Construction and Implementation of a Bench-Top Aquaponic System as a Context for Teaching Science in Secondary Schools

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CONSTRUCTION AND IMPLEMENTATION OF A BENCH-TOP AQUAPONIC SYSTEM AS A CONTEXT FOR TEACHING SCIENCE IN SECONDARY SCHOOLS

BY

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A thesis submitted to the Department of Biological Science in partial fulfillment of the requirements for graduation with Honors in the Major.

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The members of the Defense Committee approve the thesis of Sofia Fernandez defended on November 24th, 2014.

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ABSTRACT

Aquaponics is an integrated biological system that essentially combines a soil-less garden with an aquarium. It is important because it uses less water than commercial farming, is ecofriendly, and provides a local source of food for its practitioners. Aquaponics is also important because of its capacity to serve as an authentic teaching tool in science classrooms.

This thesis is divided into three components. First we will describe the construction and implementation of our Bench-top Aquaponics System (BAS). Next, the results of an experiment that compares two methods of establishing bacteria–culture in a fishless system will be presented. Finally, the potential for use of the BAS in STEM classrooms will be discussed.

The goals of this project are to (1) create an Aquaponics system that has a small ecological footprint and not take up too much room in the classroom, (2) further the current body of research on applied aquaponic systems, and (3) provide a pedagogical tool that involves students in building equipment and solving authentic problems as a gateway for learning.

The BAS is assembled in 3 separate compartments, a plant tray, an aquarium, and a bacteria reservoir, with PVC piping connecting the three. It is designed around a wooden frame that is smaller than 18 ft$^3$. This design allows for students (and teachers) to easily access and see the different compartments of the system. Many of the problems we encountered came from plumbing issues related to the fountain pump or the bell siphon; these were solved using applied physics principles. Other problems we faced, including biological were solved using more consistent testing and chemical reagents to stabilize our BAS. We learned ultimately that time is the key component in establishing a bacteria colony in any aquaponic system. We also learned that establishing bacteria is the most important step in setting up a successful aquaponic system whether on a large or miniaturized scale. Some aspects of this project that need further investigation include the importance of changing out the water of the system, whether dissolved oxygen is necessary for bacteria, and how/why consistently adding bacteria may stunt the ability of a bacteria colony to form.

Conclusively we have found that it is not only possible to establish such an aquaponic system that is built by students, but it is also possible to maintain it. Further research is needed to estimate the Benchtop Aquaponic System’s teaching potential within STEM classrooms.
ACKNOWLEDGEMENTS

I would like to thank Lowe’s our unofficial sponsor, for allowing us to “never stop improving,” or spending our paychecks. Although we were not able to secure corporate sponsorship, we may as well have based on our loyalty to their establishment. I would also like to thank Scott Berke from Ecological Labs who gave us good advice and some free stuff.

A huge thank you goes out to another Scott in our lives, that is “Uncle Scott” otherwise known as Scott Ames. Scott has been our primary collaborator in the STACT project and has been a wise and experienced voice throughout the design of this system.

I would also like to thank Sherry Southerland, who has taught me that most graduates from MIT don’t know what a log is made of. In doing so, she has challenged me to learn and teach with purpose so as to deeply embed knowledge and understanding. I would like to thank Logan Chalfant, my professor and mentor, who has taught me that I should never stop going to therapy. Logan has been a model of motherhood in my life and her constant guidance has encouraged me to become extraordinary. I would also like to thank Scott Steppan who, at the beginning of this thesis reminded me, “Scientists measure things.” In wake of this news, my thesis took on a whole new meaning, and I truly began to think not as an unfocused enthusiast, but as a curious scientist. Of course, I cannot help but thank our honorary “p. chem momma,” Mrs. Dr. DePrince. Her assistance, enthusiasm, and presence has made working with Dr. Goldsby a more bearable experience.

I would like to thank my lab members who not only kept me company during those long and cold nights in the lab, but who also contributed to the development of this project. These people include Dana Lev Ran, Dan Stribling, Chris Brewer, and Amanda Gorgy. In a special way, I would like to recognize Luke Williams who has been my big brother, singing duo, and partner in crime. Also, I am indebted to Rose Winkler, who has devoted her time and expertise this semester to the development of this aquaponics project. From collecting data to mourning at fish funerals with me, she has been a great help and I could not have done this without her.

I could not end this acknowledgement without thanking my friends and family who have loved, encouraged, and even fed me on occasion. I would like to thank my family for allowing
me to chase my dreams, and supporting me even when I didn’t know what my dreams were. I would like to thank my friends for being my family away from home and most importantly for encouraging me not to turn to alcohol when I couldn’t get the bell siphon to trigger.

I would also like to thank Goldsby for being my thesis director, mentor, professor, and dad away from home, over the last 5 years. I would also like to thank his wife Nancy for allowing me to jeopardize their marriage for this project. As a freshman at Florida State, I remember failing my first chemistry exam and crying in Goldsby’s office. Now as a 5th year senior, I often find myself making Goldsby cry and I wonder what has changed, and since Goldsby is too old to change… I figured it must be me. As a freshman, Goldsby changed my life by providing me with an opportunity to fall in love with chemistry. I fell for it, and I fell hard. By challenging me, he has developed my capacity to think critically about all aspects of life. Goldsby is often known for answering a yes or no question with a 30-minute monologue spiced with old school references about things that simply go over my head. Not in spite of his character, but rather because of it, can I say that it an honor to have known him and to have worked side by side with him. I love and care about him not just for what he has done in my life, but for who he is, not just to me, but to our lab, our school, and our community.

Finally, I would like to thank God. I would like to thank God for the gift of knowledge, perseverance, and humility, all of which he has given me opportunities to grow in these last two years. As St. Augustine once said, “The two forces that lead us to knowledge are faith and reason.” It is no small act of God that I have accomplished this thesis, and it has been a wonderful adventure to seek Him in this pursuit of truth. I must also thank God for James Joseph Kane. A fellow student at FSU, who’s disappearance and death has taught me to believe that there is more to life than just me; there is You.

In conclusion, I sincerely and unabashedly like to thank God, simply, because it is over.
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LIST OF ABBREVIATIONS AND SYMBOLS

In addition to the abbreviations listed below, standard SI units and abbreviations are used throughout this thesis.

AOB  ammonia oxidizing bacteria
AMO  ammonia oxygenase
ATP  adenosine triphosphate
BAS  bench-top aquaponic system
d    diameter
DO   dissolved oxygen
g    gram
h    height
HAO  hydroxylamine oxidoreductase
Hb   hemoglobin
in   inch
lb   pound
m    mass
n    number of moles
NAD  nicotinamide adenine dinucleotide
PVC  polyvinyl chloride
r    radius
SRS  Simple Recirculating System
**INTRODUCTION**

Aquaponics is a bio-integrated system that links recirculating aquaculture with hydroponic vegetable, flower, and/or herb production.\[1\] The development of aquaponics can be traced back to hydroponics, the “soil-less systems of crop production” proposed by William Gericke at the University of California in 1929, based on the theory that plants can receive all of the nutrients they need to flourish in a calculated combination of chemicals and water.\[2\] The next advancement towards aquaponics occurred in the early 1970s when aquaculture researchers experimented with raising fish in land-based tanks with continuously recycled water (e.g., recirculating aquaculture systems or RAS).\[3\] Modern aquaponics is a sustainable farming practice that reuses waste products, integrates plant and aquaculture, recycles water, and provides a local source of food. It is a dynamic and rapidly growing field with participants who are actively experimenting with and adopting new technologies. A survey of international aquaponic practitioners found that “Respondents were most often motivated to become involved in aquaponics to grow their own food, for environmental sustainability reasons, and for personal health reasons.”\[4\] The goal of the project described in this thesis was to design and build a small-footprint aquaponic system, the Benchtop Aquaponic System (BAS), with three intentions: first, to determine if a fully functional aquaponic system could be sustained within the limited space a secondary science teacher could provide. Second, once determined to be viable, show that this system can be used to teach science. A third goal that emerged from discovering the robust and lively community of aquaponic hobbyists was to further the field of applied biological research in a manner that is accessible.

**BACKGROUND SCIENCE**

An aquaponics system can be conceptualized as consisting of three components: (1) a tank or aquaria containing fish; (2) a reservoir for the bacteria, or in some systems, earthworms, that convert the ammonia waste from the fish into nitrite, and then nitrate; and (3) a grow bed in which the nitrate is removed by plants which use it as fertilizer. The synergy in this system is illustrated in Figure 1.
In practice, the bacteria reservoir may be omitted as a separate compartment because the support material in the plant bed can also provide the surface area and necessary conditions to support the bacteria; however, it is useful to separate the processes as shown above for the purposes of discussing the chemical and biological dynamics involved in aquaponics. These components will now be considered separately.

**Fish**

Mammals convert ammonia, produced as a byproduct of metabolizing amino acids, to the less toxic compound urea. Compared to ammonia, urea is much less toxic, allowing mammals to then carry the waste in their bladders until it can be eliminated as urine. Fish, however, eliminate waste nitrogen directly as ammonia through their gills. Ammonia is toxic to freshwater fish at concentrations greater than 2.97 mg/L, so it is important to remove the ammonia in order for the fish to live. Following ammonia intoxication, convulsions and death soon follow in all vertebrates. The water-saving advantage of aquaponics relies on having a biological system that converts the ammonia to a less toxic form, nitrate. The conversion of ammonia to nitrate, however, involves a middle step in which nitrite is produced as an intermediate. Nitrite in ambient water can be actively taken up across the gill epithelium and can accumulate to very
high concentrations in the body fluids. Nitrite concentrations of roughly 50 mg/L or higher can cause mass fish mortality.\[6\] The nitrite taken up from the gills enters the blood plasma, and ultimately enters the red blood cells. Within the red blood cells, nitrite will promote oxidation of the iron in hemoglobin (Hb) to the +3 oxidation state, forming methemoglobin and causing the fish to die due to affixation.\[6\] As a rough rule of thumb, methemoglobin concentrations in excess of 50% of the original Hb concentration are considered life-threatening to fish.\[7\] Using fish within an aquaponics system begs the question of what type of fish to use. Many aquaponic practitioners base this choice on whether or not the fish in their systems are being grown for human consumption. If the aquaponics practitioners are fish farmers, then tilapia \((Oreochromis niloticus)\) and catfish (members from the genus \(Siluriformes\)) are the most common fish grown; however, other types of edible fish have been used, for example, bluegill \((Lepomis macrochirus)\). On the other hand, others who are uninterested in eating their fish may choose to stock goldfish \((Carassius auratus)\) or koi \((Cyprinus carpio haematopterus)\) in their tank. Given the need to keep the ammonia concentration within a range that can be managed by the bacteria population, an important consideration in designing an aquaponic system is determining the number of fish the system can support. Finally, whether the fish are dead or alive, if kept inside a tank they will produce ammonia. Gerking developed the following formula to estimate the amount of ammonia created by one fish:

\[
\log y = -0.0282 + 0.5394 \log(x)
\]

where \(y\) = milligrams of nitrogen excreted per day and \(x\) = beginning body weight in grams.\[9\] Using this formula, one can estimate how the addition, subtraction, or even multiplication of fish can affect the amount of ammonia in the aquarium. For example, we can use this calculation to estimate that a healthy bluegill of average weight (150 gram), with a metabolic rate of 1 kg calorie / day at 25°C, would excrete roughly 23 mg of ammonia per day. Taking into account ammonia production and the volume of water in the fish tank, the general rule for noncommercial purposes is one pound of fish for every 5 to 10 gallons of tank water. This rule would translate to three average-sized bluegill for every 5–10 gallons of water.\[8\]

In addition to water quality, fish have other requirements that need to be provided and monitored, including water temperature and dissolved oxygen, along with other biotic and
abiotic factors specific to the species of fish used in the system. Many but not all fish are pokliotherms, which means that unlike humans and other mammals, they do not maintain a fixed body temperature independent of their surroundings. There are some however that do in fact regulate their body temperature like Therefore, the temperature of the water must be kept within a suitable range. While this can be a challenge with outdoor aquaponic systems, it is generally not an issue with indoor systems in a climate-controlled building. Oxygen needs vary based on the species of fish and their natural habitat, however, most aquaponic systems err on the side of caution and use a water-aeration mechanism to provide an oxygen-rich environment for the fish. One way this is accomplished is through developing an aeration system within the tank. An example of this would be to use a bubbler. The type of fish also plays a factor in what other biotic and abiotic factors are optimal for fish life.

**Bacteria**

Arguably, the most important component in the aquaponics system is the bacteria culture. The bacteria culture allows the system to work. Most colonies are comprised of some mixture of bacteria from the phylum Proteobacteria. Some, including genus *Nitrobacter* are from the class α-Proteobacteria and others including *Nitrosomona* and *Nitrospira* are from the class β-Proteobacteria.

Overall these bacteria function similarly in that they are all chemolithotrophic, which means that these bacteria are able to drive nitrification through oxidation. Through ATP synthesis or CO$_2$ fixation, chemolithotrophs are able to use reduced inorganic chemical compounds to harness energy. Although nitrifying bacteria are primarily obligate autotrophs, which consume carbon dioxide as their primary carbon source, and obligate aerobes, which require oxygen to grow, *Nitrosomonas* for example are able to drive nitrification in anaerobic conditions. In fact, *Nitrosomonas* and *Nitrobacter* are even able to drive denitrification in anaerobic conditions; however this does occur by differing chemical processes! Nitrification can be affected by many factors: pH, light, alkalinity, oxygen, and temperature. The optimum pH for nitrification can range from 7.0 to 9.0 with the optimum pH range from 7.2 to 8.8 for *Nitrosomonas* and 7.2 to 9.0 for *Nitrobacter*. In order to create a successful balance in any bacteria culture it is necessary to make compromises when necessary to provide the best context for all living organisms. Another factor to consider in the implementation of a bacteria
colony is temperature. Bacterial reaction rates tend to increase with rising temperatures for suspended film filtration systems while no significant effect has been acknowledged for other models, such as the fixed film series bioreactors. Within the last 20 years, much progress has been made in the effect of such factors in RAS and aquaponic systems; however, for the purposes of this thesis they will not be investigated further.

Bacteria from the genus *Nitrosomona* convert ammonia into nitrite. One common example is *Nitrosomona europaea*. *Nitrosomonas* are a type of Ammonia Oxidizing Bacteria (AOB); they oxidize ammonia (NH$_3$) to nitrite (NO$_2^-$) by the successive action of ammonia monooxygenase (AMO) and hydroxylamine oxidoreductase (HAO):

\[
\text{NH}_3 + \text{O}_2 + 2\text{H}^+ + 2e^- \rightarrow \text{NH}_2\text{OH} + \text{H}_2\text{O} \quad (2a)
\]

\[
\text{NH}_2\text{OH} + \text{H}_2\text{O} \rightarrow \text{NO}_2^- + 5\text{H}^+ + 4e^- \quad (2b)
\]

Two of the four electrons return to the AMO reaction, and two are either reductant for biosynthesis or pass to a terminal electron acceptor. This process occurs at a preferred pH between (7.8–8.0). The overall reaction from ammonia to nitrite is as follows:

\[
\text{NH}_4^+ + 1.5\text{O}_2 \rightarrow \text{NO}_2^- + 2\text{H}^+ + \text{H}_2\text{O} + \text{energy} \quad (3)
\]

Bacteria from *Nitrospira* and *Nitrobacter* oxidize nitrite into nitrate. One example is *Nitrobacter winogradskyi*. The equation that describes this conversion is given below:

\[
\text{NO}_2^- + 2\text{O}_2 \rightarrow \text{NO}_3^- + 2\text{H}^+ + \text{H}_2\text{O} + \text{energy} \quad (4)
\]

Both *Nitrospira* species and *Nitrobacter* species oxidize nitrite (NO$_2^-$) into nitrate (NO$_3^-$) at a preferred pH (7.3–7.5). In this reaction, nitrite functions as an electron donor for the reduction of NAD via reverse electron flow and the generation of ATP by oxidative phosphorylation:

\[
\text{NO}_2^- + \text{H}_2\text{O} \rightarrow \text{NO}_3^- + 2\text{H}^+ + 2e^- \quad (5)
\]

**Plants**

Plants are essential to the aquaponic system because they reduce the amount of nitrate in the system by taking it up as nutrients. This process essentially filters the water, removing toxins and providing clean water for the plants, which allows for transpiration and other necessary plant processes. In an aquaponics system, plants are usually grown in a hydroponic manner – without soil. In order to give the roots a sturdy foundation to anchor onto, aquaponics practitioners have come up with several ways to provide stability to their plants. Nutrient film technique (NFT) is
one such way. NFT consists of several narrow plastic troughs (~6 in wide) in which plant roots are exposed to a thin film of water that flows down the troughs. Constant or intermittent circulation provides the plants’ roots with water, oxygen, and nutrients. \[15\] Another type of system is a floating or raft hydroponic system. The raft system involves using long channels with closed-cell polystyrene sheets to support the plants, while the roots are submerged in the water. The method provides the root with maximum culture water exposure; however it does increase the likelihood of solid buildup in the roots. Finally, there is a reciprocating system model, which is common in small aquaponic undertakings. To ensure adequate aeration of plant roots, gravel beds are operated in a reciprocating (ebb and flow) mode, where the beds are alternately flooded and drained.

Since plants have complex nutritional needs, it is important to take into consideration the macro and micronutrients that plants need in nature to sustain themselves. Hydrogen, carbon, and oxygen can be derived from the air and water. \[8\] The other elements must be supplemented. One important element that is taken up by the plants is nitrogen, which can be taken up in the form of ammonia or nitrate. Some argue that ammonia is volatile and energetically costly to uptake for plants. \[18\] Whereas other experts argue just the opposite, “Although plants do take up nitrates, ammonia is the favored nitrogen form. Ammonia uptake requires less energy than nitrate uptake, resulting in full plant growth potential.” \[19\] This apparent conflict within the literature is an interesting question and should be investigated further. Nevertheless, aquaponics relies on the uptake of nitrate by plants as is made available by oxidation in two sequential processes, changing ammonia to nitrite and nitrite to nitrate. Perhaps it is for the sake of the fish that ammonia is not used, as ammonia is severely toxic to fish.

A few criteria were essential in deciding which types of plants would be used within the BAS. Some examples of those criteria are photoperiod and popularity among other aquaponic practitioners (perhaps an indicator of plant success growing in aquaponics systems). Respondents to an International Aquaponics Practitioners Survey (2014) raised edible crops, with leafy greens, herbs, and tomatoes reported as the most popular. \[4\] Among correspondents for this study, 60%-80% grew basil (Ocimum basilicum), 40%-60% grew heads of lettuce (Lactuca sativa) and peppers (members of the genus Capsicum), and 20-40% grew collard greens (Brassica oleracea) and onion (Allium cepa). In an effort to use what is already successful, we relied heavily on this data in our own plant choices. Additionally, to avoid the conflicting
sunlight needs of plants of different species, we chose to grow plants that had a long day (short night) photoperiod. Basil is a facultative long day plant, lettuce is a quantitative long day plant, bell peppers are also long day plants (16 or 20 hours), and so on.

Finally, the plants in the aquaponics systems must be able to keep up with the ammonia production of the fish, and the nitrate production of the bacteria. Another aquaponics rule of thumb is that the ratio of plant or grow bed volume to fish tank volume is 1:1 or 2:1.\textsuperscript{[8]} Ratios in this range promote the balance necessary so that ammonia toxicity does not overwhelm the system, nor does it kill the fish and underwhelm the system and failing to provide sufficient nutrients for the plants.

**THE STACT PROJECT**

The Science and Technical Arts Collaborative Teaching (STACT) Project is an effort to encourage conversations and stimulate relationships between science teachers and shop teachers... and then get out of their way. Beyond providing science teachers with demonstrations and shop teachers with new projects for their students, we believe these collaborations will provide students with the opportunity to design, build, test, and redesign experimental apparatuses in a manner not unlike the way experimental science is actually done in a research laboratory. Working with shop teachers at public schools in north Florida, we have developed over a dozen projects that to show how teachers might forge similar partnership at their schools, but so far these projects have fallen largely within the physical sciences. An important consideration when considering potential STACT projects is that students in a middle school or high school shop class (or a similar technical program or activity, such as pre-engineering or robotics) should be able to build and test the equipment under appropriate supervision using the tools and materials available at a typical 6-12 school with technical arts program that includes building and construction in its curriculum. The BAS project described in this thesis is our first effort to extend this idea to the biological sciences, and various aspects of this project span biology, physics, chemistry, environmental science, and engineering, global citizenship.
**EXPERIMENTAL**

In addition to the goal of designing and implementing the BAS, the ultimate goal of the STACT Project is to provide examples of apparatuses for scientific demonstrations that could be built by teachers and their students at middle and high schools; therefore, we purchased materials (components of the apparatuses) and supplies (consumables used to assemble the materials) from local stores whenever possible. If it was necessary to order materials, we tried to use the same vendors that a secondary school teacher might use. Vendors and part numbers for specialty items are included in the materials list. The tools used to cut materials and assemble the apparatuses are standard for any industrial arts program with a construction course (e.g. woodworking) in its curriculum. The total estimated cost for the materials used in the construction of this system is between $100 and $150. Bearing in mind the resourcefulness of the shop teachers we are aiming to target, supplies like wood and light fixtures may be available for repurposing and may bring down the cost significantly.

*Standard safety rules and practices were followed, including (but not limited to) wearing safety glasses when cutting and assembling materials.* \(^{[16]}\)

**BENCH-TOP AQUAPONIC SYSTEM (BAS)**

*Materials:*

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<th>Item</th>
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<td>Good Choice 24-Hour Lighting Timer</td>
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**Supplies:** Black Rubber Sealant (Permatex); PVC glue; cork-rubber gasket sheets, 3 sq ft (Fel-Pro, Advance Auto); polyurethane or varnish, Red Oak Minwax Wood Finish (Lowe’s), #9 × 3-in deck screws (Lowe’s).
CONSTRUCTION OF THE BENCH-TOP AQUAPONIC SYSTEM

Frame. The structure support for the BAS was built from #2 yellow pine studs cut to the appropriate lengths and assembled as shown in Figure 2. The joints were made with #9 × 3-in deck screws. Once assembled, the frame was stained (Minwax Wood Finish, Red Oak) for aesthetics, followed by two coats of varnish to protect the frame from water damage.

Figure 2. Sketch showing dimensions and assembly of the BAS frame.

Bacteria Reservoir. The bacteria reservoir was constructed by modifying a Rubbermaid container as shown in Figure 3. The container was outfitted with two ½-in PVC elbows following a procedure developed in our lab. The lower PVC elbow (left side in Figure 3) is threaded and fitted with a ½-in CPVC Coupling. The upper PVC elbow (right side in Figure 3) has a slip connection to accept a short piece of ½-in PVC for drainage into the plant bed. The container was charged with Sunleaves Rocks, a highly water-absorbent growing medium commonly used in aquaponic system to support plants and provide a large surface area for housing bacteria.
**Plant Bed and Bell Siphon.** A Hefty 34-quart tote served as the plant bed. A ¾-in wood bit was used to create overlapping holes in the front-right corner of the tote and underlying shelf of the frame to accommodate the bell syphon. The components of the bell syphon are shown in Figure 4. Holes were drilled along the bottom edge of the Charlotte fitting, and it was affixed to the container with Permatex Black Rubber Sealant. (Note: Silicone does not bind well to the plastic tote.) The remaining connections were made as shown in the figure and holes drilled in the cap provide greater aeration of the water when the bell siphon was triggered. The outer diameter of various the glass jars was matched to the inner diameter of the Charlotte fitting until a good match was found, and then the outer diameter of the glass jar was built up with tape to get a snug fit.
The plants were supported in Sunleaves Rocks in plastic Solo cups, commonly used in noncommercial aquaponic systems. Prior to introducing the plants and support media, numerous holes were melted into the cups using a soldering iron working in a fume hood. The cups were placed in holes cut in a foam board (Figure 5) to form the growth tray for the plants, and the growth tray was supported above the plant bed by a rack made from CPVC pipe and connectors (Figure 6).
Figure 5: Growth tray for supporting plants.

Figure 6: PVC frame for supporting the growth tray above the plant bed.

**Pump and Plumbing.** The pump was connected to the bacteria reservoir using CPVC pipe and fittings. Inserting a small section of the smartpond Water Garden ½-in vinyl tubing into the CPVC pipe, which allowed a tight fit to be made with the smartpond 80-GPH Submersible Pump. The CPVC pipe was run from the pump to the bacteria reservoir, making two 90° turns with CPVC elbows, and the final connection to the reservoir was made using a Genova ½-in CPVC coupling. A short section of ½-in PVC was attached to the upper elbow to help direct the exiting water to the plant bed.

**Lighting.** The lighting system for the plant bed consisted of two 2 bulb × 2-ft fluorescent light fixtures obtained as surplus from the FSU Department of Chemistry Electronics Shop. The fixtures were attached to two 1-in × 4-in planks as shown in Figure 7, which allowed the fixtures to hang above the plant bed as shown in Figure 8.

Figure 7: BAS lighting system.
Aquarium Tank. In the spirit of using materials easily accessible and affordable for classroom teachers we utilize a 70-quart stackable plastic bin manufactured by Sterilite® as our aquaria tank. We filled the aquarium with approximately 15 gallons of de-ionized (DI) water. The BAS was stocked a one bluegill and one warmouth fish each, both types of freshwater sunfishes. These fish are omnivores and so can tolerate a wide variety of food. [17] In order to ensure the breakdown of amino acids, we chose to feed these fish chichlid pellets from Top Fin® because the composition is high in protein. (Crude Protein <43.0%)

Figure 8. Fully-assembled Bench-top Aquaponics System (BAS).

Methods. In the BAS described here, we chose to allow the fishes’ habitat to occupy a small section inside a teacher’s classroom. We chose to do this so that the tank temperature would not vary considerably due to regulation by a thermostat that presumably controls the temperature for the entire building if not the classroom. While we understand that many schools turn off heating and electricity to conserve energy and financial resources, the temperature of the tank can vary (+/- 3 degrees) without a harmful effect on the fish, plants, or bacteria. However, this is largely dependent of the species or type of fish, plant, and bacteria. Another low cost solution that may
be implemented would be a small 150 watt submersible heater, which automatically turns on and off in accordance with temperature fluctuations of more than 1 degree Celsius.

In our case, we designed our bell siphon so that it regularly discharged ~18 liters of water into the aquarium tank every 8 minutes. This water did not simply trickle down over several minutes, but instead came out through a “shower head” attached to the PVC pipe in an effort to maximize the amount of air, and therefore oxygen, being pulled down into the tank.

**Simple Recirculating System**

*Materials:*

<table>
<thead>
<tr>
<th>Item</th>
<th>#</th>
<th>Vendor; Item number</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 gallon aquarium tank</td>
<td>1</td>
<td>Walmart</td>
</tr>
<tr>
<td>smartpond 80-GPH Submersible Pump</td>
<td>2</td>
<td>Lowe’s; 58375</td>
</tr>
<tr>
<td>smartpond Water Garden 1/2-in Vinyl Tubing</td>
<td>1</td>
<td>Lowe’s; 63082</td>
</tr>
<tr>
<td>Rubbermaid Dry Food Container 16 Cup, Model 1776472</td>
<td>2</td>
<td>Walmart; 125262</td>
</tr>
<tr>
<td>1/2-in x 5-ft CPVC Pipe (Hot/Cold)</td>
<td>5</td>
<td>Lowe’s; 23811</td>
</tr>
<tr>
<td>LASCO 1/2-in Dia 90-Degree PVC Sch 40 Elbow; Socket Thread</td>
<td>4</td>
<td>Lowe’s; 23935</td>
</tr>
<tr>
<td>LASCO 1/2-in Dia PVC Sch 40 Adapter</td>
<td>4</td>
<td>Lowe’s; 23855</td>
</tr>
<tr>
<td>Genova 1/2-in CPVC Coupling</td>
<td>1</td>
<td>Lowe’s; 23761</td>
</tr>
<tr>
<td>Sunleaves Rocks, 0.25&quot; - 0.5&quot;, 13 lb</td>
<td>1 bag</td>
<td>ESPOSITO Garden Center</td>
</tr>
</tbody>
</table>

*Supplies:* Permatex ultra rubber gasket sealant 1 dressing; PVC glue; cork-rubber gasket sheets, 3 sq ft (Fel-Pro, Advance Auto); polyurethane or varnish, MINWAX Wood Finish, Honey 272 (Lowe’s), finishing nails.

**Construction of the Simple Recirculating System**
Standard ten-gallon fish tanks were used for the Simple Recirculating Systems. The bacteria reservoirs were constructed as described above for the BAS, except that the inlet and outlet holes were cut on the same side of the container, displaced horizontally as well as vertically so that water flowing out of the upper outlet would not hit the plumbing leading to the lower inlet. The reservoirs were charged with 2.5 L of Sunleaves Rocks, and supported on 11½” \times 7½” platforms cut from ½” planks set on one side of the tanks. The platforms were held in place by strips of quarter-round molding, affixed with glue and secured with 1-in finishing nails, positioned to fit the inner dimensions of the tank (see Figure 9). The platforms were stained for aesthetics, and two coats of polyurethane were applied to minimize damage due to water splashing up from the tank.

![Figure 9. Simple Recirculating System (SRS) Platforms](image)

The tanks were filled with roughly 30 L of distilled water, and the pump was set to the third highest setting (can we give the flow rate corresponding to this setting instead?) and connected to the inlet as described done with the BAS. A short piece of ½-in PVC was inserted into the slip fitting on the upper outlet to help direct the water down to the tank. It was necessary to add roughly 500 mL of water was added every week to replace that lost by evaporation.
Methods. After allowing the water to cycle for 24 hours, the water was tested for initial readings of pH, ammonia, nitrites, and nitrates. Following the initial measurements, 5 mL of 1.8 M concentrated ammonia hydroxide, which is often written as NH₄OH consistent with the name, but predominantly existing in solution as NH₃. After allowing 15* minutes for cycling, each tank was tested again for pH, ammonia, nitrites, and nitrates. Tank #1 was given 4 mL of Nite-out II Nitrifying bacteria on October 8th, 2014, and no additional bacteria was added for the duration (45 days) of the experiment. Tank #2 was also given 4 mL of Nite-out II Nitrifying bacteria; however, an additional 4 mL was added every other day, also for the duration of the experiment. The pH and the concentration of ammonia, nitrite, and nitrate were measured and recorded every day between October 9th, 2014 and November 13th, 2014 except for the following days: October 12th, October 13th, October 14th, October 18th, October 23rd, October 26th, October 31st, and November 11th, 2014.

RESULTS AND DISCUSSION

The goal of this project was not to reinvent the "aquaponics" wheel, but rather to reimagine its application. Our system measures 4½ ft × 1½ ft × 2½ ft – small enough to fit on a counter top in a middle school or high school science classroom. Hence, it is a Bench-top Aquaponics System (BAS). Once built and charged with an initial concentration of ammonia from reagent-grade concentrated ammonium hydroxide, the concentrations of ammonia, nitrite,
and nitrate, and the pH levels measured and recorded roughly every two weeks. The volume of water added to the system (to replace that lost to evaporation), the amount of buffer added, peroxide levels, and water temperature were also recorded on a regular basis. Ultimately fish were introduced and fed for demonstration purposes.

In addition to the quantitative data presented here (“scientists measure things”), much of the data is qualitative; for example, did the plants grow? No attempt was made to measure the amount or rate of plant growth. This thesis project was driven by the question: Can a fully-functional aquaponics system be sustained within the limited space a 6-12 grade science teacher might be willing to provide. What problems might be encountered and how could they be addressed?

A few mechanical problems were encountered that had to be solved before introducing the biological materials. The bell siphon, sometimes called an automatic siphon, is a device used to automatically drain water from the plant bed on a regular basis set by the flow rate of the pump, the size of the bed, and the height of the internal tube in the bell. The water is drained to a level determined by holes at the bottom of the bell syphon. Once the water falls to the level of the holes, the siphon is broken, and the bed begins to fill again. It was necessary to optimize the length of the internal tube by trial and error, in terms of both the height of the tube in the bell and the length of the exit tube at the bottom. If the tube is too short then the gravitational pull of the water will not be great enough to initiate the siphon. Additionally, a short exit tube caused a lot of splashing from the water reentering the aquarium tank. Although water aeration is essential for the fish, extreme splashing can remove excessive water from the tank, and any water that hits the wood frame and bench top can potentially damage the frame. By elongating the PVC pipe and then attaching a head-piece (2-in bushing and cap) with small holes drilled in the cap, we were able to maximize the aeration to the aquarium and minimize water loss due to splashing.

Another problem involved the glass jar, which served as the “bell” for the bell siphon. If it sat loosely on the PVC (Charlotte) fitting, then it would not create an air–tight seal. This alone can prevent the siphon from triggering. In order to remedy this problem, the glass jar was removed and the outer edge of the opening was wrapped with several layers of Parafilm. The increased the width of the mouth of the jar, along with a waxy nature of the Parafilm, formed a tight seal.
Once the bell siphon was in order, we found other issues that prevented it from triggering. For example, we observed that sometimes the bell would fill with water up to the top of the inner PVC tube and then leak water at a constant rate, maintaining that height without triggering the syphon. That meant that water flowed into the plant tray from the bacteria reservoir at the same rate it flowed out through the bell siphon, never getting higher than the inner PVC tube, hence never initiating the siphon. Water must exit the bacteria reservoir (and enter the plant bed) faster than it trickles out of the bell syphon so that the bell will continue to fill above the height of the inner tube until it reaches a point where the water level will begin to undulate just before the siphon is triggered.

A related aspect of this problem occurred within the actual bacteria chamber. In our first edition of the bacteria chamber, we use a square recycled peanuts container and filled it with Bio-Film, a type of bacteria encouraging growth media found at a local pet shop (PetCo). Although this biofilm did promote bacteria growth, it also promoted algal growth, floated, and collected solid waste sediments ranging from fecal matter to uneaten fish food. The combination of these circumstances reduced the water flow rate into and out of the bacteria chamber. By reducing the amount of Bio-Film within the bacteria chamber, by roughly 50%, we were able to greatly increase the flow rate into and out of the bacteria chamber and subsequently, the plant tray. In the final BAS design described in the Experimental section, we utilized a different storage container that is more rectangular in shape, and instead of loading it with Bio–Film, we packed it with Sunleaves Rocks, which reduced the clogging problems that occurred with Bio-Film material.

Once mechanical problems with the BAS were addressed, the next imperative question was whether or not the system would facilitate the conversion of ammonia into nitrate? After all, the aquaponics cycle requires the oxidation of ammonia to nitrate via nitrite as shown in Figure 1. It is necessary to establish a thriving bacteria colony before fish or plants can be added to the system, so a common practice discussed in online aquaponics communities is the addition of ammonia in the form of aqueous ammonia. The BAS was completed at the end of the Spring 2014 semester, and ammonia hydroxide was added to bring the concentration of $\text{NH}_3/\text{NH}_4^+$ to roughly 10 ppm to give time for the bacteria colony to be established before the beginning of the Fall 2014 semester when the thesis project would resume. Concentrations of ammonia, nitrite, and nitrate were measured on an occasional and irregular basis. The data, shown graphically in
Figure 11 illustrates the length of time it took, roughly 40 days, for the ammonia concentration to drop to a safe level for fish to survive. Note that detectable concentrations of nitrite were not observed during this period; however, the absence of nitrite may be due to the gap in data in the range between day 18 and day 38. The gap in the data prompted further questions regarding the establishment of a bacteria colony and led to the simple recirculation system experiments described below.

The growth tray was populated by removing small plants from their containers and soaking the root systems in DI water. Soaking the plants in DI water allowed the to bulk of soil that was attached to the roots to come off easily without disturbing the roots. As described before, the plants were then transplanted into black solo cups with 2 to 3 rows of holes at the bottom to allow for water exchange. Sunleaves Rocks were added to the solo cups to “anchor” the roots and provide support for the plants. By the time all plants were added, the bed contained one tomato plant, two red pepper plants, two collard greens plants, one basil plant, three onion bulbs, and one red romaine lettuce plant. All plants exhibited growth after being added to the BAS, with no chemical fertilizers added to the water. Over the course of the study, the plants grew several inches in both stem and leaf foliage. The tomato plant “outgrew” the plant bed in

![Figure 11. The Bench-top Aquaponic System Data - First 50 days](image)
terms of root length and stem height, and it developed mildew, so it was removed from the bed to prevent the mildew from spreading to the rest of the plants. The pepper plants produced small peppers, most of which did not survive for long beyond initial formation. One pepper reached a size of 3-in* by 1 1/2-in* at the time of this writing (Figure 12), which is remarkable given the nutrient demands to grow fruit to maturity in an aquaponic system.

![Bell Pepper Fruit from the BAS](image)

**Figure 12.** Bell Pepper Fruit from the BAS

Given more time, and perhaps with the addition of a few key micronutrients, it seems likely that the BAS would produce fruit in greater quantities.

After the 43 initial days of the BAS, we did not add any more bacteria or non-organic ammonia to the system. The lack of nitrite data prompted additional questions that were investigated in a second experiment; how long does it take for the bacteria colony to establish to the point that a reduction in ammonia and the appearance of nitrate is observed? Is it possible to observe the intermediate nitrite in this process? Does adding more bacteria at regular intervals reduce the time required to establish the bacteria colonies?

In an attempt to answer these questions, the bacteria circulation tank experiments described in the Experimental section were carried out. The tank that received only one dose of bacteria was nicknamed “One Hit Wonder,” and the tank that received regular doses of bacteria was given the more utilitarian perfunctory name “Do It Like the Directions Say.” According to the directions listed on the bottle, 4 mL of the bacteria solution should be added every other day until the ammonia levels drop below 0.6 mg/L, which is equivalent to 0.6 ppm in water. Figure 13 shows the results for the “One Hit Wonder.”
The graph shows the length of time needed to begin cycling a system of this size and configuration. Even for this small system, it took approximately three weeks before any changes were noticeable. Although we were able to capture the initial changes in ammonia, nitrite, and nitrate we stopped data collection at day 36. However, on day 42 and 43 of the experiment we collected two more data points to observe whether the changes we expected to happen did in fact happen. As expected, the nitrite concentration decreased to zero and the nitrate concentration leveled off between 20 to 40 ppm. Unexpectedly, “Do It Like the Directions Say” did not show any conversion of ammonia over the duration of the experiment, in spite of receiving additional bacteria on alternating days. Throughout the 42 days the experiment was allowed to run, the concentration of ammonia remained at 4.0ppm and the concentration of nitrites and nitrates in a

Figure 13. Graph of concentration versus number of days for ammonia (♦), nitrite (■), and nitrate (▲).
similar manner remained at 0 ppm, despite adding 76 mL of nitrifying bacteria in a manner consistent with the directions on the bottle. In an effort to better understand this surprising result, we turned to the aquaponics community via the Backyard Aquaponics Forum.

Many people in this forum informed us that it was because we didn’t have any carbonate alkalinity or KH. Though throughout most of the testing of the aquaponics systems, we didn’t test for KH. Therefore, we decided to go ahead and purchase a KH test kit. Our readings indicated that we had approximately 50ppm of KH, which although low, should be sufficient for nitrifying bacteria. According to Ebeling (2006) for every gram of ammonia-nitrogen converted to nitrate-nitrogen 4.18g of dissolved oxygen and 7.05 grams of alkalinity are consumed. Alkalinity here is described as CaCO$_3$. As it turns out, for every one gram of ammonia-nitrogen that is oxidized, 5.85 grams of CO$_2$, along with ~0.2grams of microbial mass, is produced. This information, although realized later on in the experiment did in fact change how we understood the role that carbon dioxide plays in the process of nitrifying bacteria.

Another member of the aquaponics community, after seeing a photo of our set-up, urged us to add air stones to the tank to allow more dissolved oxygen in our system. Since this occurred at the end of the trial, and a DO meter was unavailable to us, we tried to figure out whether our system was getting any oxygen from the air. As it turns out, in our design of the experiment, the water we had flowing from the bacteria reservoir back to the tank was being aerated due to the head space of air that was above the rocks in the bacteria chamber. This allowed the system to be aerated, however it is possible that not enough oxygen was made available for such a high quantity of bacteria. Additionally, in the literature, instances where nitrifying bacteria have been able to thrive in anoxic environments have recently emerged. Although the role that bacteria play in such environments usually requires NO (g).

**Pedagogical Purposes.** In all of these experiments, with the BAS and the two-tank system, there is another underlying yet overarching theme that is yet to be discussed: its pedagogical advantages. If we begin with the BAS, we must first consider that its very design took into account a bench-top, the maximum amount of space that most secondary education teachers are willing to give up. The design was maximized to take advantage of limited resources that teachers may and regularly do face. These limitations include but are not limited to: time, financial support, and space within the classroom.
The BAS system was designed with teachers in mind. Its very purpose is to provide teachers with a dynamic teaching tool that has the ability to transform the way that secondary education educators teach science. Of course this is not limited to biology; the concepts this BAS can support are wide in both breadth and depth. For example, topics from these courses are relevant to the BAS: physics, engineering, environmental science, chemistry, plant biology, and/or AP biology. Specific overarching topics from these courses include: plant biology; ecology; carbon, nitrogen, and oxygen cycle; and marine/freshwater ecosystems, just to name a few. The related concepts we found have been numerous, and we are confident that even more teaching opportunities can be derived from the BAS.

**SUMMARY**

The answer we have found through the development of the BAS is that a low–cost miniaturized aquaponic system is in fact possible. This conclusion is supported by quantitative, qualitative, and experiential evidence that has comprised this project. Throughout the development and implementation of the BAS many issues arose, providing an authentic context for us to learn more deeply about the system from a shop teacher’s perspective and well as from a science teacher’s perspective. The additional experiment developed (SRS) provided an authentic and straightforward context to learn more about aquaponics by measuring the change in ion concentration over time in an applied system. Many items, which we have addressed in the body of this thesis, should be addressed in further research. The shortcomings in our own research include inconsistency in data collected and using qualitative and subject tests as a means to quantify data. Through the development of the BAS we have created an aquaponics system that has been optimized for teaching. Although promising in its prospects, we are unsure of its power in the classroom. As we have designed this system with teachers in mind, the next logical step would be to implement it in a STEM classroom with a particular unit in mind. Once the BAS is implemented in a classroom, an inquiry based and student–centered curriculum will need to be developed which would address the various aspects of the BAS. Future development would include the integration of lesson plans with observation and manipulation of the organisms and abiotic factors (like the bell siphon) within the BAS. Additional research might also include student achievement gains using different curriculum with and without the BAS.
REFERENCES


