the selected setting. It was estimated to be functioning for 8 hours a day with its must demanding time at night when air temperatures dropped; this is a relatively high approximation. The submersible pump and aeration pump ran 24 hours a day but, they work on a low wattage. With these parameters calculated it was found that it costs approximately $7.00 a month to operate the barrel system and $12.00 for the IBC system.

Table 1. Shows the price of parts required for complete construction of an IBC aquaponic system with each items cost averaged to produce a low and high total cost. Maintenance item costs are added to produce a final low to high total.

1 Intermediate Bulk Container (food grade)	$120.00
1 550gph submersible pump	$33.00
Aeration pump	$25.00
1 1.5" bulk head fitting with O-ring	$3.50
1 300watt submersible water heater	$16.00
1 1" x 10' PVC pipe	$4.00
6' of ¾" black vinyl tubing	$7.00
6' of 3/16" clear tubing	$10.00
6 90 degree PVC 1" elbows	$4.50
1 1" threaded PVC elbow to barb	$3.25
1 12" x 2" PVC pipe	$3.00
1 2" PVC pipe cap	$2.00
1 24" x 4" PVC pipe	$6.50
1 4" PVC pipe cap	$3.00
8 50L bags of Hydroton or other grow bed media	$25-30 per bag = $200-$300 (Other media type such as pea gravel $60-100 for similar amount)
Total Amount	$340.75 (with pea gravel) $540.75 (with Hydroton)
Total Amount with maintenance materials	$437.75-$671.75 (low end – high end)

Table 2. Shows the price of parts required for complete construction of a Barrel-ponic aquaponic system with each items cost averaged to produce a low and high total cost. Maintenance item costs are added to produce a final low and high total.

3 55-gallon plastic barrels (food grade)	$20.00 each = $60.00
1 250gps submersible pump	$25.00
Aeration pump	$10.00-$25.00
6' of ¾" black vinyl tubing	$7.00
6' of 3/16" clear tubing	$10.00
2 10'x1" PVC pipe	$8.00
1 36" x ¾" PVC pipe	$5.25
2 36" x ½" PVC pipe	$12.00
2 black irrigation tube liners	$8.00
6 ½" PVC elbows	$4.50
4 ½"conduit lock nuts	$4.00
4 ¼" conduit lock nuts	$4.00
1 12"x ¼" Pex tubing	$6.00
1 1" PVC "T" fitting	$1.50
3 1" elbows	$3.50
1 1-1/2" to 1" male adapter	$2.25

4 50L bags of Hydroton or other grow bed media	$25-30 per bag = $100-$120 (Other media type such as pea gravel $30-$60 for similar amount)
Total Amount	$230.00 (with pea gravel) $290.00 (With Hydroton)
Total Amount with maintenance materials	$327.00 - $421.00 (low end – high end)

Table 3. Shows the price of items required for daily maintenance for either aquaponic system with an average low to high total.

Fish feed	$30.00 (Per Pound)
Freshwater test kit (with pH decreasing solution)	$22.00
Fish	$0-$2.00 (Varied on size and supplier)
Plants	Varies
Aquarium safe silicon sealant	$6.00
Black zip ties (10”)	$10.00
Fish net	$10.00-$20.00
Air Stone	$4.00 each
Plastic bucket	$5.00
Total Amount	$97.00-$131.00 (low end – high end)

Harvest Data

Table 4. Displays the date, amount, and weight of produce harvested from the IBC system.

June 13th (Transplant)	
July 11th (first harvest)	1 Bell pepper 56g
July 26th	6 Shishito 48g, 2 squash 786g
July 28th	6 Kale leaves ~58g (5-7in in length)
August 6th	3 Jalapenos 76.4g, 4 Kale leaves 32g
August 12th	3 Bell 222g, 1 Squash 244g, 3 shishito 23g
August 15th	1 Squash 242g, 6 Jalapenos 86.5g, 4 Shishito 24g, Kale 60g
August 22nd	2 Bell 40g, 1 squash 364g, 11 cherry tomatoes 63g
August 29th	22 Cherry tomatoes 156g, Kale 87g, 8 Jalapenos 113g, 2 Eggplant 432g, 8 Shishito 67g
September 1st	1 Squash 382g, 2 Bell 200.5g, 5 Jalapenos 80g, 16 Cherry tomatoes 124g, Kale 136g
September 5th	8 Jalapenos 176g, 17 Cherry tomatoes 112g, 1 Eggplant 248g
September 6th	3 Bell 186g, 14 Cherry tomatoes 101.5g, 7 Jalapenos 96g, 1 Squash 273g, 13 Shishito 253g, Kale 186.5g

Table 5. Displays the total amount of produce/fish harvested for the IBC and its corresponding total weight in grams.

Produce	**Total amount and weight (g)**
Bell pepper	10=704.5
Shishito pepper	34=415
Jalapeno pepper	37=627.5
Kale	6 (harvest)=559.5
Squash	7=2,071
Cherry tomatoes	80=556.5
Eggplant	3=680
Overall Total	5,614g or 12.4lbs.
Tilapia	2 at weights of 416g and 366g with an edible meat weight of 112g and 86g respectively.

Table 6. Displays the date, amount, and weight of produce harvested from the barrel-ponic system.

June 15th (transplant)	
July 26th (first harvest)	4 Shishito 38g
August 12th	2 Jalapenos 18g, 5 Shishito 44g, Kale 160g
August 22nd	1 Bell Pepper 33g, 4 Roma Tomatoes 214g
August 29th	2 Roma 86g, 6 Shishito 47g, Kale 281g, 3 Jalapenos 36g
September 1st	2 Bell Peppers 76g, 3 Roma 54g
September 5th	About 20-25 tomatoes on each plant that have not ripened yet

Table 7. Displays the total amount of produce/fish harvested from the barrel-ponic system and its corresponding total weight in grams.

Produce	**Total amount and weight (g)**
Bell pepper	3=109
Shishito pepper	15=129
Jalapeno pepper	5=54
Kale	2 (harvest)=441
Roma tomatoes	9=354
Eggplant	0
Overall Total	1,087g or 2.4lbs.
Tilapia	0

Discussion

The following section provide an in-depth analysis for each system. Factors that are analyzed include: overall system evaluation, construction process, cost benefit analysis, productivity, potential household benefits, challenges, and my personal experience throughout this project.

Evaluation of Systems

IBC

After constructing and maintaining this particular IBC aquaponic system it became evident as to why this technique is such a popular option for aquaponic enthusiasts. The benefits from its cubical shape and metal frame are numerous. These benefits include the larger water volume to surface area footprint, the metal frame's ability to support equipment (e.g. pumps, aerators, and thermometers), as well as the frame's support of the fish tank and grow bed. The construction process was much simpler than the Barrel-ponic system. The bisecting of the IBC material was manageable for a single person and did not require the construction of additional supports. This is a key factor when considering the potential range of use for this type of system. The use of a bell siphon, which initiates the drain cycle, eliminated the need for a pump timer. Additionally, the media guard component of the bell siphon prevented pipes from getting blocked by debris or roots growth.

However, there are a few elements of the IBC system that require precise adjustments for optimal performance. The flow rate of the submersible pump into the output pipes of the grow bed must be at a rate which is fast enough to activate the bell siphon, but not so great as to prevent it from shutting off. This can also be adjusted by shortening the downspout into the fish tank and allowing for more air to enter and break the bell siphon seal. Once the appropriate flow rate is perfected only then can the bell siphon operate without intervention.

Barrel-ponics

The Barrel-ponic system is a great way to construct a cheap and simple aquaponic system. Testing its functionality provides baseline knowledge for a novice practitioner on system design. However, there were several major issues that occurred during the testing of this system. First, the 55-gallon capacity of the fish tank was not enough to provide a stable environment for fish. When the reservoir barrel is filling, the water level in the tank drops to about 30 gallons and even more if the counter weight fails to open the drainage seal. The small amount of water leads to faster evaporation and plant uptake, requiring weekly additions of water to maintain the proper water volume. It is possible to fill the reservoir with extra water to increase the total amount, but this can lead to other risk factors such as the grow beds over filling. This can happen when drainage pipes become clogged and no longer drain at the desired flow rate. Edible fish also have a hard time growing in such a small space and thus make it impractical to choose anything other than fingerling sized fish. The small fish tank also makes water quality difficult to manage and susceptible to major fluctuations which could potentially kill fish.

Evaluation of Construction Process

The construction process was made easier because of the various tutorials and discussion boards available online. Step-by-step instructions for this experiment's construction process and links to sources used can be found in appendix 1 and 2. The IBC system was much easier to build and required fewer materials than the barrel system, in total taking roughly three hours to construct, while the barrel system required 8-12 hours. Both systems can be constructed by one person; however, it is recommended to have additional assistant when cutting materials. It is important to note that the use of barrels requires the construction of a frame to support the weight of the grow bed, fish tank, and reservoir barrel.

Materials used for this project were chosen to lower the initial startup cost as much as possible. IBC and plastic barrels are relatively cheap when compared to plastic water troughs or fish tanks of a similar volume. These materials can be sourced from container recycling centers or through online postings such as Craigslist.com. The materials listed in this study are by no means the only option. It is important to look on the container for documentation about what was previously stored inside. Typically, white and blue plastic containers hold non-toxic substances, while grey and black do not. In this experiment for example, the barrels once contained soy sauce and the IBC soft drink concentrate. All that is required is for the containers to be thoroughly washed out once they have been cut to size.

Site planning was necessary to determine the placement so that the system will receive an adequate amount of sunlight. If building a system on a balcony or roof top it is imperative to know the maximum weight the structure surface can support because water and grow bed media are extremely heavy, even at this scale.

System Costs Analysis

The cost of materials for construction of an IBC aquaponic system similar to the one for this project is estimated to cost between $437.75 to $671.75. The estimated cost for a three-barrel system similar to the one for this project is between $327.00 to $421.00. The prices are averaged to simplify the total amount as prices for parts and materials vary greatly. Grow bed media is the largest variable cost for both systems followed by the fish tank container and electrical equipment. Prices for fish and plants were not fully mentioned because of their high variability and low influence on total cost. The wooden support structure was roughly estimated as there are numerous ways to construct a support structure for the barrel-ponic system. Total build time for the IBC system was three hours and 8-12 for the barrel system when including a support structure. It is important to note that PVC parts, IBC tote, and blue plastic 55-gallon barrels have the ability to last for more than ten years as long as the plastic is not directly exposed to sunlight.

It is possible to decrease the total cost by using materials found at second hand hardware stores or households. By using a hybrid grow media of 50% Hydroton and 50% pea gravel costs can be reduced by $50-$100. One could completely eliminate Hydroton as the grow media with pea gravel and reduce total costs, but $100-$250. One slight drawback is that pea gravel weighs considerably more than Hydroton. Also, pea gravel does not have the same ratio of micro-pores to surface area as Hydroton which can decrease the amount of bacteria grow within the grow bed. More studied must be done to adequately determine if this is actually a significant factor for productivity in aquaponic systems.

Productivity

During the harvesting process and after when analyzing amount harvested, it was evident that some plants thrived more so than others in aquaponics conditions. Tomatoes, squash, bell peppers, kale, and jalapenos were the top producers as measured by weight. However, the squash began to lose it productive capacity towards the end of the experiment. The kale was also the only plant to be affected by Aphids, which greatly reduced its potential harvestable output. Shishito and jalapeno peppers in the barrel system were significantly less productive than their neighbors in the IBC. When the barrel system was deconstructed, the root system for the tomato plants extended along the entire length of the grow bed, far larger than any of the other plants. The nature of the tomato plant dominating the grow bed is believed to be a possible limiting factor for the productivity of other plants within the same grow bed.

It is recommended that large fruiting plants such as tomatoes, squash, and bell peppers be placed in the back of the grow bed container relative to the suns position overhead. This helps to reduce competition of sunlight between plants, as smaller fruiting plants are placed in front to allow for maximum exposure. It is also believed to be advantageous to plant vegetables with similar growth rates together so that nutrients are not restricted from slower growing plants.

The time from transplant to first harvest was surprisingly fast for both systems with the first harvest for the IBC and barrel system happening 28-31 days from the transplant date. The IBC system produced 4,527 more grams of vegetables than the barrel system. This can be attributed to the increase in size of both the fish tank and grow bed area.

Increased tank size allows for a larger number of fish to be supported and thus an increase in the amount of waste that bacteria can convert into plant available nitrogen. If Tilapia were replaced with a greater amount of smaller fish in the barrel system, then it could have been possible to see an increase in plant growth and productivity.

The most productive plants for the IBC system were squash and bell peppers with a total amount of 2,071 and 704.5 grams respectively, for the three-month period. The Barrel system was most productive with kale and tomatoes at a total harvest amount of 441 and 354 grams. The squash in the IBC system grew much faster than the same type which was growing in the neighboring soil garden. When analyzing the amount of vegetables and fish harvested to the average cost of each item at a local grocery store it is found that the barrel system produced $19.76 worth of vegetables during the grow period. The IBC system produced $56.46 worth of vegetables and $4.4 in Tilapia meat. If this level of productivity was maintained year round it would take 2-3 years to fully pay off the construction and maintenance costs. However, after the three-month data collection period ended, the systems were still operating and producing tomatoes and bell peppers at a faster rate than the month prior. Also, the fish harvested were on the smaller scale of what is an acceptable edible size. Tilapia are ready to harvest when they reach a weight of 1-2 pounds. I speculate that if grow rates were to continue to increase with the cycling of plants and fish within the system that it could become a positive investment for a household in less than 18 months.

Fish productivity was not as much as expected with only two fish growing to an acceptable harvest size of 9-12” or 1-2lbs. It was believed that since the fish used were already 3-6” in length; a significant proportion would grow to a harvestable size in 3-4 months. Within the barrel system the Tilapia had less room and seemed to be stressed by the water, temperature, and ammonia fluctuations. Tank size is believed to be responsible for the lack of significant growth within the barrel system. They would not instantly come to the surface to feed which was observed from the Tilapia in the IBC tank.

Personal experience

Building both systems was a rewarding process for me; while there were time of frustration and stress, the knowledge gained along the way was invaluable. Probably the most difficult aspect of this project was the fact that the experiment site was located 15 minutes away at my Aunt's house. This may not seem like much, but driving or biking there on an almost daily basis was taxing mentally and physically. Also, the fact that I could not quickly check water quality levels, temperature, and plumbing components made it difficult to address any serious issue that could arise. Therefore, I would recommend that domestic aquaponics facilities are built on-site, within easy access of the owner's residence. I do not think it would be a major inconvenience for a household to share the daily tasks required for maintaining such a system.

During this experiment the barrel system had a catastrophic failure when the weight did not successfully open the drainage valve. This caused the reservoir to fill to 35 gallons and begin to drain into the overflow pipe that was connected to the grow bed. Normally, this would be okay overnight, but the drainage pipes to the fish tank were also severely clogged with roots enabling it to drain efficiently. This ultimately led to large amounts of water being stored in the reservoir as well as some exiting the grow beds. When I arrived the next day, the water level in the fish tank was so low that about 3" that the pump was running dry. Fortunately, all the fish were still alive and I was able to fix the drainage issues and flow rate back to normal. Later that month, night time air temperatures dropped to 45 F and the heater in the barrel system was not able to maintain temperature above 68F. Two fish were killed by this and then the next week I moved the three remaining fish into the IBC and shut down the barrel system in the beginning of September to continue the grow period outside of the experiment.

During the experimental grow period I was amazed at the growth rate and output of the bell peppers and squash. It was impossible to distinguish a difference between the squash from the IBC system and squash from my aunt's soil garden, they were identical in appearance and weight. One difference was the rate at which squash were produced in the IBC system, in August there was at least one squash ready to harvest every three days. This made me consider what other vegetable options could be produced if I were to continue this in the following years.

Building and witnessing firsthand the successes and failures of these two aquaponics designs made me consider other ways to configure IBC totes and plastic barrels. Increasing the size of the fish tank, especially for the barrel-ponic system is a definite prerequisite for next year if I were to use the same design. While the IBC tote was productive at its scale, it would be interesting to increase volume of both the grow bed and fish tank by using additional IBC or barrels. I had finally understood what people on aquaponics discussion boards meant when they said, "once you start an aquaponic project it can become highly addictive" (Backyard Aquaponics).

Household Benefits

The most obvious benefit of a small-scale aquaponic system is the ability to harvest vegetables and fish stock, thus providing a sizable amount of carbohydrates and protein for household consumption. The quality of both food sources were extremely high and consistent throughout the growing period, which could easily be extended with a greenhouse enclosure. The aquaponic method allows efficient and repetitive use of a given amount of water in the production of virtually any vegetable or freshwater fish species. Overtime aquaponic food production would lower the total expenditures a household would normally spend at a traditional grocery store.

When contemplating the construction of an aquaponic system at this scale for household use it is important to understand some of the benefits and weaknesses associated with this system compared to a traditional soil garden. The most intimidating factor is the high startup cost for any aquaponic system. Other weakness of this system include a reliable access to an electrical grid, daily maintenance, optimal temperature range, and knowledge of the biological processes within the system. While a soil garden requires far less of a start-up cost and no electrical input there are benefits that cannot be attained from a soil garden alone.

Some of these benefits include high water efficiency, two product sources, no soil amendments, harvesting is less labor intensive, and these systems can be used in areas of soil degradation. The high efficiency of water use and lack of fertilizer inputs help to decrease the cost of maintenance when compared to a soil garden. Harvesting and daily monitoring can be done by almost all age groups within a household. The production of two different food groups can greatly benefit households where fish or vegetables are not commonly consumed especially in areas of drought. Additionally, growing interest into this field has produced numerous amounts of informational guidelines for starting and maintaining a successful aquaponic system. If the start-up cost, knowledge, input requirements, and optimal temperature range can be easily met by a household, then the benefits of operating an aquaponic system seem to be greater than a traditional soil garden.

A personal benefit of embracing the aquaponic method of food production, is the satisfaction of knowing all aspects about how the food was produced and an appreciation of the effort it takes for those who engage in this type of activity. Additionally, all members of a household would gain valuable knowledge in the areas of biological processes, plant and fish cultivation, and project development. Finally, all age groups within a household have the ability to participate during some phase of the aquaponic experience.

Challenges

Aquaponics design, construction, and management can become complex and overwhelming without knowledge of fish, bacteria, and plants. It can have high initial startup costs depending on how the system is constructed. It also requires constant access to a reliable electrical grid to power the pumps and aeration devices. The system must be monitored daily and any mistakes or accidents have the potential to cause a total collapse of the system. Climate is a large limiting factor and systems such as these should be constructed and operated in areas with little seasonal change with moderate to hot temperatures for optimal productivity and stability.

Recommendation

Further research is needed for long term productivity levels of aquaponic systems at this scale; based on initial startup and maintenance cost to determine its potential economic feasibility for an average household. An investigation into prices of materials used in this study in various regions of the world would help to identify the cost of such a system for various income-level households. It is also suggested that different types of vegetables and fish be tested at this scale in order to identify the most beneficial arrangement. Lastly, an in depth study on the cost-benefit analysis of an aquaponic system against a traditional soil garden of a similar scale would help to determine the economic feasibility of this system over conventional soil gardening.

Conclusion

After analyzing the construction process, the required operating procedures, and the productivity of both aquaponic systems, several important factors were discovered that help determine the feasibility of implementing a system of this scale for a household. These include: access to building materials and tools, prior knowledge about construction and aquaponic elements, appropriate amount of available space, regional climate, and sufficient monetary funds to complete the system.

The building materials in this study were chosen because they were easily accessible in Colorado and have the most documented use in the aquaponic practitioner community. These materials can be easily substituted for cheaper options for a particular region to expand implementation range. The design plans for both systems are offered as a downloadable PDFs and there are other numerous blueprints for similar designs. Access to the recommended tools may be the most difficult part of the construction process. While the power tools listed are common in many American homes, they may not be available to some households, so it can be expensive to purchase used ones. There are organizations such as Center for ReSource Conservations that offer tool libraries where individuals can rent out various power tools for a fraction of the cost of owning one. This can increase the incentive to start an aquaponic system if they will only be using the tools once during construction. Lack of knowledge about the various biological elements (plants, fish, bacteria) can be discouraging for individuals who wish to start their own small-scale system. However, as stated before, there is an abundance of information on the subject from aquaponic books such as *Backyard Aquaponics* and free documents online from professionals and hobbyists.

Limiting factors such as space and geographic location play the largest role for determining if a small-scale aquaponic system will work for a particular household. This study, for example, had to be dismantled because of dropping temperatures during the fall and winter season in Colorado. Erecting a greenhouse is one way to continue the growing season in cold climates, but it can be costly and the low level of light in the northern hemisphere winter season reduces productivity. Growing inside with artificial lights is a possibility and people do it, but the electricity costs with the productivity at this scale are just not economically viable. Small-scale outdoor systems would do best in regions with stable yearlong temperatures ranging from 70-90F and adequate sunlight more most of the year. Space is another important variable one must consider before building any size aquaponic system. The IBC and barrel-ponic systems are among the smallest designs capable of raising edible fish, but still have some limitations as to where they can be built. Water and grow bed media weight can become excessive, so balconies and rooftops must be carefully chosen to ensure they can support the weight. Backyards with open south facing skies seem to be the best options for outdoor use.

I believe that the estimated initial material investment for both systems to be on the higher end of the spectrum such that lower income families may have difficulty implementing a system. Paying $300-600 for plastic containers, pumps, and gravel may be too much of an expenditure for some households. There is also a need to have access to reliable sources for fish fingerlings and plant seedlings in order to keep the harvesting cycle continuing throughout the year. Given the productivity rate and amount of produce harvested during this three-month study it seems that the use of small-scale aquaponic system can be a promising way to produce nutritious food for household consumption. Reduced startup costs and access to materials would provide compelling incentives for a larger percentage of households to implement an aquaponic system of their own.

Appendix 1: Materials

IBC Tote System

- 1 275-gallon Intermediate Bulk Container
- 1 400 gallons per hour submersible pump with 6ft. of head (or larger)
- At least 6' of ¾" flexible black tubing for submersible pump (or size of pump outlet)
- 1 air pump 10 liters per minute (or larger)
- At least 6' of 3/16" clear tubing for air pump (or size of air pump outlet)
- 2 4" cylinder air stones
- 1 10' x 1" PVC pipe
- 1 24" x 2" PVC pipe
- 1 12-24" x 4" PVC pipe
- 1 2" PVC cap
- 1 4" PVC lid
- 6 1" PVC 90 degree elbows
- 1 1" PVC "T"
- 1 1" PVC threaded "T"
- 1 1" threaded barbed elbow
- 1 1" threaded bulk head fitting with rubber gasket on either side
- 1 1 ½" threaded coupling to slip fit
- 1 1 ½" to 1" reducer coupling
- 200-600 liters of grow bed media (Hydroton, river rock, volcanic rock, or mixture)

Barrel-ponics System

- 3 Food grade 55-gallon plastic barrels
- 1 80-250 gallons per hour pump with 5ft. of head
- At least 6" of ¾" flexible black tubing for submersible pump (or size of pump outlet)
- 1 air pump 10 liters per minute or less
- At least 6' of 3/16" clear tubing for air pump (or size of pump outlet)
- 1 4" cylinder air stone
- 1 10' x 1" PVC pipe
- 2 36" x ¾" PVC pipe
- 2 36" x ½" PVC pipe
- 3 1" PVC elbow
- 4 ¾" PVC elbow
- 1 1" PVC "T"
- 200-300 liters of grow bed media (Hydroton, river rock, volcanic rock, or mixture)
- Reservoir materials found in appendix 4 PDF link

Both systems

- Fish feed
- Freshwater test kit (with pH decreasing solution)
- Fish
- Plants
- Aquarium safe silicon sealant
- Black zip ties (10")

- Fish net
- Air Stone
- Plastic bucket

Appendix 2: Tools

- Angle Grinder with cutting wheel and grinding disk
- Power drill
    - ¼”, ½”, ¾”, 1”, 1 ½” bits (include other bits) (screw, circular bits…
- Miter saw or pipe cutter or hacksaw (pre-cut wood pieces or table saw required to build barrel-ponics frame)
- Safety glasses
- Exacto knife
- Flat or curved hand file
- Hammer
- Wood screws/wood nails (2-4”)
- Vice or table surface to hold piping
- Flat head and Philips screwdriver
- Tape measure, ruler and/or measuring string
- Pen
- Hose
- Sandpaper (optional)
- Weather resistant wood stain (optional)

Appendix 3: Step by Step IBC Construction

The first step is to remove the plastic tote from the metal housing, this may require the removal of metal cross beams on the top, usually they are held in place by several screws. Next, the metal frame and plastic tote must be cut to produce the grow bed. Cut the metal frame with a circular saw all the way around, directly above the first horizontal support, this way the base of the tote will act as a support for the grow bed. Next, Measure the height of the metal frame on the base section that was just cut, this will determine the depth of the grow bed. For my system I chose to cut the plastic tote 13 inches down from the top. Take this measurement and with a straight edge mark a cut line all the way around the tote. With the tote cut into roughly 1/3 and 2/3 sections it is time to wash the plastic. While the containers I used were food grade and previously contained agave nectar it is important to thoroughly wash out any remaining residue.

Next, unscrew the top lid from the grow bed section and place it in the middle of the base so that the opening is facing down; check to see that the grow bed is at the desired height. The top lid has a smaller inner opening with a 2 inch threading, a hole will be cut into the base where this smaller opening is so the pluming will exit to the fish tank. Use a 3 1/3-inch drill bit to cut a hole in the plastic of the base section. With this hole cut you will now be able to put together the plumbing components.

Plumbing requires the construction of the bell siphon, drainage pipe into the fish tank, and the input pipes on the top of the grow bed. The bell siphon uses four differently size PVC pipes which will need to be cut to these sizes: one 4” x 13-15” (this piece must be higher than the grow bed), one 2” x 11-12” (this is the bell part of the bell siphon and it should be 1-2” taller than stand pipe), last is 1”x 9-10” this is the stand pipe.

For the 4” x13-15” pipe holes/ slits must be drilled in alternating lines from the base to 9-10” up. To put this all together the stand pipe must be connected to the bulk head fitting which has been screwed into the lid of the IBC tote which now is facing down towards the rest of the fish tank. Once in, the stand pipe should sit 2-4” below the top of the plastic grow bed. Next the bell pipe is placed over the stand pipe and a 2”cap is places on the top end, this is what will create the vacuum to initiate the siphon. After that, the 4” wide pipe is placed over the bell and stand pipe. This acts as a media guard which allows water to flow through from the holes drilled into it previously while also preventing any media debris from entering and clogging the stand pipe.

At the other end of the stand pipe (side that faces the fish tank underneath) the drainage system will be connected. This includes a straight pipe about 8-10” extending down from the stand pipe opening. Next, a 1” elbow attachment is placed on to divert the flow horizontally. Next, a new pipe section is connected to the elbow, about 3” in length. After that, a 1” “T” is attached to the end of the previous pipe with the bottom of the “T” part facing upwards to the grow bed. This “T” section allows air to travel up the drainage pipe and disable the siphon action when the grow bed has almost drained completely.

Construction of the input pipes from the fish tank to grow bed is fairly easy. First, measure the inside perimeter of the grow bed. 1” PVC pipe is then cut for each side length with the exception of one side (the side of the IBC which you designate as the front). This piece must be cut in two sections about .5” shorter than measured because another 1” “T” attachment will connect them in the middle. This “T” attachment is where the tubing from the submersible pump connects to the whole structure via a 1” barbed to 1” slip on elbow. Elbows are placed on all the corners to connect the 5 pipe pieces cut above so that it forms a rectangle inside the grow bed. Next, ¼” holes must be drilled 1.5” apart on each straight section of this rectangular section. This is where water will exit into the grow bed.

After all of the cutting and plumbing assembly the IBC is now ready to fill with the media of your choice (Hydroton, pea gravel, river rock, etc). Once filled about 2” below the media guard fill the fish tank with roughly one third water to test the bell siphon. This is done by connecting the submersible pump to the input pipe and adjusting the flow rate of the pump so that the bell siphon will start and stop without any interference from you. Once the rate is dialed in the cycling process may begin followed by the addition of plants, fish, and the rest of the maintenance components. Further information on the construction of the IBC aquaponic system can be found at:

http://www.backyardaquaponics.com/Travis/IBCofAquaponics1.pdf

Appendix 4: Step by Step Barrel-ponic Construction

The first step is to begin cutting the barrels to form the fish tank, grow beds, and reservoir basin. On these plastic 55-gallon barrels there is a mold line which runs from the top, between the two barrel caps, all the way around the sides of the barrel. Lay one barrel on its side so the mold line and caps are parallel to the ground. Next, measure 6” from either end and mark this point, from these two points measure a straight line 6” above and below the point. Connect all of these points, this will create a rectangle, use the angle grinder with plastic cutting attachment to cut out this rectangle. This opening will act as the fish tank lid to provide access to the fish and operational equipment.

Next, the grow beds will be cut using one barrel. Identify the mold line and use this to mark around the entire barrel so that the line marked evenly splits the barrel into two halves. Have one person hold the barrel in place while another uses an angle grinder to cut the line previously marked. After this step, the drainage holes must be cut in the bottom of the barrel halves on the side without the cap. For further, more detailed, instructions please view the link below.

The reservoir basin is the last barrel to cut. Measure 15” from the top side which has the caps and from this point draw a line around the entire barrel. Once again, using the angle grinder cut along this line so that the barrel is split into one 2/3rd sections and 1 1/3rd section. The larger 2/3rd section is what will be used for the basin. After all the cuts are made take a file or low grit sandpaper to smooth out the cut edges. For more information on cutting and attaching the plumbing features for the reservoir basin, fish tank, and grow beds please view the link for Travis W. Hughey’s Barrel-ponic PDF.

http://www.aces.edu/dept/fisheries/education/documents/barrel-ponics.pdf

Bibliography

Ako, Harry., Clyde, Tamaru., Kanae, Tokunaga., PingSun, Leung. (2014). Economics of Commercial Aquaponics in Hawaii. 2014 World Aquaculture Society Meeting. Conference Paper.

Al-Hafedh, Y. S., Alam, A., & Beltagi, M. S. (2008). Food Production and Water Conservation in a Recirculating Aquaponic System in Saudi Arabia at Different Ratios of Fish Feed to Plants. *Journal of the World Aquaculture Society*, *39*(4), 510–520. http://doi.org/10.1111/j.1749-7345.2008.00181.x

Backyard Aquaponics Forum, http://www.backyardaquaponics.com/forum/

IBC of Aquaponics PDF - Backyard Aquaponics. (n.d.). http://www.backyardaquaponics.com/Travis/IBCofAquaponics1.pdf

Bernstein, S. (2011). Aquaponic gardening: A step-by-step guide to raising vegetables and fish together. Gabriola, BC: New Society.

Blidariu, F., & Grozea, A. (2011). Increasing the Economic Efficiency and Sustainability of Indoor Fish Farming by Means of Aquaponics - Review. *Scientific Papers Animal Science and Biotechnologies*, *44*(2), 1–8.

Buzby, K. M., & Lin, L.-S. (2014). Scaling aquaponic systems: Balancing plant uptake with fish output. *Aquacultural Engineering*, *63*, 39–44. http://doi.org/10.1016/j.aquaeng.2014.09.002

Danaher, J. J., Shultz, R. C., Rakocy, J. E., & Bailey, D. S. (2013). Alternative Solids Removal for Warm Water Recirculating Raft Aquaponic Systems. *Journal of the World Aquaculture Society*, *44*(3), 374–383. http://doi.org/10.1111/jwas.12040

Datta, Subhendu. (2014). Aquaponics – A Modern Tool for Integrating Farming with Agriculture. Central Institute of Fisheries Education. DOI: 10.13140/2.1.545.3766.

Enduta, A., Jusoh, A., Ali, N., & Nik, W. B. W. (2011). Nutrient removal from aquaculture wastewater by vegetable production in aquaponics recirculation system. *Desalination and Water Treatment*, *32*(1-3), 422–430. http://doi.org/10.5004/dwt.2011.2761

Ghaly, A. E., Kamal, M., & Mahmoud, N. S. (2005). Phytoremediation of aquaculture wastewater for water recycling and production of fish feed. *Environment International*, *31*(1), 1–13. http://doi.org/10.1016/j.envint.2004.05.011

Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K. V., Jijakli, H., & Thorarinsdottir, R. (2015). Challenges of Sustainable and Commercial Aquaponics. *Sustainability*, *7*(4), 4199–4224. http://doi.org/10.3390/su7044199

Graber, A., & Junge, R. (2009). Aquaponic Systems: Nutrient recycling from fish wastewater by vegetable production. *Desalination*, *246*(1–3), 147–156. http://doi.org/10.1016/j.desal.2008.03.048

Hughey, W. Travis. (2005) Barrel-ponics: Aquaponics in a Barrel. PDF.

Klinger, D., & Naylor, R. (2012). Searching for Solutions in Aquaculture: Charting a Sustainable Course. *Annual Review of Environment and Resources*, *37*(1), 247–276. http://doi.org/10.1146/annurev-environ-021111-161531

Lam, S. S., Ma, N. L., Jusoh, A., & Ambak, M. A. (2015). Biological nutrient removal by recirculating aquaponic system: Optimization of the dimension ratio between the hydroponic & rearing tank components. *International Biodeterioration & Biodegradation*, *102*, 107–115. http://doi.org/http://0-dx.doi.org.libraries.colorado.edu/10.1016/j.ibiod.2015.03.012

Lennard, W. A., & Leonard, B. V. (2004). A comparison of reciprocating flow versus constant flow in an integrated, gravel bed, aquaponic test system. *Aquaculture International*, *12*(6), 539–553. http://doi.org/10.1007/s10499-004-8528-2

Love, D. C., Fry, J. P., Genello, L., Hill, E. S., Frederick, J. A., Li, X., & Semmens, K. (2014). An International Survey of Aquaponics Practitioners. *PLoS ONE*, *9*(7), e102662. http://doi.org/10.1371/journal.pone.0102662

Love, D. C., Fry, J. P., Li, X., Hill, E. S., Genello, L., Semmens, K., & Thompson, R. E. (2015). Commercial aquaponics production and profitability: Findings from an international survey. *Aquaculture*, *435*, 67–74. http://doi.org/10.1016/j.aquaculture.2014.09.023

NEHER, D. (1992). ecological sustainability in agricultural systems - definition and measurement. Journal of Sustainable Agriculture, 2(3), 51-61.

Rakocy, James. (2012). Aquaponics Integrating Fish and Plant Culture. *Aquaculture Production Systems.*

Rakocy, J. E., Bailey, D. S., Shultz, K. A., & Cole, W. M. (2000). Development of an aquaponic system for the intensive production of tilapia and hydroponic vegetables.

Rupasinghe, J. W., & Kennedy, J. O. S. (2010). Economic Benefits of Integrating a Hydroponic-Lettuce System into a Barramundi Fish Production System. *Aquaculture Economics & Management*, *14*(2), 81–96.

Small-scale aquaponic food production. integrated fish and plant farming. (2015). FAO Aquaculture Newsletter, (53), 67.

Turcios, A. E., & Papenbrock, J. (2014). Sustainable Treatment of Aquaculture Effluents—What Can We Learn from the Past for the Future? *Sustainability*, *6*(2), 836–856.

http://doi.org/10.3390/su6020836

Tyson, R. V., Simonne, E. H., Treadwell, D. D., White, J. M., & Simonne, A. (2008). Reconciling pH for Ammonia Biofiltration and Cucumber Yield in a Recirculating Aquaponic System with Perlite Biofilters. *HortScience*, *43*(3), 719–724.

Tyson, R. V., Treadwell, D. D., & Simonne, E. H. (2011). Opportunities and Challenges to Sustainability in Aquaponic Systems. *HortTechnology*, *21*(1), 6–13.

USDA. Definitions of Food Security. http://www.ers.usda.gov/topics/food-nutrition-assistance/food-security-in-the-us/definitions-of-food-security/