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Mixed Methods Analysis of Two Inexpensive and Simple Aquaponics Systems for School Use

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ABSTRACT

Aquaponics is the conjoined farming of fish and plants in the same system. Researchers have found that aquaponics can provide many educational and nutritional benefits to schools such as educational opportunities and access to fresh food, but many schools lack the funds to build them (School Systems, n.d.). This finding from previous studies sparked this study's question: How Can a High School Student with Little to No Building Experience, Construct an Inexpensive and Reliable Aquaponics System for School Usage? To answer this question a convergent parallel mixed study was conducted, comparing the fish and plant growth, ease of maintenance, and construction of 2 different aquaponics systems, one of a raft design and another based on a pipe design. It was concluded that a pipe system would be better for schools, as it resulted in a better growth rate of both plants and fish, along with lower costs, easier maintenance and simpler construction.

Introduction

Aquaponics is a subset of the larger farming method of hydroponics, growing plants without soil. Aquaponics uses fish to provide fertilizer in the form of excrement (i.e. feces) as well as a food source for humans. Aquaponics is an ever-growing market and is gaining traction around the world as a way to effectively farm in small spaces (Shahbandeh, 2021).

This farming method has been around for most of human history in South East Asia, Africa and South America. They did this by building floating rafts on lakes where the roots of the plants would float in the water (Keeper, 2016). However, it is only in recent years that this method of cultivation is coming back into common use (Keeper, 2016). The idea behind aquaponics is to grow fish and plants together in a single system, with fish creating fertilizer for the plants (i.e. feces). This type of farming often uses fast-growing and hardy fish that also serve as food. In this way, two food sources can be created in one system.

Schools have been known to use aquaponics for food production, as a community project and learning piece (Rains, 2018). Unfortunately, not all schools have access to aquaponics due to the price and complexity that can come with maintaining such a system. Therefore, this study seeks a solution to address both the price and complexity issues schools face with aquaponics. The ultimate goal of this study is to provide schools with a sustainable, replicable, and cost-effective method for agriculture, food production, and education.

Literature Review

General Aquaponics Uses and Benefits

A study conducted by marine scientists in 2016 (Mamat et al., 2016) found that catfish aquaponics production is an effective and timely manner to cultivate plants and fish for consumption. Another study of carp and watercress growth in an aquaponics farm, found that all carp grew rapidly in just a few weeks and suffered no mortalities (even in the limited space of the tank), leading to the conclusion that aquaponics is an effective form of farming (Irhayyim et al., 2020). Additionally, in a study of low-income Hawaii residents, easy access to fish and vegetables from a low-cost aquaponics system was found to reduce rates of diabetes and other diseases, as well as obesity (Beebe et al., 2020).

School Uses for Aquaponics

A look at another source shows that aquaponics can be useful in classrooms and schools as a tool for educating students (Stroud, 2018). Schools should be teaching students about future technologies and emerging markets like aquaponics. Aquaponics is becoming an increasingly popular agricultural option around the world, as evidenced by the continued rise and projected growth of this market. This market is projected to increase from a value of $523 million in 2017 to over $870 million in 2022. (Shahbandeh, 2021)

Therefore, it is beneficial to teach students about this different form of agriculture as it is seen by many as the solution to food shortages and the future of agriculture. Not only that, if you look at a school in Chattanooga, Tennessee, the students were very excited to talk about their farm. As such, teachers taking students to the farm would be a good way to teach students about future forms of agriculture and how nutrients move around an ecosystem, instead of using a video or a model (WDEF CBS Chattanooga, 2015). But while this is all useful, it won't matter if they can't procure a system due to the costs and complexity involved in purchasing one (School Systems, n.d.).

Literature Gap

When schools build an aquaponics system, they often bring in professionals from a company like Nelson and Pade (an aquaponics construction company that sells to schools) to build a large-scale system. This can be a complicated process because of the required technology, large temperature controlled space, water access and the overall assembly and upkeep. A limiting factor in large scale aquaponics is price (Chattanooga, 2015). A large-scale, piped system built at Chattanooga School, cost according to Nelson and Pade Aquaponics between $84,000 and $114,000. This puts such a system out of reach for the vast majority of schools as they cannot afford such a complicated and advanced system. No study currently places a focus on the implementation of aquaponics, rather than its effectiveness.

This study determines whether a student can build and later maintain an aquaponics system. And whether it can be done reliably and with little monetary investment but great yield of fish and plants. This can be determined by comparing the weight gain of the fish and plants with the weight gain of other types of cultivation. The aquaponics design should be compact, inexpensive, but simple enough that an average high school student can build it with as little difficulty as possible. The people this would affect the most would be those who work and learn at a school, as the owners and principals can decide what to do with their system, whether it be to reduce food production costs or to introduce their futuristic system to others.

The goal of this study is to construct a system on a smaller scale that is far less costly, so that any school that builds such a system would not have spent a lot of money if it failed. In this way, even schools with fewer resources can use aquaponics. Some may argue that there is no need for this study because other studies have already been done on the low-cost production of aquaponics, such as studies on the production of systems in Hawaii where aquaponics was used to feed native Hawaiians living in poverty (Beeb et al., 2020). The topic of this academic study is to construct and maintain inexpensive aquaponics systems for each school with the research question, "How can a high school student with little to no construction experience construct an inexpensive and reliable aquaponics system for school usage? The results of this study determined which aquaponics system would be easier for a high school student with little construction skills to build and maintain in order to construct a system for a school to reap all the benefits of aquaponics.

Design and Prototype

There are many limitations to a project like this, but the most important are those of price, space and skill. The average school may not be willing to buy a $50,000 Aquaponics System, and it is even less likely to provide large sums of money to a student attempting to build such a facility. But most schools have two hundred dollars that can be used to build an aquaponics farm. The solution to this problem was using inexpensive materials such as plastic containers and PVC (Nelson, 2019). Space was taken into consideration. Therefore, the study was limited to a small space, a small part of an empty balcony in the school. This was to simulate the small space a school might have for such a project. The skills of the students were also taken into consideration. Not everyone can handle power tools, so as few power tools or complex building techniques as possible were used in these designs.

Project

To gather information on the topic and search for designs, a focus was placed on scholarly sources from online databases such as Gale. This study was a convergent parallel mixed study, using a true experimental design. The growth of tilapia and watercress were measured in 2 separate systems and recorded on a spreadsheet over two weeks.

Methods

Research Methods

After consideration, a 2-system convergent-parallel mixed study was chosen. In this study, plant growth and fish growth were measured in 2 systems, along with notes on how the systems performed and any errors that occurred (Appendix D). The quantitative portion of this study was inspired by previous aquaponic growth studies (Irhayyim et al., 2020). The fish and plant measurements make up the quantitative part of the mixed methods, while the notes and history make up the qualitative part of the study.

Study Subjects

The fish chosen for this study was the Red Tilapia (*Oreochromis Niloticus*) because it is very hardy and thrives in hazardous conditions as well as having a rapid growth rate. Six specimens were taken from a school pond. The plant chosen was watercress (*Nasturtium Officinale*), due to its history of aquaponics growth and cultivation. It was also chosen because of its rapid growth rate, which would enable a short growth study, such as this, to show much clearer results. The size of the watercress when they entered the aquaponics system varied from 0.2 cm to 1.6 cm. This can perhaps be attributed to uneven exposure to sunlight as they were covered with an umbrella during germination to protect them from heavy rain.

Ethical Considerations

This study used live organisms, as such, measures were put in place to ensure their health and comfort. The fish chosen were from a local pond at the Singapore American School, as there was a very large population of tilapia and removing six fish would not injure the ecosystem. They were placed in bins with adequate water supply, fed conventional aquarium food, and given cover to keep them safe throughout the study. The fish were measured only twice throughout the study's duration so that they would not experience stress. In the event of a fish casualty, however, they would not be replaced, as that would be altering the qualitative data from the study. Once the study was over, the fish were released to their native pond.

Instruments

A ruler was used to measure plant height and an electric scale was used to measure the weight of the fish. In the construction of the systems, a focus was placed on economical and simple materials. Rather than using PVC in the pipe system, a rain gutter was chosen (Figure 1). The choice was made after consulting with an experienced builder, who had worked with PVC pipe before, who said that PVC pipe is difficult to work with, even with access to power tools, while rain gutters have an open-top already, eliminating the need to cut holes. For the ponds, plastic bins were used, as they are inexpensive and common (Figure 2). Aquarium filters were chosen due to their low price, easy repair, and large availability. It should be noted that the price of the fish, feed, and seeds are not included in the overall budget as worldwide prices and availability vary. The pipe system cost $136.8 Singapore dollars (Appendix B) and the raft system cost $75 Singapore dollars (Appendix B).

Figure 1. Pipes used in the construction of the pipe system

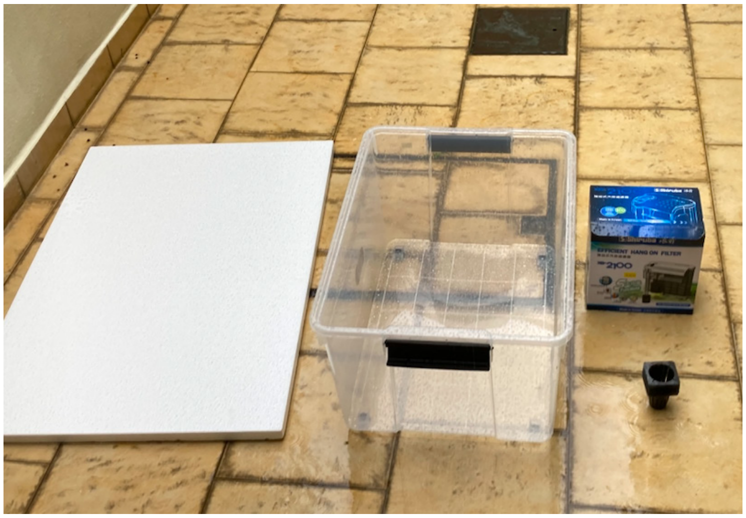

Figure 2. The Raft System materials before assembly

Procedures

Two aquaponics systems were constructed differing in design and prices. One being of the floating raft (Appendix A: Figure 1) variety and the other being of pipe design (Appendix A: Figure 2). These designs were chosen as they were shown to be mechanically simple systems. Approximately five days before the study began the watercress was 'started'. This process involved soaking a sponge with water, making a small cut, then placing the seed inside. This allowed the plant to germinate and grow to a seedling (see Figure 3). The sponge was periodically checked for signs of mold, which could damage the seedlings. While the plants were germinating the two systems were constructed.

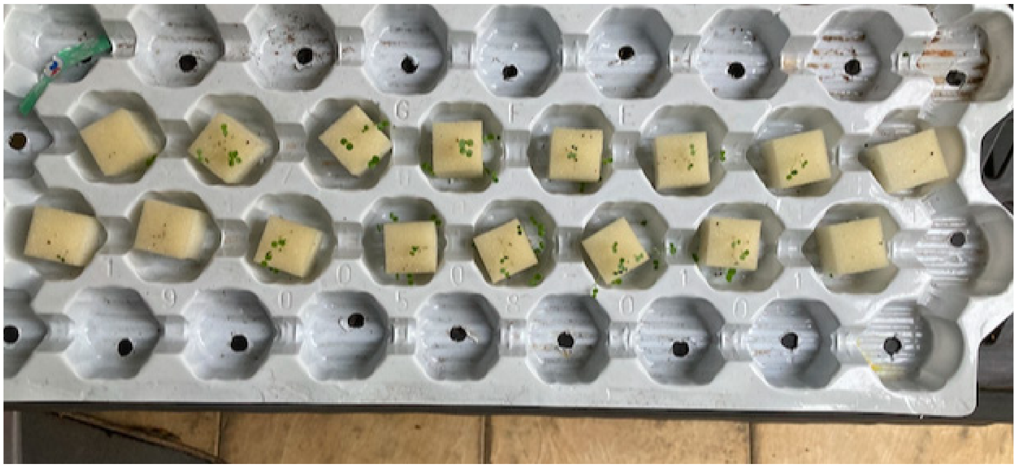

Figure 3. Watercress seeds being started in damp sponges before the study

The first system built was the raft system. It was built by first pouring water into the tub, fitting the filter, letting it cycle to clean the water, and test that it was working properly. The system was then left to run for four days to let the chlorine dissolve. While the water was filtered and cleaned, the styrofoam was cut into a rectangle that covered about half of the water's surface (see Figure 4). The plant holding baskets were measured and holes were cut for them in the styrofoam, being careful that the holes were smaller in diameter than the basket’s lip. For this study, the ratio used was two plants per fish as suggested by other researchers (Brooke, n.d.); once the baskets had been placed, the leca balls were deposited, so that bacteria could start growing and prepare the water for the Watercress. Figure E shows the fully assembled pipe system during the several days in which water was filtered in order to get rid of any chlorine or chemicals.

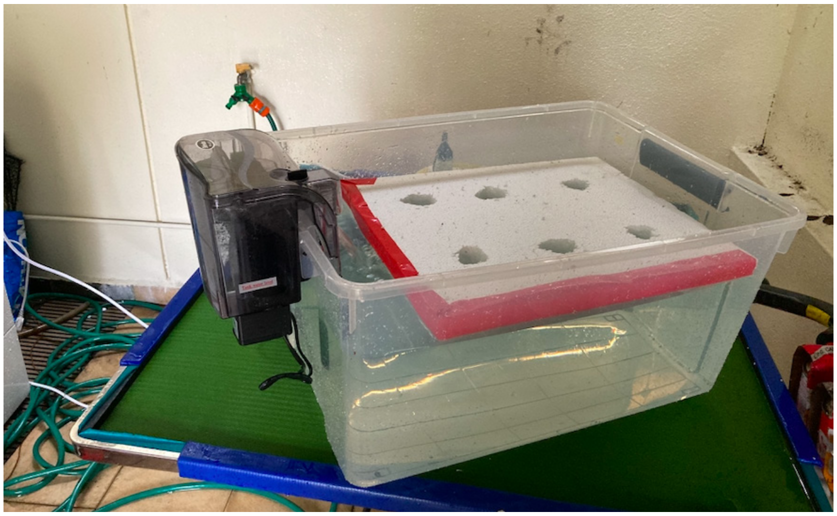

Figure 4. The Raft System fully assembled during building process

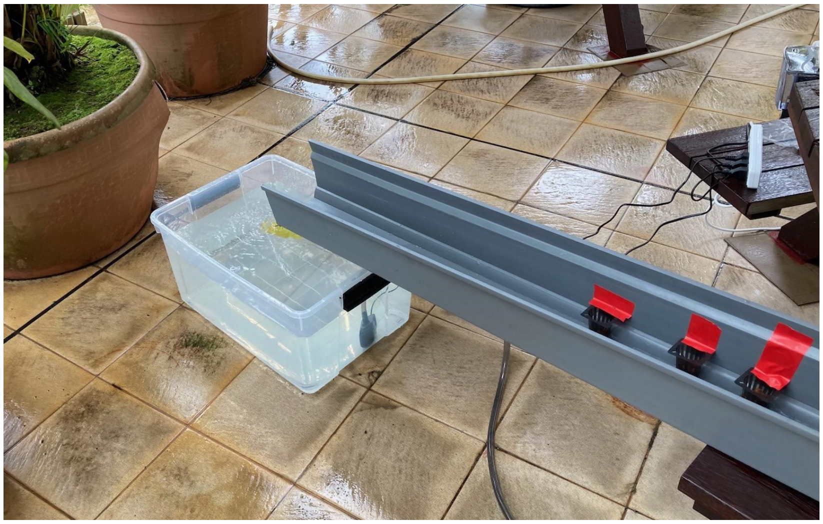

Figure 5. The Pipe System fully assembled at the start of the water sterilization process

Next, the water was allowed to cycle for two days, before the fish were introduced and measured. The fish were given two days to acclimate before the plants were measured and added to the system. Figure F and Figure G showcase the layout of the plants on both the pipe and raft system. The plants in the diagrams have been numbered, in order to better understand the results discussed later.

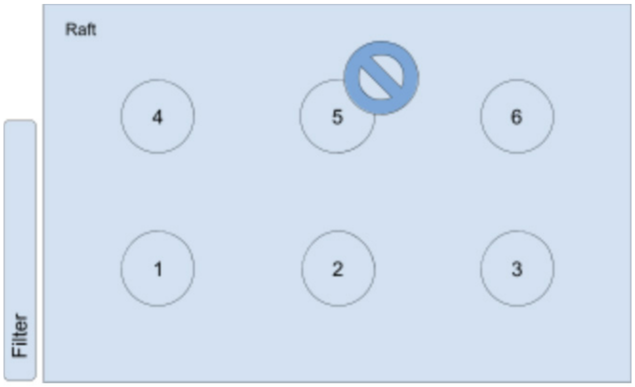

Figure 6. Raft System plant Layout. Note that plant 5 has a cross over it, illustrating that it died during the study.

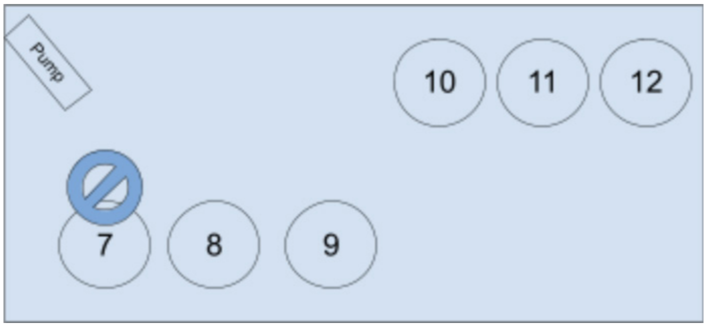

Figure 7. Pipe System plant Layout. Note that plant 7 has a cross over it, illustrating that it died during the study.

Variables

This experiment had one dependent variable, the subject growth. Their growth was dependent on the effectiveness of the system and the ability of the researcher to maintain it. The independent variable was the system, as that was the variable that was changed to see the differences in the growth. The dependent variable could be altered or tampered with by a change in weather conditions (rain, excessive heat, etc.) but the comparative portion of the study would be unaffected by this as both systems are in the same location and environment, and suffer the same conditions.
A variable that had not initially been taken into consideration was pests such as ants. After the loss of several crops to ants, a nontoxic solution was devised by using a two-inch tall barrier of Vaseline and baby powder. (Appendix A, Figure 3) The ants were stopped as they would slip off the barrier. Using pesticides ran the risk of water contamination and possibly killing the fish or harming the plants.

Assumptions

In the study, it was likely that the raft system would overall be slightly more effective in plant growth and fish growth. The pipe system pump had the possibility of being jammed by a leaf that falls into the pond or a leftover piece of fish feed. This would be easy to fix but would take time to do so. The filters could fill with waste, causing them to become near useless in terms of cleaning the water. In the event of nitrification, the fish could run out of oxygen in the water and possibly suffocate. Regarding the results, it was determined that some of the plants would not have grown. Mr. Andrew Grant, a project consultant who has a background in agriculture, said that some plants are ‘fussy’ in the sense that they simply will not grow, which is a factor that was carefully observed and included in the qualitative notes.

Threats to validity

In the study, larger fish were selected for the systems. The rationale behind this choice was the presence of large cats and birds at the school. A cat would be more able to eat and kill a smaller fish, while a larger fish has a better chance of survival. If a fish or plant were to die, and the researcher replaced it then another threat to validity will have been created, as the study would have been compromised due to tampering of the dependent variable. But, if a piece of technology fails such as the filter or pump and a repair is unable to be done, then a new one shall be procured, and the price be included in the 200 dollar budget of the design. In the event of an animal or external threat, the necessary precautions will be taken, and the price for such be added to the overall budget. There was also a threat in the form of other humans tampering with the systems. This could ruin the data collection of the whole study.

Planned Analysis

Quantitative

A T-test was conducted on the quantitative data collected to determine the average growth of both plants and fish in each of the systems and determine any outliers or strange results in the data. Graphs were generated in R, a coding program that is used specifically for data and statistical analysis.

Qualitative

The notes taken daily, which included observations on the functionality of the system and subject condition, were analyzed together with the research mentor, Mr. Andrew Grant, and presented in the final conclusions. These results could change the outcome of the study, as a system may grow both plants and fish incredibly effectively. But if the system requires constant maintenance and parts replacement then it would not be an effective system.

Data Gathered

Plants

Plant growth averaged 1.08 cm for the Raft System and 1.32 cm for the Pipe System, therefore the Pipe System plants grew more, on average, than the plants in the Raft System. However, both systems lost plants. Plant five died on day 11, while Plant seven died on day six (Figure 8, Figure 9 and Figure 10).

Day	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6
1	0.2	1.4	1	0.3	1.2	1.5
2	0.2	1.4	1	0.5	1.2	1.5
3	0.3	1.5	1	0.7	1.3	1.7
4	0.4	1.6	1.1	0.7	1.3	1.7
5	0.5	1.6	1.1	0.7	1.3	1.7
6	0.5	1.6	1.1	0.7	1.3	1.7
7	0.5	1.7	1.2	0.7	1	1.8
8	0.5	1.8	1.2	0.8	1	1.9

9	0.6	1.8	1.2	0.7	1	1.8
10	0.7	1.9	1.4	0.8	1	1.9
11	1	2.1	1.7	0.9	0	2
12	1.2	2.4	2.1	1	0	2.1
13	1.3	2.9	2.4	1.2	0	2.4
14	1.4	2.1	2.5	1.3	0	2.5

Figure 8. Chart of Raft System Plant growth, all values are in CM. The day the value becomes 0 is the day a Plant dies.

Day	Plant 7	Plant 8	Plant 9	Plant 10	Plant 11	Plant 12
1	1.1	1.4	1.5	0.5	1.6	1
2	1.1	1.4	1.5	0.5	1.6	1.2
3	1.4	1.6	1.8	0.7	1.8	1.5
4	1.5	1.9	1.9	0.9	2.3	1.7
5	1.6	2.2	2	1.1	2.4	2.1
6	0	2.2	2	1.1	2.4	2.1
7	0	2.4	2.1	1.2	2.6	2.2
8	0	2.6	2.1	1.2	2.8	2.5
9	0	2.7	2.3	1.3	2.9	2.7
10	0	2.7	2.4	1.3	2.9	2.7
11	0	2.7	2.5	1.3	2.7	2.9
12	0	2.7	2.5	1.3	2.7	2.9
13	0	2.8	2.6	1.3	2.7	3
14	0	2.9	2.6	1.3	2.8	3

Figure 9. Chart of Pipe System Plant growth, all measurements are in CM. The day the value becomes 0 is the day a Plant dies.

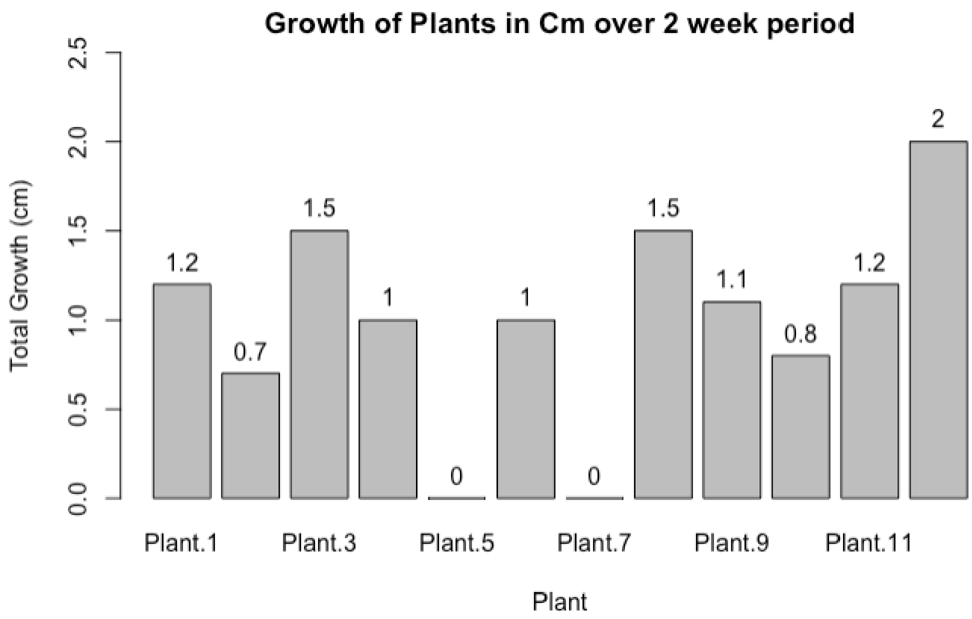

Figure 10. Growth of Plants in Cm over a 2-week period. The plant value of 0 indicates that the plant died.

Fish

Figure 11 shows that fish 4-6 in the Raft system grew an average of 15.74 grams over two weeks, and the fish 1-3 in the pipe system grew an average of 12.62 grams over that same period. In the raft system, it should be noted that fish six died due to nitrification (when an algal bloom consumes oxygen in the water), while fish four grew 4.61 grams and fish 5 grew 26.88 grams, causing the high average growth. Whereas in the Pipe system all three fish survived, fish one with a weight increase of 19.77 grams, fish two with 11.87 grams, and fish three with 6.22 grams (Figure 11).

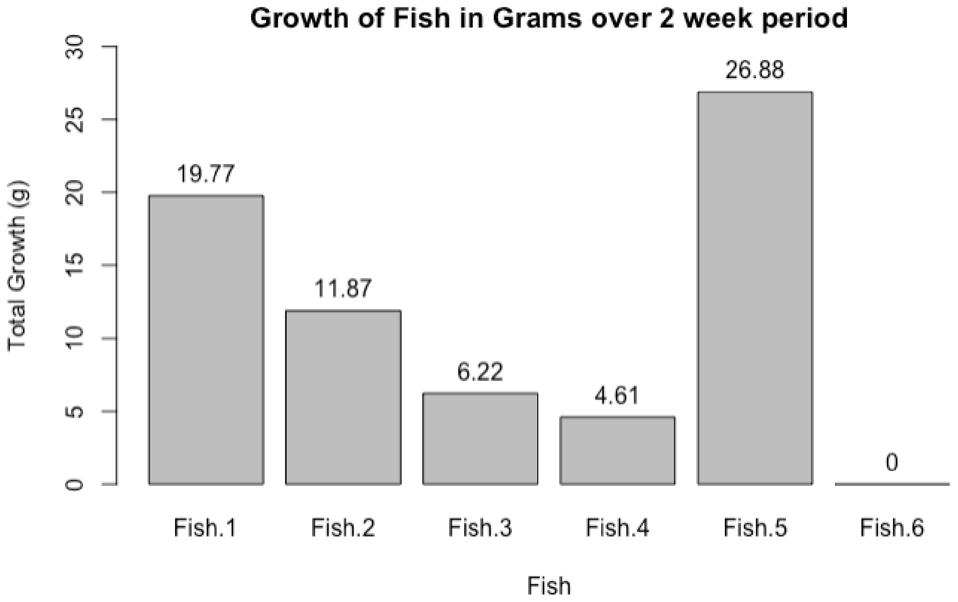

Figure 11. Growth of Fish in Grams over a 2-week period. Fish 1 through 3 were in the Pipe System, Fish 4 through 6 were in the Raft System. The value of 0 indicates that the fish died.

Casualties

It was noted that both systems had one plant casualty, plant five in the raft system and Plant seven in the pipe system. Plant seven died due to biological material (i.e. feces, fish food, plant matter, bacteria) getting carried up by the pump, and blocking water from reaching the watercress roots (Figure 13 and 14). The raft system had a larger issue in the form of nitrification. An algal bloom occurred and began to consume much of the oxygen out of the water, causing fish six to suffocate to death. This was determined to be the cause as previous attempts at the test had had similar results happen, and they happened during an algal bloom. Along with fish six's death in the raft system plant five died, but its death has been determined to be caused by 'fussiness' or an unwillingness to grow. This was determined as parasites or chemical imbalances would have affected the plants around it, rather than just affecting plant five.

Quantitative Analysis

Fish growth

The variable measured for the tilapia was their weight increase. The growth rate of the fish in the pipe system (.9 grams a day) was fast for tilapia, which can range from .1 grams a day to 1.9 grams a day in a professional aquaponics farm. (Santos, 2018) This makes this system (if scaled up) a feasible form of small-scale food production for schools. But after conducting a t-test in R, the p-value was found to be 0.06213 meaning that there is a ~6% chance that the differences between fish weight could be attributed to a random variable (genetics, age). The most likely candidate for a random growth would be fish five, as it gained 26.88 grams in the study, above the average.

Day	Fish 1	Fish 2	Fish 3	Fish 4	Fish 5	Fish 6
1	112.94 g	98.6 g	86.73 g	89.52 g	74.83 g	42.62 g
14	132.71 g	110.47 g	92.95 g	94.13 g	101.71 g	Dead (day 5)

Figure 12. Chart of Fish Growth. Fish 1 through 3 were in the Pipe System, Fish 4 through 6 were in the Raft System. The day the value becomes 0 is the day a Fish died.

Plant Growth

The growth of the pipe system plants was an average of .09 cm per day, although it should be noted that plant ten reached its height of 1.3 cm on day eight, then proceeded to stop growing. Whereas plant 12 grew consistently over the two weeks with one centimeter gained per week. This does show that not all plants are the same, and some will inherently grow better than others. This is interesting as, due to the plant layout (Figure 7), plant 10 would get more water than plant 12, despite this plant 12 grew incredibly quickly.

Failures Analysis

The pipe system had several issues with its maintenance as the pump in the system would pick up solid matter (i.e. feces, fish food, plant matter, bacteria) and pump it directly into the pipe (Figure 13). This resulted in a large amount of solid waste entering the pipe causing blockage and overall issues for the pump's ability to operate, as some of the matter was stuck in the pump, decreasing the water flow through it (Figure 14). This could harm the longevity of the system but can be fixed by placing filter sponges on the outside of the pump. In the case of the raft system, the nitrification that occurred would cause problems for the long-term use of the system. The nitrification caused the fish to suffocate. This could damage the farming ability and upkeep of the system as one mistake could kill every fish in the pond.

Figure 13. Biomatter in the Pipe System carried by pump. A mix of fish feces, algae and leaves that had fallen in.

Figure 14. The large biomatter buildup that suffocated Plant 7 in the Pipe System. Note how the biomatter is clogging the basket.

Qualitative Analysis

Cost Analysis

In an effort to produce low-cost aquaponics for schools, some trade-offs had to be made to keep it cost-effective, one of those trade-offs being the price and quality of the material (see Figure 1 and 2). This resulted in unexpectedly inferior materials being used. Specifically, the filters had to be changed every five days because they were clogged with algae. In addition, the plastic tanks had problems with flexing from the volume of water inside pushing on the walls. The first problem could be solved by using larger filters, while the second problem could be solved by placing one tank inside another to increase the structural integrity of the entire system.

Unexpected Results

Interestingly, in the pipe system, the fish spawned. This fact has large implications, as this can lead to a replicating farm and serve as a teaching opportunity to possible students about the spawning of fish, their life cycle, and the conditions required for it. This can also help with system longevity, as the young fish can be moved to another new system if the school ever decided to expand their systems.

Building and Maintenance Process

The building process for both systems was quite simple. (Refer to the methods section for building process). Once all materials had been collected the building was simple, it took two hours to fully build both systems. Importantly, no power tools were used as they require a level of skill to use effectively and are expensive. The only tools used for building were scissors, duct tape, and box cutters. The only time the box cutter was used was when cutting out holes in the Styrofoam for the plant baskets to hang from. With these common tools, a simple design, and adaptable materials the ability to easily build and maintain aquaponics can become far more open to schools.

Limitations

There have been limits to what this study accomplished. The largest of those is the materials list and their pricing. The materials used were purchased in Singapore, and while chosen due to their nature as common materials, students at schools in less developed regions may have trouble replicating these designs precisely. As such these designs should serve as a general guideline, with materials being very general and subject to differentiation based upon the location of the school building these systems. The price is subject to the same implications. In this study, pH and Nitrate levels were not measured, as it had not initially been planned to measure them.

Conclusion

Overall, the better system was the pipe system, as it grew plants faster, had better survivability, and created a good habitat for the fish to spawn in. While it is true that the pipe system had more pieces that could fail, these could be solved with ease. For example, a filter sponge on the pump intake would solve matter being carried to the pipe. As such the death of plant seven could have been avoided as the water's flow would not decrease due to clogging. Additionally, the flowing water would prevent nitrification in the tub, keeping the fish more comfortable and alive.

In contrast with the raft system, where the repairs required were minimal, but the algal bloom was a large failure, which can destroy a system. Further research can be done on these systems involving a longer study with more controlled conditions (weather, temperature). If schools use this study to begin the building of aquaponics, high school students will begin to build and encounter obstacles similar to the ones encountered here. This research allows them to innovate over what has been experimented on, expanding the knowledge base of how to build a cost-efficient and functional Aquaponics system for schools around the world.

Acknowledgments

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