Quaquaponics:

Incorporating Tilapia into an Automated Aquaponics System to Grow Lettuce, Chard, Spinach, and Kale

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Abstract

This research paper investigates the feasibility and efficacy of constructing a remotely-monitored aquaponics system. Specifically, this paper discusses an aquaponics system that uses water from tilapia tanks to nourish lettuce, swiss chard, spinach, and kale; additionally, this system is connected to the Internet for remote monitoring. Through a combination of literature review and observational data, the paper explores the technical aspects of constructing and maintaining such a system, as well as the benefits and challenges associated with implementing both fish water and remote monitoring. The findings detail a viable approach to implementation of remotely-monitored aquaponics systems to maximize space and resources when feeding a planet on the brink of an overpopulation crisis.

Index Terms

- **Hydroponics:** an energy-efficient form of agriculture in which plants are grown without soil in an artificial environment with carefully controlled nutrients.
- **Aquaponics**: a subset of hydroponics that uses nutrient-rich water from fish tanks as fertilizer for plants.
- **Websocket**: an Internet protocol providing two-way communication between a browser and a server over a persistent connection.

Introduction

As the world population continues to grow rapidly and is expected to reach 9.7 billion by 2050, food security has become a major concern, especially in urban areas, where land and water are scarce and polluted (Baus, 2017). Open-land farming currently provides the majority of the world's farmed food, but it is environmentally taxing and placed in jeopardy as urbanization continues to expand (Baus, 2017). Thus, the agricultural industry is investing in greenhouses, which allow plants to grow year round, in climate controlled environments, for a more efficient configuration. Although greenhouses have a higher initial investment than traditional outdoor farming, they protect plants from insects and disease and optimize plant growth, paying for themselves over time (Bartzas et al., 2015).

One relatively new method of greenhouse farming is hydroponics, which grows plants in nutrient-rich water instead of in soil. Hydroponics offers a sustainable and efficient alternative to traditional agriculture that can produce higher yields and quality with less resources and environmental impact. Additionally, this method of farming doesn't use environmentally harmful pesticides and chemicals. Hydroponics can also ensure food security and sustainability in urban and peri-urban areas, where land and clean water are not readily available (Velazquez-Gonzalez et al., 2022).

However, hydroponics also comes with several disadvantages. One is that it requires a high initial investment and highly trained labor to operate the system. Furthermore, this method of farming may cause environmental pollution if the residual nutrient solution is not properly disposed of or recycled, as it can stimulate algae growth and oxygen depletion in water bodies (Velazquez-Gonzalez et al., 2022). Finally, because of its reliance on technology, hydroponics is extremely vulnerable to technical failures and power outages unlike traditional open-land farming.

Aquaponics, a subset of hydroponics, is a method of agriculture that uses nutrient-rich water that results from raising fish to serve as fertilizer for plants (Ako & Baker, 2009). It is more efficient than conventional hydroponics, where nutrients are added, because the fish provide the nutrients for the plants, through their waste, and also act as a source of food. Therefore, instead of building a system that only grows plants, through the method of aquaponics, the same system can provide two different sources of food within the same footprint.

Due to access limitations, it was necessary for the aquaponics system to be remotely accessible via a website. However, a significant design problem existed: the lack of an open-source library to integrate an aquaponics system with a web server for remote monitoring and control of water pumps. Aquaponics itself is a closed-loop system that efficiently utilizes nutrient-rich water from fish tanks to nourish plants, reducing environmental impact and resource consumption. However, the integration of aquaponics with web server technology holds tremendous significance. Remote monitoring and control via a web server can revolutionize aquaponic systems, allowing growers to oversee and adjust system parameters from anywhere, improving resource management, and crop yield (Velazquez-Gonzalez et al., 2022). In previous research, engineers have used Raspberry Pis and Arduinos to wirelessly control an NFT hydroponics farm, allowing them to record water metrics remotely and automate the nutrient control process (Crisnapati et al., 2017). Having remote monitoring on a website enabled us to make sure the aquaponics system is working properly, and if any problems arose unexpectedly, we could be notified to fix them before the plants die. This research has the potential to advance the field by enabling real-time data collection, analytics, and automation. Further refinement could lead to applications in commercial agriculture, urban farming, and sustainable food production, enhancing the scalability and accessibility of aquaponic systems while promoting efficient and eco-friendly food production (Velazquez-Gonzalez et al., 2022). Another future improvement is automating the amount of water reaching each channel, instead of the whole system, to optimize watering for each plant species (Krishan et al., 2020).

Grow lights prolong the growth cycle of the plants. Whereas with traditional farming, the amount of light plants receive is solely dependent on the day-night cycle, grow lights in a greenhouse can turn on when the sun goes down. This is especially useful on short winter days or cloudy days, where grow lights can substitute the light lost from suboptimal lighting. Furthermore, LED strips in the red-blue spectrum can efficiently turn electricity into plant growth; since chlorophyll in the plants reflects green light, there is no need to emit green light (Kulikova et al., 2019).

There are other factors to consider when developing an aquaponics system such as water circulation and type of plants. There are many different types of water circulation systems for aquaponics, but Nutrient Film Technique (NFT) is the most cost effective (Heredia, 2014). It is also one of the most effective because it allows the roots of the plants to be aerated in addition to being submerged in water, which is important for proper plant growth (Ako & Baker 2009). It is important to choose the right plant for an aquaponics system because different plants have different root structures, which favor different water circulation systems: lettuce and other leafy greens grow well using NFT (Heredia, 2014) because they are very low maintenance ("How to grow lettuce," 2022). In addition, it is important to choose a plant that thrives in the same pH range as the fish used: lettuce works well with tilapia (Ako & Baker, 2009.

It is important that the frame be built to the specifications required both for a proper NFT system and to effectively grow lettuce. In an optimal NFT system, the growth channels are square ("What is the nutrient," 2022). We used rectangular vinyl downpipes rather than round PVC pipes. To effectively grow lettuce, a 7.5 cm (or about 3 in) pipe is best ("What is the nutrient," 2022). We decided to use 3 in by 4 in downpipes and placed them on their side so they have a depth of 3 in and a width of 4 in. The plants were also placed in net cups, which are filled with clay pebbles ("What is the nutrient," 2022). Growing plants in pipes stacked above each other in a vertical NFT allows for efficiency of space and better airflow, which reduces the chance of diseases. So, we placed our pipes on racks above each other, but tilted the frame so the plants had room to grow. Lettuce is best grown at least 7 inches apart ("How to grow lettuce," 2022), which is why we chose to have 8 plants in each 5 ft pipe, allowing them to have ample room to grow.

One of the major disadvantages of developing an aquaponics system is the high initial investment. In our project, we attempted to lower the cost of the system by using cheaper materials and 3d printing expensive parts. Although PVC pipes are often used in hydroponics because they are readily available and easy to work with, we decided to use aluminum downpipes not only due to their rectangular shape, but also because they are significantly cheaper than PVC pipes. Purchasing 5 3 in. x 4 in. x 10 in. aluminum downpipes is about 50% less expensive than purchasing 5 3 in. x 10 ft. PVC pipes. Additionally, we 3D printed custom 2020 brackets for parts of our frame, which not only worked better for our design, but were significantly less expensive than 2020 brackets sold by the manufacturer. We also laser cut end caps for the downpipes instead of buying them to reduce their cost.

Requirements

Structure and Cultivation

- Construct a 10-channel NFT aquaponics farm using tilapia water
- Construct the farm to fit within a 10 x 3 x 6 ft space
- Connect the farm to the web to control pumping and grow lights remotely
- Construct channels such that water flows through without being blocked by the roots of the plants
    - 3D print caps and supports for the channels
    - Position the channel supports to tilt the channels at a 5° angle
    - Construct each channel to contain 7 hydroponics cups with clay pebbles and 7 plants without collapsing
- Construct farm and channels such that channels are easily removed and opened for cleaning
    - Channels will be constructed with buckles on each end so one half can lift from the other. These buckles will rest in grooves made in the downpipe so that they do not move unless unbuckled
- Fully grow 10 5-ft channels of leafy greens by the end of the school year

    - (Fully grown means that the plants reach their maximum supported size of an 8 inch diameter and 1 ft height. If the plants grow any bigger than this theoretical cylinder, we will have to prune them down by harvesting the leaves so they don't grow too big and steal the nutrients of plants downstream)
    - Grow 3 channels of lettuce, 3 channels of swiss chard, 2 channels of Spinach, and 2 channels of kale
    - Grow at least 14 plants of each type at the same time within 35 days of germination

<u>Pumping</u>

We will add a water pump to the fish tank and create a water tube network to deliver nutrient filled water to all 10 hydroponic channels.

- Deliver nutrient filled water to all 10 hydroponic channels
    - Transport water from fish tanks to channels
- Control the amount of time the pump is pumping
    - Automate electronically
- Control the amount of water pumped to any individual channel by adjusting the valve respective to the channel
- Pump water to each channel for 12 hours a day (7am - 7pm)
    - Cut off water for the remaining 12 hours a day (7pm to 7am)
    - Sync pumping with grow light automation
- Pump water for a whole week through the inflow pumping without any manual adjustments
- Create an inflow piping system without leaks

    - Construct all breaks in the tubing (t connections, valves, ending at the NFT channel) so they are dry after heavy use
        - Put ph paper at the bottom side of each connection that will not change color after 1 week

<u>Internet Connection and Electronics</u>

We will connect the raspberry pi inside the greenhouse to a web server on TJ director for remote monitoring and long-term analytics for plant-growth optimization.

- Construct the farm so that it is controllable through a Raspberry Pi internet connection
    - Wire the Raspberry Pi to Arduinos controlling the pumps
    - Program the Raspberry Pi to automate the water to be on for 12 hour cycles (on 7 am-7pm)
    - Program the Raspberry Pi to update the server with pumping statistics, and environmental data like the temperature/humidity in the greenhouse. This data will be stored in a database for future analysis and optimizations.
- Position the Raspberry Pi so it can connect to the TJ internet continuously. This metric will ensure we don't face buffering when accessing the website (this assumes the TJ wifi doesn't shut off/restart every night at midnight, but we'll see how this turns out)
    - Program the Raspberry Pi to maintain a continuous websocket connection with the director server
- Develop a website on TJ's director server that has 100% uptime so we can go to the website at any time during the week and get a webpage without any errors
    - Program the website to display a dashboard with live farm data
- Install automated grow lights system

- Connect to Raspberry Pi, which makes calls to a weather API

Significance of Research

This research project is significant for several reasons. First, hydroponic farming is an understudied practice, yet seems to be the most promising and sustainable method for agriculture in the future. By implementing an aquaponics farming system, students will be able to research sustainable farming practices firsthand and see the role automation plays into farming, applying their STEM knowledge to a more humanitarian effort. Furthermore, most hydroponic farms are currently run with many external nutrients, a time consuming process for farmers (Crisnapati et al., 2017). However, by incorporating tilapia into our system, we remove the need to use external nutrients, saving nutrient costs and time for farmers who might want to have a farm that requires less management (Ako & Baker, 2009). Although manual aquaponics farms exist, combining remote control via web servers with a partially self-regulating fish and plant system is yet to successfully be implemented and documented (Crisnapati et al., 2017; Ako & Baker, 2009).

Application Potential

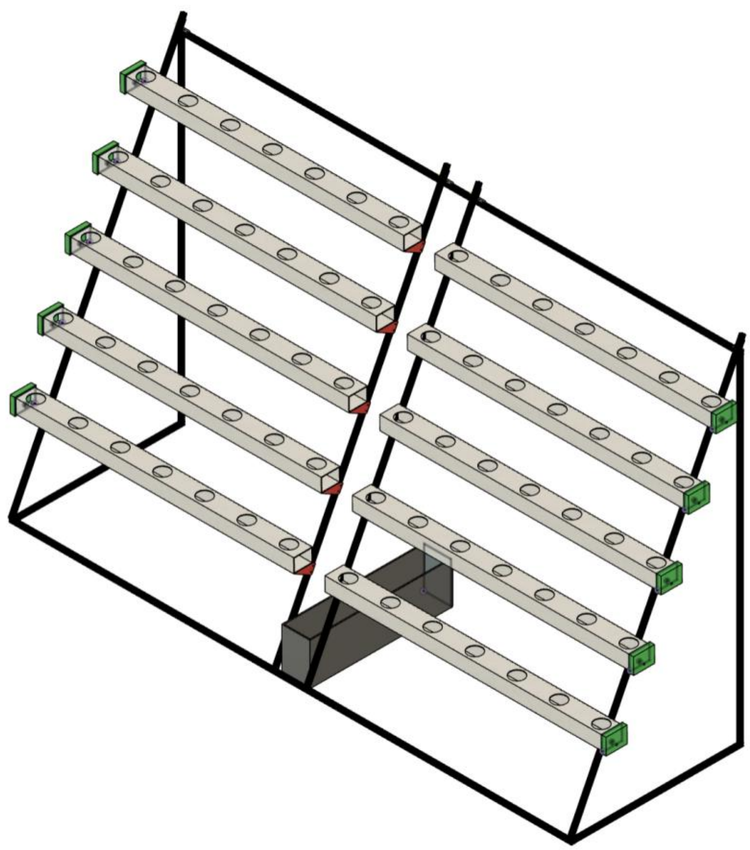
Our aquaponics system design can be used in various settings, including backyard gardens, urban rooftops, community farms, and educational institutions seeking sustainable food production methods. Its adaptability and scalability make it suitable for both small-scale hobbyists and large-scale commercial ventures aiming to integrate aquaculture and hydroponics efficiently.

If the system we built is further developed in future years, a larger scale of our farm could be implemented within the greenhouse, since our farm design is modular and easily expandable.

If the farm was expanded to be large enough to produce a significant output, service and charity organizations could use the output to donate to communities around our school.

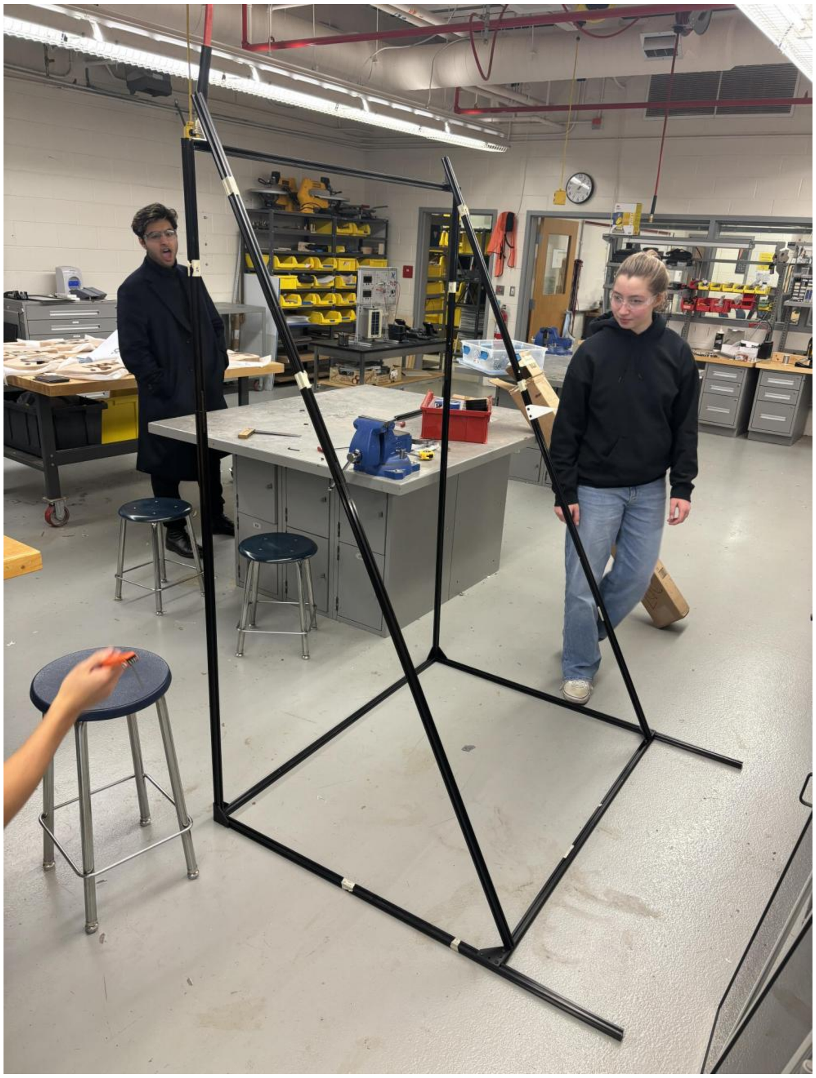
Procedures

In the initial planning stage, we delved into researching materials and potential designs for our hydroponics system. We took our ideas and translated them into a CAD model, ensuring everything was meticulously planned.



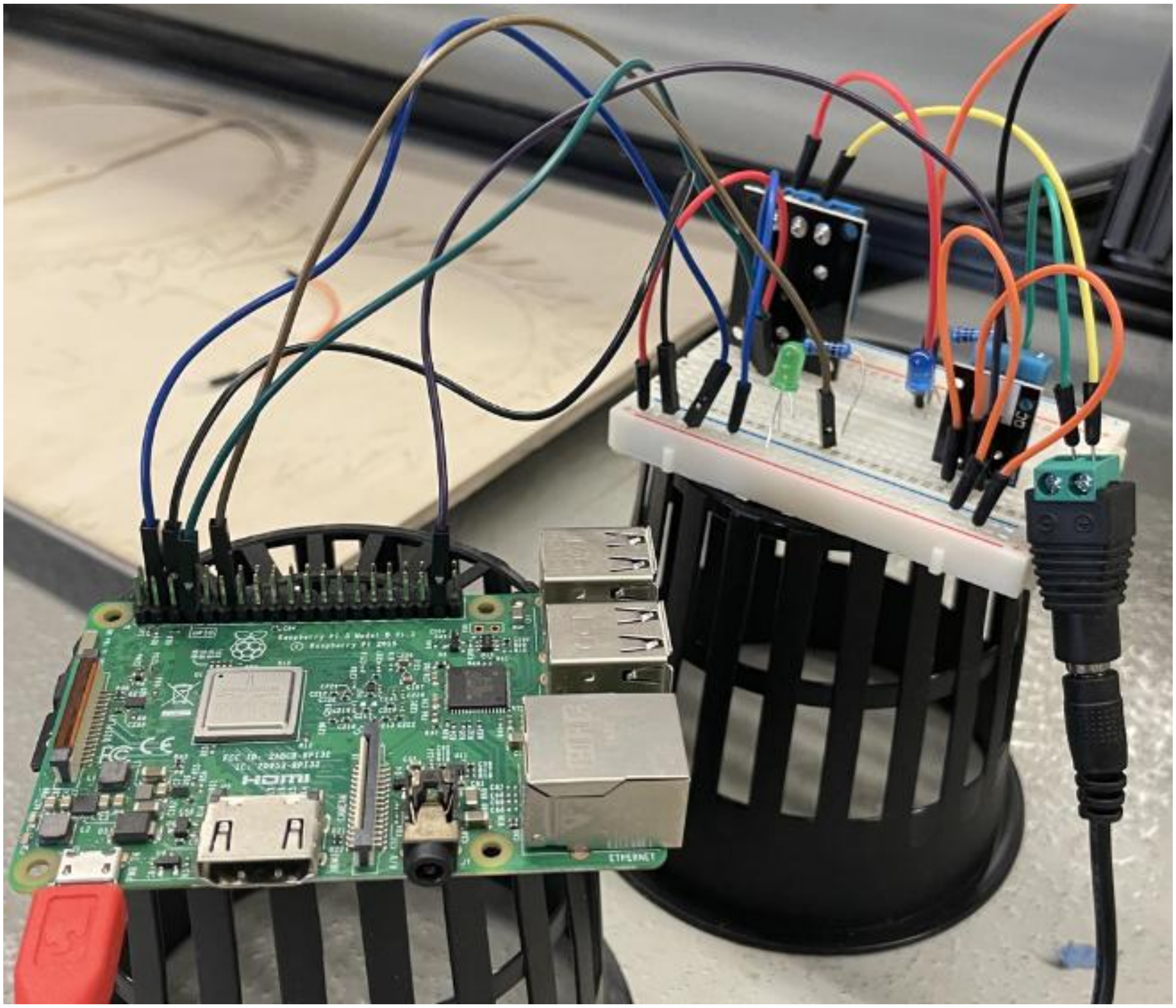
Once the design was finalized, we created a comprehensive bill of materials to guide our procurement process.

Moving on to the frame construction, we began by connecting 2020 aluminum to form the skeleton of our system. We crafted a sturdy base and added diagonal bars for structural support. We connected the base and diagonal bars with vertical bars, ensuring the frame was sturdy. To reinforce the structure, we printed brackets and laser-cut channel holders before subjecting the frame to a rigorous stress test to ensure it could bear the weight of our hydroponic setup.



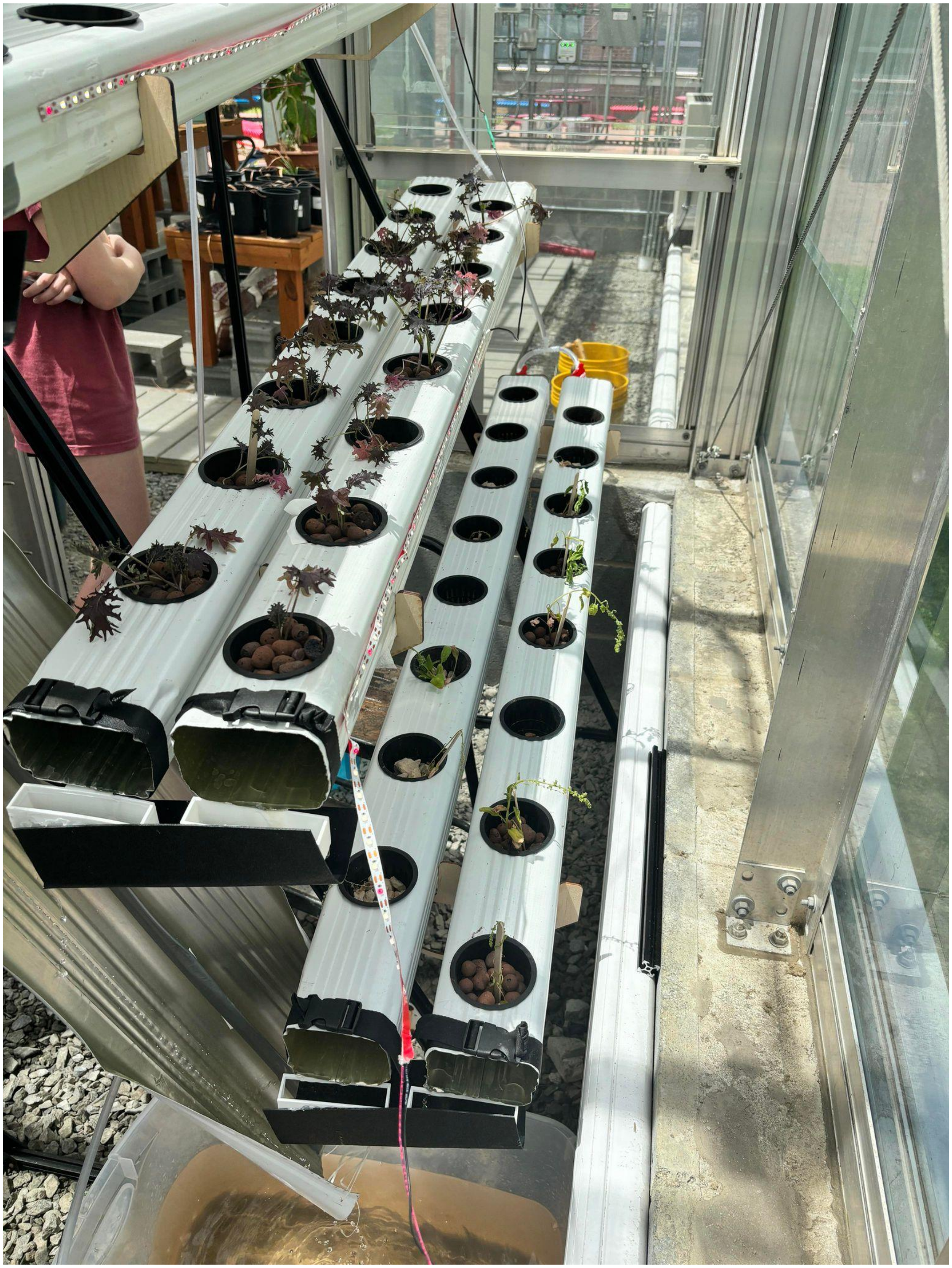
Transitioning to the pump and piping phase, we focused on establishing a reliable water system. We tested the pump and adjusted water flow using valves to achieve optimal performance. We used gutter downpipes for the horizontal channels, and used a hole saw to cut 3” holes for the net cups. Carefully, we added piping to the frame, waterproofing and monitoring for leaks during testing periods. To facilitate water distribution, we installed bent plastic chutes at each level to prevent splashing.

Incorporating electronics and a Raspberry Pi into our system was the next logical step. We coded a dedicated website and integrated it with the Raspberry Pi, enabling remote monitoring and control. Additionally, we added indicator LEDs and sensors to monitor temperature and humidity. With the integration of relays, we automated functions such as water pump operation and grow light control.



On the side, we pursued plant germination. We started with paper towel germination, and planted a couple bags each of lettuce, swiss chard, kale, and spinach. After facing issues like red spots of mold, we transferred the plants to soil cup germination. Once the plants had matured sufficiently, we transferred them from germination cups to hydroponic net cups filled with clay pebbles. These net cups went in the final frame.

Finally, the culmination of our efforts led us to transfer the system to a greenhouse environment. We dismantled the frame, relocated it to the greenhouse, and reassembled it. With the addition of a power source and extension cord, we ensured uninterrupted operation. Though we encountered challenges such as failing to utilize tilapia water, we remained adaptable and continued to refine our aquaponics system for sustainable plant growth.



Schedule

Week	Progress
1	Completed CAD of frame with channels, completed bill of materials
2	Assembled basic frame
5	Installed diagonal channel-support bars to the frame, launched website
7	Connected Raspberry Pi to FCPS WiFi, programmed Raspberry Pi to power basic circuits
8	Connected Raspberry Pi to website for data transferring
9	Began cutting hydroponic channels and germinating plants
10	Transferred germinated plants to peat pods, laser cut channel holders
11	First test of water flow through the farm
13	Finished cutting, drilling, and installing all

	channels, channel holders, and end caps to the frame
14	Installed pipes and pumping into the completed frame, installed drainage channel
15	Coded and wired Raspberry Pi to power water pump with timed on/off cycles
17	Installed end-of-channel water ramps
18	Programmed email notifications from Raspberry Pi to website, finished fixing water leakage
19	Moved farm to greenhouse, installed and programmed grow lights

Testing Methods

Our first test was aimed at ensuring the structural stability of our frame design. Our frame test was conducted via pullup test from the top horizontal bar to see if the frame could handle the weight of a pullup. Although the horizontal bar was bent during the test, it went back to its natural position after the test, resulting in no permanent deformation.

The next major testing milestone was ensuring the water systems were functioning properly. We started by testing the head of our water pump, to validate that water could reach the top of our 6ft tall frame, which worked perfectly. Next, we split the tubing to two levels to make sure the pump could evenly distribute water. Unfortunately, we discovered that water always chooses the path of least resistance, meaning the water always chooses the lowest level, leaving the top channels dry. As a result, we added valves at each level, set to a different open percentage, to balance the pressure throughout the different levels. Our final water test occurred after fitting the final tubing system to the frame, and we ran the pump all day to test for leaks. The first two weeks of running the pump resulted in leaks. The first culprit was an insufficient angle of descent for the channels (we increased the decline from 2 degrees to 5 degrees) that caused the water to pool up and leak out the back of the channels. The second culprit was water shooting too far out the front of the channels, passing over the drainage tank. We solved the overshooting problem by 3D printing channel end walls, a drainage pipe out of an extra downpipe cut in half, and more drainage walls to direct the water from the end of the channels into the drainage downpipe. The combination of waterproofing measures made our system leak-free. We were able to successfully complete a day-long water test without any leaks.

Our last test was with the raspberry pi. We ran our automation program over the course of a long weekend with pings to our Director server every hour to see if the raspberry pi could stay online. The raspberry pi successfully stayed online all weekend, which ment we could trust it to control the watering cycle for our plants without shutting off.

Results

In this study, we found that constructing a remotely monitored aquaponics system was quite feasible. We were able to construct an aquaponics farm equipped with grow lights using easily purchased materials, and we were also able to automate the farm's pumping cycles using a

Raspberry Pi. Furthermore, the farm was able to communicate with a website, facilitating monitoring.

As for efficacy, however, the farm yielded mixed results. One issue was that water flow throughout the hydroponic channels was not consistent; both the amount of water flowing and the flow path varied over time. Because of this, the water moved away from the roots of some plants, which led to their eventual death. Additionally, the farm was able to connect to WiFi via the Raspberry Pi, but the school network to which it was connected was unstable. This resulted in several "black-out" periods where the farm could not send updates to the website, which consequently emailed warning notifications to us. These were misleading notifications, since the farm had not actually shut off; the network had just been too unstable. Lastly, we found that setting up an aquaponics farm required extensive effort, which is noticeably less efficient than the setup for conventional farming. However, once the system was set up, the automation did most of the work, making it more efficient than conventional farming after everything was planted.

Overall, our research yielded a farm that could be used for aquaponics. We were unfortunately not able to integrate tilapia water into our farm, since the available fish water had salt levels that were too high for plants to survive in. However, the farm itself was a functional design for aquaponics.

Discussion

Although we were not able to achieve the entire scope of a remotely-monitored aquaponics system as we originally intended, we had several successes. Our first, and largest, success was our frame, the structure that held the plants and directed water flow. The farm easily fit within the 10 x 3 x 6 ft space we originally budgeted, filling half that space, as we were able to maximize space efficiency by placing two channels next to each other on each level. This design not only minimized the space the frame occupied, but also reduced the cost required to build the structure. We used any extra material we had to support the diagonal bars, which received the most load from the channels. Additionally, we fulfilled our requirement of constructing channels that allowed water to travel through them without obstruction by roots, supported by 3d printed and laser cut brackets. Through trial and error we discovered that 3d printing was best for manufacturing irregularly shaped brackets, like the ones that supported the diagonal bar, but laser cutting was best for machining the flatting brackets, like the channel holders because it was faster and used cheaper, more readily available materials—wood instead of PLA.

Unfortunately, we did not meet all of the requirements we originally outlined for our structure. Instead of 10 channels, we decided to cut down to 8 channels, due to space limitations in the greenhouse. We also decided not to cut our channels in half for easy cleaning because we did not want to have too many moving parts to our channels to assure they would fulfill their role of directing the water and supporting the plants stably. If we had the chance to design the frame differently, we would shorten the channels, simultaneously decreasing the number of plants to maintain, as well as allowing easier cleaning without splitting the channel in half.

The next section of our project was pumping, which we were able to develop successfully, although not without leaks along the way. We originally planned to use plastic tubing and simple barb T valves to direct water from the pump to the different levels of channels, but that method was ineffective without adding barb valves as well. Without the barb valves, the water would travel to whichever path was easiest—the one that had the least gravity resistance.

The bottom channels received almost all of the total water flow, while the top channels received none. Adding barb valves to the tubing in front of each channel allowed us to control the pressure leading to each channel, so we could equalize it to force the water to travel equally to each channel. We also found that, after leaving the pump running for a few minutes, water would pool in the top of the channels and leak out. We discovered that tilting the channels to 7 degrees instead of 5 degrees as originally planned and bending the lip of the channel to keep the water contained fixed this issue.

The main issue with water flow originated from the other side of the channels, where water flowed into the collection tank. We intended for water to fall from the channels and directly into the collection tank, but we discovered that the height was a problem. Water splashed in all directions as it fell. In order to solve this problem, we added both a main collection channel to direct water from all of the channels into the collection tank, and smaller collection channels to direct water from each level to the main collection channel. We paired these with funnels we attached to the end of each channel. Although we were able to successfully direct the vast majority of the water from the channels into the collection tank, it was an unreliable solution because water was still dripping, and therefore was not completely controlled. In a similar situation, we propose funneling water directly into tubing, which minimizes the unpredictability of open falling water.

For the electronics part of our project, we fulfilled our goal of using a Raspberry Pi to automate the pump and the grow lights, but ran out of time to integrate this functionality into the website, as well as send data to the website to allow remote monitoring of growing conditions. We developed the two parts separately—the Raspberry Pi, which powers the pump 12 hours each day and controls the grow lights, and the website, which has the capability to display data, but were not able to integrate them. Instead of using Arduinos to control the pumps, as originally intended, we used a relay to add current to a circuit controlled by the Raspberry Pi, which reduced the cost involved with the project. We connected the Raspberry Pi to school wifi and programmed it to access the website, which would send us an email letting us know that the system was still up and running. Unfortunately, we have reason to believe that the connection with school wifi was not great because we also programmed the website to send us emails when the Raspberry Pi did not access it on schedule, and it would sometimes send us emails repeatedly for hours, signaling that there was an error with the Raspberry Pi, but the pump still ran properly during that time. We also intended to control the grow lights based on data from a weather API, but also did not have time to make that happen. We would not do anything differently with the electronics and website, just ensure we have enough time to integrate the two.

We received mixed results with the success of our plants. Both the spinach and kale seeds germinated well and were large and leafy enough to be transferred to the hydroponics system. Once they were planted in the channels, the majority of the kale survived, while the majority of the spinach wilted, although that might be due to unstable water flow in those channels. On the other hand, the lettuce and swiss chard seeds failed in the germination stage and were not ready in time to transfer to the channels. Overall, we were not able to fulfill our objective of growing 10 full channels of leafy greens.

Our largest failure, and biggest limitation, was our lack of access to nutrient-rich water produced by raising fish, which prevented us from practicing aquaponics rather than hydroponics. Although testing the success of aquaponics was one of the main goals of our project, we decided to continue with testing on our hydroponics system (we used a nutrient solution instead of nutrient-rich water from tilapia) in order to determine the effectiveness of our automation, which could be incorporated into an aquaponics system in the future.

Conclusion

In this research paper, we investigated the feasibility and efficacy of constructing a remotely-monitored aquaponics system, which is effective in feeding a growing population when resources such as land, labor, and money are scarce. Our objective was to grow four types of leafy greens—lettuce, swiss chard, spinach, and kale—in 10 channels, each pumped with water from a tilapia tank. A website paired with the system would be updated with pumping statistics and environmental data and would have the capability to make calls to a Raspberry Pi to adjust a pump and grow lights remotely.

Our project was not entirely successful, as we failed to enable remote monitoring through the website, fill 10 channels with thriving leafy greens, and use nutrient-rich water provided by fish, but it was not unsuccessful. We implemented automation of the pump and the grow lights using the Raspberry Pi and filled two channels with thriving kale. We believe further research should involve the areas of the project we did not complete, namely aquaponics, the incorporation of nutrient-rich water created as a byproduct of raising fish into a hydroponics system, and the implementation of remote-monitoring using a website.

Appendix

Original Design

The following figures and descriptions detail the original design of the farm. Figures 1 and 2 show the original design of the full farm.

Figure 1

CAD of the full frame (excludes pumps, pipes, fish tank, electrical components, hydroponics cups, and plants)

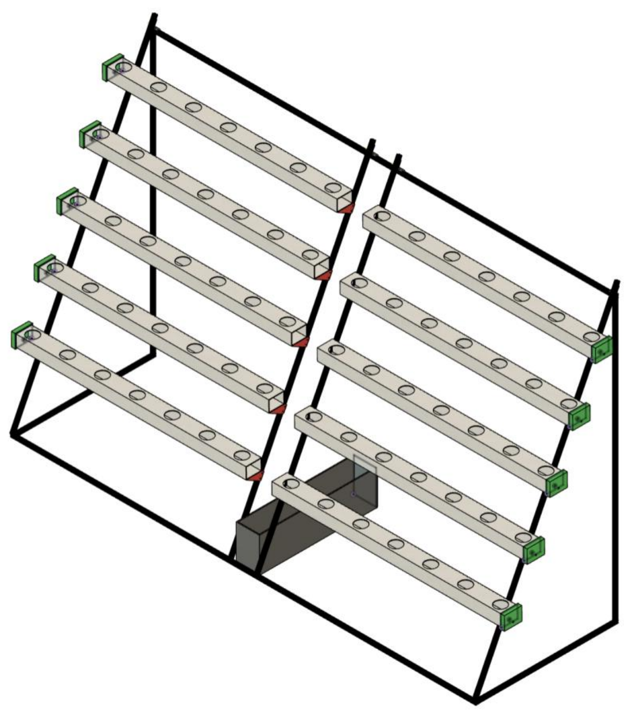
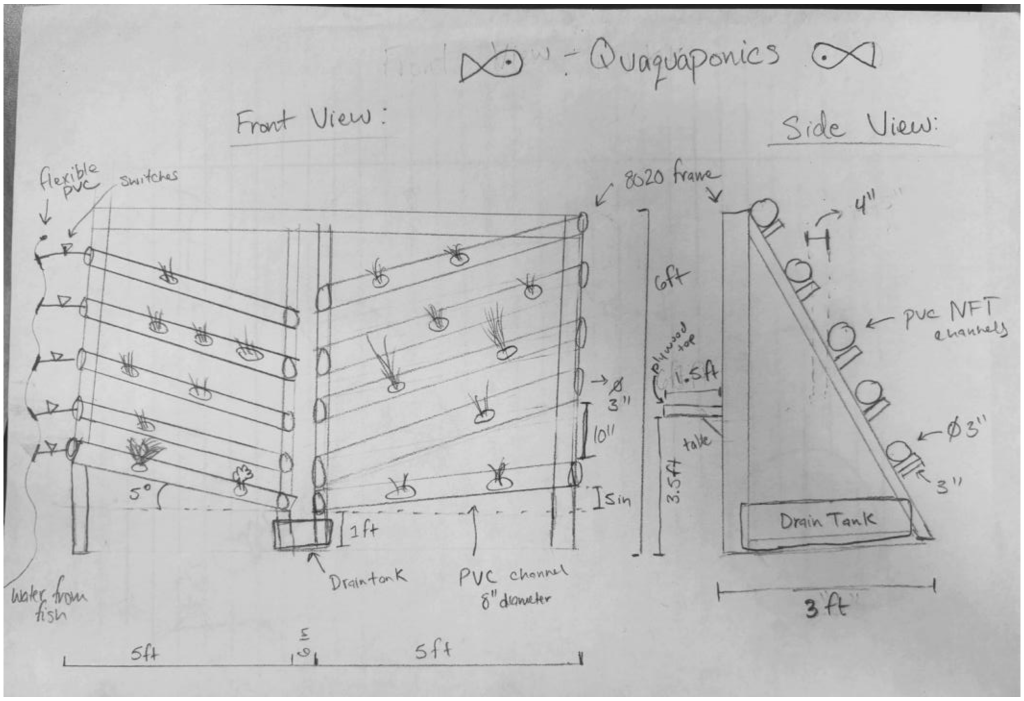


Figure 2

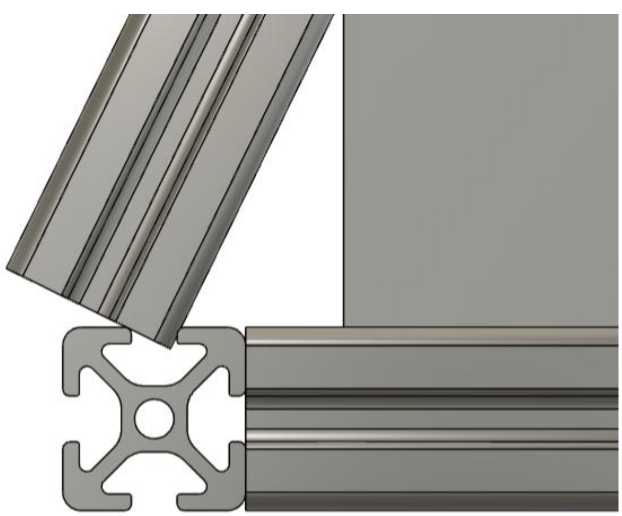
Sketch of full frame



As shown in Figure 3, the slanted channel-support bars simply rest on the bottom.

Figure 3

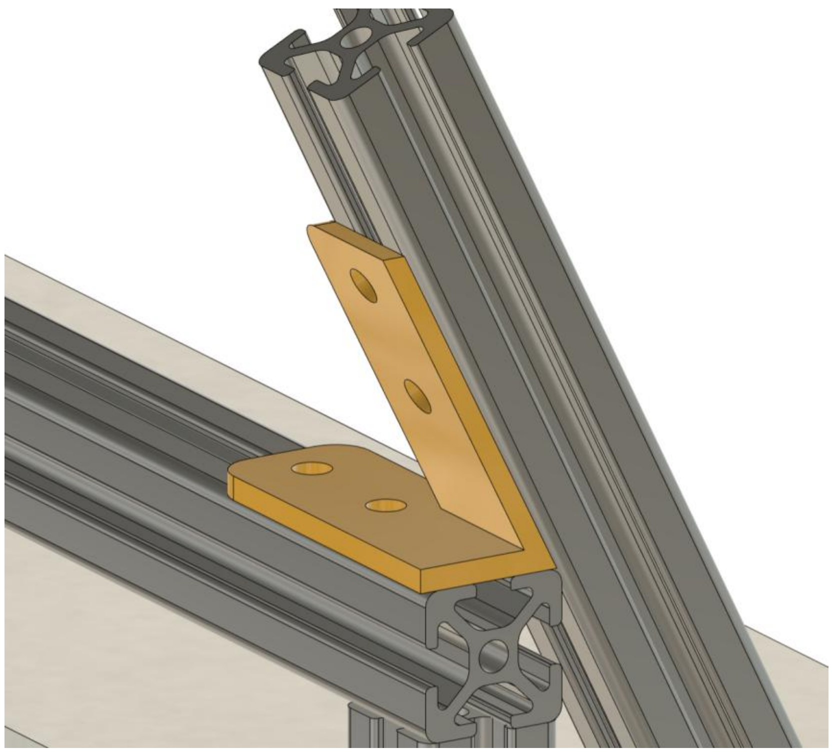
Bottom slant bar connection - not secured permanently, just sitting in the slot



This slanted bar is fastened to the frame at the top with a 3D-printed PLA bracket, as shown in Figure 4.

Figure 4

Top Bracket (Yellow) to secure the Slant Bar to the rest of the frame



Figures 5 and 6 show the hydroponic channels in which the plants grow as well as the 3D-printed end caps and supporting brackets.

Figure 5

Sketch of an NFT Channel with holes for hydroponics net cups

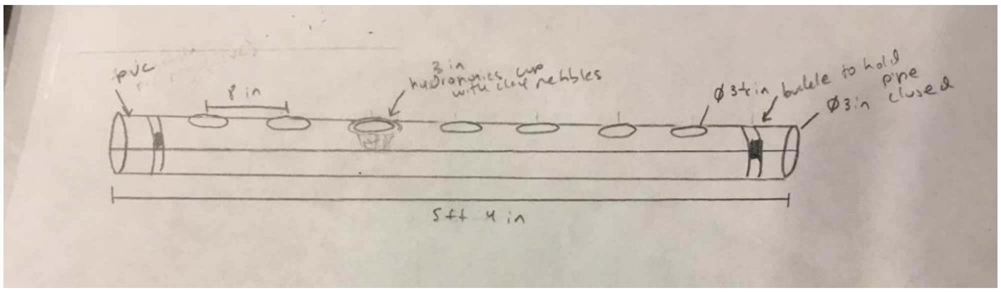
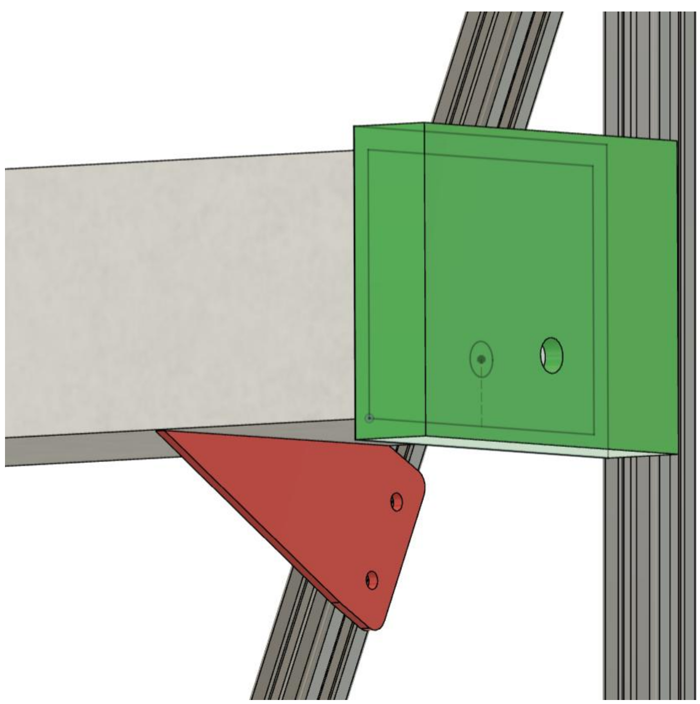


Figure 6

Channel End Cap (Green) has a hole for the tubing

Channel Support Bracket (Red) connects the channel to the Slant Bar and keeps the channel parallel to the ground



Figures 7 and 8 show the drainage tank and its dimensions.

Figure 7

Drainage tank; pumps will be installed to take the tank's water back into the fish tank

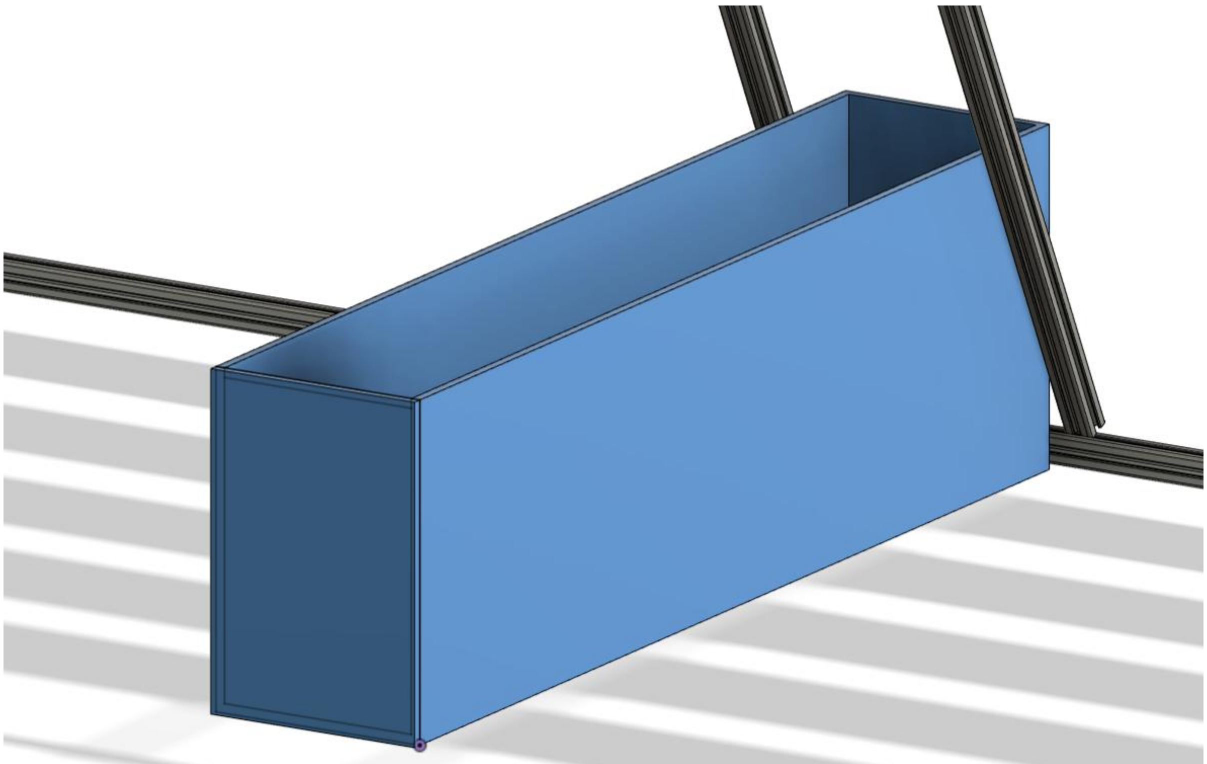


Figure 8

Sketch of drainage tank

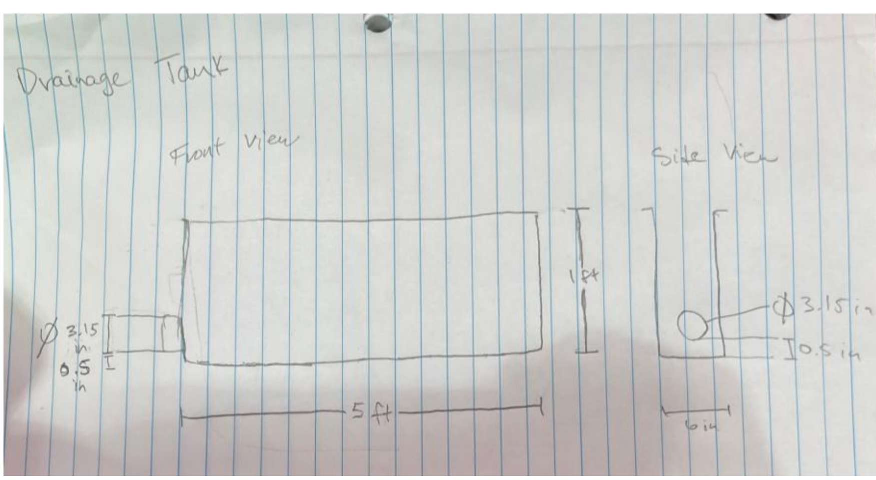
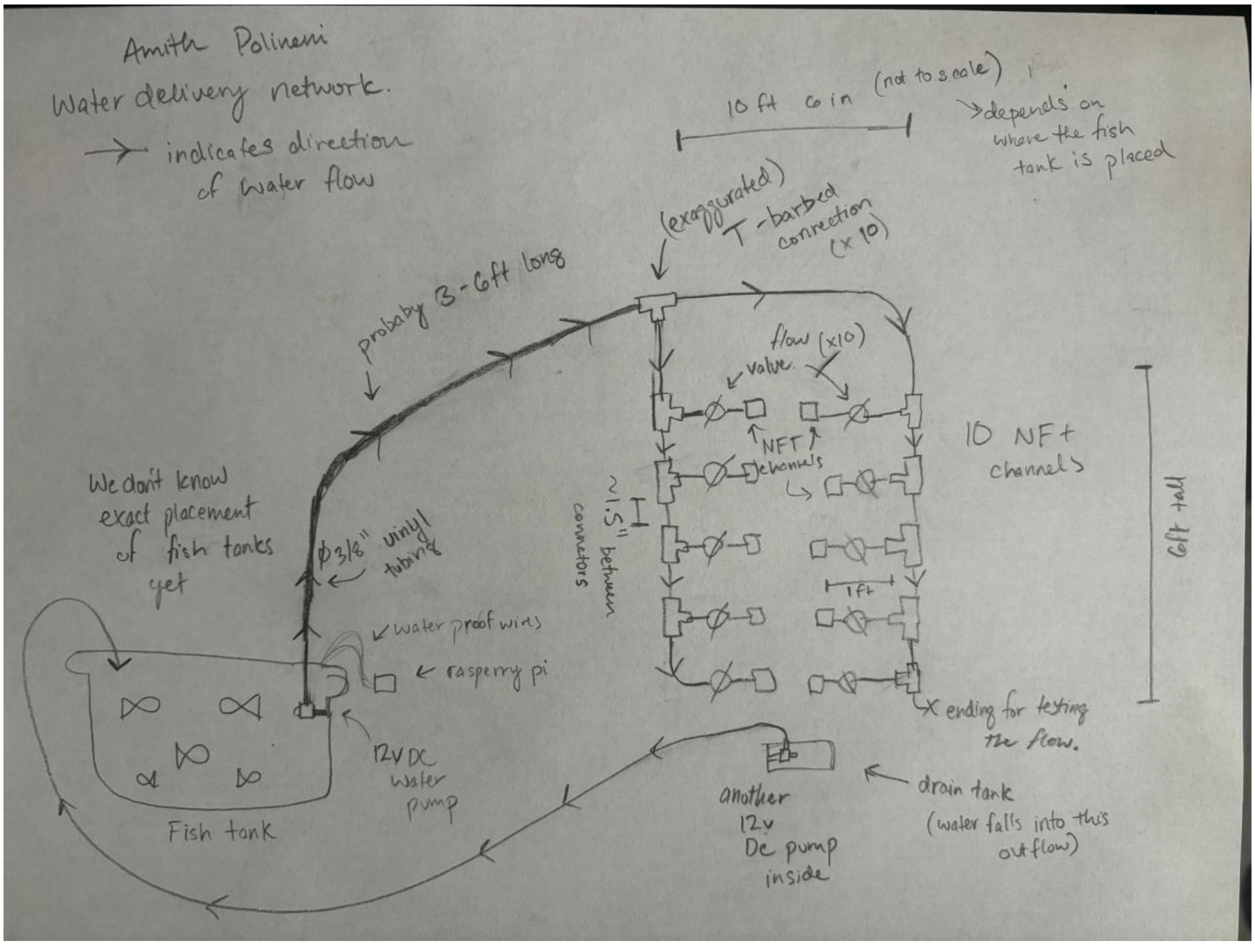


Figure 9 details the piping system.

Figure 9

Water Delivery Network (pumping schematic) from fish tank to the NFT channels with the various PVC connectors



Figures 10 and 11 are flow charts for the Raspberry Pi and website.

Figure 10

Web Server Flowchart

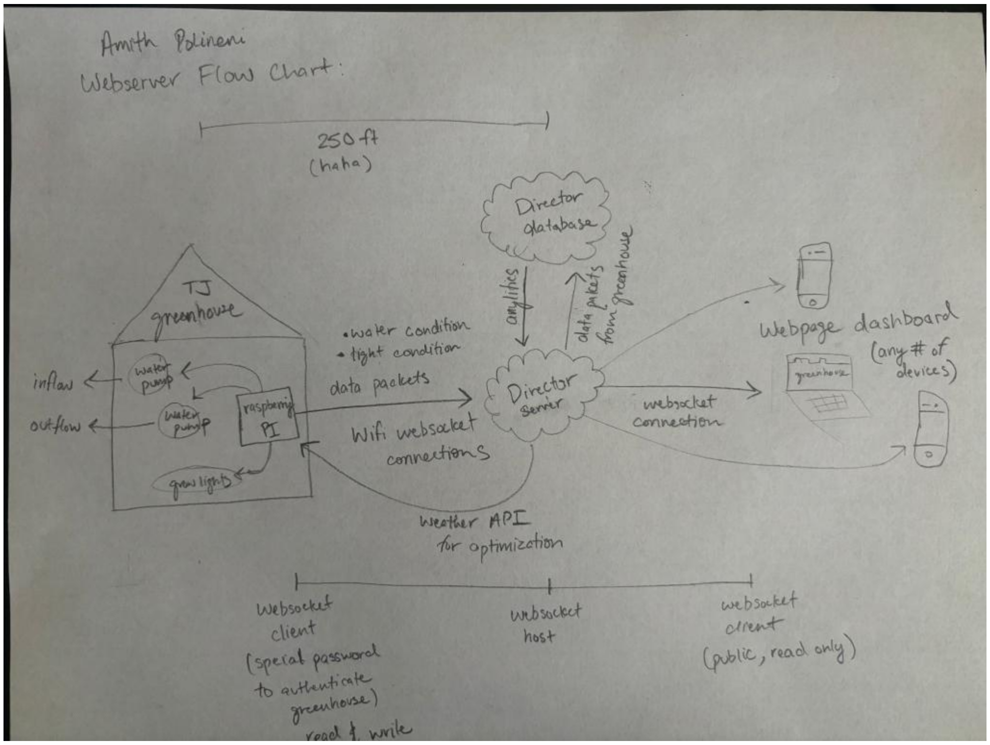


Figure 11

Grow Light to Raspberry PI flowchart.

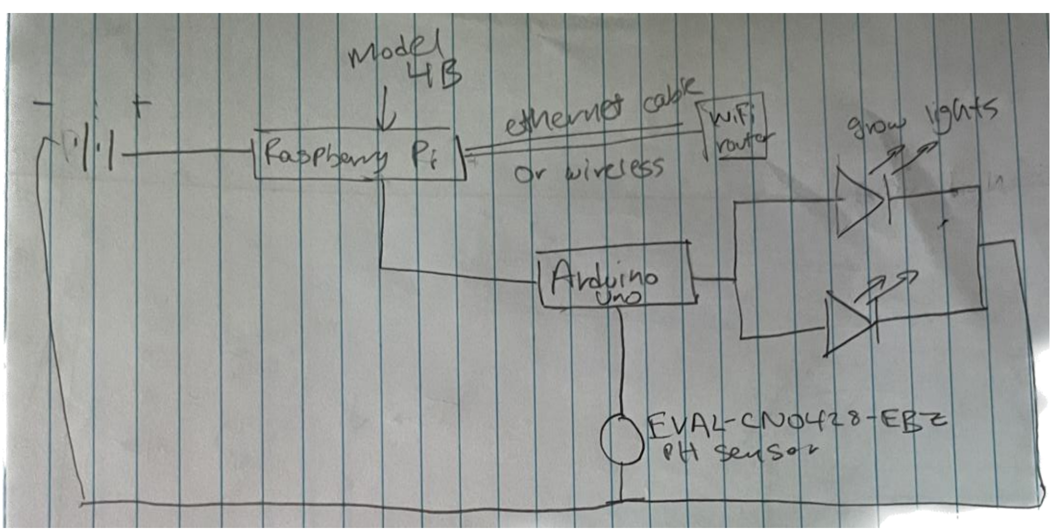


Table 1 is our bill of materials, a list of all the items we needed to build our original design. Items for the frame are highlighted in green, items for plant cultivation are highlighted in red, and items for electronics are highlighted in yellow.

Table 1

Bill of Materials

Component	Quantity	Cost
2020 Aluminum Extrusion	2	$149.60
2020 Corner connectors	1	$14.99
2020 Straight connectors	3	$36.75
2020 10mm Screws	1	$13.88
2020 Slide In Nut	1	$9.99
Plywood	1	$29.88
3 in. x 4 in. x 10 ft. White Vinyl Downspout	5	$69.90
Flexible PVC (Vinyl)	2	$41.98
PVC Barb T connection	1	$8.99
PVC Barb Valve	2	$21.98
Channel Holder (3D printed)	20	$4.80
Channel Connection Bracket (3D printed)	4	$0.60
Channel End Cap (3D Printed)	10	$16.30
Fish Tank	1	$14.99

Hydroponics cups	1	$23.99
Clay pebbles	1	$11.95
Buckles and straps	1	$8.99
Kale seeds	1	$3.99
Green ice lettuce seeds	1	$4.49
Spinach seeds	1	$2.99
Swiss chard seeds	1	$4.39
Seed Starting Pods (for manual germination)	1	$11.97
Grow lights	1	$22.99
Arduino Uno	1	$16.99
Raspberry Pi	1	$35.00
Ethernet cable	1	$6.99
ESP8266 - WiFi module	1	$19.90
Water Pump	1	$13.69
12V Power Supply	1	$7.89
TOTAL COST		$630.84

Actual Product

The following photos show what we actually built.

Figure 12

Assembled 4ft frame prototype

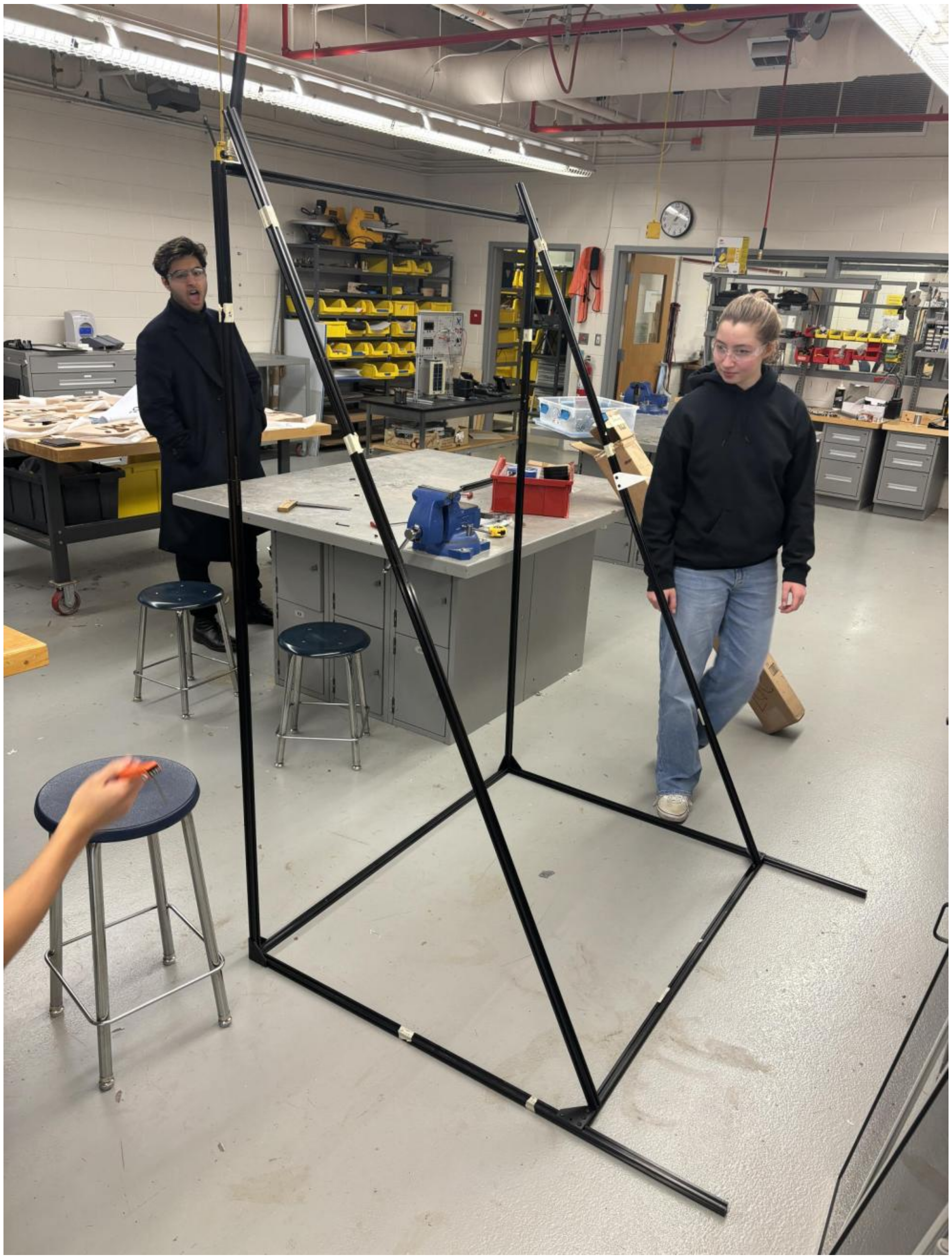


Figure 13

Stress testing the frame

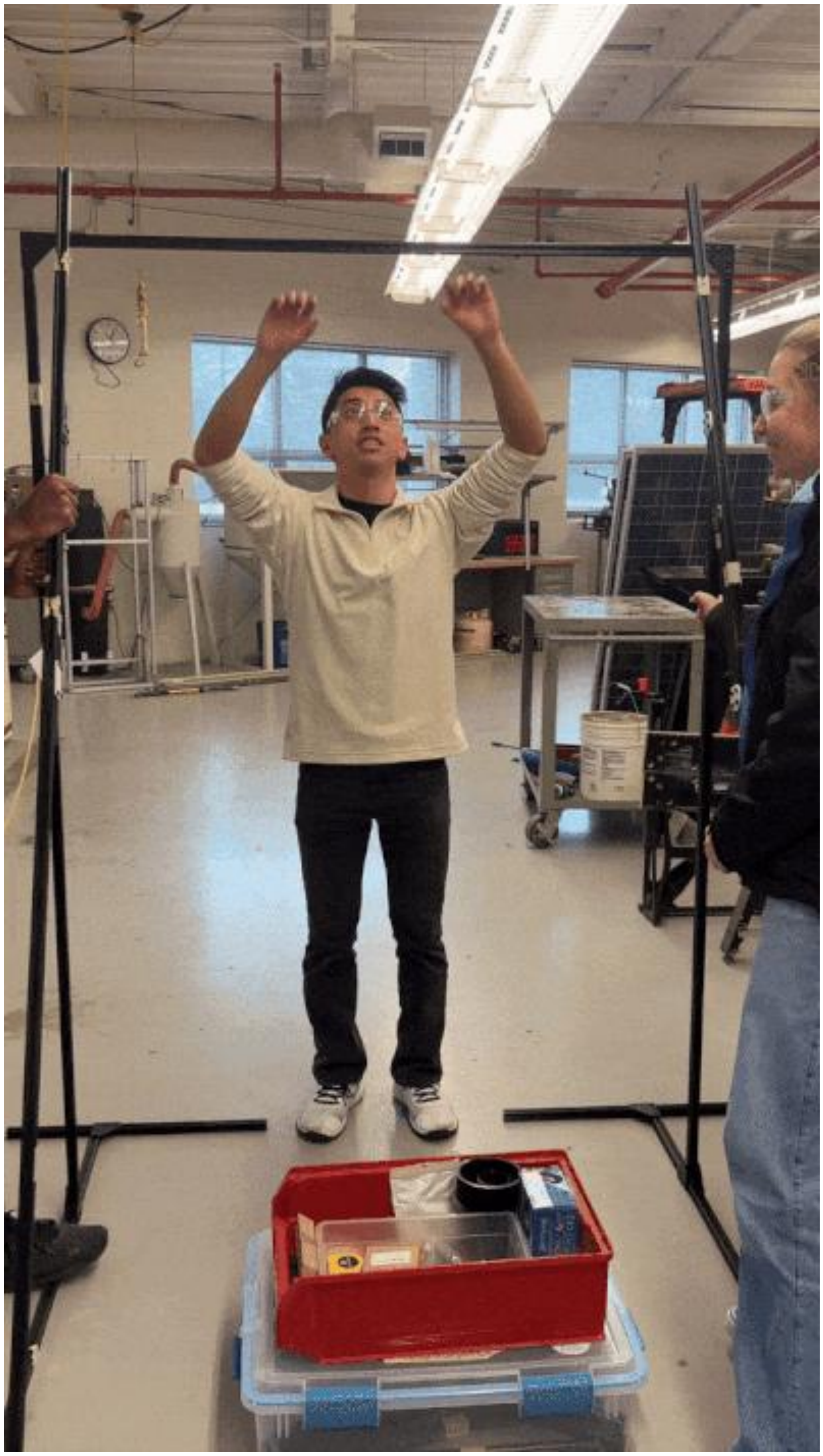


Figure 14

Water flowing through one channel

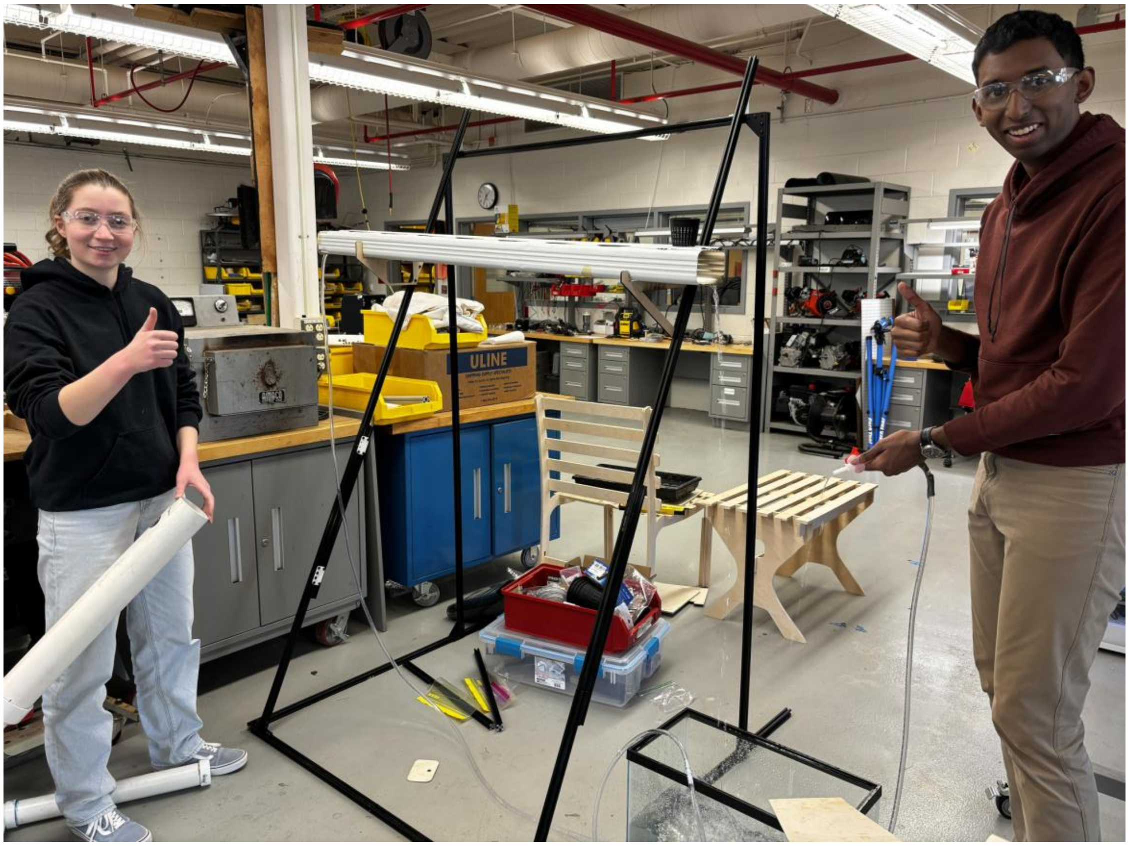


Figure 15

Frame with channels and channel brackets

Figure 16

Drainage system

Figure 17

Raspberry Pi and circuitry

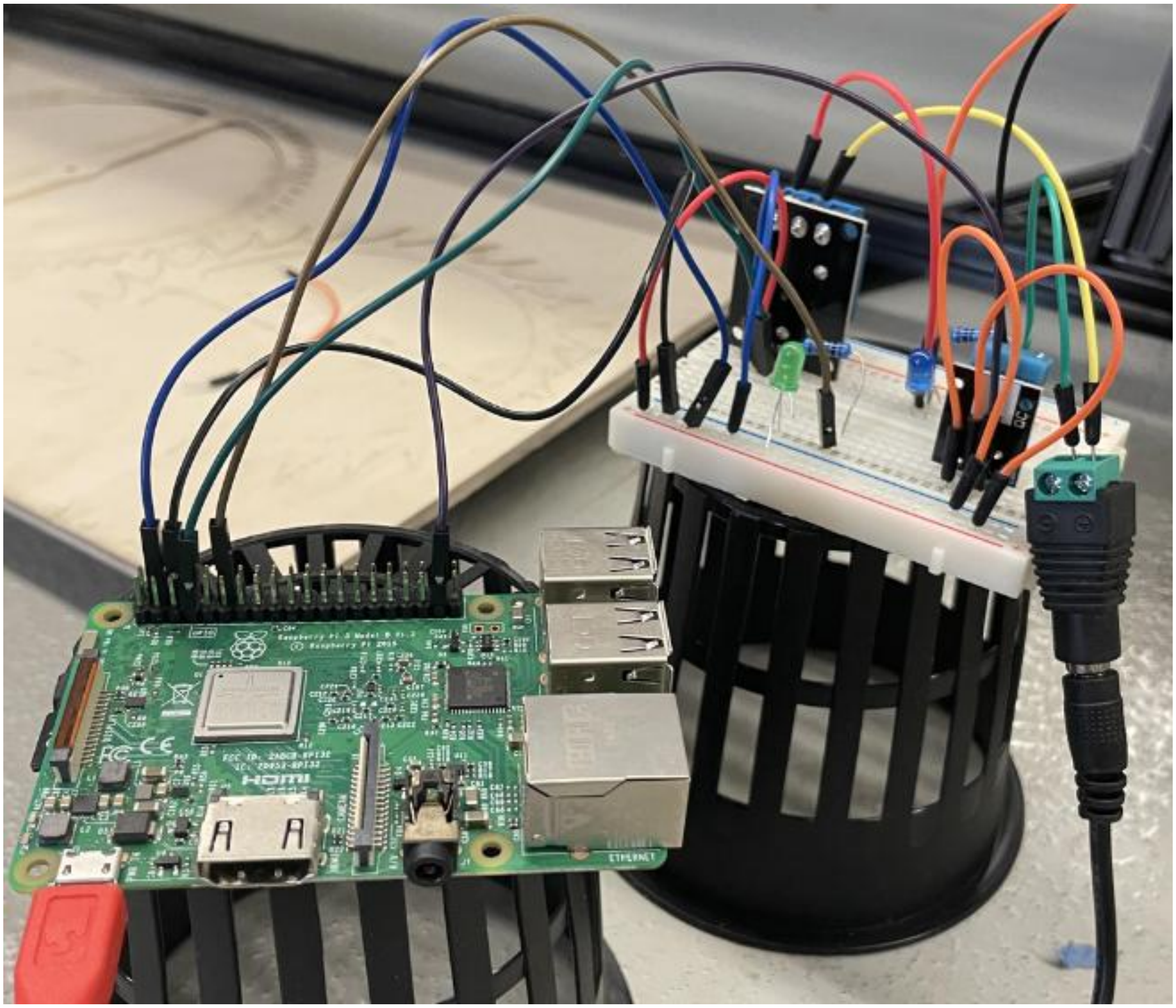


Figure 18

Completed frame water tank, drainage channels, and full waterproofing.

Figure 19

Plants in with clay pebbles in net hydroponics cups

Figure 20

Completed farm with plants inside the greenhouse!

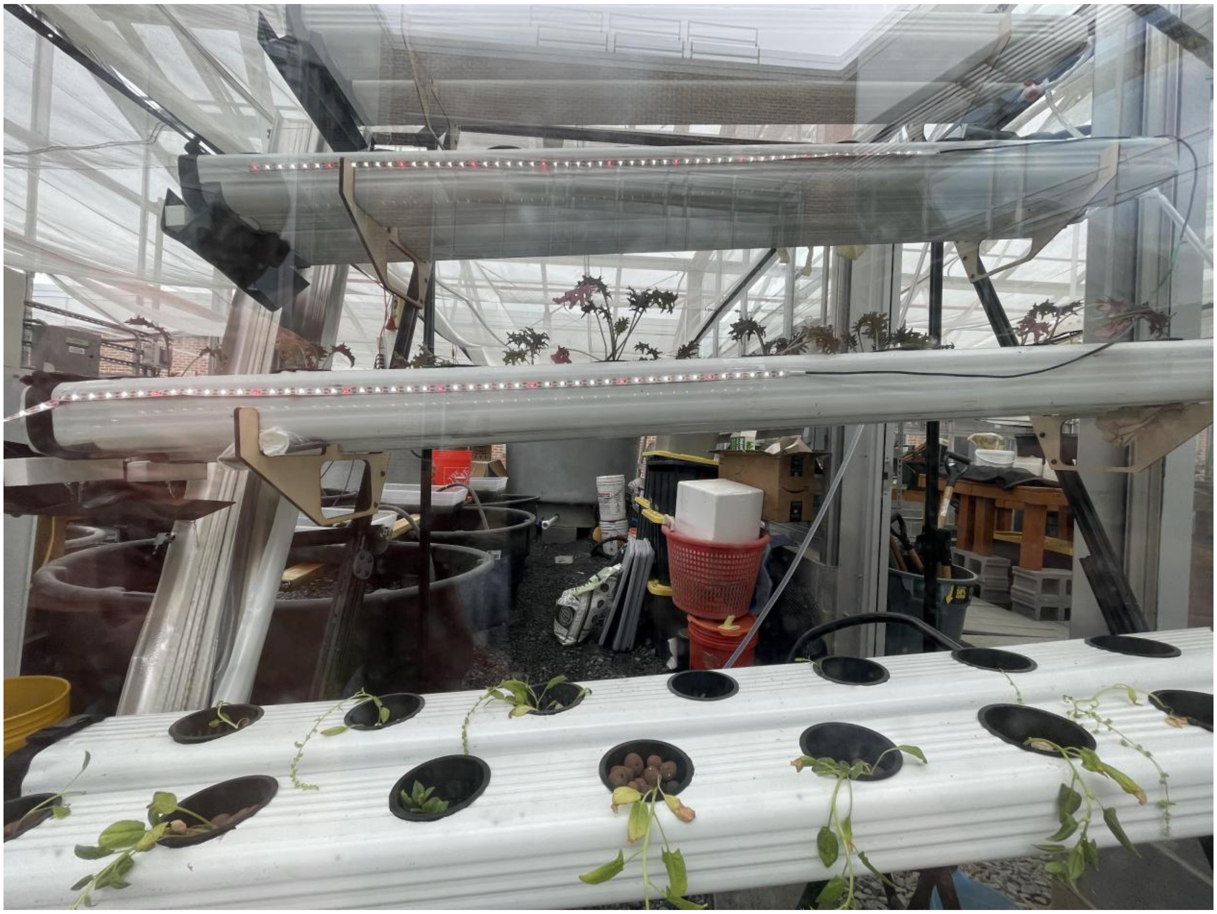
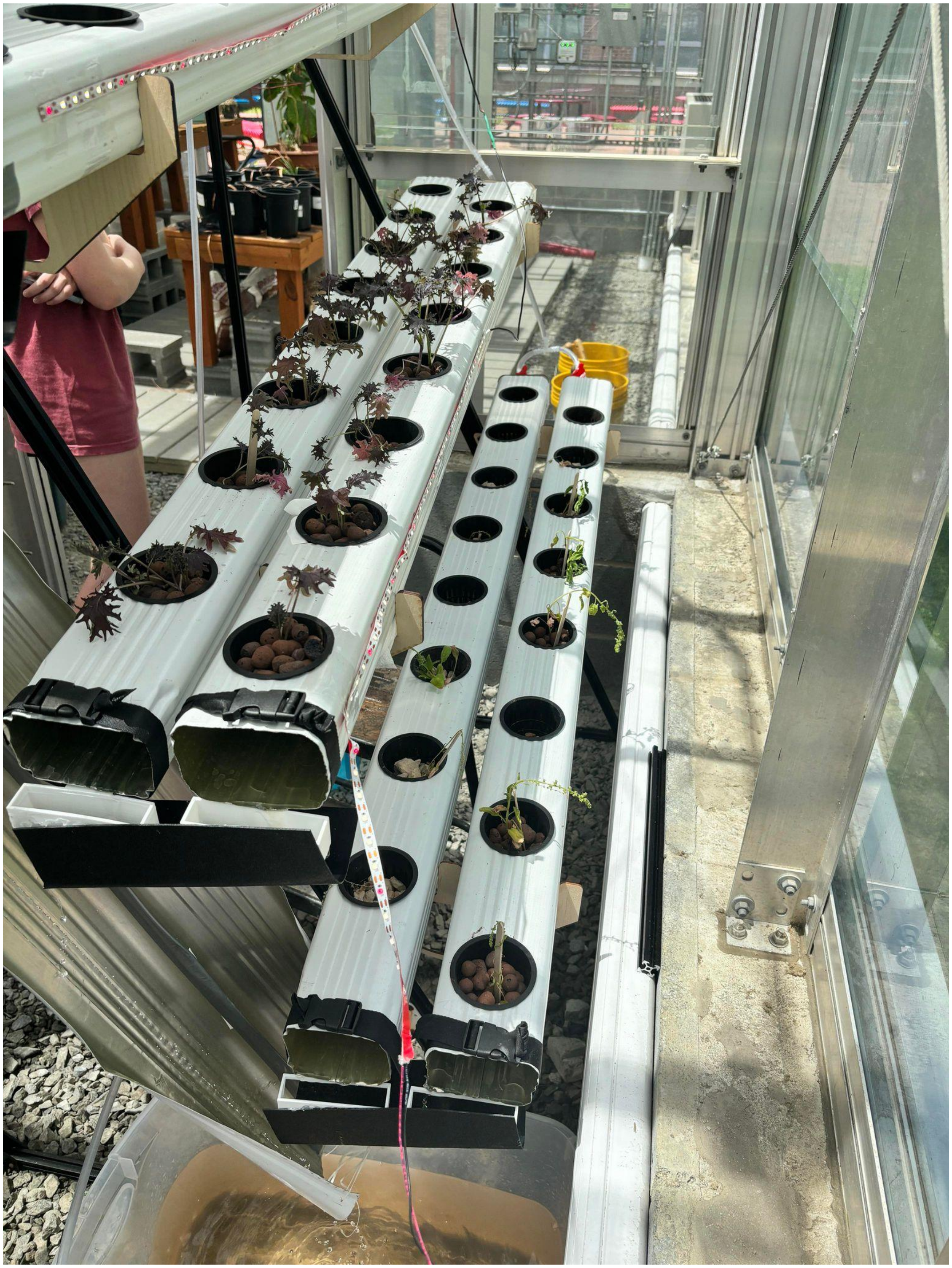


Figure 21

Another picture, this time from inside the greenhouse, with plants in our system.



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We would also like to extend a thank you to the oceanography lab director Dr. Stickler for allowing us to place our farm in the greenhouse, technology teacher Ms. Geiger for opening the greenhouse for us, and English teacher Ms. Klein for not only opening the greenhouse for us but also providing us with aquaponics advice.

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Finally, we would like to thank our parents for supporting us throughout our project. Not only did they provide us with encouragement throughout the year, but they also watered our plants and found materials at home for us to use, reducing our project expenses. This project owes much to their unwavering support.

References

Adams, H. W., Stewart, S. S., Kelvakis, A. E., & Bay, B. C. (2022). Hydroponic system and apparatus having removable growing structures for multiple types of plants (U.S. Patent No. US11337387B2). U.S. Patent and Trademark Office.

Ako, H., Baker, A. (2009, October). *Small-Scale Lettuce Production with Hydroponics or Aquaponics*. Scholar Space. https://scholarspace.manoa.hawaii.edu/items/77b0e874-0c46-410d-8b71-9955e99b005a

Bartzas, G., Zaharaki, D., & Komnitsas, K. (2015). Life cycle assessment of open field and greenhouse cultivation of lettuce and barley. Information Processing in Agriculture, 2(3-4), 191-207. https://doi.org/10.1016/j.inpa.2015.10.001

Baus, D. (2017). *Overpopulation and the impact on the environment* [Doctoral dissertation, City University of New York]. CUNY Academic Works. https://academicworks.cuny.edu/gc_etds/1906

Crisnapati, P. N., Wardana, N. K., Aryanto, K. A. A., & Hermawan, A. (2017). Hommons: Hydroponic management and monitoring system for an IOT based NFT farm using web technology. In 2017 5th International Conference on Cyber and IT Service Management: Convention Hall, STIKOM Bali, August 8-10, 2017 (pp. 1-6). IEEE. https://doi.org/10.1109/CITSM.2017.8089268

Heredia, N. A. (2014, March 21). *Design Construction and Evaluation of a Vertical Hydroponic Tower*. Digital Commons @ Cal Poly. https://digitalcommons.calpoly.edu/braesp/86/

How to grow lettuce in Aquaponics. Go Green Aquaponics. (2022a, March 6). https://gogreenaquaponics.com/blogs/news/how-to-grow-lettuce-in-aquaponics

Krishan, K., Agrawal, E. R., Tripathi, D. M., & Yadav, U. (2020). Fabrication and performance evaluation of A shaped frame hydroponic system for leafy garlic. *Journal of Pharmacognosy and Phytochemistry*, *9*(3), 688-692. https://doi.org/10.22271/phyto.2020.v9.i3k.11351

Kulikova, E., Efremova, S., Politaeva, N., & Smyatskaya, Y. (2019). Efficiency of an alternative led-based grow light system. IOP Conference Series: Earth and Environmental Science, 288(1), 012064. https://doi.org/10.1088/1755-1315/288/1/012064

Velazquez-Gonzalez, R. S., Garcia-Garcia, A. L., Ventura-Zapata, E., Barceinas-Sanchez, J. D. O., & Sosa-Savedra, J. C. (2022). A review on hydroponics and the technologies associated for medium- and small-scale operations. *Agriculture*, *12*(5), 646. https://doi.org/10.3390/agriculture12050646

What is the nutrient film technique (NFT) in Aquaponics?. Go Green Aquaponics. (2022b, May 11). https://gogreenaquaponics.com/blogs/news/nutrient-film-technique-in-aquaponics

Biographies

Dora Bowen-Glazeroff

For as long as Dora can remember, her parents, witnessing her skill with jigsaw puzzles, have foretold a career for her in engineering. Only after a detour into architecture, which was quickly rerouted once she discovered its focus on art, did Dora start to believe them. She plans to pursue a path in the field of civil engineering, in the hopes that she can help rebuild the planet’s failing infrastructure someday. Outside of her academic pursuits, Dora enjoys playing the baritone saxophone, reading, and playing sports.

Daniel Chua

Daniel first got interested in engineering when he was six years old, visiting a car factory with his dad. After watching robot arms lifting incredibly heavy car frames, he knew he wanted to be an engineer. This love for robotics pushed Daniel to attend TJ after being homeschooled from kindergarten through 8th grade. Although he hasn't yet made one of those cool robotic arms, he still dreams big and hopes to make something even cooler one day. Outside of school, Daniel loves to swim, play the drums, and eat food! His favorite thing to do, though, is laughing and making others laugh, so you'll usually catch him with a smile on his face.

Amith Polineni

Amith was always involved in engineering from a young age, and his passion really took off after joining his middle school robotics team. Since then, he's gained a knack for combining cutting edge technology with ethical debates and hydroponics systems. His foray into hydroponics started in the Robotics class at TJ, where he delved into a small prototype for his final project, subsequently securing a summer internship at a greenhouse to deepen his understanding. This experience catalyzed his senior research, where he further explored hydroponics systems. Beyond academia, Amith debates in ethics bowl discussions, showcases his athleticism on the Ultimate Frisbee team, and works on his website, amithp.com.