PREDICT, CREATE, CONTROL, AND MAINTAIN OPTIMUM LIVING CONDITIONS FOR FISH AND PLANTS OF AN INDOOR AQUAPONICS SYSTEM

by

Md. Muzaffer Hosen Akanda, B.Sc.

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Committee Members:

Bahram Asiabanpour, Chair

Heping Chen

Mar Huertas

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ABSTRACT

Access to clean water and food are the basic needs for everyone. The growth of population, changes in lifestyles, and pollution of resources have made access to these basic needs more difficult. To support the growing need for food the agriculture should be increased. Agriculture is one of the biggest consumers of fresh water and habitable land. Water and soil quality also deteriorates in many regions around the globe due to the growth of pollution activities like over-exploiting of soil, fertilizer and pesticides runoff, and other contaminants.

To solve this crisis indoor vertical farming methods such as aquaponics, hydroponics, aeroponics, are well-proven solutions, which can create a more sustainable and efficient way to produce food. Aquaponics is a combination of farming fish and growing plants in a recirculating water media. Although the aquaponic system comes with a lot of advantages, the commercial success for the aquaponic system is not simple. The major challenge of the aquaponic system is the initial investment and the operation cost. The operation is labor-intensive and requires an expert operator.

This research used computational fluid dynamics simulation software to predict the ambient conditions like the temperature of the indoor aquaponics system. With the known temperature the design and selection of different components like water and air cooler, heater, and other necessities became more accurate and reliable.

Aquaponics design and operation can be improved by eliminating possible errors with an established method like Failure mode and effect analysis (FMEA). FMEA can be used at various steps in a design process to identify issues that can affect the reliability of the process. Identifying weaknesses in the process design of aquaponics systems can allow engineering controls to be implemented long before the process is operational.

To operate an aquaponic system smoothly it is needed to monitor and control a lot of parameters. Plants and fish in the system have a different range and a desirable point for each of these parameters including temperature, dissolved oxygen, pH, ammonia, etc. To operate an aquaponics control system the optimum range of each parameter for the plants and fish was identified, measured, and adjusted. This research is focused on the implementation of microcontroller-based automation and digital twin are utilized to predict and the system with less error and greater reliability.

To implement the developed control system one complete aquaponic system was built from design to operation. Microcontroller-based smart automation and monitoring system was deployed for the smooth operation of the system. The system ran and monitored for a long period with living fish to demonstrate the accuracy and consistency of the system. This research revealed the impacts of different factors for simulation, design, build, automate, and operations of the successful aquaponics system. The successful operation of the complete system verified the simulation and design, which will help future research with the larger-scale commercial operation of an aquaponics system.

1. INTRODUCTION

The world population is increasing and estimated to be 9.7 Bn by 2050. With population growth and a rise in household income, the demand for food is estimated to increase by 70–100 percent within this time [1]. To provide food for this increased population, we need to boost agriculture and raising more animals. Agriculture is considered the highest consumer of the world's freshwater which is about 70% [2] and 40% of the world's population faces water scarcity at least for a month each year [3]. On the other hand, for agriculture, almost 50% of habitable land is in use, and it will increase with the increased population [4]. Scientists and researchers are working to find a suitable solution to this problem. With modern vertical farming systems such as hydroponics, higher yield is possible with much less water and fertilizer than conventional farming and is considered a viable approach [5][6]. To design an aquaponics system the considerations, and the weather data simulation is a tedious process.

As aquaponics is replicating the natural system, it is recognized as a form of sustainable agriculture. The efficiency of the water is dramatically increased and has fewer environmental impacts [7]. As a sustainable, efficient, and intensive low-carbon production mode in the future, the aquaponics system has realized the transformation from waste to nutrients. It has effectively solved the problem of environmental pollution [8]. The global application of aquaponics will succeed in helping the food crisis and world sustainability if it becomes widely spread as a commercial alternative. Only 31% of the commercial aquaponics facilities were reported to be profitable and 47% rely on other products or services for additional income [9]. With all these advantages, the aquaponics system has many challenges to build and operate. To overcome these challenges, this research focused on solutions that would lead to a sustainable and efficient aquaponics system. Aquaponics control and operation are always labor-intensive, this research will be focused to find reliable control and operations methods and develop the system to make a more successful sustainable agriculture.

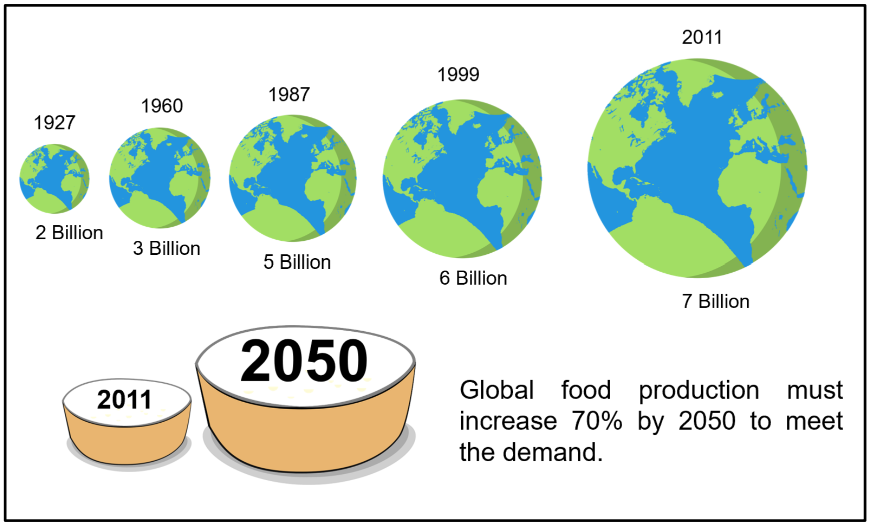


Figure 01: Global food production challenges [10].

1.1 Problem Statement

Although the aquaponics system comes with many advantages, it has a lot of limitations as well. The aquaponic systems are costly and have a low margin of profit. Some major constraints to aquaponics operations include high initial investment costs, the labor intensity of the operations, high use of electricity, and sensitivity of profits to output prices. Other risks include plant losses due to plant diseases and pests. The design and management of an aquaponic system are challenging when trying to achieve high yields and quality. To design an indoor aquaponics system prediction of the ambient condition is much challenging with the historical weather data. Without knowing the possible ambient condition throughout the year, the necessary consideration for the selection of different components like water and air cooler, heater, and other necessities became tough. As aquaponics has a lot of variables for different parameters that depend on the type and size of fish and plant make it is challenging to operate without errors. The parameters and factors (light, temperature, pH, moisture, etc.) that need to be controlled are diverse. This makes the task of manually analyzing and managing such systems exponentially hard when scaling the system up to commercial levels.

1.2 Hypotheses

To address the above problems, this research intends to develop predictable ambient of indoor vertical farming through software simulation, implementation of error elimination methods, the introduction of automation, and validation by building an aquaponics system to operate with all subsystems. This investigation requires the following set of hypotheses to be assessed and confirmed.

Hypothesis 1: *Aquaponics ambient system can be predictable. A simulation system can model the ambient (temperature) of the fish and plant grow areas as well as heating/cooling/gassing instruments (by considering the outside ambient).*

Hypothesis 2: *Aquaponics design and operations can be more accurate. Many mistakes can be preventable before it happens by the FMEA (Failure mode & effect Analysis) method.*

Hypothesis 3: *Aquaponics operation and feeding mechanism can be optimized and automatic. Correlation between instrument settings (e.g., pump flow, heat/cooling/gassing hrs., and feeding setting) and by considering outside ambient can be found that maintain the system near optimum conditions.*

Hypothesis 4: *All subsystems can be connected via hardware and smart logic to operate automatically and flawlessly*.

1.3 Impact of Work

Food and water are the basic needs of our growing population which is very difficult to fulfill daily due to our change of lifestyle, scarcity of land, and limited source of freshwater. Aquaponics or integrated farming can create a more sustainable way to produce foods. To solve this crisis vertical farming is a well-proven solution, which includes hydroponics and aquaponics. Simulation of the ambient temperature of an indoor aquaponics system will help to understand the transient analysis of the temperature of the air and water in the different tanks. With a proper FMEA analysis, the probable errors are predictable, and elimination can be done even before they occur to achieve a better and efficient aquaponic system. The control of the aquaponic system is tedious and has a diverse variable for the control system. The proposed control strategy will help to implement an efficient control system for various aquaponic system sizes. The build and flawless operation of the aquaponic system with all systems and subsystem validates the simulation and design of the aquaponics system.

1.4 Literature Review

1.4.1 Aquaponics Fundamentals

Indoor Vertical farms can be of different shapes and sizes, but the types of soil-free vertical farming are aquaponics, hydroponics, and aeroponics. Hydroponics is growing plants in recirculating nutrient water solution, where aquaponics grows fish and plants together in a recirculating media with additional filtration. On the other hand, aeroponics grows the plant in an air or mist environment.

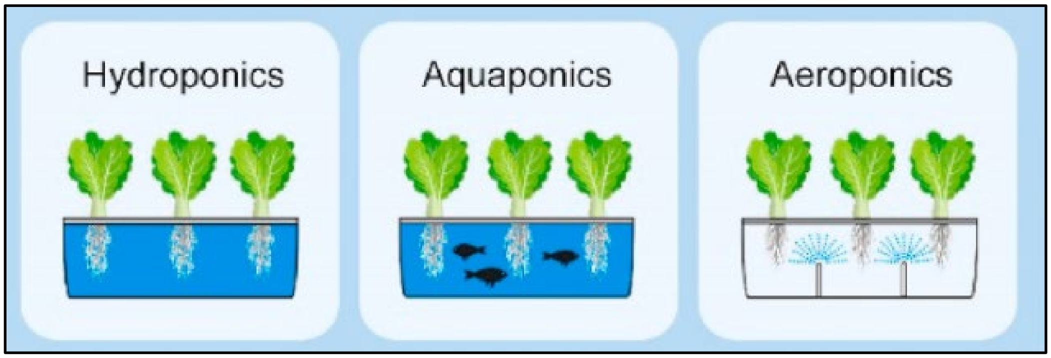


Figure 02: Different types of vertical farming [11].

The concept of aquaponics is not a recent thing. Other than the natural aquatic ecosystem the aquaponic first start back at the Aztecs in 1,000 AD who grew their plants on rafts on the lakes' surfaces. The Aztecs worked out a system of artificial agricultural islands called "chinampas." They used fish waste to fertilize their crops and were able to grow squash, maize, and other crops [12]. Even, it has been practiced in China for more than 1500 years ago. Farmers used to raise duck on the pond and the leftover food and waste were used as food for fish and the water used for the cultivation of rice [13]. Open field agriculture is not enough to meet the food demand and also with the challenge of limited water resources [14]. To solve the recent agricultural challenges and feed the increased amount of people utilizing less amount of water modern aquaponics is a great solution [15]. We can get both fish and plants at the same time from aquaponics. Although the aquaponics system has a lot of advantages there is a lot of room to improve.

Up to today, the focus of aquaponics systems is mainly on fish culture and treatment of RAS (Recirculating aquaculture system) effluent for optimal use in HP(Hydroponics), and systems are designed and sized with the rule of thumbs of plant growth, evapotranspiration and nutrient needs [16].

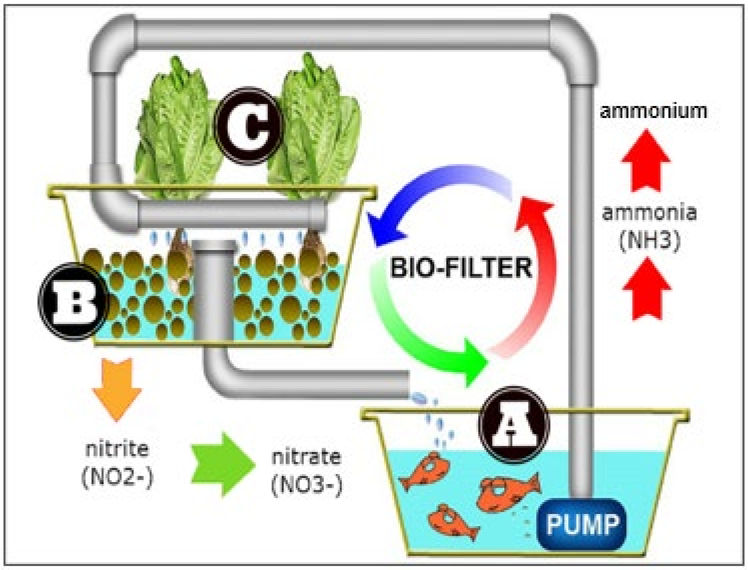


Figure 03: Basic aquaponic system [17].

1.4.2 Approaches

The growth of fish and plants happen in hours or days and are a slow process while photosynthesis and transpiration in crops happen in seconds or minutes and are fast processes [18]. As in a closed-loop system, the main water use is due to plant transpiration, the necessary sizes of system and sub-system depend on plant transpiration. This research is aiming towards creating an aquaponics simulation and implement it to a physical model to validate our findings [16]. With the introduction of automation and smart strategies, and connectivity in the firming industry we can implement them to find a better solution for the aquaponic system in terms of economic, sustainability, and ease to operate with less error [19].

1.4.3 Automation

Automation, smart strategies, and connectivity in the farming industry introduce a new era for the improvement in agriculture [20]. The benefits are expected from smart automation are a considerable decrease in manual labor, better process control by increasing the accessibility and connectivity of the parameters, and using computer capabilities to make data-driven decisions [21]. One recurrent type of research in the past years is the implementation of sensing, smart, or IoT systems in aquaponics to solve some of the challenges faces by aquaponics growers [22].

Different approaches have been taken by the scientist and researcher to obtain a better and smart aquaponics system. One of the options is the development of aquaponics system control locally by using different sensors and connected to a GSM (Global System for Mobile) communication interface that can send notifications or alarms as per the predefined set limit [23]. Further modified steps are taken to utilize Arduino and a WRTnod to monitor the data acquisition and manage the aquaponics system built which gets the data wirelessly and analyzes then in a cloud server [24]. Our goal is to minimize the overall cost and hence we will implement a strategy to control the complete system efficiently and reliably.

1.4.4 Digital Twin (DT)

Digital twins are designed to receive input signals from sensors attached to the physical object and produce real-time output or feedback that describes how the object would behave in a virtual environment. The technologies behind digital twins are the internet of things (IoT) and machine learning, a subset of artificial intelligence (AI) [25]. The IoT comprises smart, connected devices that interact and exchange information over networks. Machine learning, on the other hand, refers to statistical models and algorithms that enable computer systems to carry out specific tasks without acting on any explicit instructions [26].

The basis of interactions of these technologies is to generate data. The data allows developers to continuously optimize the virtual replica to allow it to adapt to changes to its real-world twin for days, months, or even years.

1.4.5 Nutrition

Fish waste is the source of the nutrients that are needed for plant growth in the aquaponic system [27]. Fishes mostly excrete nitrogen (N) in the form of ammonia (NH_3) through their gills [28] although while their waste contains mostly organic (N), phosphorus (P), and carbon (C) [29][30]. As in aquaponics fish waste is using as a nutrition source so the nutrients are organic in origin but conventional hydroponic cultivation techniques provide plants with inorganic nutrients [31]. It has been suggested that nutrients from aquaculture effluents may not supply sufficient levels of potassium (K), calcium (Ca), or iron (Fe) for proper plant development, therefore these need to be added as supplements to the system to ensure optimal plant performance [32][33]. However, adding these supplements requires closer management of the system and leads to greater costs [34].

Table 01: Nutrients required for plant growth.

Macronutrients	Micronutrients
N – Nitrogen	Cl – Chorine
K – Potassium**	Fe – Iron**
Ca – Calcium**	Mn – Manganese
Mg – Magnesium	B – Boron
P – Phosphorus	Zn – Zinc
S – Sulfur	Cu – Copper
	Mo – Molybdenum

1.4.6 Other Essential

There are several parameters to have close monitoring for aquaponics and temperature is one of them. We need to have close control of both air and water temperature. The temperature in the water is closely related to other water-related parameters. For example, the optimal temperature for the nitrification process is between 17-34°C [35]. If the water temperature goes below this range, the productivity of the bacteria will tend to decrease, and the nitrification process will not be successful. For different fish and plants, the suitable temperature range is different. Even the higher water temperature resists the plant from uptake calcium [36]. Air temperature has an important impact on the growth of plants [37]. The suitable temperature for most of the vegetables commonly grown in aquaponics systems is between 17-34°C [38].

Another important parameter is pH for water solution [39]. As there are three different living elements in the water fish, microorganisms, and plants and they have a different range of pH [40]. Although in the hydroponics component the optimum pH is around 6.0. It has been observed that if pH is higher than 7.0 or lower than 4.5 can cause root injury or other mineral precipitation [41]. For the aquaponic system, the optimum pH range is between 6.8 - 7 and the highest possible pH value should be consistent with the prevention of ammonia accumulation in the system [42].

Dissolved Oxygen (DO) is another important parameter. DO is a measure of how much oxygen is dissolved in the water available for the aquatic living organisms and is an important element to support aquatic life [43]. Oxygen is dissolved in water at a very low concentration and has a drastic effect on the aquaponic system[35]. Dissolved oxygen has a strong relationship with the temperature of water [44]. When the temperature goes up the amount of dissolved oxygen goes down.

The optimal ratio between fish and plants needs to be identified to get the right balance between fish nutrient production and plant uptake in each system. This could be based on the feeding rate ratio, which is the amount of feed per day per square meter of plant varieties [45]. On this basis, a value between 60 and 100 g day−1 m−2 has been recommended for leafy-greens growing on raft hydroponic systems [46].

1.4.7 Simulation

Computational fluid dynamics is a numerical tool that is highly accurate to simulate a very large number of applications and processes. Computational Fluid Dynamics (CFD) is progressively becoming a design-oriented tool in many engineering fields to solve and predict engineering problems that involve liquids and gases [47]. CFD has several attractive features: (a) easy variation of flow parameters, (b) fast changes to the geometry, and (c) detailed insight into flow behavior. CFD has proven to be accurate and beneficial in many engineering fields, including aeronautics [48], heat exchanger design [49], cooling systems [50], and wind turbines [51]. However, few studies have addressed CFD in the aquaponics system.

1.4.8 Scientific Background

Heat transfer occurs when there is a temperature difference. Heat transfer may occur rapidly, or slowly. The rate of heat transfer can be controlled by choosing, controlling air movement, or by choice of color. Heat is usually transferred in a combination of these three types and seldomly occurs on its own.

Equation 1 relates to the heat transferred from one system to another.

$$Q = c \times m \times \Delta T \quad \text{(1)}$$

Where,

Q = Heat supplied to the system

m = mass of the system

c = Specific heat capacity of the system

ΔT = Change in temperature of the system

Conduction is heat transfer through stationary matter by physical contact. (The matter is stationary on a macroscopic scale—we know there is the thermal motion of the atoms and molecules at any temperature above absolute zero.) Heat transferred between the electric burner of a stove and the bottom of a pan is transferred by conduction.

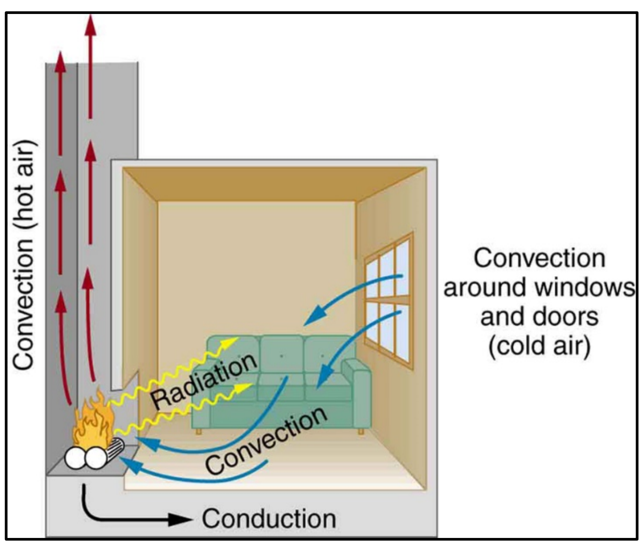


Figure 04: Heat transfer of a typical room [52].

Heat transferred by the process of conduction can be expressed by equation 2,

$Q = kA\,(T_{Hot} - T_{Cold}) / t\,d$ …………………………………………………………… (2)

Where, Q = Heat transferred, K = Thermal conductivity, T_{Hot} = Hot temperature, T_{Cold} = Cold Temperature, t = Time, A = Area of the surface, and d = Thickness of the material.

Convection is the heat transfer by the macroscopic movement of a fluid. This type of transfer takes place in a forced-air furnace and weather systems. Heat transferred by the process of convection can be expressed by equation 3,

$Q = H_c\,A\,(T_{Hot} - T_{Cold})$ ………………………………………………………… (3)

Here, H_c is the heat transfer coefficient.

Radiation is the type of heat transfer that occurs when microwaves, infrared radiation, visible light, or another form of electromagnetic radiation is emitted or absorbed. An obvious example is the warming of the Earth by the Sun. A less obvious example is thermal radiation from the human body. The Heat transferred by the process of radiation can be given by the following expression,

$Q = \sigma(T_{Hot}^4 - T_{Cold}^4)\,A$……………………………………………………………… (4)

Here σ is known as Stefan Boltzmann Constant.

For a mass M of water (specific heat per unit mass Cw) at temperature T in contact with a heat source at temperature Ts through an area A with a heat transfer coefficient H (Watt/Kelvin/m2), then the equation 5 of temperature vs time is given by,

$\frac{dT}{dt} = \frac{(Ts - T)}{Mcw}\,HA$ …………………………………………………………………… (5)

If we put $\frac{Mcw}{HA} = \tau$, then the solution for this is of the form equation 6,

$$T = T_s - (T_s - T_0)\, e^{-t/\tau} \quad (6)$$

The heat transfer coefficient will be a function of the wall construction of the container, and how well air can flow around it [53][54].

1.4.9 Similar Applications

It is important to determine the dynamics of water and nutrients in the growing substrate used for soil-less cultivation because this allows better time and space management of the water and nutrient supply according to plant needs during each step of the crop cycle. computer fluid dynamics (CFD) software was used to solve the water movement equations numerically in three dimensions [55]. The development of a root zone cooling system using a CFD simulation approach to optimize the distance of cooling pipes that can produce the optimal temperature distribution and uniformity in the planting medium for plant substrate [56].

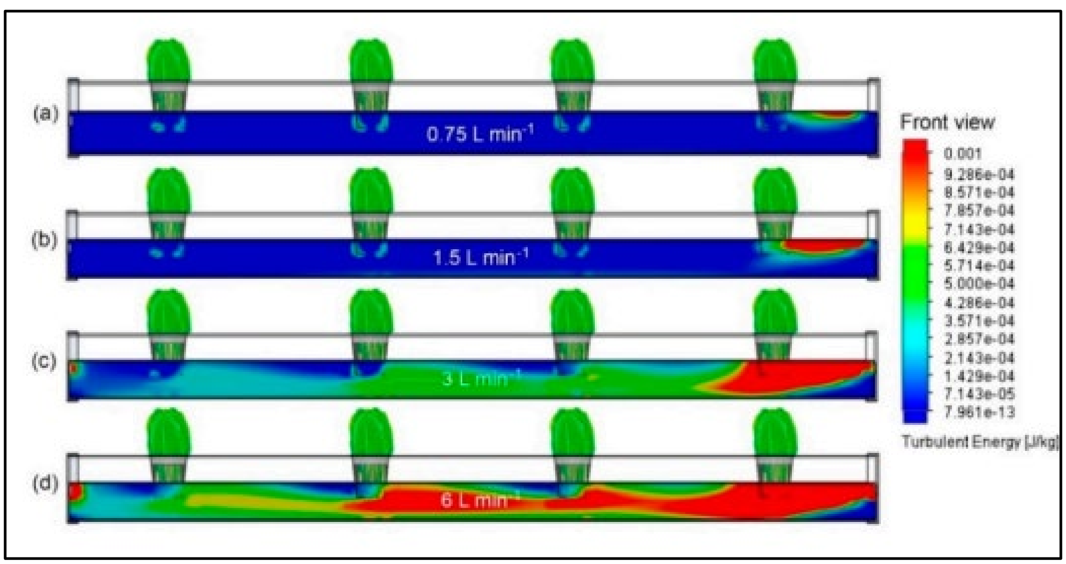


Figure 05: Simulation of turbulent kinetic energy distribution [57].

Few more attempt has been taken to use to create transient and steady-state models of fish tanks to visualize velocity profiles, streamlines, and particle movement with the use of CFD software Open FOAM [58].

1.4.10 FMEA Fundamentals

Standard techniques like Hazard and Operability studies (HAZOP) are conducted by process and chemical industries to do systematic analysis on a process and its sub-systems [59]. Failure Mode Effect Analysis (FMEA) is one such tool in a designer's toolbox and is recognized as an international standard (IEC 60812), which describes techniques to analyze processes that can affect the reliability of a process plant or determine what possible hazards could be present [60]. Many aquaponics operators are not familiar with these design processes and find design inadequacies after an event, which normally has financial consequences. This method can find the error in design and process and eventually leads to identify disturbances that could lead to product deviation and identify hazards for the aquaponic system [61].

1.4.11 Ever Green- Blue Water Aquaponics system

The Evergreen- Bluewater research lab at Freeman ranch, Texas State University has indoor vertical farming, and its goal is to find innovative solutions for the global food-water-energy. This lab has an indoor vertical farm with a complete hydroponic system and another well insulated 40 ft shipping container for the aquaponics system. The challenge was to simulate the water temperature for containers inside air and water temperature from ambient temperature and build a smart automated aquaponics system with less error and integrate with the existing hydroponic system.

Figure 06: Evergreen bluewater shipping container.

2. SIMULATION

2.1 Introduction and Problem statement

This chapter assesses hypothesis 1: A simulation system can model the ambient (temperature) of the fish and plant grow areas as well as heating/cooling/gassing instruments (by considering the outside ambient). To assess this hypothesis, a CFD simulation was carried out to know the temperature of water and air in the shipping container for different ambient temperature data. The purpose of the simulation is to know the temperature for design the aquaponics system including water and air chiller, heater even to select the right species and size of fish and plant.

2.2 Methods and Materials

The heat is from the ambient or outside was transferred to the water tanks in three steps. First, heat transfer to the wall of the shipping container by solar radiation, then heat transfers from the wall to the inside air, and finally, heat is transferred from the container inside air to water. The complete setup of the shipping container with the water tank was modeled with Comsol Multiphysics® software [62]. The simulation was following few basic steps:

1. Drawing and setting up the geometry of all components.

2. Setting up the initial and boundary conditions.

3. Adding physics and multiphysics to the model to link all the heat transfer phenomena.

3. Creating and building mesh.

4. Creating time-dependent study with multiphysics.

5. Running the simulation and analyzing the result.

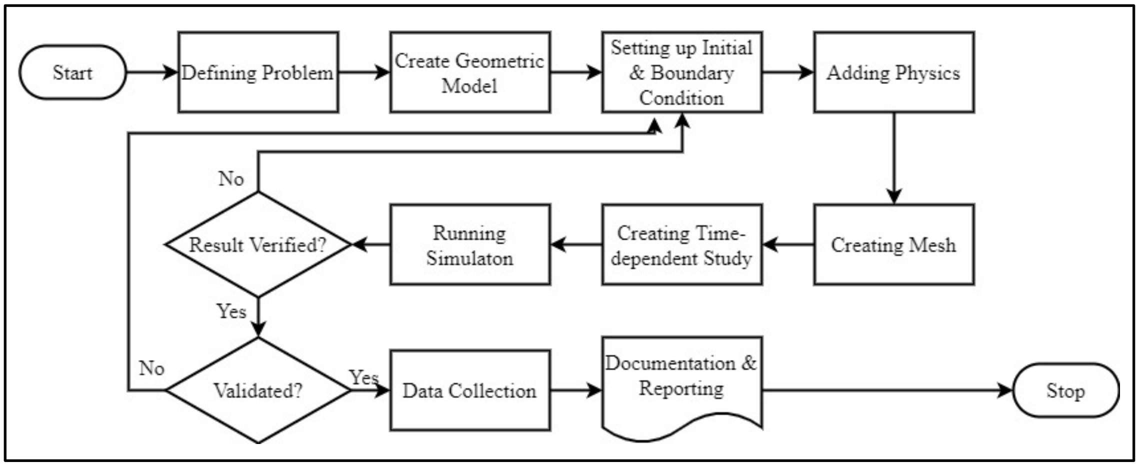


Figure 07: Steps to follow in simulation.

2.3 Geometrical Modeling

To start the simulation the full system was converted to a CAD model with actual dimensions. The actual dimension was measured from the actual model in the freeman center.

Figure 08: Indoor aquaponic system.

The water tanks are added to the model. All major components including container wall, air, water, and water tanks are defined properly.

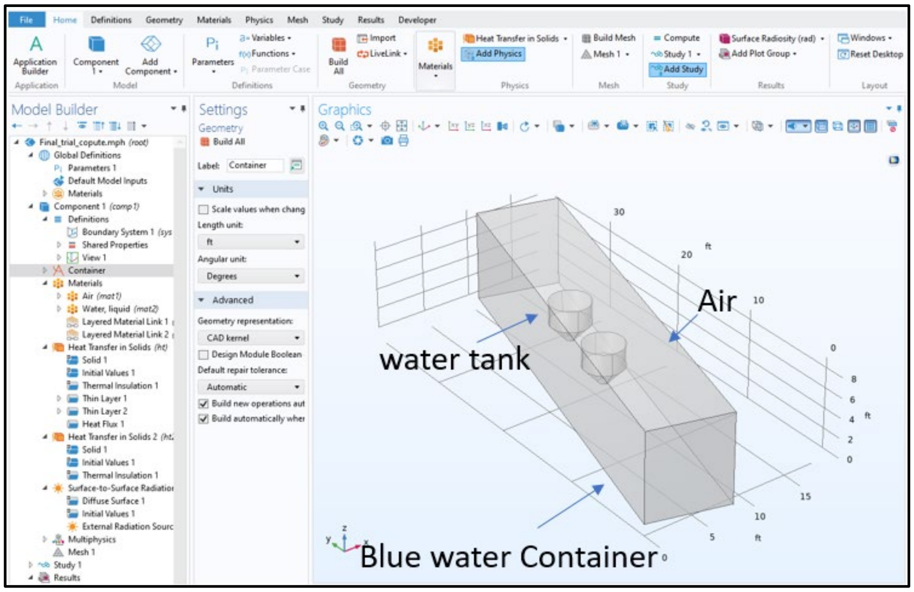


Figure 09: Shipping container geometry.

The shipping container offers many benefits to choose for an indoor aquaponics system. They are mobile, which means the farm can move wherever required and can be placed nearby the city area to minimize the food miles.

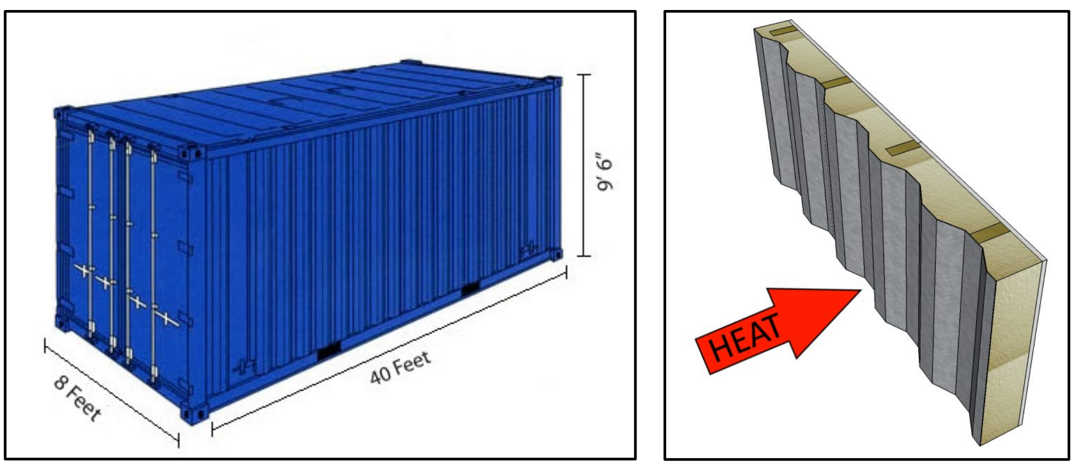


Figure 10: Shipping container cross-section.

The dimension of the shipping container is length 40 feet, width 8 feet, and height around 9 feet. The shipping container is a combination of three-layer of materials. The material is different for a different type of shipping container. The shipping container used for the research has outside Aluminum, the middle section is polyurethane and the inside is aluminum alloy.

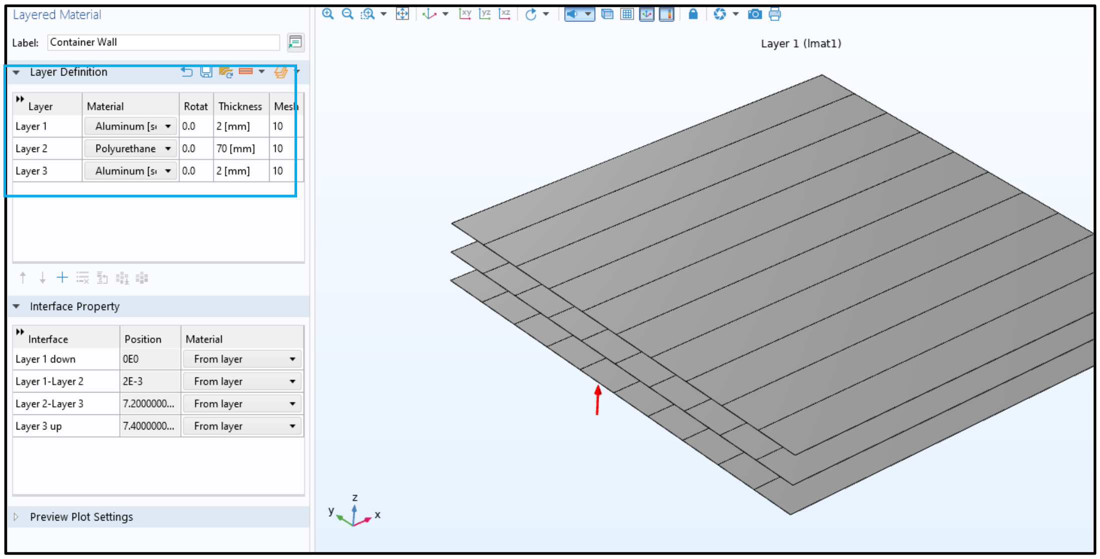


Figure 11: Container material with a thickness.

2.4 Initial and Boundary Condition

2.4.1 Ambient Properties

To set the outside ambient properties COMSOL Multiphysics® has the data of The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) for different locations all over the globe. In this simulation, San Marcos regional weather station was selected to get the ambient temperature, atmospheric pressure, wind speed, solar and atmospheric radiation.

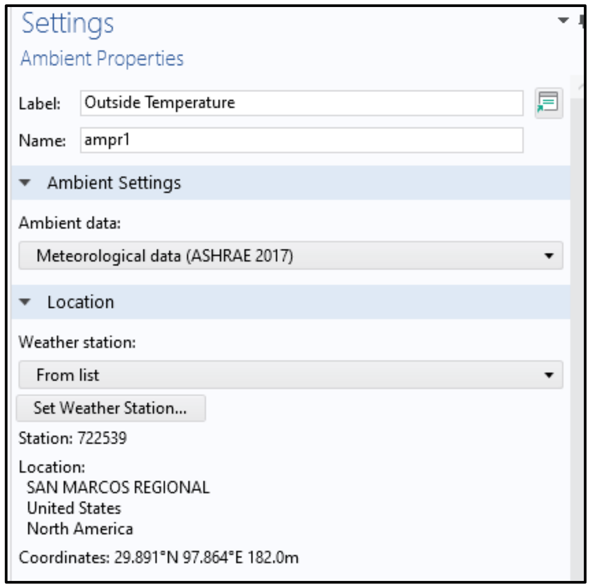


Figure 12: Setting of ambient conditions.

To run the simulation the start data was selected from 5/15/2021 for 72 hours. The initial temperature of the inside air of the shipping container was selected as 25ºC.

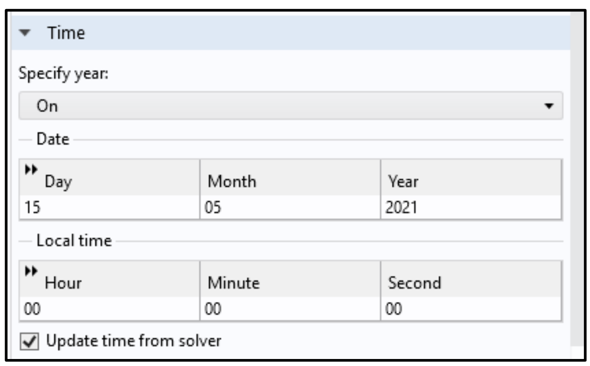
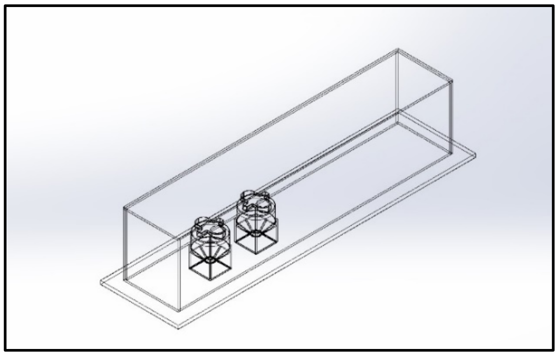


Figure 13: Selection of date and time.

2.4.2 Azimuthal

The actual azimuthal of the container was measured and use in the simulation software. The azimuth measures the angular distance of the object east from north and parallel to the observer's horizon. Along with the altitude, the azimuth of an object is used to define its position on the celestial sphere in the horizontal coordinate system.



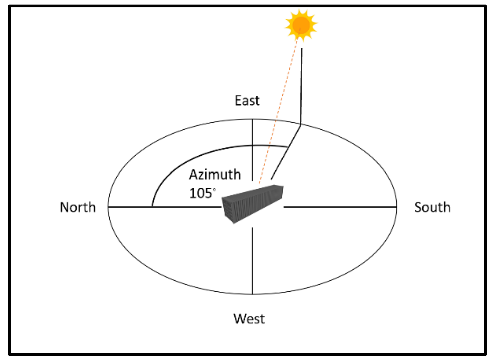


Figure 14: CAD model and azimuthal of the shipping container.

2.4.3 Physics and Multiphysics

The heat from the ambient or outside was transferred in three steps.

1. Heat transfer at the wall of the shipping container

2. Heat transfer from the wall to the inside air

3. Heat transfer from the container inside air to water.

For this study, two physics was considered. One is for conduction and convection and another is for surface-to-surface radiation.

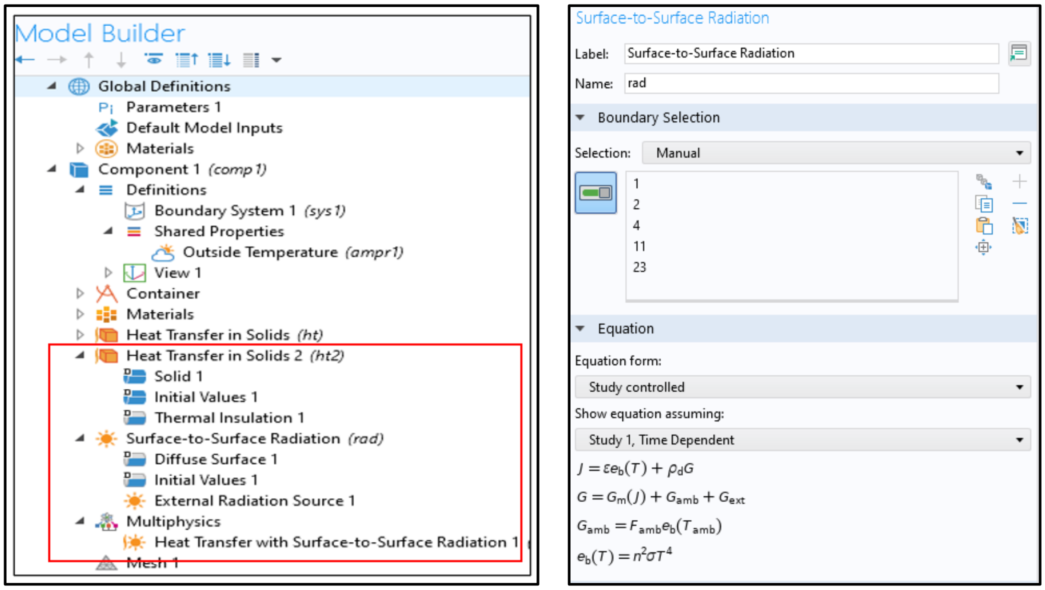


Figure 15: Heat flux and radiation in simulation.

2.4.4 Mesh Creation

Once the initial temperature was set to the actual temperature measured manually was given and no of mesh was selected the simulation software will create a mesh model to compute the whole model.

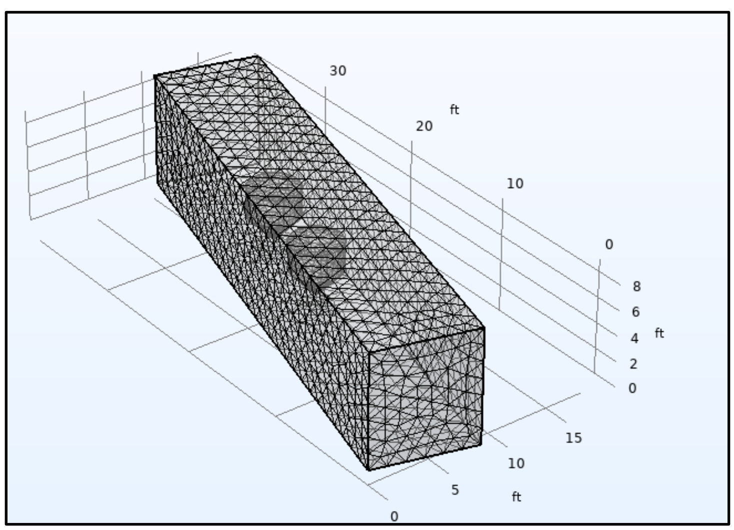


Figure 16: Mesh of indoor aquaponic model simulation.

2.4.5 Time-Dependent Study

A time-dependent study was set up for the simulation. The time unit was in an hour, the output time range was 0.5 hours, and run for 72 hours. The compute was done for the simulation and it took around 10 minutes to run the computation.

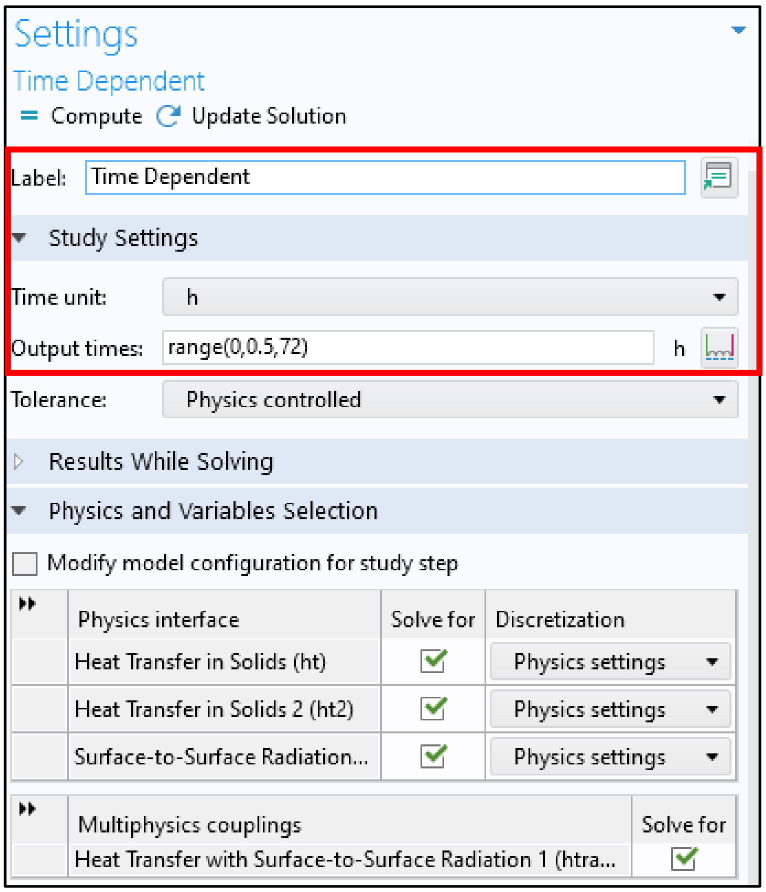
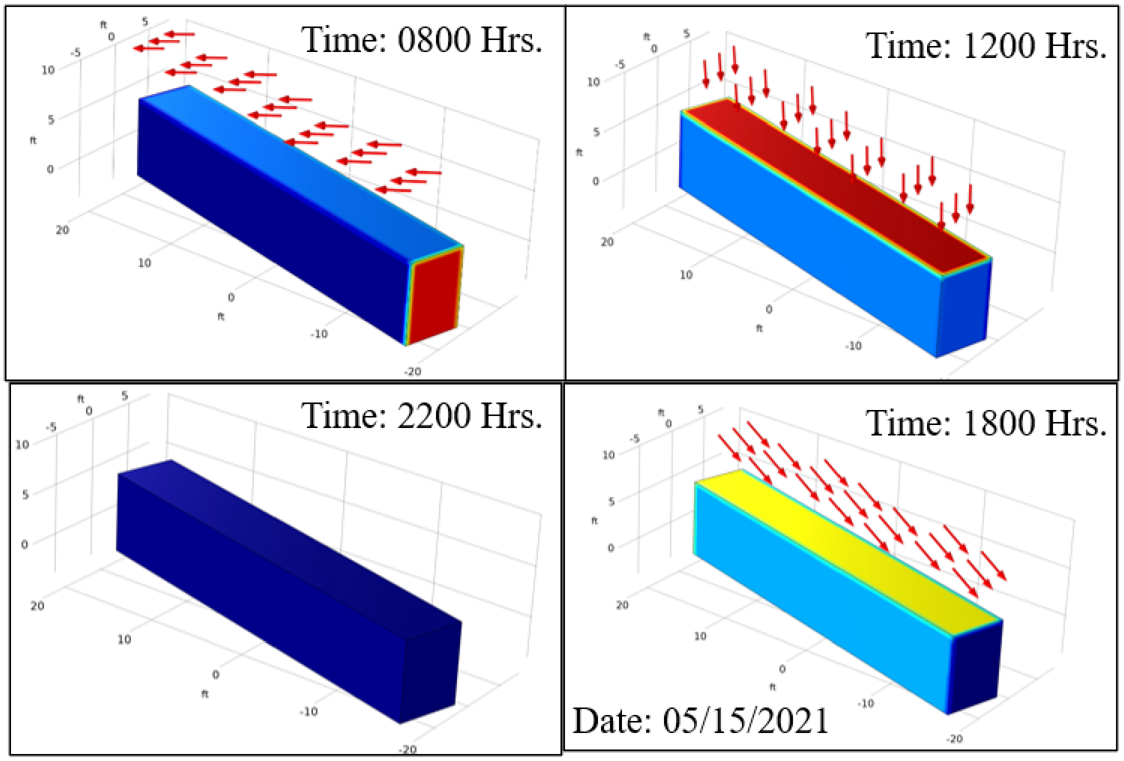


Figure 17: Time step for simulation

2.5 Result

After the simulation was carried out the result section produced simulated data based on the outside ambient data. The solar irradiance on the shipping container is shown for a different period. This simulation was carried out for 72 hours. The arrow indicates the solar irradiance from the sun to the surface of the shipping container.

Table 02: Solar irradiance on the shipping container.



From table 02 we can see that how the ambient temperature affects the container surface, air, and water. For example, in the morning 0800 hrs. the roof is not that hot compared to 1200 hrs. At night 2200 hrs. there is no solar irradiance.

From the result section of simulation software, we can generate a lot of different transient analyses of individual surfaces, the volume of different geometry. As our target is to know the water temperature of the water tank kept inside the shipping container. So, in figure 18 we plot the simulated temperature for 72 hours.

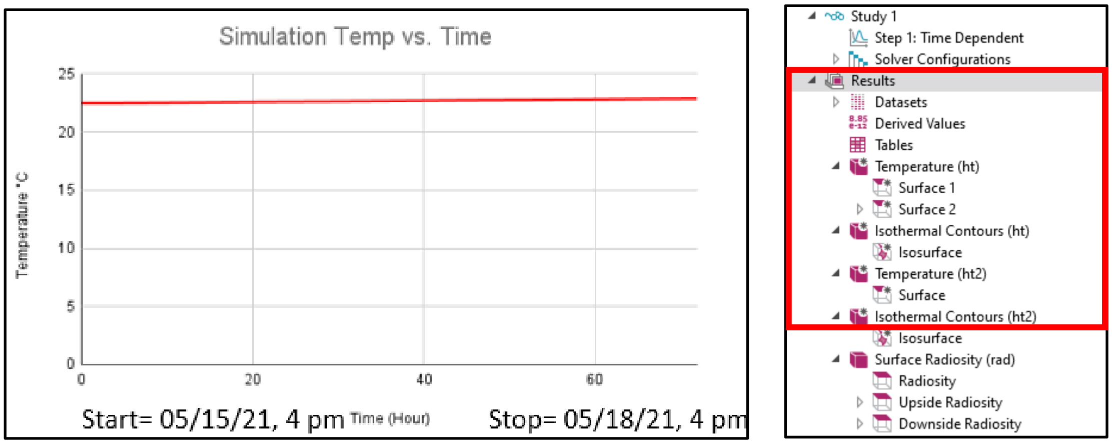


Figure 18: Simulated temperature vs time in the result section.

From figure 18 we can see that, inside water temperature is not influenced that much by the outside air temperature. But there is very little change in water temperature because there was no external heating source (lights) in the system, and it needs a significant amount of heat to change the temperature of 300 gallons of water.

2.6 Validation

To validate the simulation few temperature loggers were used to get the actual temperature of the water, the air inside the shipping container. The outside temperature data was gathered from the weather station of the freeman ranch, situated nearby the shipping container. This temperature was gathering and plotted to compare with the simulation data. A sample data table is listed in appendix A-1.

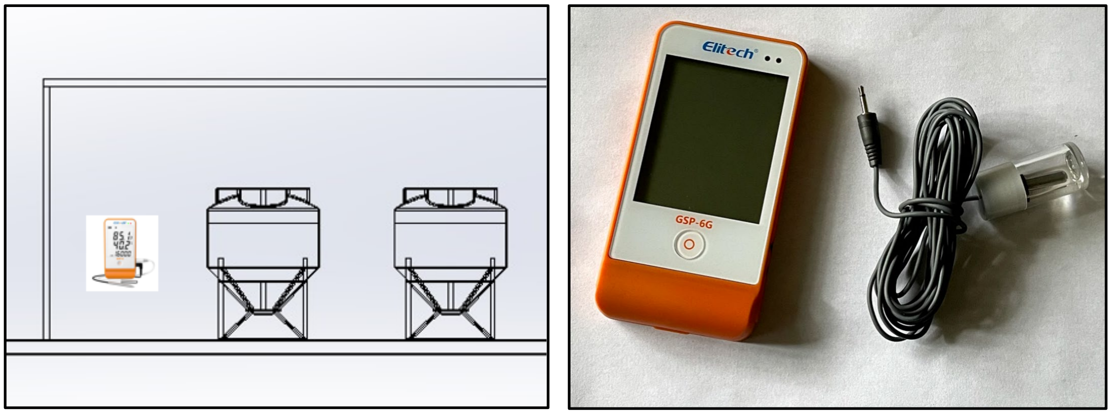


Figure 19: Measuring actual temperature with a temperature logger.

The temperature data logger (Elitech GSP-6G) ® [63] was used which can measure and store the temperature of air and water every 15 minutes and can record up to 16000 records. It has a wide temperature measurement range from -40°F to 185°F, max with accuracy up to ±0.5°F.

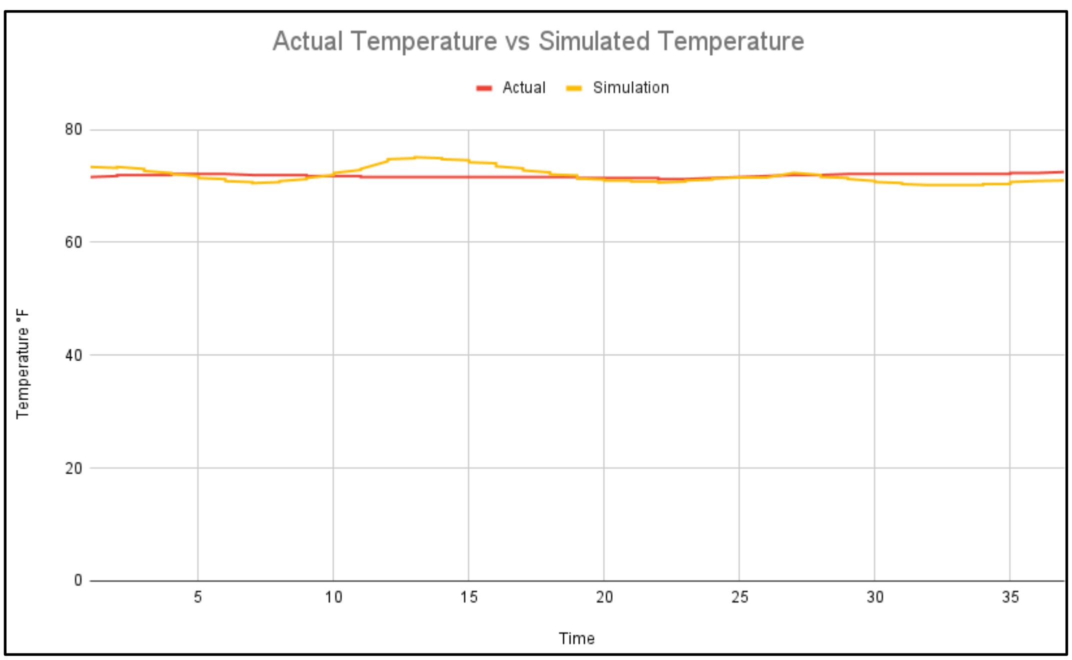


Figure 20: Comparison between actual and simulated temperature.

Figure 20, describing that the temperature data from the simulation and the actual data are almost matches with each other except at times where there is a very little deviation.

Paired T-Test and CI: Actual, Simulation

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Actual	73	71.834	0.311	0.036
Simulation	73	71.856	1.368	0.160

Estimation for Paired Difference

Mean	StDev	SE Mean	95% CI for μ_difference
-0.022	1.513	0.177	(-0.375, 0.331)

μ_difference: population mean of (Actual - Simulation)

Test

Null hypothesis	H_0: μ_difference = 0
Alternative hypothesis	H_1: μ_difference ≠ 0

T-Value	P-Value
-0.12	0.903

Figure 21: Statistical analysis of actual and simulated temperature.

From figure 21, the paired T-test with a 95% confidence interval showed that the simulated data and actual temperature data are almost similar. The possible reason for this deviation is that the actual condition cannot be considered properly in the simulation model or there could be small leakage of air that can lead to error.

2.6.1 Additional Scenarios

Once the model is validated in the simulation additional water tank was added to check the temperature profile. The additional water tank is of the same dimension and materials.

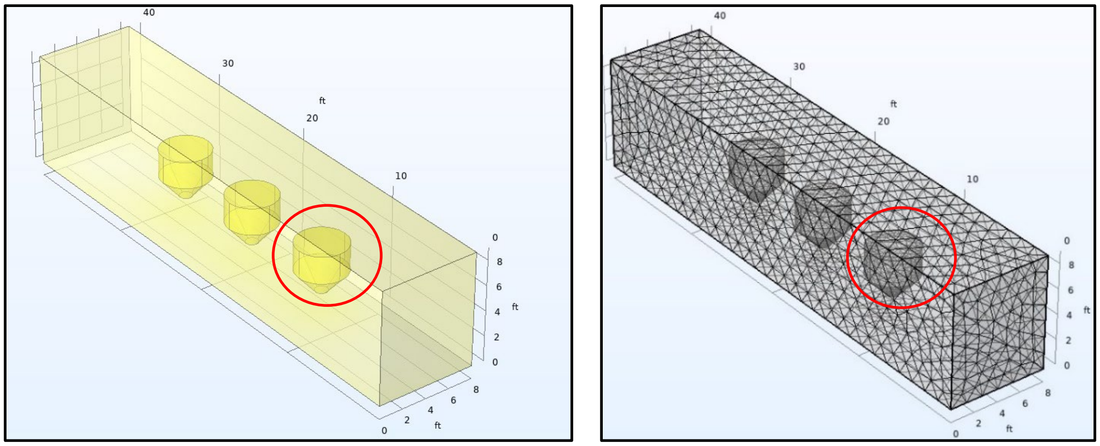


Figure 22: Adding a third tank for simulation.

From figure 22, the third water tank was added with the existing model, and the mesh has been created. With the same date and initial and boundary condition, the simulation was computed to get the average temperature of three water tanks and compared with the existing result for two water tanks.

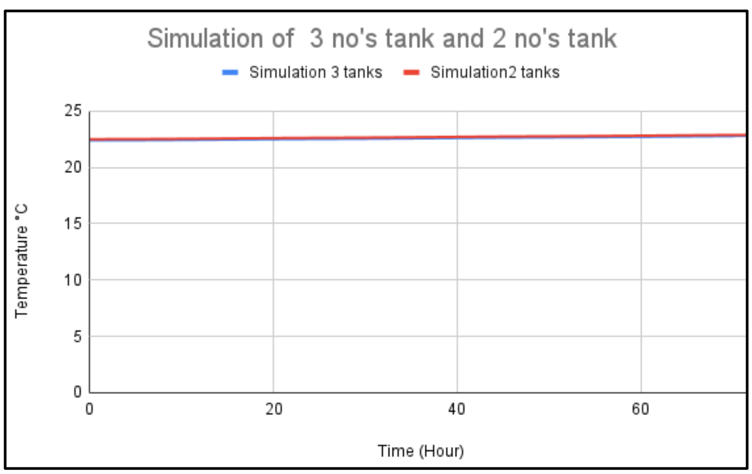


Figure 23: Comparision between 3 water tanks and 2 water tanks simulated temperature.

From figure 23, the comparison of simulated temperature between 3 water tanks and 2 water tanks is plotted and found that the temperature is almost the same even with an addition of a water tank.

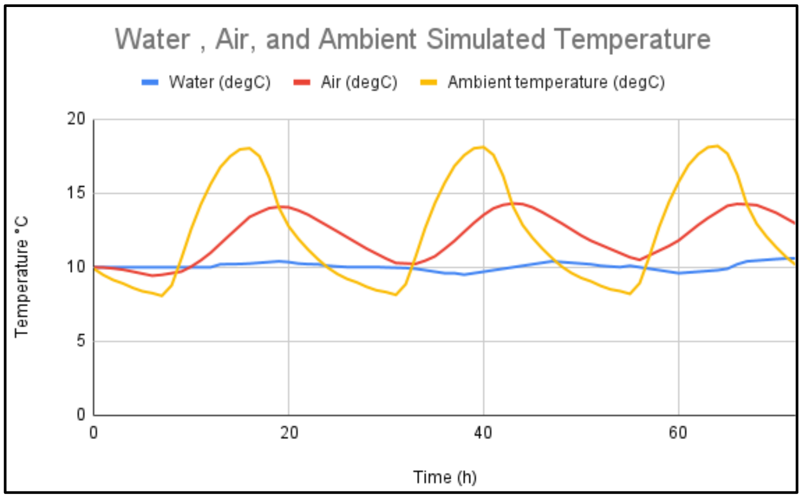


Figure 24: Simulated temperature of water and air of typical winter days.

Figure 24 represents a simulation for 72 hours of two water tanks during a typical winter season. The initial temperature for air and water was considered 10 °C and during the period the change of ambient temperature creates a good amount of change in the air temperature but the water temperature remains more steady. It is understandable from the simulated water temperature profile that, during this time the water heater will remain operational and the specification of heating capacity can be selected for a certain type of fish of any aquaponics.

2.7 Conclusion

From the simulation, it was observed that the actual temperature and simulated temperature are almost similar for any given amount of water. From the paired T-test between actual and simulated temperature, we found that there was no statistically significant difference between them and accepted the claim of hypothesis 1. The suitable type and number of fish and species can be decided for the indoor aquaponics setup based on the computer model. With the simulation of temperature, it is easy to design the cooling and heating instrument and their necessary setup for the smooth operation.

3. FAILURE MODE AND EFFECT ANALYSIS

3.1 Introduction and Problem Statement

This chapter assesses hypothesis 2: Aquaponics design and operations can be more accurate. Many mistakes can be preventable before it happens by the FMEA. Many mistakes can be preventable before it happens by the FMEA method. FMEA can be used at various steps in a design process to identify issues that can affect the reliability of the process. Ideally, a group of multifunctional engineers or designers that have skill sets in various disciplines could carry out the FMEA. Identifying weaknesses in a process design early in the concept and design phase of the project can allow engineering controls to be implemented long before the process is operational. The score identifies areas that can be of concern and where engineering controls could be implemented to prevent or mitigate the identified systems or subsystems of the process. The engineering controls do not necessarily need to be automation controls but could be in various other forms such as additional engineering reviews or mitigating hazards by alternate design.

O – the probability of occurrence, S – the severity of occurrence

D – the probability of detection

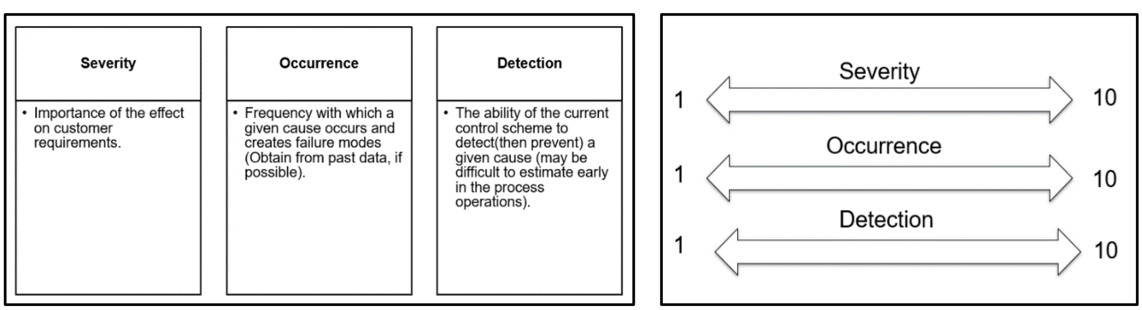


Figure 25: (a) Functions of FMEA (b) Scoring system [64].

3.2 Methods and Materials

FMEA is generally used for analyzing new designs or processes, modifying an existing product design or process, and using a design or process in a new environment. It is usually recommended to use FMEA periodically throughout the life span of a product or service. FMEA can be of many types, still, it is divided into two main groups. For evaluating any process, it is known as PFMEA and for any design, the FMEA is known as DFMEA. Usually, a group of experts of that different sector forms a team to conduct the FMEA. The FMEA review results are documented in a table to record any responses and to determine the RPN score. Design notes were also taken at this stage as the analysis also identified possible design solutions. Recording the outcomes of the analysis will aid in the design process as it allows validation data to be collected that can be referred to for verification as the design develops.

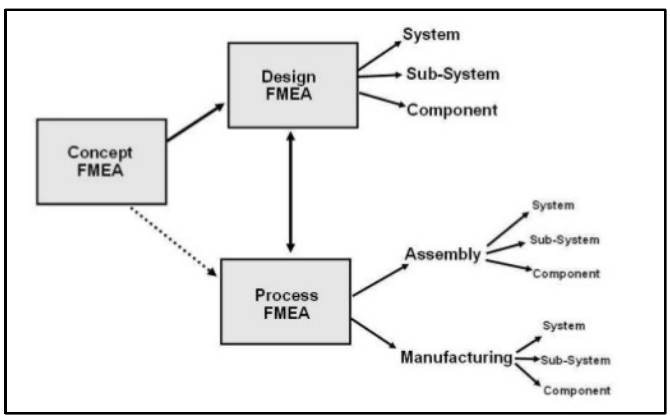


Figure 26: Process of FMEA analysis [65].

To conduct the FMEA analysis for the indoor aquaponics system the process flow chart is considered as the basic document to learn about the design and process. The steps required to conduct FMEA are described below:

	Project Name: Ever Green- Blue Water			FMEA									
	Location: Freeman Ranch, Texas State												
	San Marcos, Texas												
									Control Methods				
System	Item	Functions	Requirement	Failure Mode	Effects	Severity	Class	Causes	Prevention Control	Occurrence	Detection Control	Detection	RPN

Figure 27: FMEA for aquaponics.

STEP 1: Review the process

A process flow chart for PFMEA or details design documents for DFMEA is considered as the base document for FMEA. For the indoor aquaponic system one general FMEA analysis is prepared. For this FMEA the process flow chart was used to identify each process component.

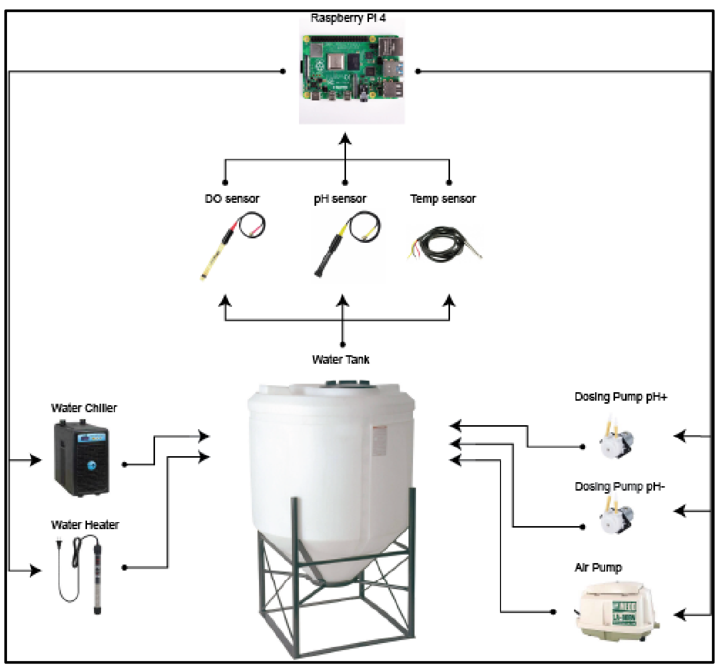


Figure 28: Process flow chart.

As aquaponics has lots of variables so the overall process is divided into subcategories like mechanical, Electrical, Physical, Nutrition, and Data.

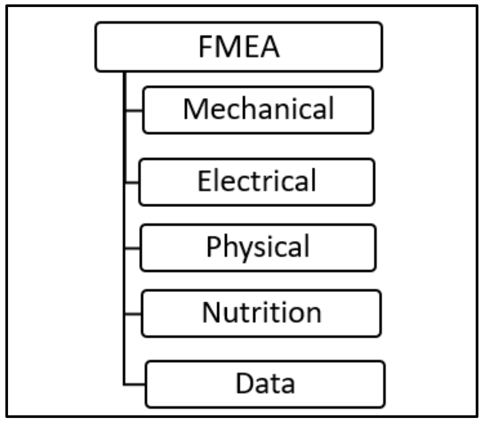


Figure 29: Subsystem of FEMA of aquaponics.

For each system, there are several subsystems. For example, the mechanical system is a combination of several mechanical components like water tanks, biofilter tanks, pipe and hose, the growing rack, and many others. For this research, the most important components are considered.

STEP 2: Brainstorm potential failure modes

To identify the potential failure, it is necessary to know about the design and function of that item. For example, the mechanical item has some specific requirements, and this requirement will help to evaluate the severity of any failure that happened for that item. This list of failures is from the expertise of the team member or review existing documentation and data for clues about all the ways each component can fail. There will likely be several potential failures for each component.

Table 03: Item, function, and requirement for any aquaponics FMEA.

System	Item	Functions	Requirement	Failure Mode	Effects	Severity	Causes	Control Methods: Prevention Control	Occurrence	Detection Control	Detection	RPN
Mechanical	Pipe	Transfer water between tanks	Required to transfer the nutrition in solution for fish, plant and drainage.	Leakage or broken	Nutrition rich water or return water may leake from the system.	4	Improper joint on pipe or hoses.	Use proper fittings with expert installation	3	Monitor water consumption regularly	5	60
				Algae grown	Consumes the nutrition	5	May be there is presence of sunlight or not well balanced nutrition in water.	Proper design of lighting	5	Visual inspection	2	50
				Clogged	Hamper the flow rate of nutrition	5	Sediments or improper bending of hose and pipe may create sediments.	Periodic cleaning	2	Flow rate monitor	4	40
				Degraded	Posses a risk of breakdown for possible leakage	4	Material defect	Proper materials	3	visual inspection	4	48

From table 03 for the mechanical system, one of the items of that system pipe was shown. The necessity of the pipe and its requirement for the aquaponic system were listed. The possible failure of the pipe could be broken, clogged, algae were grown or degraded.

STEP 3: List potential effects of each failure

The effect is the impact the failure has on the product or subsequent steps in the process. There will likely be more than one effect for each failure. For example, from figure 26 the effect of a particular failure mode of the pipe may affect the disturbance of the flow of nutrient-rich water from the fish tank to the plant.

System	Item	Functions	Requirement	Failure Mode	Effects	Severity	Causes
Mechanical	Pipe	Transfer water between tanks	Required to transfer the nutrition in solution for fish, plant and drainage.	Leakage or broken	Nutrition rich water or return water may leake from the system.	4	Improper joint on pipe or hoses.

Figure 30: Effect of the failure mode.

STEP 4: Assign Severity rankings

The Severity Ranking is an estimate of how serious an effect would be if it occurs. Based on the severity of the consequences of failure the severity for that specific failure is ranked between 0 to 10. In this research for any failure that can kill the fish or plant is considered most severe and ranked accordingly.

System	Item	Functions	Requirement	Failure Mode	Effects	Severity	Causes
Mechanical	Pipe	Transfer water between tanks	Required to transfer the nutrition in solution for fish, plant and drainage.	Leakage or broken	Nutrition rich water or return water may leake from the system.	4	Improper joint on pipe or hoses.

Figure 31: Severity for that failure.

STEP 5: Assign Occurrence rankings

The occurrence ranking is based on the possibility of regularity that the cause of failure will occur. Once the cause is known to the team the data was captured on the frequency of the cause. For example, for the pipe leakage, the cause can be an improper joint between the pipe and hose, and the chance to repeat the problem is 3 out of 10. As the chance of repeat is lower so the raking is lower too.

System	Item	Functions	Requirement	Failure Mode	Effects	Severity	Causes	Control Methods			
								Prevention Control	Occurrence	Detection Control	Detection
Mechanical	Pipe	Transfer water between tanks	Required to transfer the nutrition in solution for fish, plant and drainage.	Leakage or broken	Nutrition rich water or return water may leake from the system.	4	Improper joint on pipe or hoses.	Use proper fittings with expert installation	3	Monitor water consumption regularly	5

Figure 32: Occurrence for that failure.

STEP 6: Assign Detection rankings

To assign detection rankings, we need to identify the process or product-related controls in place for each failure mode and then assign a detection ranking to each control.

Table 04: Occurrence ranking for any failure.

Detection	The likelihood that the defect will be detected	Ranking
Almost Certain	Easy or almost certain to detect	1
Very high	Very high chance that the current control method will find the defect.	2
High	High chance to detect the failure.	3
Moderately High	Moderately chance to detect the failure	4
Moderate	Moderate chance to detect the failure.	5
Low	Low chance to detect the failure	6
Very Low	Very low chance to detect the failure with the existing method	7
Remote	Remote likelihood to detect the failure	8
Very Remote	Very remote likelihood to detect the failure	9
Almost Impossible	No methods are known to detect the failure	10

Detection rankings evaluate the current process controls in place. A control can relate to the failure mode itself, the cause (or mechanism) of failure, or the effects of a failure mode. To make evaluating controls even more complex, controls can either prevent a failure mode or cause from occurring or detect a failure mode, cause of failure, or effect of failure after it has occurred.

System	Item	Functions	Requirement	Failure Mode	Effects	Severity	Causes	Control Methods				RPN
								Prevention Control	Occurrence	Detection Control	Detection	
Mechanical	Pipe	Transfer water between tanks	Required to transfer the nutrition in solution for fish, plant and drainage.	Leakage or broken	Nutrition rich water or return water may leake from the system.	4	Improper joint on pipe or hoses.	Use proper fittings with expert installation	3	Monitor water consumption regularly	5	60

Figure 33: Detection for any failure.

STEP 7: Calculate the RPN

RPN gives us the relative ranking between the errors. It is calculated by multiplying three rankings together. After calculating all the RPN for all the failures the priority was set up according to the RPN value. The more the RPN the most critical that failure is.

System	Item	Functions	Requirement	Failure Mode	Effects	Severity	Causes	Control Methods				RPN
								Prevention Control	Occurrence	Detection Control	Detection	
Mechanical	Pipe	Transfer water between tanks	Required to transfer the nutrition in solution for fish, plant and drainage.	Leakage or broken	Nutrition rich water or return water may leake from the system.	4	Improper joint on pipe or hoses.	Use proper fittings with expert installation	3	Monitor water consumption regularly	5	60

Figure 34: RPN for any failure.

STEP 8: Develop the action plan

Once the RPN is calculated and the highest RPN will get focus and taken care of first. The next step is to assign someone for mitigation of that specific error.

Action Recommended	Responsibility	Action Taken
What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure that the actions are completed?	What actions were completed (and when) for RPN?

Figure 35: Responsibility for the defined actions.

STEP 9: Actions Taken

Implement the improvements identified by the FMEA team. The Action Plan outlines what steps are needed to implement the solution, who will do them, and when they will be completed. Most Action Plans identified during a PFMEA will be of the simple "who, what, & when" category. Responsibilities and target completion dates for specific actions to be taken are identified.

Action Recommended	Responsibility	Action Taken
What are the recommended actions for reducing the occurrence of the cause or improving detection?	Who is responsible for making sure that the actions are completed?	What actions were completed (and when) for RPN?

Figure 36: Action is taken to reduce the RPN.

STEP 10: Calculate the resulting RPN

Re-evaluate each of the potential failures once improvements have been made and determine the impact of the improvements. This step in a PFMEA confirms the action plan had the desired results by calculating the revised RPN. To recalculate the RPN, reassess the severity, occurrence, and detection rankings for the failure modes after the action plan has been completed.

Recommended Action				Re-Evaluation			
Action	Responsibility	Target Finish Date	Actual Finish Date	Severity	Occurrence	Detection	RPN
Indentify the possible joint that might broke or leak	The operations team	6/10/2021	6/15/2021	4	1	5	20

Figure 37: Re-evaluate RPN.

3.3 Improvement in Aquaponics

In this research, a complete FMEA was carried out for Evergreen-Blue water aquaponics at the Freeman Ranch and a few of the important improvements with RPN are listed below:

Table 05: Improvements in aquaponics.

System	Improvements	RPN	
		Before	After
Mechanical	Cause of failure: Leakage in hose connection. Prevention: Eliminate improper joints or the addition of clamps in the high-pressure regions.	60	20
Physical	Cause of failure: Bubble from air pump was uncontrolled. Prevention: Put a control valve after the air pump.	90	40
Electrical	Cause of failure: Electrical relay was not placed properly causing an automation error. Prevention: Secured the relay with support for smooth operation.	80	30

The FMEA chart was divided into sub-systems like mechanical, electrical, physical and nutrition, and data. For all subsystems, the list was constructed. As the aquaponics system in this research is in the development phase so, mostly the list focuses on design and process improvement.

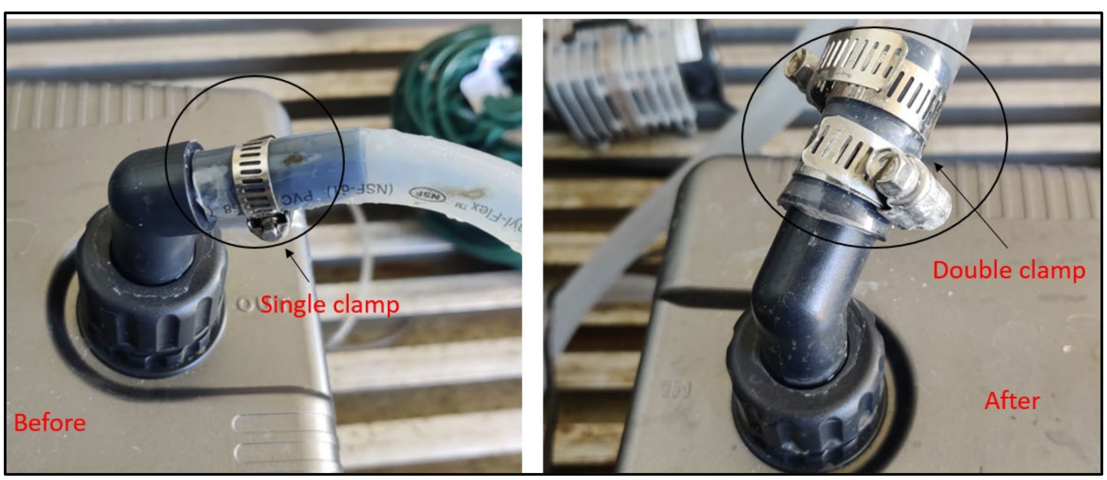


Figure 38: Improvement of water hose clamping before any leakage.

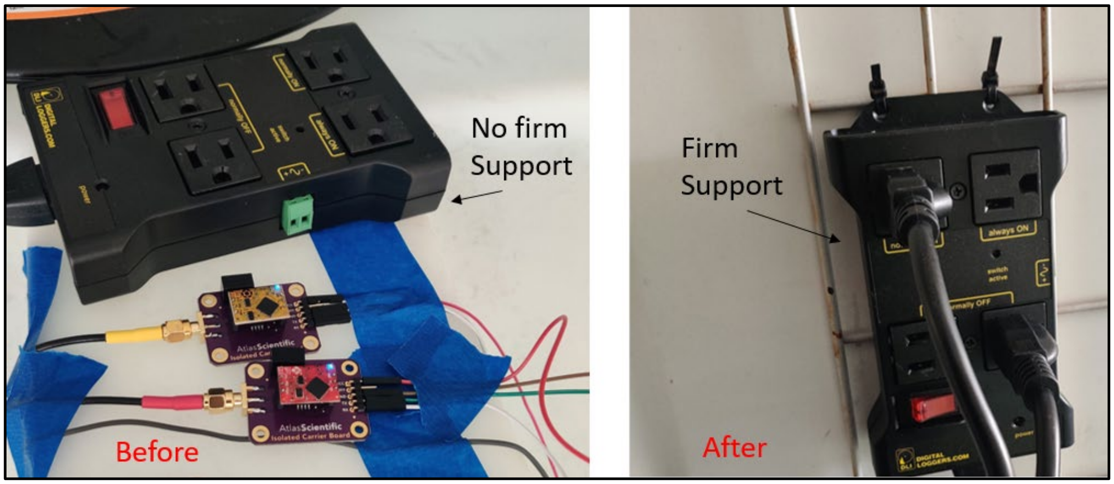


Figure 39: Improvement of electrical system before any error during operations.

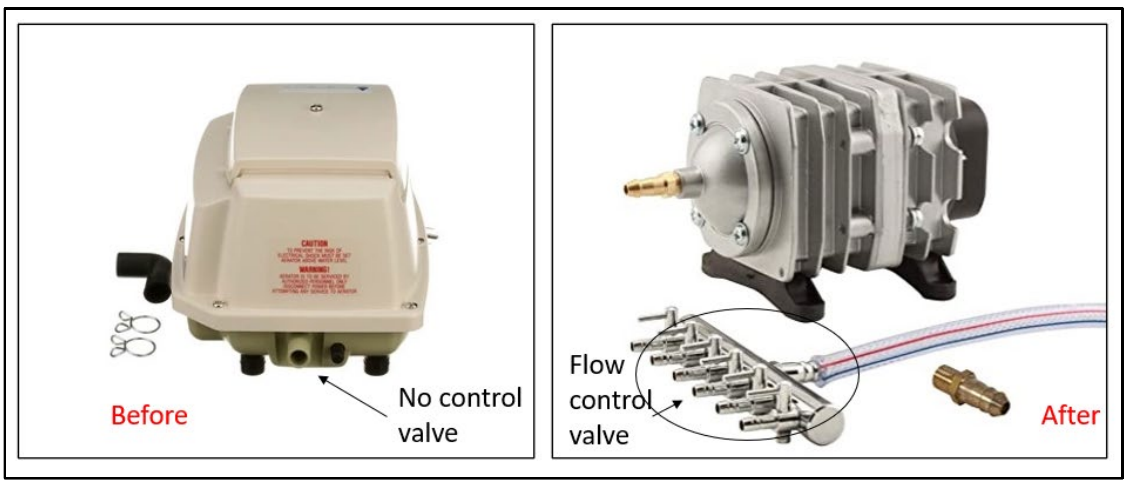


Figure 40: Improvement of a physical system before it harms the fishes.

3.4 Results

This research is based on the general FMEA for the indoor aquaponic system and one complete FMEA is listed in appendix B. The ultimate target of the FMEA is to reduce the failure and before it happens or improve the process for not happen further. The RPN is the numerical value calculated to identify the weight of that failure and its impact. The

FMEA list prepared and necessary actions taken by the concerned team can improve the RPN and hence improve the overall design and process.

			Control Methods					Recommended Action				Re-Evaluation			
Severity	Class	Causes	Prevention Control	Occurrence	Detection Control	Detection	RPN	Action	Responsibility	Target Finish Date	Actual Finish Date	Severity	Occurrence	Detection	RPN
4		Improper joint on pipe or hoses.	Use proper fittings with expert installation	3	Monitor water consumption regulary	5	60	Indentify the possible joint that might broke or leak	The operations team	6/10/2021	6/15/2021	4	1	5	20

Figure 41: Improvement with FMEA.

3.5 Conclusion

In this research, the application of FMEA helps the design, build, and operation of the aquaponic system more errorless and it showed clearly with reduction of risk priority number. Hence the claim of hypothesis-2 is accepted.

FMEA is a lean six sigma tool used to mitigate the risk of possible failures. FMEA needed to be done at the design stage, operation stage and throughout the life span of the aquaponic system and update the list and use as future references for the future grower. Although FMEA has many advantages, still there are few limitations and different improvements done so far to make it more reliable. As the risk priority no is based on the judgment of the responsible person and team, there is always a chance of human error. If the risk priority no became the same for few errors, then the priority setting might be a little confusing for the user. Updated FMEA like fuzzy FMEA and Logistic regression-based FMEA can be used to eliminate the possible error.

4. SMART AUTOMATION

4.1 Introduction and Problem Statement

This chapter assesses hypothesis 3: Aquaponics operation and feeding mechanism can be optimized. Correlation between instrument settings (e.g., pump flow, heat/cooling/gassing hrs., and feeding setting) and by considering outside ambient can be found that maintain the system near optimum conditions. The major challenge of the aquaponic system is the initial investment and the operation cost. The operation is labor-intensive and requires an expert operator. This chapter is focused on the development and implementation of automation and make the system less costly to operate. The microcontroller-based control system and digital twin are utilized to predict and control the system with less error and greater output.

4.2 Method and Materials

The control an automated aquaponic system many parameters need to be measured and controlled. Plants and fish in the system each have a feasible range and a desirable point for each of these parameters. If the condition falls outside of the feasible range (e.g., water temperature too hot), it will be fatal to these creatures. To operate an aquaponics control system, all parameters should be identified, the feasible range of each parameter for the plants and fish should be determined, measured, and adjusted. Each living element has a different range or limit of parameters based on species. So, while selecting the type of fish and plants the temperature range is a serious concern. For this complex system, the proposed solution is to separate the control paraments into two different categories. Level-01 are those parameters directly related to the life of fish, plants, or microorganisms. This continuous monitoring will be carried out by measuring temperature, Dissolved Oxygen, pH, and nitrate of the water solution by using sensors and microcontroller-based computing systems. Level-02 are those parameters needed to monitor periodically for the smooth growth of the aquaponic system. Handheld meters or sensors will be used, and the data will be recorded in a computer or any mobile application and verified with reference data. For level-02 monitoring, the nutrition level, total dissolved solids (TDS), electrical conductivity (EC), and total ammonium nitrate (TAN) of water solution are recorded.

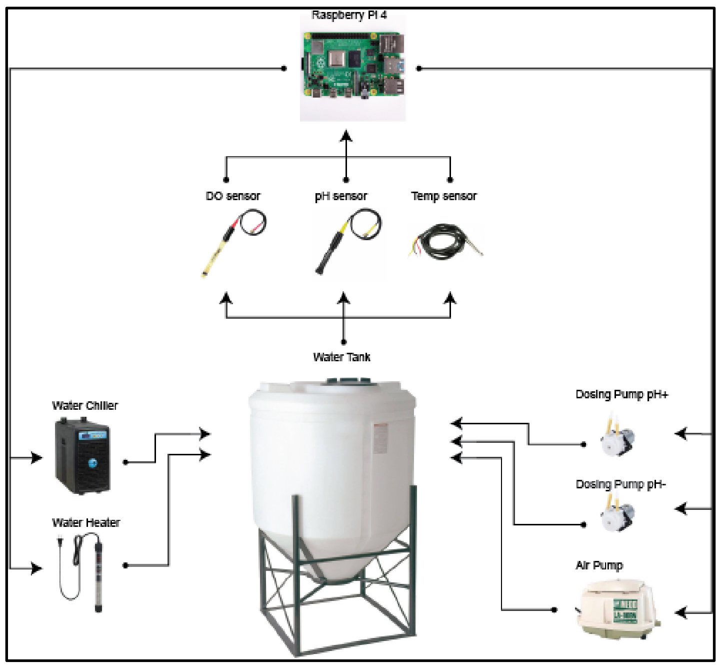


Figure 42: Automatic control of aquaponics system.

4.2.1 Temperature Control

Each plant and fish species have a level of tolerance and an optimum point for ambient temperature. The suitable temperature range for most vegetables is 18 - 30 ºC [66]. Although few vegetables like lettuce and cucumbers like temperature 8ºC – 20 ºC and some vegetables like okra, basil suited a temperature range between 17ºC – 30 ºC. Fishes are cold-blooded and can't survive with a big temperature range. For fishes like tilapia and catfish, they survive around 22 – 32 ºC. Other cold-water fishes like to have a range of temperature between 10 – 18 ºC. For microorganisms like nitrifying bacteria, the ideal temperature range should be around 17 – 34 º. To get a feasible condition for all living elements in the system, the temperature setting is set between 18- 30 ºC [67].

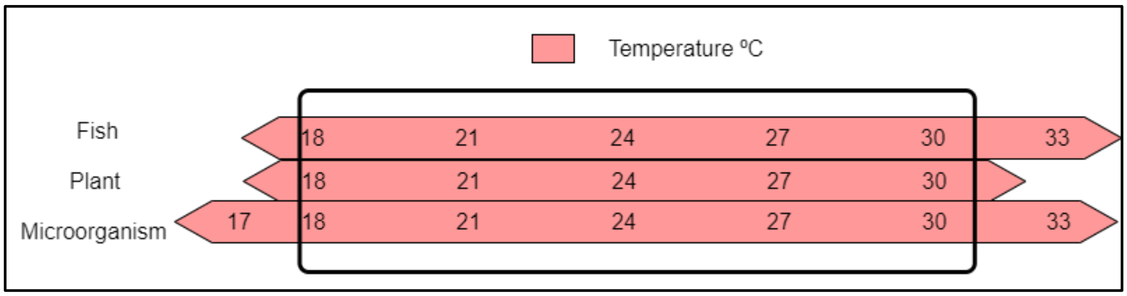


Figure 43: Temperature range for all living elements in aquaponics.

To keep the system temperature within the range, the temperature was measured with a DS18B20 temperature probe. The probe is submerged into water and based on the reading the microcontroller is deciding to on or off the water chiller or heater to achieve a controlled temperature.

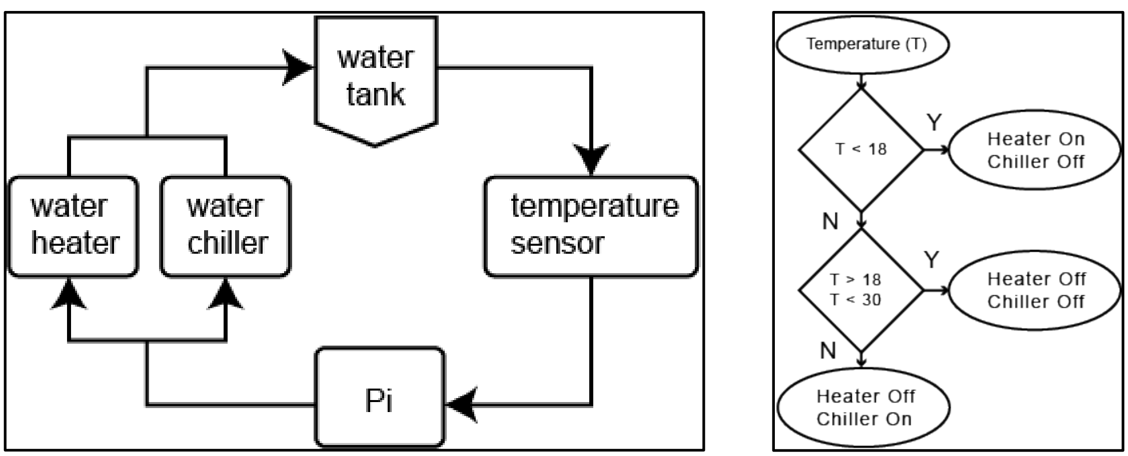


Figure 44: Temperature control logic for an aquaponic system.

4.2.2 pH Control

Another important parameter that needs to regulate is pH for water. As there are three different living elements in the water fish, microorganisms, and plants and they have a different range of pH [40]. Although the hydroponics component of the aquaponics system has the optimum pH requirement is slightly acidic (5.5-5.8) [68]. If the pH became higher than 7.0 or lower than 4.5 the plats may have root injury or other mineral precipitation on the plant roots may hamper the intake of the mineral [41]. On the other hand, fish can tolerate a wider pH range. The optimal pH for fishes is different for different fish species. For nitrification, the pH range for optimum performance of nitrifying bacteria is between 7.5 -8 [68].

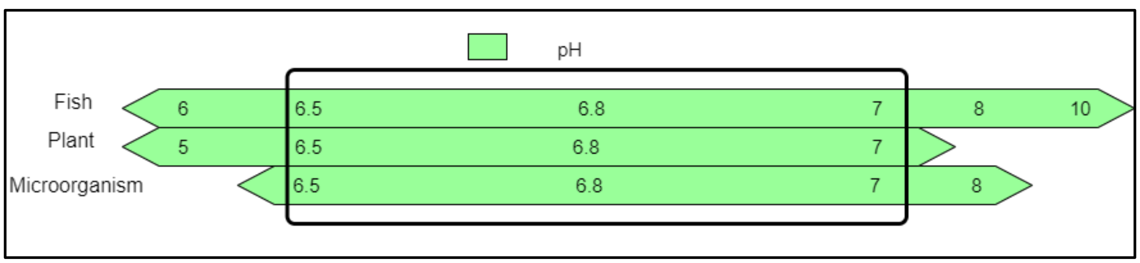


Figure 45: pH range for all living elements in aquaponics.

For the aquaponic system, the overall optimum pH range is between 6.8 - 7. To control the pH fluctuation first pH was measured with Atlas scientific pH probe connected with a microcontroller. With a pre-set pH range between 6.8 -7, the microcontroller will operate a pH increase or reducing chemical dosing pump.

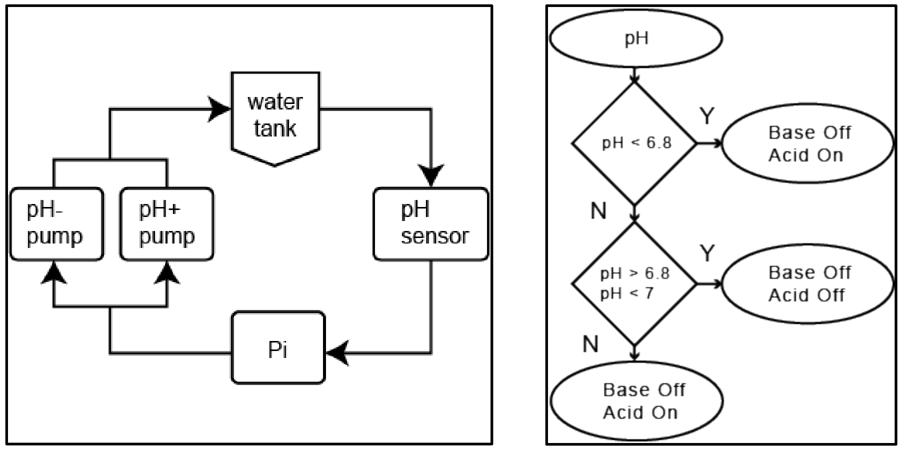


Figure 46: pH control logic for an aquaponic system.

4.2.3 Dissolved oxygen

Dissolved Oxygen (DO) is another important parameter for aquaponics. DO is a measure of how much oxygen is dissolved in the water available for aquatic living organisms. Oxygen is dissolved in water at a very low concentration and has a drastic effect on the aquaponic system [69]. Dissolved oxygen has a strong relationship with the temperature of the water. When the temperature increased the amount of dissolved oxygen goes down [67]. DO level was measured with Atlas scientific DO sensor and the microcontroller will operate the air blower to increase the DO level. The general recommendation for DO level for the aquaponic system is a minimum of 5 PPM (Parts per million) [70]. When the DO level is going down the fish will try to come on the water surface. One Atlas scientific DO sensor has been used to measure the level of DO in water. Once the Level is going down below 5 PPM, the aeration motor will be starting and will increase the DO to maintain a certain level of DO in water.

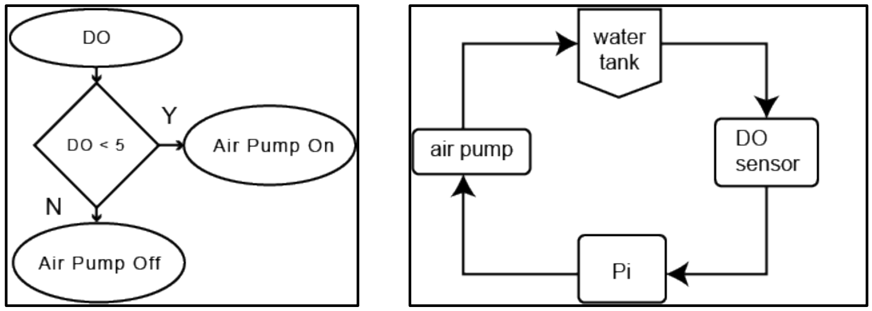


Figure 47: DO control logic for an aquaponic system.

4.2.4 Nitrate

Nitrate is a very important parameter for an aquaponics system. Fish waster and leftover fish food will be converted to un-ionized ammonia (NH_3) and ionized ammonium (NH_4^+). Un– ionized ammonia is toxic to fish. The total value of ammonia and ammonium is called total ammonium nitrate (TAN) [71]. To measure the TAN a lot of commercial methods are available. Nitrification is the process to convert toxic ammonia into nitrate (NO_3) with the help of nitrification bacteria. The nitrate level should be less than 90 mg/L for a healthy aquaponics system [40]. The plant will uptake the nitrate from the water as a nutrient. In this research, one nitrate sensor with a microcontroller has been used the measure the amount of nitrate and manipulate the fish food amount and type to controller the overall nitrification system of the aquaponic system. The overall nitrate level is recommended between 50-100 mg/L [72].

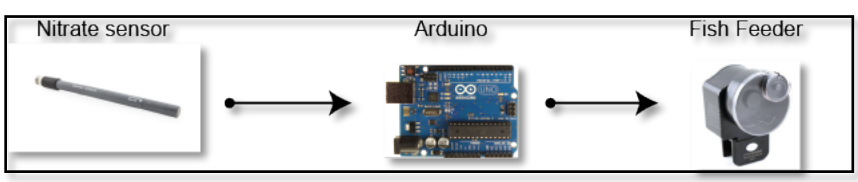


Figure 48: Nitrate control flowchart for an aquaponic system.

4.3 Digital Twin

The digital twin is the virtual representation of a physical object or system across its life cycle. It uses real-time data and other sources to enable learning, reasoning, and dynamically recalibrating for improved decision making. This research has utilized digital twin, as a tool to predict any possible error. The real-time data was saved on the microcontroller and that data was plotted to find any possible error identification and solve that before it happens.

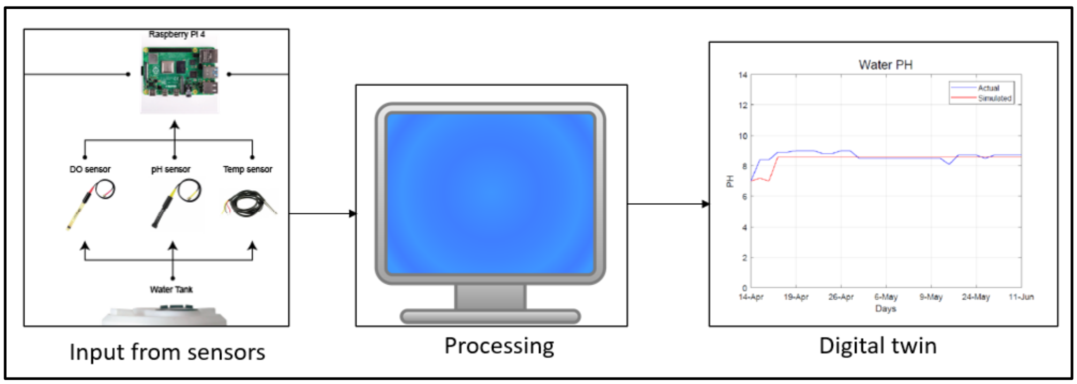


Figure 49: Digital twin methods and application in aquaponics.

4.4 Result

This section provides the result of the implementation of automation in aquaponic systems. The result is obtained after few weeks of observation on the aquaponic system. Each part of the automation was tested for its functionality. For temperature control between a range, a water chiller and heater have been used and tested separately. The return water from the hydroponic part is conditioned in a separate tank. The chiller has been used to control the temperature within the set limit. The chiller was able to maintain the water temperature at 16 °c for 12 hours of operation test for 150 liters of water.

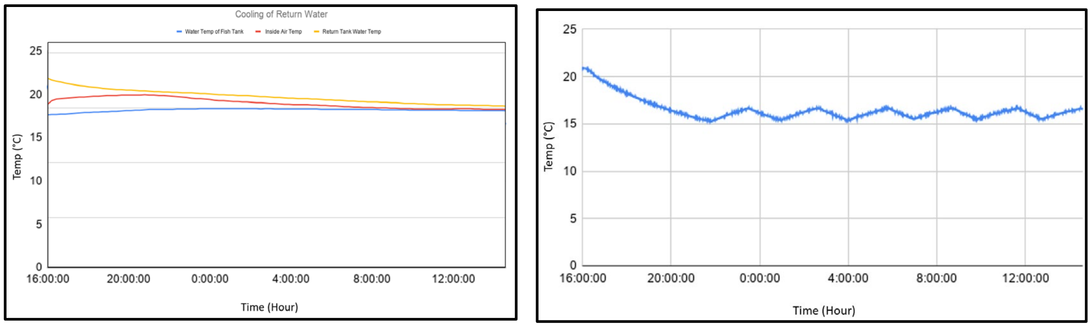


Figure 50: Temperature control with chiller and natural cooling.

The change of pH was a little slower. Almost steady pH was found during that time. The pH was measured and plotted every after 30 seconds. The pH balance was maintained by dosing pH increase and decrease solution with the help of two Peristaltic dosing pumps. The ideal range of pH was maintained between 6.5-7.

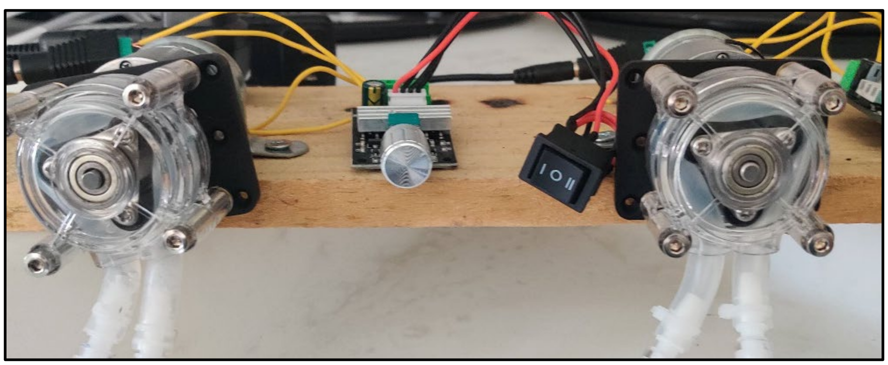


Figure 51: Development of pH control kit.

To maintain the dissolved oxygen level air pump with bubbler stone has been used. And the microcontroller is keeping the level of dissolved oxygen above 5 ppm. The data obtained from the microcontroller for DO level is plotted in figure-10.

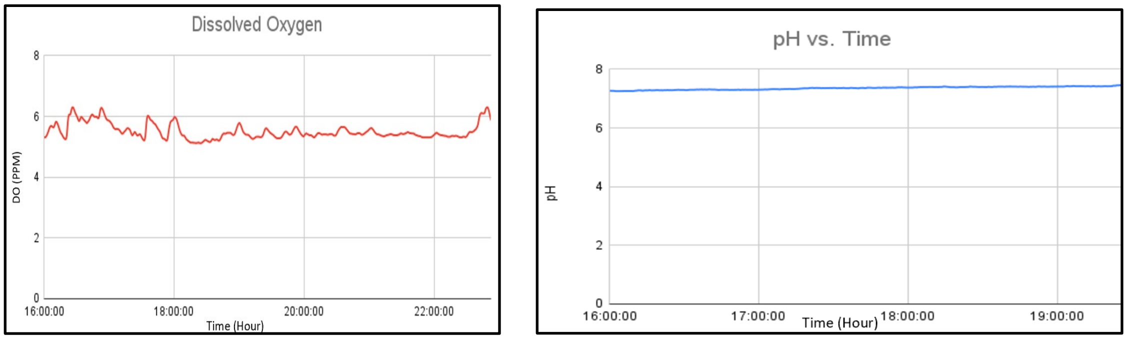


Figure 52: pH and DO level output graph.

The nitrate level has been controlled by controlling the types and amount of fish food. As nitrate is the result of the nitrification process, so the increased amount of nitrate indicates the under-designed biofilter and will be harmful to the aquatic living condition. The level of ammonia is needed to measure regularly. One portable Ammonia sensor was used to measure the ammonia and can be manipulated by changing the fish water or increasing the biofilter size or the number of plants, or the number of fish. It's always recommended not the change all water at a time for the aquaponics system.

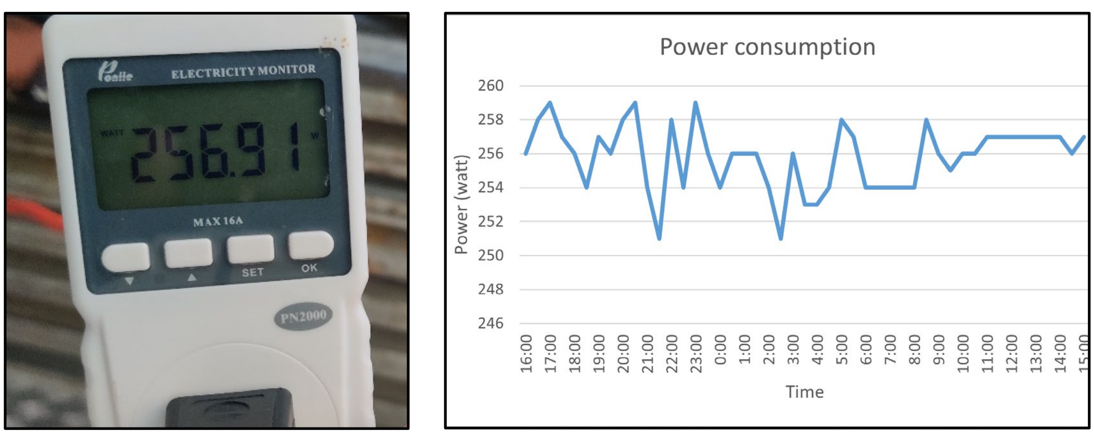


Figure 53: Power consumption per hour and monitoring for aquaponics.

The power consumption was measured manually with a digital power measuring tool and plotted the consumption to monitor the activity of the system.

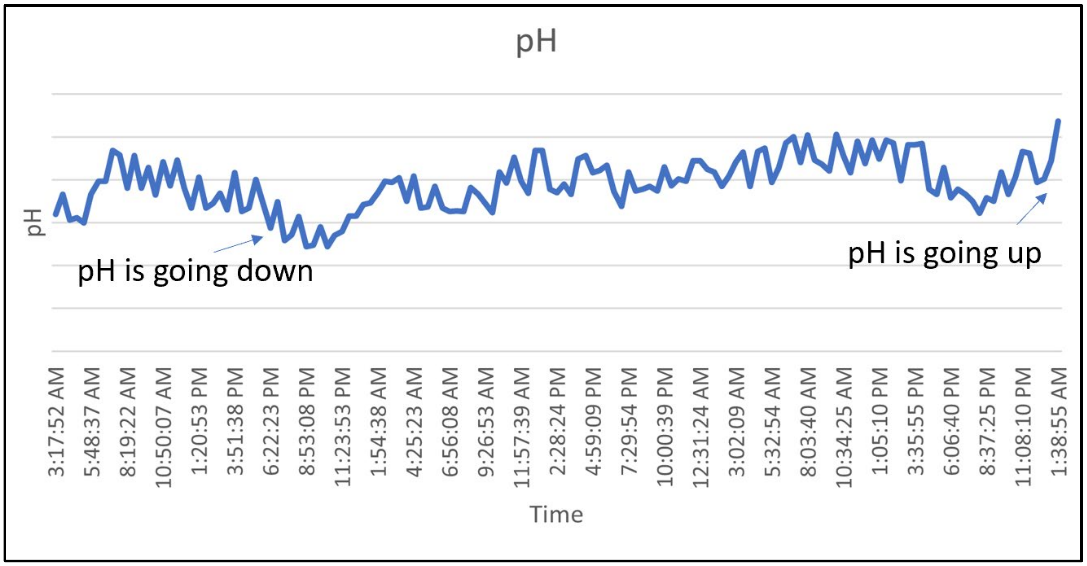


Figure 54: pH monitoring and application for Digital Twin.

Once, data from raspberry pi was transferred and plotted to prepare a digital twin of the system. With any gradual change in the trend of data, the prediction of possible error with digital twin can be possible. Any aquaponic grower can eliminate errors from the system before they happen.

4.5 Discussion and Conclusions

The claim in hypothesis 3 is accepted as the design, installation, coding, and application of automation for the aquaponic system replaced most manual activities and the digital twin brought a real-time monitoring experience. In this research, for the automation, the major challenge was the integration of different sensors for the microcontroller and controlling the flow rate with different pumps. For the limitation of nitrate sensor one Arduino-based controller use used for the control of nitrate. The ammonia sensor is required that can measure and integrate with the microcontroller is one of the future tasks. As these, sensors are monitoring the data continuously, another challenge is to calibrate the sensors to ensure data accuracy.

5. EMPIRICAL STUDY: INTEGRATED SYSTEM IN OPERATION

5.1 Introduction and Problem Statement

This chapter describes hypothesis 04: *All subsystems can be connected via hardware and smart logic to operate automatically and flawlessly.*

To verify this hypothesis, one complete aquaponic system was developed from design to operation. Microcontroller-based smart automation and monitoring system was deployed for the smooth operation of the system. The system ran and was monitored for a long period with living fish to demonstrate the accuracy and consistency of the system.

5.2 Method and Materials

The aquaponic system was developed through a standard product development process. Product development steps vary based on the nature of the product requirement and business strategy, but most products and process development follow these main steps in the development process.

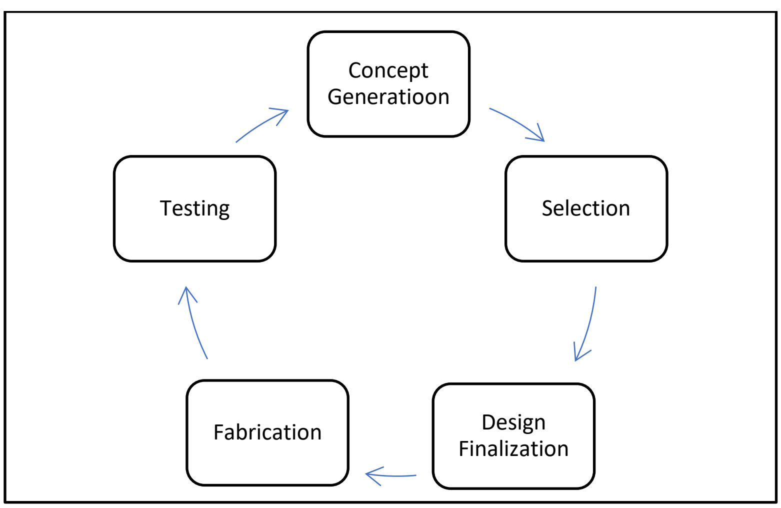


Figure 55: Product development steps.

5.2.1 Concept Generation

A literature review is the first step of concept generation. As this is not a new product so in the market there is already developed commercial aquaponics system. To adjust the system with existing hydroponic set up the necessary consideration was made, like water tank size selection, water transfer method, pump selection. To understand the basic operation of an aquaponic system one desktop commercial mini aquaponic setup was collected and observed the system to plan the operation process of the aquaponic system.

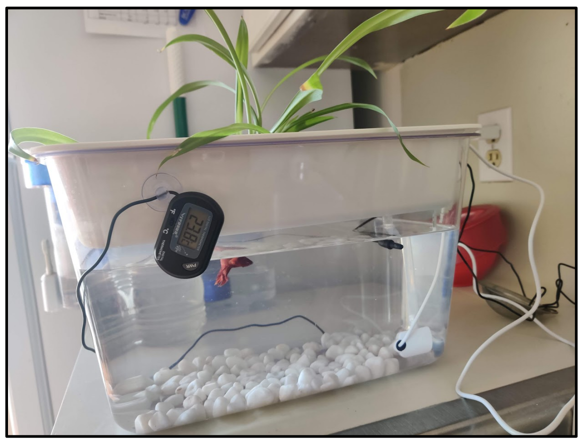


Figure 56: Mini aquaponics for process study.

5.2.2 Selection of Components

To find out the required components for the aquaponics system the process layout was created and with the process diagram the actual dimensions are taken from the research containers and the Bill of materials was developed.

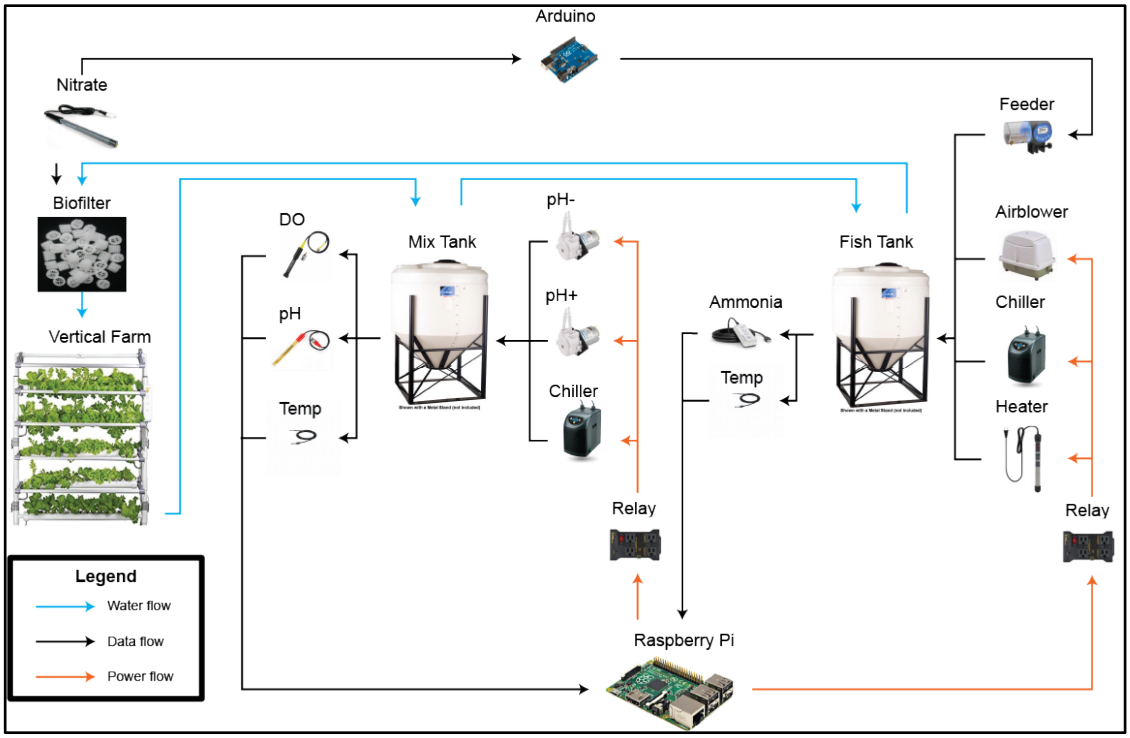


Figure 57: The process plan for the aquaponics system.

Once the process was developed the next step is the break the process into a system and sub-system. The aquaponic is divided into mechanical, electrical, and control subsystem.

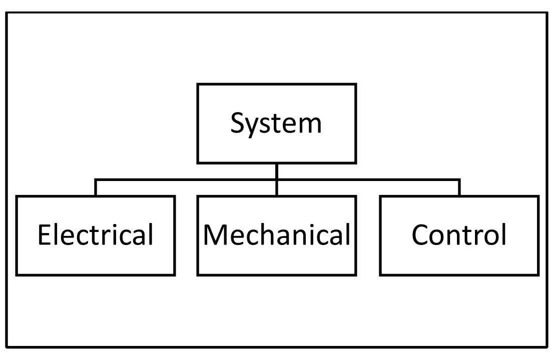


Figure 58: System and subsystem of aquaponics.

5.2.3 CAD model

Once the system and sub-system were defined then the entire model was developed into CAD software and that verifies the dimension to prepare the bill of materials.

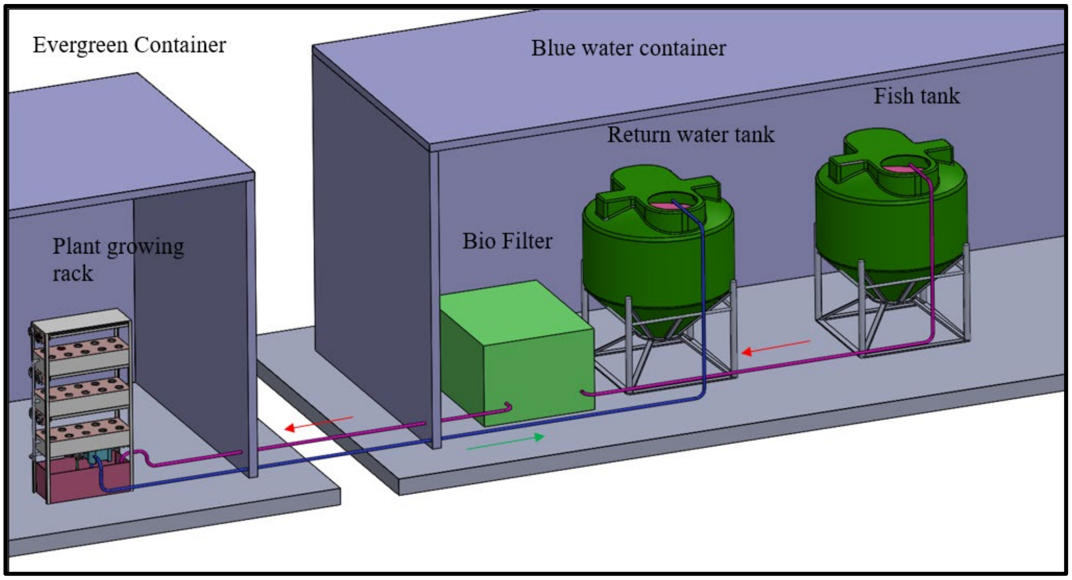


Figure 59: CAD model of aquaponics.

5.2.4 Mechanical System

The mechanical system is consisting of the following components:

Tanks

300-gallon cone bottom plastic tank is manufactured from linear polyethylene in one-piece, seamless construction, this tank series is designed for storage applications. UV stabilized for outdoor usage. One of the tanks was used for fish raising and another is used for the treatment of water that returned from the plant side.

Figure 60: Water tank and biofilter.

Pumps

To transfer the water between the tanks and container few submersible pumps were used[73]. The water flow rate can be manipulated with the control manual control valve.

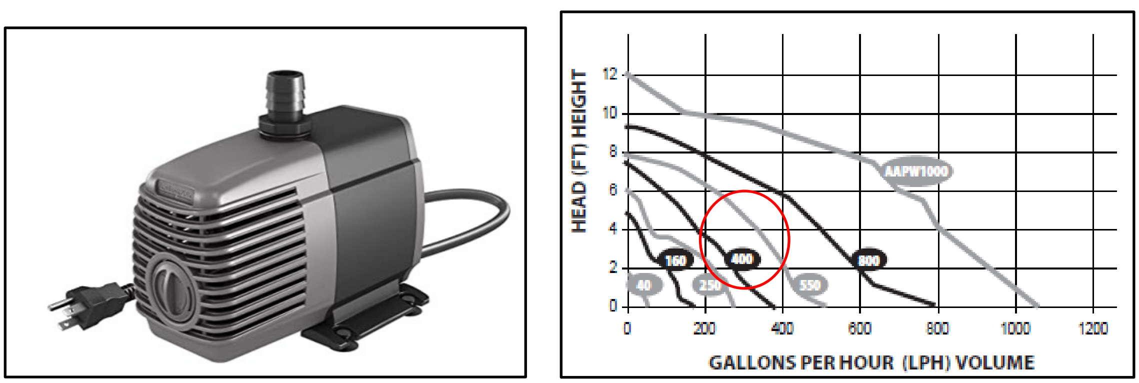


Figure 61: Water transfer pump

Specification of the pump:

1. 550 gallons per hour
2. Indoor / outdoor use

3. Oil-free / environmentally safe

Water Chiller and Heater

With the CFD simulation, the water temperature was known for weather temperature previous data and with this known temperature the maximum and minimum temperature will be considered for the selection of water chiller and heater.

1. Chiller: Large refrigeration capacity
2. Anti-corrosive pure titanium evaporator for both fresh and saltwater
3. Rate of flow: 1/10 HP (132–396 GPH 500–1500 L/H)
4. Rated BTU per hour: 1, 020
5. Operate at 10 PSI maximum

Figure 62: Water chiller and heater [74].

5.2.5 Electrical System

The electrical subsystem is comprised of the power supply to different components. The general power supply was 110 v. For different microcontrollers and sensors, the standard ac to dc power converted was used for seamless power supply.

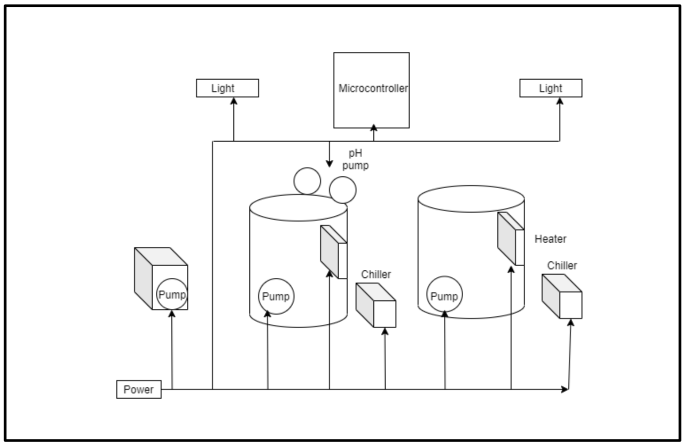


Figure 63: Power supply line diagram.

Heater

800W capacity aquarium Heater was selected considering the volume of water for aquaponics system with the following specification: Fastest 5 seconds warming, over-temperature protection prevents "cooking fish", When the heating rod is exposed to air, display fault code and the heater will shut off automatically.

5.2.6 Control

For the automatic control, a microcontroller-based control system was used. Raspberry pi was used to get input and control different parameters like temperature, pH, dissolved oxygen. The system was tested and operating with all the variables. For measuring

Ammonia one stand-alone sensor was used. From both containers, the data will be transfer towards a central raspberry pi and it will be stored in a local server.

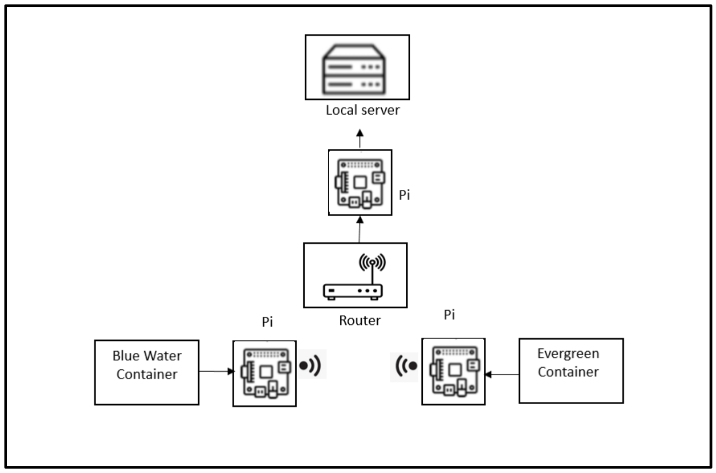


Figure 64: Data transfer plan.

5.2.7 Coding

Python was used to write the code for the raspberry pi control part. The detail's code was listed in the appendix- C1 section. For the Arduino control part, the code was written in Arduino's built-in system. The detail's code for nitrate and fish feed control is in Appendix C 2.

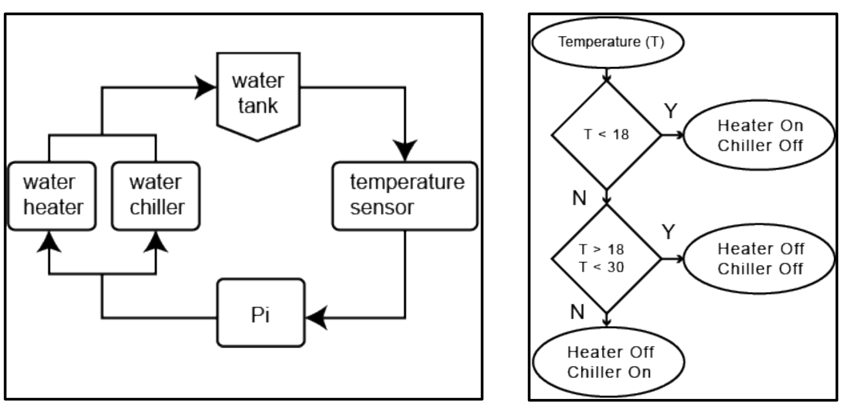


Figure 65: Temperature control logic and flow diagram for the aquaponics system.

```
main.py

import time
import states_bluewater as states
import logic_bluewater as logic
import sensors_bluewater as sensors
import csv_writer_bluewater as csv_writer


while True:
    # sensors
    ph_sensor = float(sensors.get_devices()[1])
    oxygen_sensor = float(sensors.get_devices()[0])
    temp_sensor = sensors.get_temp()

    # logic to assign state variables
    base, acid = logic.ph_logic(ph_sensor)
    airblower = logic.oxygen_logic(oxygen_sensor)
    heater, chiller = logic.temp_logic(temp_sensor)

    # GPIO control
    states.acid_outlet(acid)
    states.base_outlet(base)
    states.airblower_outlet(airblower)
    states.heater_outlet(heater)
    states.chiller_outlet(chiller)
```

Figure 66: Sample code for automation.

5.2.8 Sensors

Temperature sensor: To measure the temperature of the fish tank and return water tank two temperature sensor from Atlas scientific® PT-100 was used [75]. The specification of the sensors is given below.

Reads	Temperature
Range	-200˚C to 850˚C
Probe type	Class A platinum, RTD
Accuracy	+/- (0.15 + (0.002*t))
Connector	Male BNC
Reaction Time	90% in 13s
Cable length	81cm
Output	Analog
Time before recalibration	3–5 years
Life expectancy	15 years

Figure 67: Temperature sensor.

pH sensor: To measure the pH of the return water one pH sensor from Atlas scientific® was used. The detailed specification of the sensors is given below.

Reads	pH
Range	0 – 14
Resolution	+/- 0.001
Accuracy	+/– 0.002
Response time	95% in 1s
Temperature range °C	-5 – 99 °C
Max pressure	100 PSI
Max depth	70m (230 ft)
Connector	Male SMA / Male BNC (Optional)
Cable length	1 meter
Internal temperature sensor	No
Time before recalibration	~1 Year
Life expectancy	~2.5 Years +

Figure 68: pH sensor [76].

Dissolved oxygen: To measure the dissolved in both fish tank and returned water tank two dissolved oxygen sensors were used.

Reads	Dissolved Oxygen
Range	0 – 100 mg/L
Accuracy	+/- 0.05 mg/L
Response time	~0.3 mg/L/per sec
Temperature range °C	1 – 60 °C
Max pressure	3,447 kPa (500PSI)
Max depth	352m (1,157 ft)
Connector	Male SMA / Male BNC
Cable length	1 meter

Figure 69: Dissolved oxygen sensor [77].

Nitrate: To measure the nitrate of the aquaponics system, one nitrate sensor from vernier was used. It can measure nitrate between 1 to 14000 mg/Liter (PPM).

Figure 70: Nitrate sensor [78].

Ammonia: Seneye® sensor monitors the highly toxic free ammonia (NH3) at very low levels. That helps to prevent fishes dying from Ammonia poisoning. The only drawback of that sensor is it has to connect to a desktop computer.

Figure 71: Ammonia sensor [79].

5.3 Result

From the automation, with the microcontroller, the sensors are operating, and based on the preset value it can operate different equipment to control the parameters like Dissolved oxygen, pH, Temperature, etc. The Seneye® sensor is giving the result in the connected web application. It is an integrated sensor with Temperature, pH, and Ammonia.

Figure 72: Ammonia integrated sensor.

From figure 68, the parameters like temperature are 28 ºC, pH is 6.89, and ammonia is 0.080 mg/L. The chiller was operated as per temperature logic.

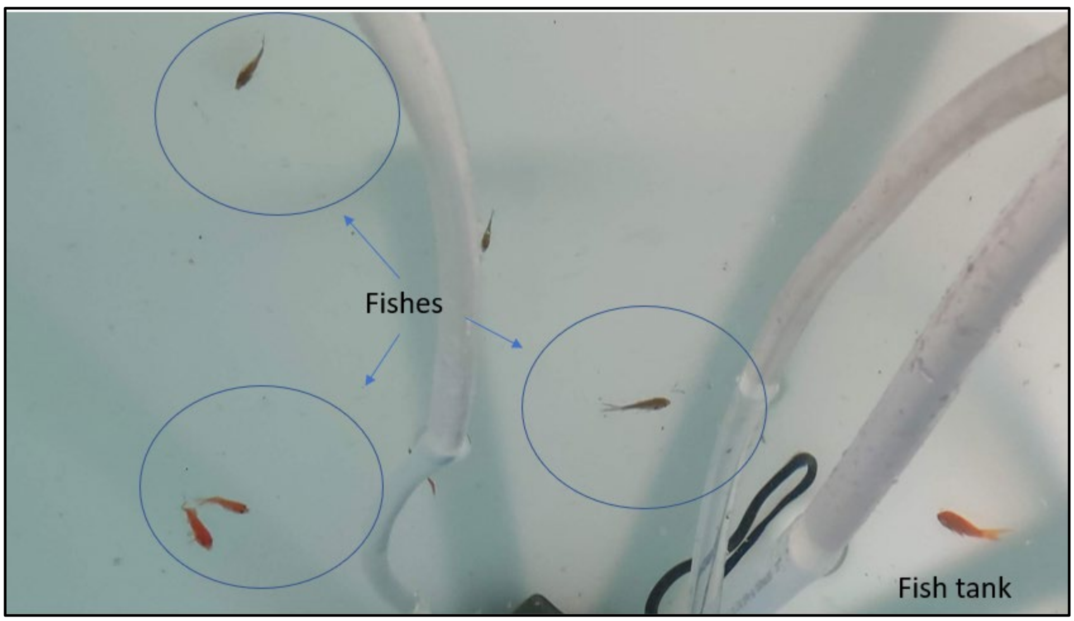


Figure 73: Live fish in the aquaponics system.

Figure 70 describing the fluctuation of temperature in the container but the water for the fish tank is much steady.

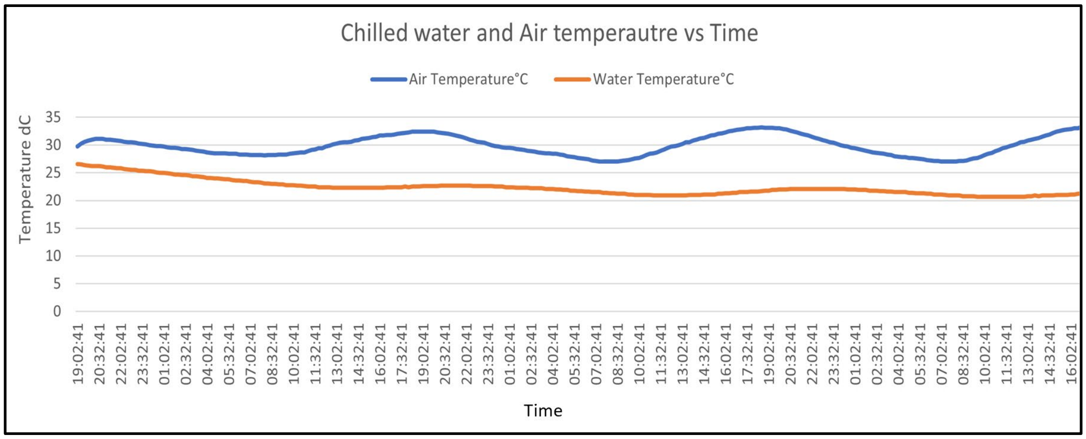


Figure 74: Chilled water and air temperature vs time.

The dissolved oxygen level has a strong relation with temperature. If the temperature of the water is getting higher the dissolved oxygen level is going down, on the other hand, if the temperature is getting down the dissolved oxygen is going high.

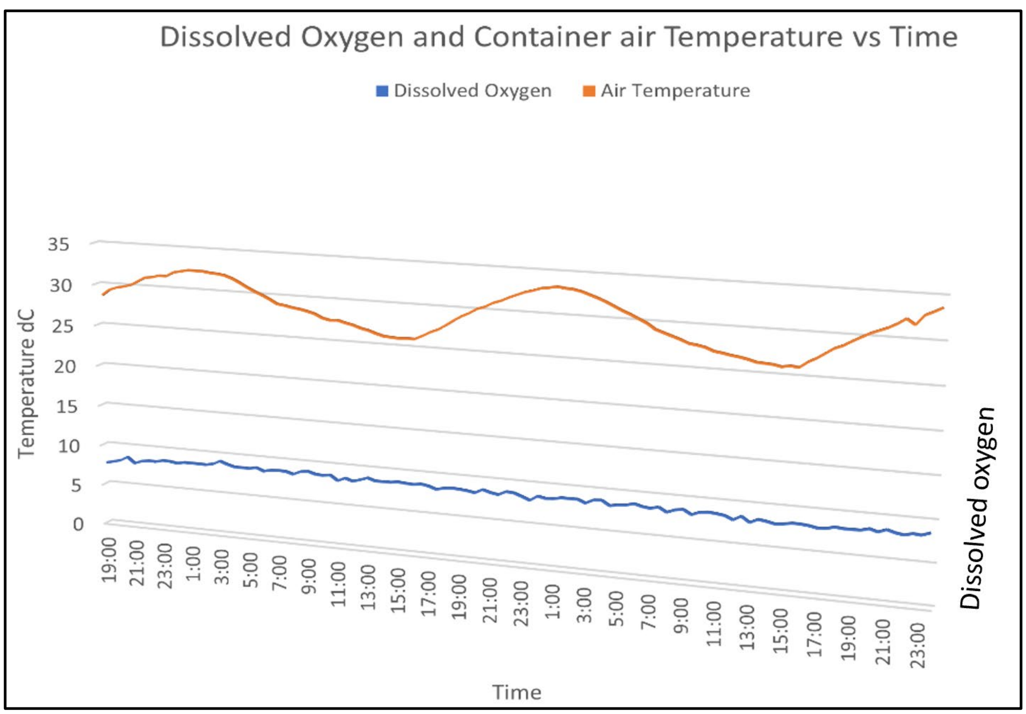


Figure 75: Steady dissolved oxygen level for varying temperatures.

From figure 70 it is proven that with a variation of the container inside temperature the water temperature is steady with the automatic operation of the water chiller according to logic. From figure 71 is it clear that with a temperature variation the dissolved oxygen level is quite steady that validates the integrity of the system and its automation.

5.4 Conclusion

The claim in Hypothesis 4 is accepted by design, build and operate the aquaponic system with fish for a long period. With the help of a process diagram, the overall process can be assessed and the programs for automation can be scripted. The integration of all systems is tedious and needed expert guidelines for different parameters. As the fish and plant grow with time and the setting of many parameters like fish food quantity needed to be adjusted. It was tough in this research to integrate the ammonia sensor with the main automation, although ammonia is a very critical parameter. A standalone sensor with an internet connection can be possible to remotely manipulate the ammonia content by taking out a certain percentage of water from the fish water tank and add the same amount of freshwater.

6. CONCLUSION AND DISCUSSION

Proper planning is the key to success for design, build and operate an aquaponics system. With the help of simulation, the water temperature in the fish water tank was available for any period from past ambient data. The suitable type and number of fish and species, the design of the cooling and heating instrument, and their necessary setup for the smooth operation were decided for the indoor aquaponics. The aquaponic system design and operations became more errorless with the application of FMEA. FMEA needed to be done at the design stage, operation stage and throughout the life span of the aquaponic system and update the list and use as future references for the future grower. Smart automation helps to operate the aquaponics system flawlessly without the presence of many operation personal. The application of the digital twin brought a real-time monitoring experience and helped to prevent any possible error by observing the trend of parameters. During the development of the aquaponics system, the process diagram and a proper bill of materials helped to prevent delays in logistics and scripting of the program for microcontrollers. Operation of the aquaponic system with fish for a longer period with automation and digital twin helps to validate the hypotheses for this research.

Future Works

During the research few observation was listed that might be helpful for future improvement of the aquaponic system:

1. For simulation of the ambient condition, there is a dependency on the historical weather data. As the simulated parameters will be used for the future, the dependency on the

previous data may lead towards the wrong design of the complete aquaponics system if there is any wrong in consideration.

2. The automation developed in this research cannot be integrated into a single automation. The ammonia sensors available in the market were found not integrated with the microcontroller. The existing standalone sensor can be integrated with image processing tools to integrate with existing automation.

3. The developed automation is connected with wires and looks messy. The operation area is not clean enough for the operators to work freely. Wireless sensors and IoT relay can be used for automation.

4. The implementation of the digital twin is still offline for this research. As sensors are connected it is quite possible to make it a real-time digital twin with the help of internet connectivity.

5. The overall system can be more optimized with better-integrated planning and development time cant be reduced with the help of any project management software.

APPENDIX SECTION

APPENDIX A: Experimental data log

Table A-1: Sample table for temperature reading for validation of simulation.

Time	Inside Water Temp°F	Inside Air Temp°F	Outside Water Temp°F	Outside Air Temp°F
14-05-2021 18:00:20	71.6	79.16	73.4	79
14-05-2021 18:15:20	71.78	77.36	73.4	
14-05-2021 18:30:20	71.78	76.46	73.58	
14-05-2021 18:45:20	71.78	76.1	73.58	
14-05-2021 19:00:20	71.78	75.92	73.58	78
14-05-2021 19:15:20	71.96	75.74	73.58	
14-05-2021 19:30:20	71.96	75.74	73.4	
14-05-2021 19:45:20	71.96	75.74	73.4	
14-05-2021 20:00:20	71.96	75.56	73.22	76
14-05-2021 20:15:20	71.96	75.56	73.22	
14-05-2021 20:30:20	71.96	75.38	73.22	
14-05-2021 20:45:20	71.96	75.2	73.04	
14-05-2021 21:00:20	71.96	75.2	73.04	73
14-05-2021 21:15:20	71.96	75.02	72.86	
14-05-2021 21:30:20	71.96	74.84	72.86	

APPENDIX B: FMEA

Table B-1: Full FMEA table for the aquaponics system.

	Project Name: Ever Green-Blue Water			FMEA								
	Location: Freeman Ranch, San Marcos, Texas											
								Control Methods				
System	Item	Functions	Requirement	Failure Mode	Effects	Severity	Causes	Prevention Control	Occurrence	Detection Control	Detection	RPN
Mechanical	Pipe	Transfer water between tanks	Required to transfer the nutrition in solution for fish, plant and drainage.	Leakage or broken	Nutrition rich water or return water may be leaked	4	Improper joint on pipe or hoses.	Use proper fittings with expert installation	3	Monitor water consumption regularly	5	60
				Alage grown	Consume the nutrition	5	May be there is presence of sunlight or not well balanced nutrition in	Proper design of lighting	5	Visual inspection	2	50
				Clogged	Hamper the flow rate of nutrition	6	Sediments or improper bending of hose and	Periodic cleaning	5	Flow rate monitor	3	90
				Degraded	Posses a risk of breakdown for possible leakage	5	Material defect	Proper materials	2	visual inspection	5	50
	Tank	Store required water for aquaponic system	Needed to store waters for operations of the aquaponics.	Tank leakage	May cause serious damage for fish and plants.	10	Loosen of any fittings connected with the tank	Use proper fittings with experts help	1	Level Switch	5	50
				Sediments	Less water in the system or can grow insects or clogges	5	Foreign materials from outside	Design Improvements.	2	visual Inspection	3	30
	Rack	Hold the plant racks for growing	Required for keepinf the plant growing tank safely.	Breakdown	If broken the tanks and plants from upper racks may create a possible damage to the bottom	8	Under design the rack materials or accessories.	Careful design.	4	Structural simulation	2	64

	Filter	Filters unwanted particles from source water	Required for both fish and plant to grow smoothly	Clogged	The operation of the aquaponics may be hampered	9	Foreign materials from outside	Change filter element on time and clean housing	5	Folow the OEM guideline	5	225
				Leakage or Broken	The operation of the aquaponics may be	10	Improper Installation and wrong material selection	Use proper materials with expert installation	3	Follow API standard	4	120
	Tempe rature	Fish, Plant & Microorganism has a optimum temprature range	Need to maintain temprature within limit	Change in Dissolved	Kills fish	10	high temp reduces the dissolbed	use chiller or heater	5	DO sensor	2	100
				Thermal shock	Kills fish	10	Thermal shock kills fishes	use chiller or heater	6	Temprature sensor	3	180
				Unionized (toxic) ammonia	Kills fish	10	increased temprature increase toxic ammonia	use chiller or heater	6	Temprature sensor	5	300
Physical	Oxygen	Fish, Plant & Microorganism has optimum DO range	Need to maintain water solution within DO range	Areation system	Kills fish or plant	10	Need to provide continious Compressed air	Compressors for redundancy or it can be stored allowing for failure to be repaired	4	DO sensor	3	120
				Power outage	Kills fish	10	DO balace fail	Compressors for redundancy or stored and use while failure.	5	DO sensor	4	200
	Lighting	Light for plant or container	Plant need growing light of certain intensity	Power outage	Grow hampers for plants or working condition	7	Complete depend on grid power	Use backup battery	5	Visual inspection	3	105
		Light for plant or container	Plant need growing light of certain intensity	Light damaged	Grow hampers for plants or working condition	7	Accident or quality problem	Keep some ready stock of light	5	Visual inspection	2	70
	Chiller	Cooling	Cooling water and space as well when	Power outage	Kills fish	10	Complete depend on grid power	Design natural cooling system	5	Temprature sensor	2	100

Electrical	Chiller	water	...well when temprature is higher.	Less cooling capacity	Grow hampers for plants & Fish	7	refrigerant leaked	Digital twin can help to detect	6	Temprature sensor	4	168
	Heating	Heating water	Heating water when temp is below the range	Power outage	Kills fish	10	Complete depend on grid power	Design natural heating system	6	Temprature sensor	4	240
	Water Delivery Pump	Supply water from different tanks	Required for transfer water	Short circuit	Creats the electrical problem for the ...	6	Loose connection of wiring	Required periodic monitoring and expert setup	5	Electrical control	3	90
				Overload/Smaller Pump selection	Cant not deliver enough water within	7	Over heating of bearing or fish may have lack	Select perfect pump size	2	Periodic monitoring	4	56
				Damaged with rain water	Pump damage or electrical problem	6	Not properly stored tor placed the electrical	Properly place the pump or select the out door	2	Periodic monitoring	4	48
				Impeller jam from debries	Pump damage or electrical problem	6	Dirts from the water source	Place a inlet strainer	3	Routine maintenace to check the inlet	4	72
	Automatic fish feeder	Deliver fish feed	feeding fish and continue aquaponic cycle.	Breakdown	Fish cant have their food to continue the	7	Wear & Tear	Have standby fish feeder	2	Periodic monitoring	6	84
				Power failure	Fish cant have their food to continue the	7	Complete depend on grid power	Having AC/DC both option	3	Periodic monitoring	5	105
	Control system	Control the operation	Smooth operation	Power failure	The operation may hamper if	9	Automation	Design backup manual survival	5	Design the system both automation and manual .	6	270
Data	Sensors	Get data	Automation	Sensor damaged	Cant not have input for the automation	10	Wrongly placed or not optimum quality	Place the sensor nicely and have better	6	Digital twin helps to reduce these problem.	4	240
				Wrong Value	imbalance the automation and whole system	10	Out of calibation	Calibrate the sensors as per recommendations.	5	Check the calibration schedule	6	300
	Computer	Process the data	Automation and control	Turned off	Can not save the data	4	Power interruption	Use UPS	2	IOT connection	4	32

APPENDIX C: Source codes used in automation.

Table C-1: Full algorithm for the Raspberry pi control part written in Python.

```
main.py
import time
import states_bluewater as states
import logic_bluewater as logic
import sensors_bluewater as sensors
import csv_writer_bluewater as csv_writer
while True:
    # sensors
    ph_sensor = float(sensors.get_devices()[1])
    oxygen_sensor = float(sensors.get_devices()[0])
    temp_sensor = sensors.get_temp()
 # logic to assign state variables
    base, acid = logic.ph_logic(ph_sensor)
    airblower = logic.oxygen_logic(oxygen_sensor)
    heater, chiller = logic.temp_logic(temp_sensor)
 # GPIO control
    states.acid_outlet(acid)
    states.base_outlet(base)
    states.airblower_outlet(airblower)
    states.heater_outlet(heater)
    states.chiller_outlet(chiller)
    # csv writer
    csv_writer.write_csv(ph_sensor, oxygen_sensor, temp_sensor)
 # optional - check if sensors work
    print(ph_sensor, oxygen_sensor, temp_sensor)
 # polling delay in seconds
time.sleep(20)
logic_bluewater.py

# Constants
PH_LOW = 4
PH_HIGH = 10
OXYGEN_MID = 10
TEMP_LOW = 20
TEMP_HIGH = 30
def ph_logic(reading):
    if (reading < PH_LOW):
        return 1, 0   # base, acid
    if (reading > PH_LOW and reading < PH_HIGH):
        return 0, 0
    else:
        return 0, 1
def oxygen_logic(reading):
    if (reading < OXYGEN_MID):
        return 1
    else:
        return 0
def temp_logic(reading):
```

```
    if (reading < TEMP_LOW):
        return 1, 0    # heater, chiller
    if (reading > TEMP_LOW and reading < TEMP_HIGH):
        return 0, 0
    else:
        return 0, 1
sensors_bluewater.py
import time
import re
from w1thermsensor import W1ThermSensor
from AtlasI2C import AtlasI2C
def get_temp():
    water_temp_sensor = W1ThermSensor()
    water_temp_in_celsius = water_temp_sensor.get_temperature()
    return water_temp_in_celsius
# gets DO, pH from I2C bus
def get_devices():
    device = AtlasI2C()
    device_address_list = device.list_i2c_devices()
    device_list = []
 for i in device_address_list:
        device.set_i2c_address(i)
        device.write("R")
        time.sleep(2)    # default is 2
        raw_output = device.read()
        temp_output = raw_output.split(':')[1]
        clean_output = re.search(r"[.\d]+", temp_output).group()
        device_list.append(clean_output)
    return device_list
state_bluewater.py
import RPi.GPIO as GPIO
# GPIO setup
GPIO.setmode(GPIO.BCM)
GPIO.setwarnings(False)
# assign GPIO pins
ACID_PIN = 16
BASE_PIN = 20
AIRBLOWER_PIN = 21
HEATER_PIN = 22
CHILLER_PIN = 23
# setup pins
GPIO.setup(ACID_PIN, GPIO.OUT)
GPIO.setup(BASE_PIN, GPIO.OUT)
GPIO.setup(AIRBLOWER_PIN, GPIO.OUT)
GPIO.setup(HEATER_PIN, GPIO.OUT)
GPIO.setup(CHILLER_PIN, GPIO.OUT)
# Output
def acid_outlet(state):
    if state == 0:
        GPIO.output(ACID_PIN, GPIO.LOW)
    if state == 1:
        GPIO.output(ACID_PIN, GPIO.HIGH)
def base_outlet(state):
```

```
    if state == 0:
        GPIO.output(BASE_PIN, GPIO.LOW)
    if state == 1:
        GPIO.output(BASE_PIN, GPIO.HIGH)
def airblower_outlet(state):
    if state == 0:
        GPIO.output(AIRBLOWER_PIN, GPIO.LOW)
    if state == 1:
        GPIO.output(AIRBLOWER_PIN, GPIO.HIGH)
def heater_outlet(state):
    if state == 0:
        GPIO.output(HEATER_PIN, GPIO.LOW)
    if state == 1:
        GPIO.output(HEATER_PIN, GPIO.HIGH)


def chiller_outlet(state):
    if state == 0:
        GPIO.output(CHILLER_PIN, GPIO.LOW)
    if state == 1:
        GPIO.output(CHILLER_PIN, GPIO.HIGH)
csv_writer.py
import csv
import time
def write_csv(ph_sensor, oxygen_sensor, temp_sensor):
    row = []
    time_current = round(time.time(), 0)    # Unix epoch time
    row.append(time_current)
    row.append(ph_sensor)
    row.append(oxygen_sensor)
    row.append(temp_sensor)
    print("appended to list")

    with open("sensor_data.csv", 'a') as f:
        writer = csv.writer(f)
        writer.writerow(row)
```

Table C-2: Full algorithm for nitrate control with arduino part.

```
Nitrate sensor operation code:
#include "VernierLib.h"
VernierLib Vernier;
float sensorReading;
float Eo = 252.72; //Enter the values from your calibration here
float m = -7.59; // Enter the values from your calibration here
void setup()
{
  Serial.begin(9600);
  Vernier.autoID();// this is the routine to do the autoID
  printSensorInfo();
}

void loop()
{
  sensorReading =Vernier.readSensor();
  double(val) = ((sensorReading-
Eo)/m); // calculates the value to be entered into exp func.
  float concentration = exp(val); // converts mV value to concentrat
ion
  Serial.print(sensorReading);
  Serial.print(" ");
  Serial.print(Vernier.sensorUnits());
  Serial.print("\t");
  Serial.print(concentration);
  Serial.println("   mg/l");
  delay(500);//half a second
}
 void printSensorInfo()
 {
   // print out information about the sensor found:
   Serial.println("Sensor Information:");
   Serial.print("Sensor ID number: ");
   Serial.print("\t");
   Serial.println(Vernier.sensorNumber());
   Serial.print("Sensor Name: ");
   Serial.print("\t");
   Serial.println(Vernier.sensorName());
   Serial.print("Short Name: ");
   Serial.print("\t");
   Serial.println(Vernier.shortName());
   Serial.print("Units: ");
   Serial.print("\t");
   Serial.println(Vernier.sensorUnits());
   Serial.print("ID voltage level: ");
   Serial.print("\t");
   Serial.println(Vernier.voltageID());
   Serial.print("Page: ");
   Serial.print("\t");
   Serial.println(Vernier.page());
   Serial.print("slope: ");
```

```
  Serial.print("\t");
  Serial.println(Vernier.slope());
  Serial.print("intercept: ");
  Serial.print("\t");
  Serial.println(Vernier.intercept());
  Serial.print("cFactor:");
  Serial.print("\t");
  Serial.println(Vernier.cFactor());
  Serial.print("calEquationType: ");
  Serial.print("\t");
  Serial.println(Vernier.calEquationType());
}
```

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