The Fertilizer Frontier

The Creation of a Solar Powered and Fully Automated Dual Tank Fertilizer Mixing System for Reduced Environmental Impact

An Interactive Qualifying Project (IQP) submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the degree of Bachelor of Science

Submitted By:
Max Berman
Elie DeLaVille
Maggie Kirwan
Gabriel Montalvo Reyes

Submission Date:
February 28, 2024

Submitted to:

Project Advisors
Professor Isa Bar-On
Professor Michele Feme-Bagwell

Project Sponsor
Gai Boger (גיא בוגר) and NESS Fertigation

Abstract

Current fertilizer-mixing processes cause damage to soil, crops, and water sources by ineffective use of water, fertilizer, and energy. NESS Fertigation has created a preliminary fertilizer-mixing prototype with reduced environmental impact. We improved this design by creating a prototype that is scalable to any size field, increases resource efficiency, and further reduces negative environmental impacts, proved through a Rapid Impact Assessment Matrix. A design/user's manual was created for the prototype's reproducibility, and recommendations were provided for future implementation.

Acknowledgements

Our team would like to extend our gratitude towards the individuals and organizations that made our project possible. The success of our project serves as a testament to their unwavering guidance and support.

- NESS Fertigation for sponsoring this project and giving us the opportunity to work with them. We would like to express our gratitude to Gai Boger for his support and mentorship.

- Professors Dr. Isa Bar-On and Dr. Michele Femc-Bagwell, for advising our project, and for their generous assistance and guidance that made our project a reality.

- Professor Seth Tuler, for introducing us to our project and providing us with research strategies that propelled our project forward.

- The Venice Project Center, where our project took place, for their adaptability with relocation and generosity in accommodating us.

- Worcester Polytechnic Institute for the opportunity to partake in the Interactive Qualifying Project experience.

Table of Authorship

Section	Primary Author(s)	Secondary Authors(s)
Abstract	All Members	
1.0 Introduction	Kirwan	Montalvo
2.1 Agricultural Practices	Montalvo	Kirwan
2.2 Fertilizer: Composition, Function and Effects	Kirwan	DeLaVille
2.3 Fertigation	DeLaVille	Kirwan
2.4 Environmental Impact Assessment	Kirwan	DeLaVille
2.5 Kibbutz Neot Semadar	Kirwan	
2.6 NESS Fertigation	Kirwan	
2.7 Current NESS Fertigation System	DeLaVille	
3.1 Methods for Environmental Assessment	Kirwan, Montalvo	
3.2 Design Methods	DeLaVille, Kirwan	Berman
4.1 Design Requirements	DeLaVille	Berman
4.2 Schematic of Final Prototype	DeLaVille	
4.3 Microcontroller System Iterations	DeLaVille, Berman	Montalvo
4.4 Final Design Product	Berman	DeLaVille
4.5 Code Implementation	Berman	
4.6 Energy Consumption Calculations	DeLaVille	
4.7 Solar Panel System Calculations	DeLaVille	Kirwan
4.8 Housing	Kirwan	
5.1 Definition of Parameters of Impact	Kirwan	
5.2 PC: Physical/Chemical Parameters	Kirwan	Montalvo
5.3 BE: Biological Ecological Parameters	Montalvo, Kirwan	DeLaVille
5.4 SC: Social/Cultural Parameters	DeLaVille, Kirwan	Montalvo

5.5 EO: Ecological/Economical Parameters	Montalvo, DeLaVille	
5.6 Performance Assessment Results	DeLaVille	
5.7 Performance Assessment Discussion	DeLaVille	
6.0 Recommendations	Berman, Kirwan	DeLaVille
7.0 Conclusion	DeLaVille, Kirwan	Montalvo

Table Of Contents

Table of Figures

Chapter 1: Introduction

Fertilizer is a necessary component of farming processes as its release of nutrients into soil stimulates the growth and productivity of crops in order for them to reach their maximum genetic capacity. With the Earth's population expected to surpass nine billion by the year 2050, fertilizer will become exceedingly important to boost crop growth (*Fertilizer 101*, 2014). Fertigation combines fertilization methods with irrigation of a field into one process. Fertilizer mixing is a key part of the fertigation process, however current systems used in conventional agricultural practices overuse water, fertilizer, and energy resources. Synthetic fertilizers, while effective in their ability to stimulate crop growth, have proven to be harmful when used in excess. This may lead to the leaching of nutrients into the soil, runoff into bodies of water, and wasting valuable resources.

Kibbutz Neot Semadar, located in Israel, strives for a healthy way of living that benefits both their community and the environment around them. This Kibbutz focuses specifically on organic agriculture. A startup based in Neot Semadar, NESS Fertigation, has successfully developed an initial prototype for a more sustainable fertigation system. They are currently working on an improved design to help other communities around the world in their efforts of promoting an eco-friendly way of life.

Our sponsor, NESS Fertigation, has instructed us to improve their current fertigation system by making it more efficient, scalable to any size field, and entirely autonomous. We outlined the following objectives to complete this goal:

Objective 1: Research and identify the impacts that different fertigation systems impose on the environment.

Objective 2: Design and develop an improved prototype using NESS Fertigation's preliminary design concept.

Objective 3: Develop a design/user's manual to ensure reproducibility.

Chapter 2: Background

2.1 Agricultural Practices

World agriculture predominantly uses unsustainable farming practices where large crop yields are prioritized over the protection and preservation of the environment. There are many ways to classify agriculture, one of them being by the sustainability of their methods and practices. Unsustainable practices are mainly used to maximize yield, using processes such as overfertilization and slash-and-burn methods that damage the soil, crops, human health, and our environment as a whole (CELDF, 2021). Sustainable practices, on the other hand, grow healthy crops, efficiently use resources, and prioritize the health of the soil while still benefiting from a sufficient amount of yield.

2.1.1 The Current State of Agriculture

Present-day agriculture primarily consists of unsustainable practices. Techniques such as the overuse of chemicals and growing genetically modified (GMO) crops are commonly used because farmers are expected to produce larger amounts of product every year (Greentumble, 2016; Nunn, 2018). These processes contaminate the soil and groundwater, decreasing the quality of habitable land every year. The production of GMO crops introduces new allergens into the human immune system and decreases the effectiveness of medicine by increasing the resistance to antibiotics (Greentumble, 2018; Greentumble, 2023). There is also an increased risk in food security and human health due to water scarcity and a decline in land productivity, combined with the health concerns imposed by the use of high-risk pesticides (Rashid, 2018).

A large increase in yield also results in the overproduction of crops, which creates excessive waste due to fluctuating prices throughout the year (Greentumble, 2016). This results in the loss of soil, which on a global scale, costs around $400 billion every year. (Rashid, 2018). Unsustainable practices have also contributed to a 3-7% decrease in Gross Domestic Product (GDP) of emerging countries.

The reason why most farmers have not implemented sustainable practices is because they simply don't have the money to do so. According to TIME Magazine, "Farm debt, at $416 billion, is at an all-time high. More than half of all farmers have lost money every year since 2013" (Semuels, 2019). In the United States, this has led to farmers renting their land to big corporations or risking bankruptcy (ibid., 2019; Nunn, 2018). According to a study done by the USDA in 2014, around 54% of cropland and 28% of pastureland is rented. (Leffer, 2021; ERS USDA, 2022).

2.1.2 Sustainability in Agriculture

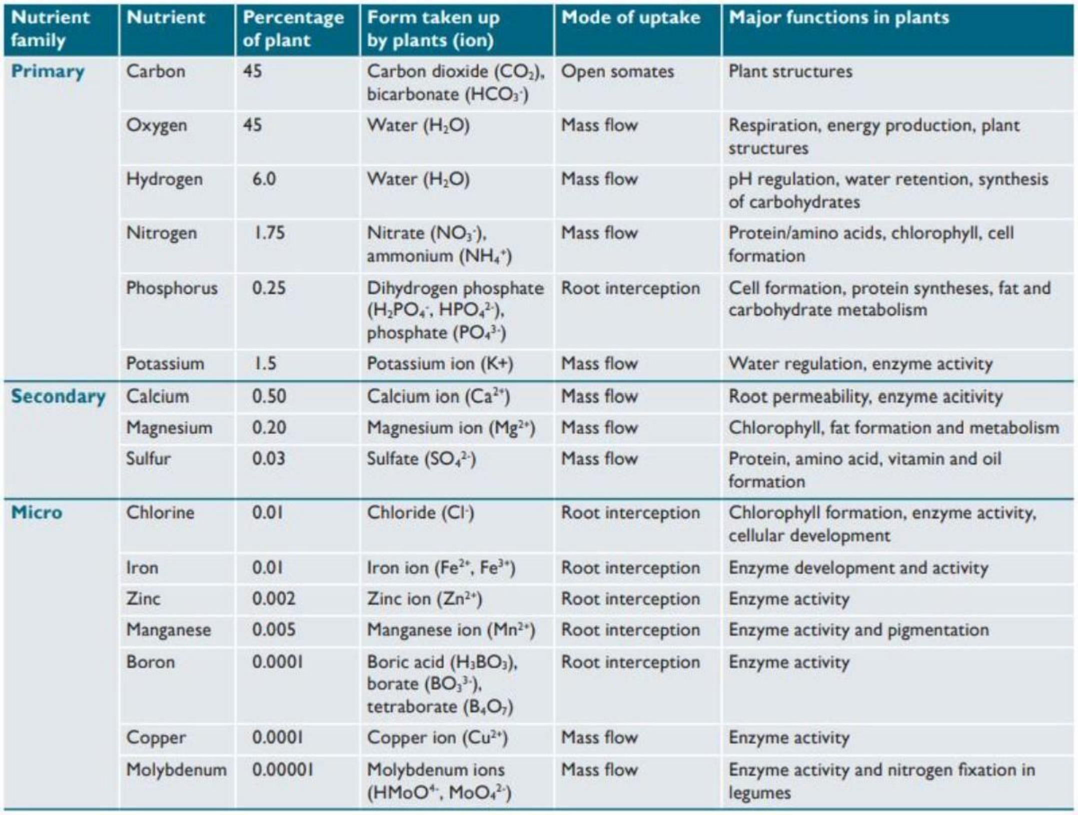
Sustainable practices in agriculture aim to produce the necessary quantity of crops to feed the world's population while still preserving the environment for future generations (Dubey, 2024). Techniques such as polyculture, where multiple crops are grown together, and crop rotation, where a set of different crops are grown in a certain order, help with soil health and decrease the need for chemical pesticides and fertilizers. Additionally, using residues from these crops as compost helps "recycle nutrients back to the farmland" (ibid., 2024). Following these techniques would reduce the amount of soil loss every year and increase land productivity over time, decreasing the amount of money spent on wasted resources.

2.2 Fertilizer: Composition, Function, and Effects

2.2.1 Composition and Function

Fertilizer consists of 16 essential elements (Table 1), that allow plants to reach their genetic potential. The three main macronutrients in fertilizer are Nitrogen (N), Phosphorous (P), and Potassium (K), each of which have a specific task aiding plant growth and maintenance processes. Nitrogen is a vital part of cell development leading to tissue synthesis of plants as it is found in proteins, amino acids, and chlorophyll (John Hill et al., 2019). Nitrogen is known to be the most important element in fertilizer production as it is absorbed in larger amounts than any other element. Phosphorus is essential in plants' energy storage and usage mechanisms, such as photosynthesis, due to its aid in metabolic processes in addition to cell formation and protein synthesis. Potassium is essential in plants' resistance to diseases and environmental factors as it regulates water processes and enzyme activity (*Fertilizer 101*, 2014). These three macronutrients are taken up in larger quantities in comparison to the other 13 elements given in Table 1, and each crop requires different ratios of these essential nutrients for proper stimulation of growth processes. As we can see from Table 1, the forms in which these nutrients are taken up are different from their naturally occurring elemental counterparts. This is because the elements themselves are not used in fertilizer, but rather compounds of these elements in their ionized form, making them easier to absorb.

Table 1: Form, source, mode of uptake and major functions of the plant essential nutrients (“Farming and Chemicals- Fertilizers,” 2019).



Nutrient family	Nutrient	Percentage of plant	Form taken up by plants (ion)	Mode of uptake	Major functions in plants
Primary	Carbon	45	Carbon dioxide (CO_2), bicarbonate (HCO_3^-)	Open somates	Plant structures
	Oxygen	45	Water (H_2O)	Mass flow	Respiration, energy production, plant structures
	Hydrogen	6.0	Water (H_2O)	Mass flow	pH regulation, water retention, synthesis of carbohydrates
	Nitrogen	1.75	Nitrate (NO_3^-), ammonium (NH_4^+)	Mass flow	Protein/amino acids, chlorophyll, cell formation
	Phosphorus	0.25	Dihydrogen phosphate ($H_2PO_4^-$, HPO_4^{2-}), phosphate (PO_4^{3-})	Root interception	Cell formation, protein syntheses, fat and carbohydrate metabolism
	Potassium	1.5	Potassium ion (K+)	Mass flow	Water regulation, enzyme activity
Secondary	Calcium	0.50	Calcium ion (Ca^{2+})	Mass flow	Root permeability, enzyme acitivity
	Magnesium	0.20	Magnesium ion (Mg^{2+})	Mass flow	Chlorophyll, fat formation and metabolism
	Sulfur	0.03	Sulfate (SO_4^{2-})	Mass flow	Protein, amino acid, vitamin and oil formation
Micro	Chlorine	0.01	Chloride (Cl^-)	Root interception	Chlorophyll formation, enzyme activity, cellular development
	Iron	0.01	Iron ion (Fe^{2+}, Fe^{3+})	Root interception	Enzyme development and activity
	Zinc	0.002	Zinc ion (Zn^{2+})	Root interception	Enzyme activity
	Manganese	0.005	Manganese ion (Mn^{2+})	Root interception	Enzyme activity and pigmentation
	Boron	0.0001	Boric acid (H_3BO_3), borate (BO_3^{3-}), tetraborate (B_4O_7)	Root interception	Enzyme activity
	Copper	0.0001	Copper ion (Cu^{2+})	Mass flow	Enzyme activity
	Molybdenum	0.00001	Molybdenum ions ($HMoO^{4-}$, MoO_4^{2-})	Mass flow	Enzyme activity and nitrogen fixation in legumes

The process of converting an element into its easily absorbable form in fertilizer is dependent on what the primary element of the fertilizer is. Naturally occurring nitrogen (N2) can be hard for crops to break down due to specific bacteria being necessary for its decomposition (Lindwall, 2022). Nitrogen fertilizers are created through the Haber-Bosch process, where ammonia (NH3) is directly created from hydrogen supported by methane (CH4) and nitrogen (N2) from the atmosphere (*Technique Could Enable Cheaper Fertilizer Production*, 2020). This transformation process is resource intensive and is prone to poorly acting with other aspects of the environment when used in excess (Lindwall, 2022). While healthy soil can use this nitrogen effectively, practices such as monocropping and only planting seasonal crops deplete the soil of necessary nutrients. Phosphorus fertilizers are created through the extraction of phosphate from different rocks and minerals (“Farming and Chemicals- Fertilizers,” 2019). This process is often chemically enhanced to create synthetic versions due to limited phosphorus availability and high transportation costs (Omo-Okoro & Pillay, 2023).

Organic fertilizers have gained popularity in recent years as efforts to reduce the input of chemicals in the environment have increased. Organic fertilizers are typically composed of the byproducts of living things such as manure, poultry droppings, domestic sewage, or even the previously living things themselves, such as different composted plants and vegetables (Lewu et al., 2020). While shifts towards organic fertilizers are good in theory, their usage does not directly increase crop yields to the extent chemical fertilizers do (Moridani et al., 2023). Instead, the long-term application of organic fertilizers is mainly used to maintain the organic carbon content and fertility of soil by adding a variety of organic nutrients. Organic fertilizers are then used in combination with synthetic fertilizers as a supplement to provide a larger yield without compromising the health of soil (ibid., 2023).

2.2.2 Effects of Fertilizer on the Environment

While chemically enhancing fertilizers create a boom in crop production, imprecise fertilizer and water ratios can add excess chemicals to the soil. Fertilizer is designed to be water-soluble so it can dissolve into the soil, however, if more fertilizer is applied than crops are able to take up this leads to fertilizer runoff. This results in chemicals seeping into groundwater, nitrogen oxide production, and negative effects to aquatic ecosystems. The water soluble nature of nitrate, nitrogen in its absorbable form, allows for its leaching into groundwater, as well as lakes, rivers, and oceans (Dontigney E., 2018). The discharge of nitrogen and phosphorus fertilizers into larger bodies of water can create conditions that reduce the overall biodiversity of the aquatic ecosystems. Phosphorus is known to be a major factor in this process as it stimulates the development of cyanobacteria and algae that deplete water of oxygen (Tremblay, 2021). The process of over-enriching bodies of water with these nutrients is called Eutrophication, and the depletion of dissolved oxygen in the water is known as Hypoxia (Korpinen & Bonsdorff, 2015). Long term hypoxic conditions can lead to “dead zones” resulting from the inability of life to be sustained there (Tremblay, 2021). Elevated nitrate and phosphorus levels in drinking water can pose major health risks, and water treating processes can be difficult and costly. These risks apply to humans and animals alike, with nitrate poisoning in livestock interfering with oxygen uptake in the circulatory system. These effects can accumulate throughout the food chain to affect the entire ecosystem (“Farming and Chemicals- Fertilizers,” 2019).

One supplement used with phosphate fertilizers are phosphites, which boost root strength, help lock the phosphates around the roots, and help prevent fungal diseases. The side effects of using such a supplement can be deadly to humans and animals alike. When fertilizers containing phosphite are exposed to intense heat, they release phosphine gas (PH3), a deadly poison. Inhaled phosphine is absorbed by the lungs and distributed throughout the body. Acute effects of phosphine inhalation include dyspnea, vertigo, bronchitis, convulsions and even death if an excessive amount gas is inhaled. In addition to phosphorus gasses being harmful to the environment, excess nitrogen due to the overapplication of fertilizer can also lead to the creation of nitrous gasses in the atmosphere, a contributor to greenhouse gasses (University of Massachusetts Amherst, 2021). Synthetic nitrogen-based fertilizers alone account for more than 2.4% of global emissions, proving to be a significant contributor to global warming and climate change (Huber, 2021). Since 2006, the application of synthetic chemically enhanced fertilizers has been controlled increasingly, however, precision in fertilizer application remains a problem seen around the world (“Farming and Chemicals- Fertilizers,” 2019).

2.3 Fertigation

Fertigation works by mixing liquid fertilizer with water before distributing the mixture to crops through an irrigation system. This way, every crop that the water reaches will also get essential nutrients to help it grow. Since the concentration of the fertilizer-water mixture can be changed, each type of crop can get the necessary amount of nutrients. Figure 1 shows the results of a study done at the University of Florida comparing the use of granular fertilizer and fertigation against the crop nutrient uptake. When using granular fertilization, the soil nutrient concentration spikes immediately after every application. The use of fertigation allows for a more uniform distribution of nutrients which aligns with the crop nutrient uptake.

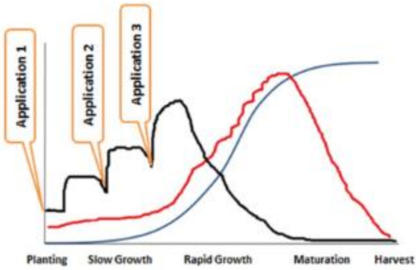


Figure 1: Graph comparing granular fertilizer and fertigation against crop nutrient uptake

Graph showing the soil nutrient concentration by three applications of dry granular fertilization (black) or by fertigation (red), and rate of crop nutrient uptake(blue). (Dixon & Liu, 2022)

2.3.1 Advantages of Fertigation

Uniform distribution of nutrients results in higher crop yield while using less fertilizer and less water. With 70% of freshwater withdrawals globally being used by the agriculture sector, it is crucial to utilize this water in efficient processes (*Water in Agriculture*, 2022). The moisture level of soil is usually measured using electric conductivity, with the most common method being a watermark sensor (Krevh & Dvorski). If operated correctly, no excessive amounts of water are used in fertigation because the crops continuously receive water until the desired soil moisture level is reached. Not only does this save water but also results in little to no runoff which prevents the fertilizer from damaging the environment around the farm. One other advantage is that weeds are less likely to grow when using fertigation because of the lack of excess water and nutrients in the soil (Dixon & Liu, 2022).

2.3.2 Disadvantages of Fertigation

Fertigation designs used commonly in fields today have problems regarding their implementation and operation. One issue is the high initial cost of the systems. Apart from the main components, the user would need to get large and expensive equipment to install or maintain the system (ibid., 2022). This can be very discouraging to smaller scale farmers because they either do not have the budget or facilities to install it. On the other hand, it also poses a problem for corporate scale farmers because they would need a very large tank and more powerful pumps to distribute a large amount of water, increasing the costs further. Another major concern with current systems is that they require constant care. Any fault in the system may lead to lower crop yield, damage to equipment, and inconsistent growth throughout the field (ibid., 2022). Training and keeping an expert on the system on hand can be costly and inconvenient. The system must be working reliably with minimal room for human error and preventative measures to stop components from breaking.

Over-watering and over-fertilization are other concerns that can arise when the system isn’t being regulated closely (Cherlinka, 2023). These issues often occur as a result of manual control or operation. This creates an opportunity for human error, and if the operator isn't an expert on the inner workings of the system it may be difficult to repair or maintain it correctly.

2.3.3 Energy Sources for Farms

Modern fertigation systems need electrical power to control valves and get sensor readings, which can be difficult to acquire in remote farming locations. A majority of farms that do use off the grid electricity do so with a diesel generator which produces a byproduct of over 1500 g of CO_2 per kWh including installation and operation (Woodstock Power, 2024; Mérida García et al., 2019). An alternative to diesel power is the use and storage of solar energy. While this adds an extra component to the system and results in a higher initial cost, it only produces around 120 g of CO_2 per kWh (ibid., 2019) for the first year. This number includes manufacturing and installation as there are no carbon emissions from the general operation of solar panels. In addition to producing less emissions, solar systems require no money to be spent on inputs, while for a generator, diesel fuel must be purchased to supply the correct amount of energy. For farming locations that have an abundance of radiant sunlight, solar energy is also more convenient to acquire.

2.4 Environmental Impact Assessment

Environmental Impact Assessments (EIA) are used to identify and provide information on how a project may positively or negatively affect the environment. EIAs are often a tool utilized in decision making stages of a project's development in order to weigh design ideas against their potential problems. Traditional EIAs, however, often lack the ability to include many case components, as their evaluation methods are largely subjective and do not account for the reasoning behind judgments. This makes further study confusing and furthers the variability of assessment outcomes. New methods of conducting EIAs have allowed for both quantifiable data and subjective judgments to be included, as all categories can be consistently compared on a common basis, and decision-making strategies are recorded to ease re-evaluation efforts. In this section, we will discuss the design of the Rapid Impact Assessment Matrix (RIAM) method of conducting our EIA.

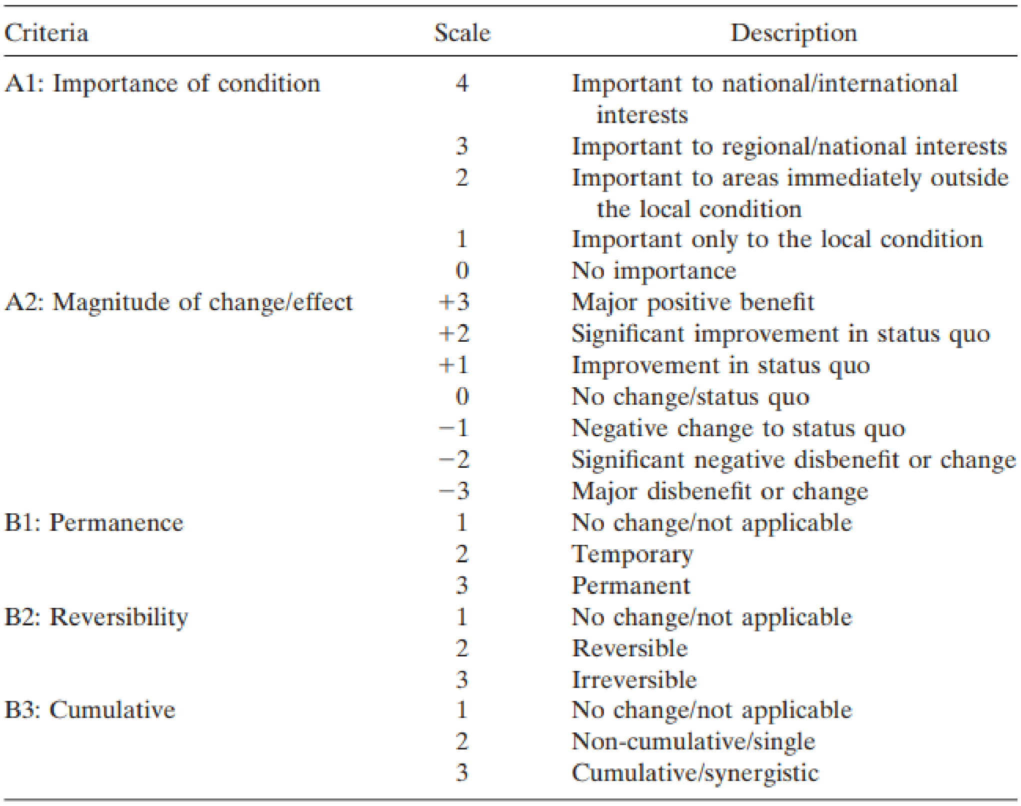
2.4.1 Environmental Components

The RIAM method considers the parameters of impact within the systems being scored against the standard for systems used globally. Each parameter is placed into the following four categories based on what aspect of the environment they affect: Physical/Chemical (PC), Biological/Ecological (BE), Sociological/Cultural (SC), or Economic/Operational (EO) (Pastakia & Jensen, 1998). The Physical/Chemical category encapsulates all parameters of impact whose processes affect the chemistry or terrain of surrounding areas. The Biological/Ecological category addresses the ecological effects stemming from system processes often outlined in the Physical/Chemical category. The Sociological/Cultural category contains all human elements of a study, including cultural components. The Economic/Operational category allows for quantitative data points to be included to represent the economic problems posed by environmental systems. This category accounts for both short and long term economic goals of a system. Through defining these four categories, this matrix allows the use of both qualitative and quantitative aspects of a system.

2.4.2 Assessment Criteria

The criteria for the assessment are subdivided into two categories. Criteria (A) can be understood through the analysis of Importance of Condition (A1) and Magnitude of change/effect (A2), while Criteria (B) can be understood through the analysis of a condition’s Permanence (B1), Reversibility (B2), and Cumulative effects (B3).

Table 2: Assessment Criteria, scoring, and descriptions. (ibid., 1998)



Criteria	Scale	Description
A1: Importance of condition	4	Important to national/international interests
	3	Important to regional/national interests
	2	Important to areas immediately outside the local condition
	1	Important only to the local condition
	0	No importance
A2: Magnitude of change/effect	+3	Major positive benefit
	+2	Significant improvement in status quo
	+1	Improvement in status quo
	0	No change/status quo
	−1	Negative change to status quo
	−2	Significant negative disbenefit or change
	−3	Major disbenefit or change
B1: Permanence	1	No change/not applicable
	2	Temporary
	3	Permanent
B2: Reversibility	1	No change/not applicable
	2	Reversible
	3	Irreversible
B3: Cumulative	1	No change/not applicable
	2	Non-cumulative/single
	3	Cumulative/synergistic

2.4.3 Environmental Score and Range Bands

Once each of the parameters of impact are scored on the conditions according to criteria descriptions, the final Environmental score is calculated using Eq. (1) - Eq. (3) (Pastakia et al., 1998). This formula accounts for Criteria (A), defined by Eq. (1), and Criteria (B), defined by Eq. (2), with different values to ensure their correct representation in the Environmental Score:

$$A1 \times A2 = A_{Total} \tag{1}$$

The multiplication of criteria allows for the scoring of parameters of impact by Criteria (A) standards to have a higher impact on the Environmental Score than the following categories of Criteria (B):

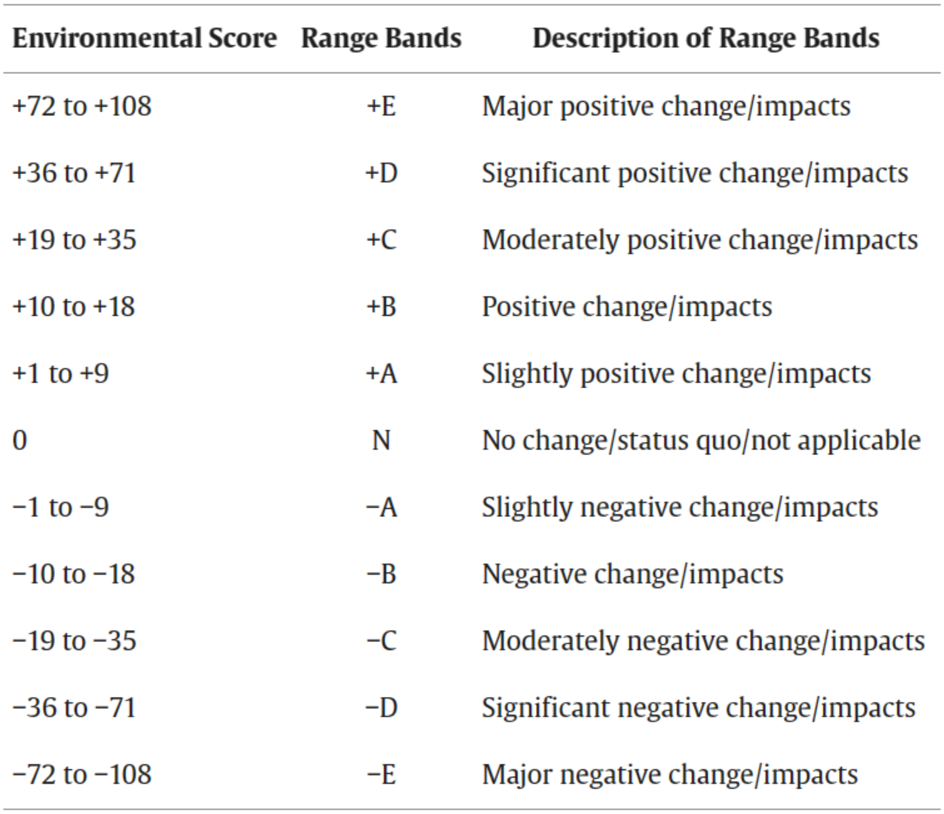
$$B1 + B2 + B3 = B_{Total} \tag{2}$$

The addition of criteria allows for the scoring of parameters of impact by Criteria (B) standards to still have an effect on the Environmental Score, however, this alone cannot dramatically change the environmental score. The total Environmental Score is calculated using Eq. (3):

$$A_{Total} \times B_{Total} = Environmental\ Score \tag{3}$$

Range Bands are calculated using the final Environmental Score and are used to further understand how certain components impacted the fertigation systems. As seen in Table 3, Range bands categorize Environmental Scores, with each category being given a specific letter value correlating with a description of impact on the full system.

Table 3: Assessment of Environmental Score using Range Bands. (ibid., 1998)



Environmental Score	Range Bands	Description of Range Bands
+72 to +108	+E	Major positive change/impacts
+36 to +71	+D	Significant positive change/impacts
+19 to +35	+C	Moderately positive change/impacts
+10 to +18	+B	Positive change/impacts
+1 to +9	+A	Slightly positive change/impacts
0	N	No change/status quo/not applicable
−1 to −9	−A	Slightly negative change/impacts
−10 to −18	−B	Negative change/impacts
−19 to −35	−C	Moderately negative change/impacts
−36 to −71	−D	Significant negative change/impacts
−72 to −108	−E	Major negative change/impacts

Environmental Scores are used to quantify the impact of each system based on each given parameter. The Range Bands are the classifications of environmental scores, used to visualize the total effect of a system over a span of parameters.

2.5 Kibbutz Neot Semadar (נאות סמדר)

Kibbutz Neot Semadar, located in Israel, is a unique place in its efforts of environmental preservation. Members of Neot Semadar believe in prioritizing the ecological balance of their land in all of their endeavors. Located in the Negev desert, Neot Semadar’s 124 acres of plantations can be described as a man-made oasis in the barren desert landscape. (Neot Semadar, 2023). While rainfall may fluctuate yearly, average annual rainfall spans from 80mm in the southern Negev desert to 120mm in the north (Avni, 2005). Great lengths must be taken to preserve water for personal and agricultural uses with members utilizing an operative reservoir (Neot Semadar, 2023). The reservoir allows for reduced water transportation to the area while serving as a home for aquatic plants and animals, however, such little rainfall calls for the conservation of this water. Water is a key component of the fertilizer mixing process, where fertilizer is mixed with water before its fertigation to surrounding crops.

2.6 NESS Fertigation

NESS Fertigation, a startup aiming to enhance resource management and usage, has created a preliminary prototype for an automated solar powered fertilizer mixing system. NESS Fertigation's goal with this project is to provide an improved system that is fully automated and solar powered, with calculated ratios of fertilizer to water that are dictated by soil sensors. Accuracy in ratios of fertilizer to water, based on what is needed in context of the specific crop, allows for their effective use in the mixing process. This allows for the overall reduction of fertilizer and water being used. Since NESS Fertigation is based in the Negev desert, solar power is easily accessible and an efficient form of energy. The Eilat region receives over nine hours of sunlight per day which is over two and a half hours more than the average sunlight per day in Europe (Climate Guide, 2024; Copernicus, 2019).

2.7 Current NESS Fertigation System

The prototype system currently used by NESS Fertigation is a low cost, low power consumption, and low maintenance prototype (shown in Figure 2). The system is powered by two solar panels and is partially manually controlled. The current system uses two SolTag controllers, the microcontrollers made by Sol-Chip Agriculture, to manage the valves and sensors which need manual inputs for operation. Two sensors read the water and fertilizer levels in the soil, and the information is sent to the two controllers managing the valves. Based on the sensor readings, the system calculates the necessary ratio of fertilizer to water. The main tank fills by opening and closing valves, which moves the water and liquid fertilizer through separate pipes using the pressure generated by waterflow. The tank uses a float sensor to measure the level of the mixture and to determine how long the valves for fertilizer and water need to stay open to ensure the desired ratios. The float sensor uses a small floatation device connected to a potentiometer. When the water level rises, the potentiometer spins and the resistance through it changes. This change in resistance affects the output voltage of the sensor, which can be used to determine the height of the water. Once the water reaches the top of the tank, it closes the valves and empties into the field through the irrigation system.

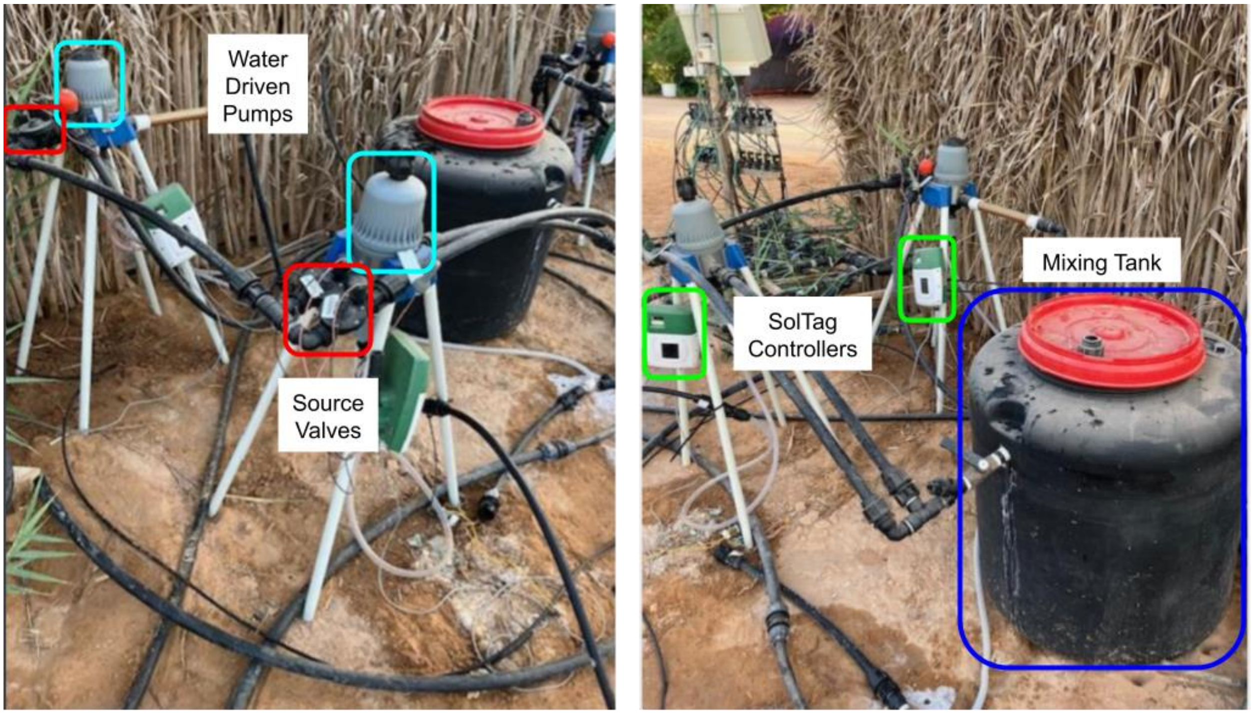


Figure 2: Photographs of the current fertigation prototype from NESS Fertigation

The current NESS Fertigation system is controlled manually. The timing of when to start and stop the entire fertigation process is controlled by the operator. This requires a person experienced in the system to always operate it. Any overuse of water or fertilizer by the operator would result in lower efficiency of the system. Introducing a fully automated process that is easy to use would increase the efficiency of the system and increase the number of places it could be implemented. In this context, fully automated would entail the SolTag controller communicating with NESS Fertigation's software, and after receiving an initial fertilizer to water ratio, it will run without any manual input. It would continue to run by receiving information from sensors in the soil to determine when to start and stop watering. The prototype was designed to provide water and fertilizer to a field of about half an acre. To make this system applicable for any location, the capacity would need to be increased. The current prototype has one tank and, in order to scale it to a three or five acre field, the tank size would need to be much larger, making it very difficult to transport and install. This produces even more problems for remote farming locations as it is challenging to get large trucks or installation equipment through rough terrains and to the farm.

Chapter 3: Methods

3.1 Methods for Environmental Assessment

The goal of our project is to improve NESS Fertigation's current fertilizer-mixing system by making it more efficient, scalable to a larger size field, and entirely autonomous. In this chapter we discuss the methods used to complete Objective #1, researching and identifying the impacts that different fertigation systems impose on the environment. We have created a Rapid Impact Assessment Matrix (RIAM) to assess the impact of our improved NESS Fertigation system, as well as the impact of other fertigation systems used globally.

3.1.1 Systems for Comparison in RIAM Assessment

The following systems, alongside our improved NESS Fertigation system, were used in our Environmental Impact Assessment through RIAM scores. This was used as context for the scoring of each system included in Chapter 5 and Appendix A.

System 2: NESS Fertigation’s Current System

NESS Fertigation’s current system consists of a low cost, low power and low maintenance prototype. The design includes one large tank being manually controlled with two microcontrollers, which are powered by two solar panels.

System 3: Manipal University’s Automated Fertigation Prototype

This on-grid, automated fertigation system consists of plastic tanks, and injectors that control different mixtures of Nitrogen, Phosphorus and Potassium being pumped to the mixing tank (Joseph et al., 2017). The entire process is controlled by an Arduino microcontroller with an

ESP8266 Wi-Fi module, used to store data from a soil sensor and a user interface that communicates with the system. In case of soil sensor failure, there is an alternative method used to maintain moisture content in the soil. In order for this failsafe to work, the user must manually input the activation times for the pumps and the time intervals between successive watering of crops. Figure 3 provides a simplified version of the design found in the document published by the authors in the 2017 9th International Conference on Information Technology and Electrical Engineering (ICITEE).

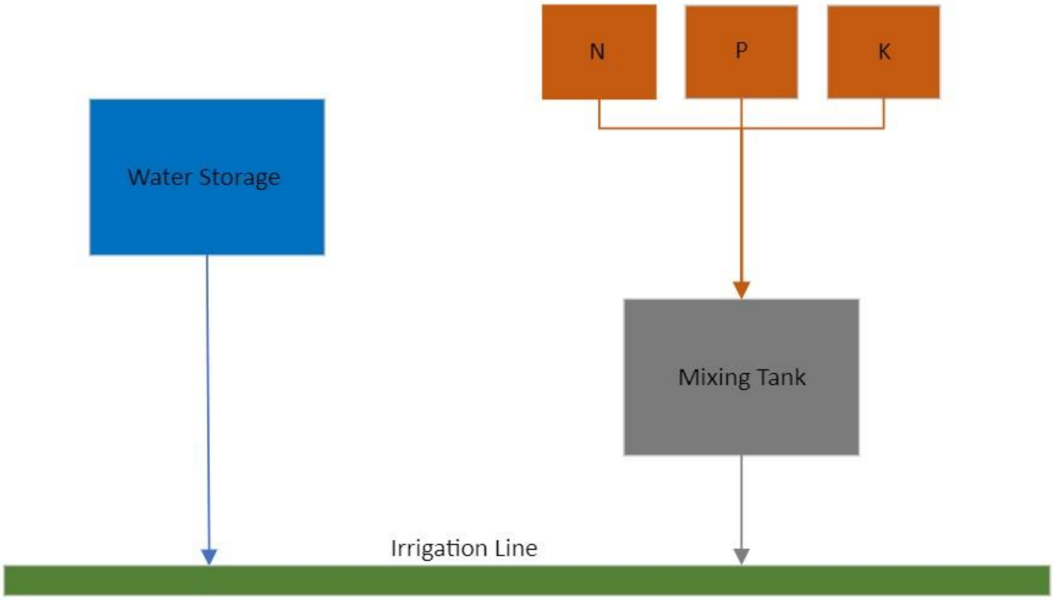


Figure 3: Simplified diagram of the automated fertigation system

System 4: FertiOne™ Plus by Netafim

The FertiOne™ Plus is an on-grid fertigation system that is fitted for both manual and automatic use (Netafim, 2020). As described on page 8 of their operation and installation manual, this system is used to dose fertilizers/acid with source water as a "homogeneous nutrient solution", which is then injected into the irrigation water main line. The FertiOne™ Plus "can be incorporated in any existing or planned project", and to "fully computerize" the system, it must be connected to a 24 VAC controller. Figure 4 includes a front and back view of the system, obtained from the FertiOne™ Plus manual published on Netafim's website.

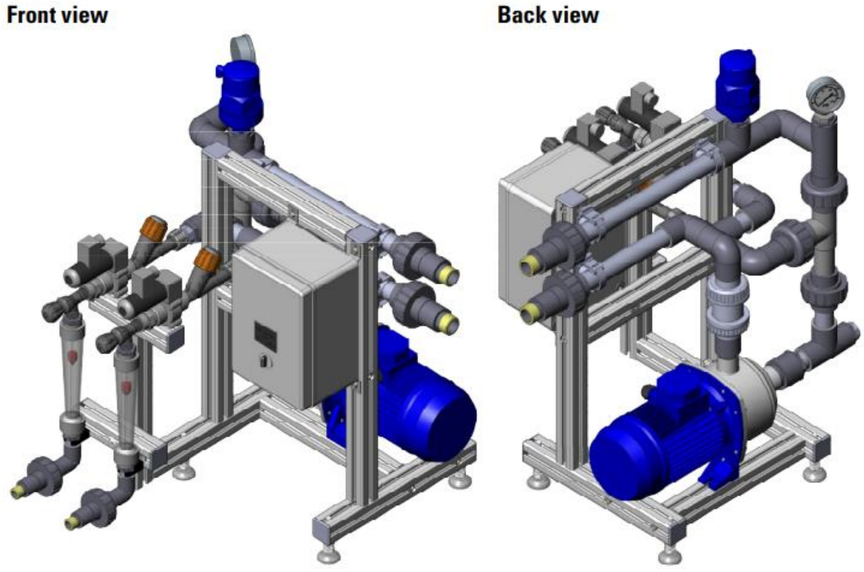


Figure 4: Front and back view of the FertiOne™ Plus system

3.2 Design Methods

3.2.1 Stepwise Design Process

We used a step-by-step approach to complete the objectives for our improved design. Each iteration focused on achieving a specific mechanism of the system and they were fully tested before moving onto the next step, shown in Figure 7 of Section 4.3.

3.2.2 Power Consumption Calculation

The total power consumption of the prototype is calculated as the sum of the power consumption from the Arduino Nano ESP32, the microcontroller used in our final prototype, and the motor driver. Since the Arduino goes into a deep sleep state when not active, the sum of both awake and sleep states is taken into account. Eq. (4) and Eq. (5) is used to determine the average amount of power the prototype uses in its active state each day.

$$(I_{Nano} * V_{Nano}) + ((I_{MotorDriver1} + I_{MotorDriver2}) * V_{MotorDriver}) = P_{Active\ State} \quad [W] \quad (4)$$

$$h_{Active\ State} * P_{Active\ State} = P_{Active\ Daily\ Consumption} \quad [Wh] \quad (5)$$

The average amount of hours per day that the machine is active is shown by $h_{Active\ State}$. The equations for the average amount of power the prototype uses in its sleep state each day are shown below in Eq. (6) and Eq. (7):

$$(I_{Nano\ Sleep} * V_{Nano}) + ((I_{MotorDriver1} + I_{MotorDriver2}) * V_{MotorDriver}) = P_{Sleep\ State} \quad [W] \quad (6)$$

$$(24 - h_{Active\ State}) * P_{Sleep\ State} = P_{Sleep\ Daily\ Consumption} \quad [Wh] \quad (7)$$

The last step in determining the overall power of the prototype was to add the daily power used in the active and sleep states to get the full daily power consumption of the design. This formula is shown in Eq. (8):

$$P_{Active\ Daily\ Consumption} + P_{Sleep\ Daily\ Consumption} = P_{Daily\ Consumption} \quad [Wh] \quad (8)$$

3.2.3 Solar Panel Capacity Calculation

The capacity of the solar panel system is dependent on the power consumption demand and the average amount of sunlight hours available each day. Eq. (9), shown below, is used to determine the amount of power that needs to be produced daily in order to sustain the prototype (*A Complete Guide on Solar Panel Calculations*, 2023).

$$P_{Daily\ Consumption} / \eta_{System} = P_{Produced\ Daily} \quad [Wh] \quad (9)$$

$P_{Daily\ Consumption}$ is the power found in Eq. (8) and η_{System} is the efficiency of the system. The theoretical capacity of the system is shown in Eq. (10) (ibid., 2023):

$$\frac{P_{Produced\ Daily}}{Average\ Daily\ Sunlight\ Hours} = Theoretical\ Capacity_{\ Solar\ Panel} \quad [W] \quad (10)$$

To determine the actual capacity of the solar panel system, we divided the theoretical capacity by the derating factor, represented by k, to account for efficiency losses in Eq. (11) (ibid., 2023):

$$Theoretical\ Capacity_{Solar\ Panel}\ /\ k = Actual\ Capacity_{Actual\ Solar\ Panel} \quad [W] \quad (11)$$

For use of a solar panel that is rated for $E_{\text{One Panel}}$ watts, Eq. (12) is used to determine how many of these panels will need to be used for achieving the correct amount of power to run the prototype (ibid., 2023).

$$Actual\ Capacity_{Actual\ Solar\ Panel}\ /E_{One\ Panel} = Number\ of\ Panels \quad (12)$$

Using all of these equations, we calculated the amount of energy needed and the number of any specific solar panel chosen.

3.2.4 Final Prototype Housing

Housing requirements included a custom fit to the microcontroller system for reduction of material and build efficiency, security of all components, reproducibility, and ability to maintain the electronic components’ performance under weather conditions that presented extreme heat, and rainfall.

Custom fit was ascertained by measuring the length, width, and height of the full microcontroller system with a set of standard electronic calipers. These dimensions were checked using the product dimensions listed for the Arduino Nano ESP32, DC Motor Driver Boards, and Breadboard. Security of the DC motor driver boards was provided by means of standoffs modeled into the housing. The location of these standoffs was modeled in context of the full system to allow the breadboard to drop into place between the DC motor driver boards. The breadboard was secured with extrusions modeled into the housing. The location of the breadboard was selected to create distance from the heatsinks located on the DC motor driver boards. This is because the heat sinks may reach a maximum temperature of 130℃, while the breadboard, which is made of ABS plastic, can only withstand a temperature of 108℃ before its material properties may begin to deteriorate (Smart Prototyping, 2024; MatWeb, LLC., 2024) Sun conditions required our housing to withstand up to 50℃, as this is the maximum temperature recorded in Israel according to climate and temperature data (Worlddata.info, 2024). It was necessary to select a material to properly withstand these temperature needs, and to implement ventilation into the model for the cooling of electrical components. When selecting the correct material, we looked at their material properties, specifically the glass-transition temperature, defined as the temperature at which amorphous polymers within the material transition from a hard and glassy state to a soft and rubbery state (Protolabs, 2024). Ventilation methods were selected by assessing their reliability and feasibility. While fans are often used to cool electronics within a housing, they would require constant power to be applied, which increases the overall power of our system beyond our energy consumption goals. Additionally, fans are unreliable and prone to break, which would prove to be complicated to replace in the remote locations where our system may be implemented. Instead, it would be necessary to use passive cooling methods that may be modeled into the housing, without compromising water resistance goals.

Rain conditions required our housing to withstand liquids from entering the enclosure. This requires water protection methods where a shadowed interior in reference to overhanging exterior is used, as water protection cannot infringe on ventilation models. Additionally, it was necessary to implement an extruded wire cover for the sealing of holes connecting wires from within the microcontroller system to peripheral components.

Reproducibility of housing was ensured by the standardization of all dimensions added to the SolidWorks Computer Aided Design (CAD) model. All design features have dimensions that are only referenced to the features themselves or constants within the system (such as the origin or design planes). This allows the geometry of each design feature to be easily adjusted without affecting subsequent design features.

3.2.5 Design/User's Manual

We created a manual so our sponsor could recreate our prototype and operate it themselves (See Supplemental Material). The design section of the manual documents all the components in the prototype, providing the bill of materials (BoM), a full schematic, linking the code and the Arduino Nano ESP32 datasheet. The user's section of the manual gives directions on how to use the prototype. This includes step by step instructions on the preliminary procedures of operating the system. In addition, all the messages sent to and from the Arduino Nano ESP 32 are detailed. This includes how to start and stop the system, how to update the percentage of fertilizer, and how to read all of the error messages.

Chapter 4: Design of Dual Tank Fertigation System

4.1 Design Requirements

The main goal for the design of this prototype is to create a microcontroller-based system that reduces cost and power consumption compared to the current NESS Fertigation prototype. The improved prototype must be able to sustain two alternating tanks, one filling from the fertilizer and water sources and one emptying into the field through the irrigation system. Incorporating this feature allows for the improved prototype to constantly supply the water and fertilizer mixture instead of waiting for a single tank to fill before emptying it into the field. NESS Fertigation’s current prototype is managed by SolTag, a controller that can read from multiple sensors, control solenoid valves, and process information. SolTag connects to NESS Fertigation’s database using LoRaWAN, a long range wide area network. SolTag reads data from a sensor to determine moisture and amount of fertilizer in the soil. It uses this information to determine the necessary fertilizer percentage and relays that value to our microcontroller. The controller chosen was the Arduino Nano with an ESP32-S3 core to make use of the various sleep modes available in the ESP system and for the accessibility of Arduino boards. C++ is used to program the microcontroller because of the strict typing and object-oriented structure of the language which allows for more flexibility in coding than other languages.

Figure 5 displays a simplified version of all the physical and electrical connections in the improved prototype. The controller communicates with the SolTag controller through two digital inputs and one analog pin. The digital pins receive the ratio of the water-fertilizer mixture as well as whether the system should be distributing the mixture into the field. The analog connection reports any errors found from fault detection to the SolTag controller. In addition to communication, the Arduino controls six two-wire solenoid valves in order to transport the water and fertilizer through the system.

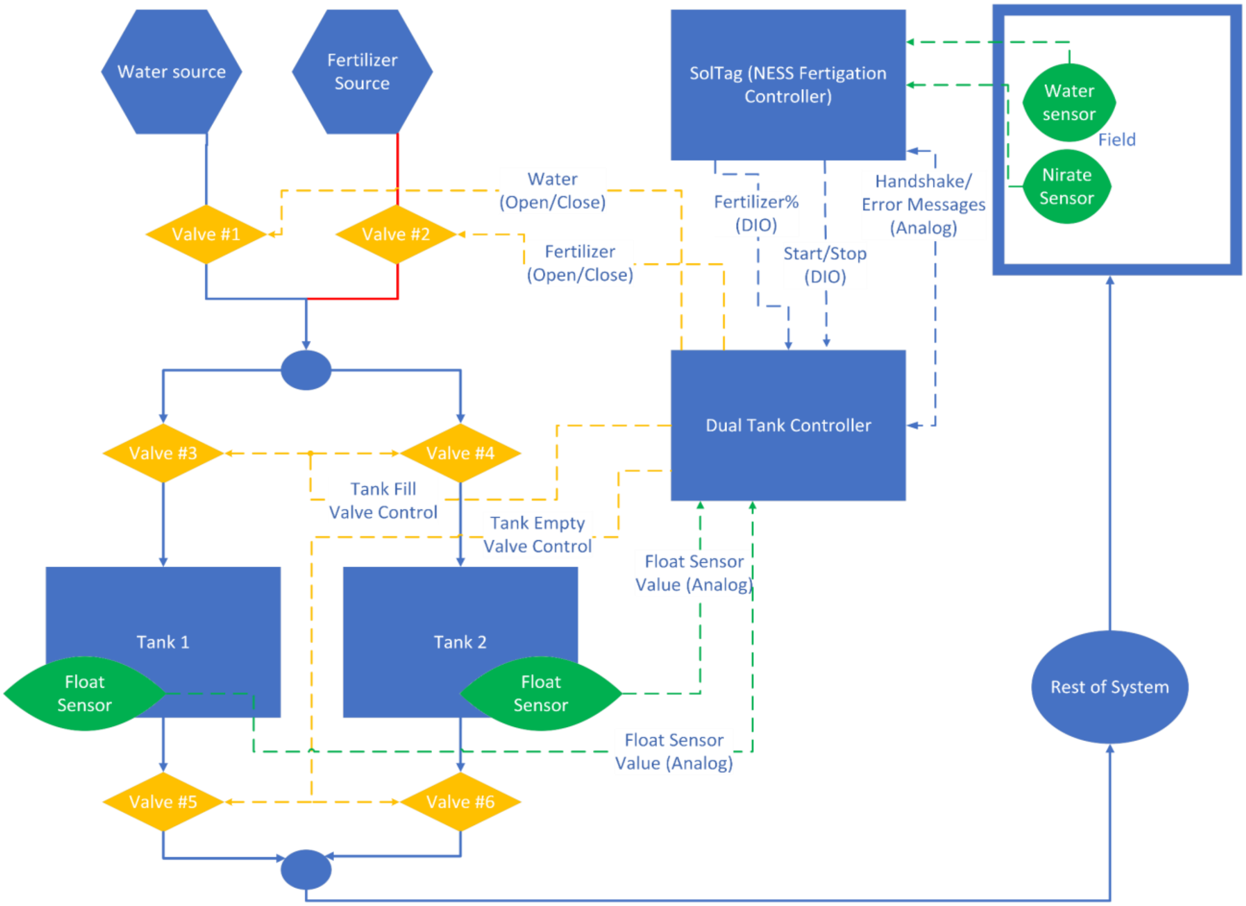


Figure 5: Simplified connections diagram of the system

Physical connections being shown by solid lines and electrical connections being shown by dashed lines.

Valves 1 and 2 in Figure 5 are used to fill the tanks from the water and fertilizer sources. The tanks fill up with fertilizer first and then the rest of the tank fills with water. After the correct ratio is achieved, both valves close until the next tank is ready to be filled. Valves 3 and 4 control what tank is being filled and must always be in opposite states. Similarly, valves 5 and 6 control which tank is being emptied onto the field and must also be in opposite states. This way, both tanks cannot be filling or emptying at the same time.

4.2 Schematic of Final Prototype

Figure 6 shows the schematic of our finalized prototype including the necessary solar panel system components.

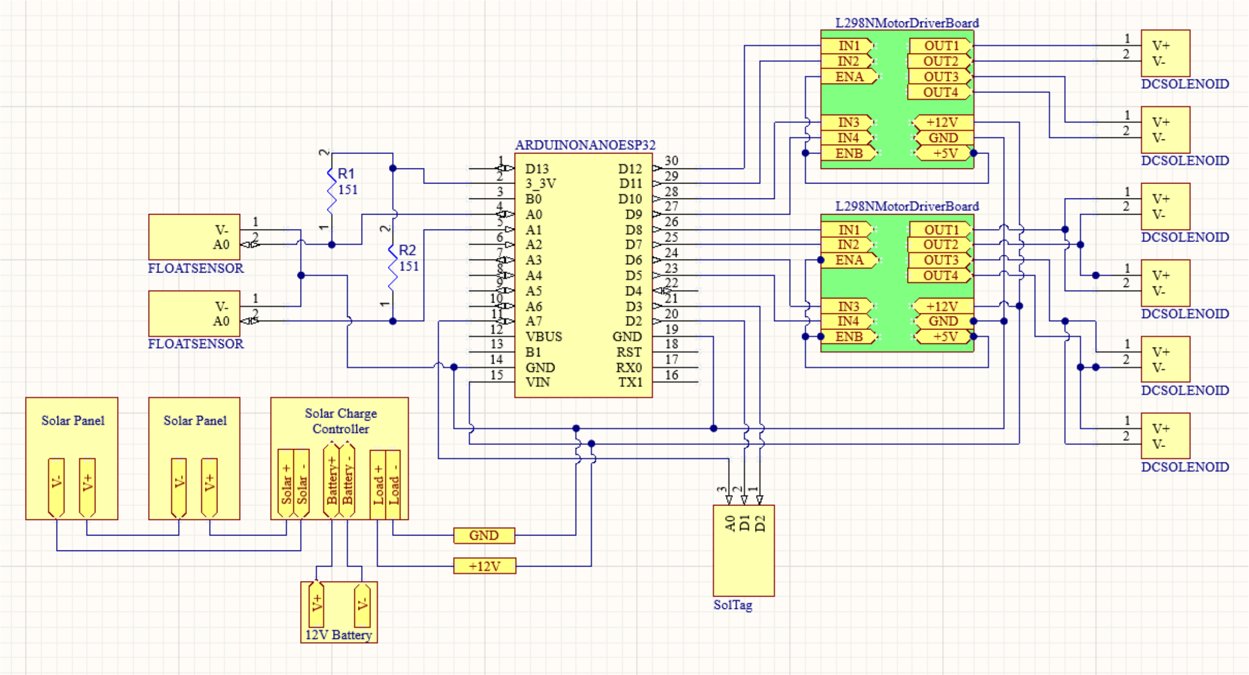


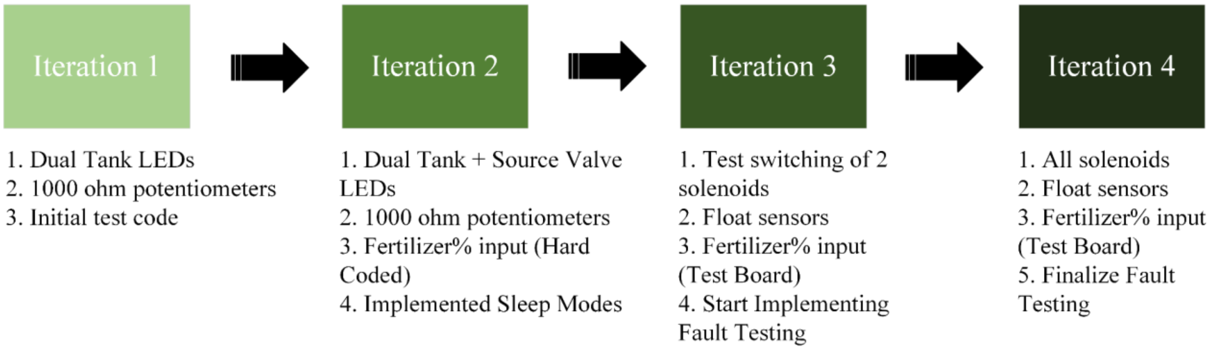
Figure 6: The schematic of our finalized prototype.

Schematics of L298N Motor Driver can be found in Appendix B

In Figure 6, the Arduino Nano was assembled on a breadboard and the power rails were connected to a 12V power source and ground. Every +12V in the schematic is connected from the same power source and similarly every GND is a common ground. The connection between the +5V output and the enable pins on the motor driver board are hardwired through a jumper. The solenoid valves are connected to the outputs of the motor driver to control whether positive or negative voltage is sent through the solenoid, changing the position of the valves. The float sensors are connected to ground and an analog pin in the Arduino through a voltage divider to read the value.

4.3 Microcontroller System Iterations

We developed multiple iterations of our design to test each of the requirements. The first two iterations were proof of concept designs. In these models, the valves were replaced by light emitting diodes (LEDs), with on and off modes representing the open and closed tank valves respectively. The float sensor values were simulated with potentiometers and the same Arduino Nano ESP32 board was used to test the code. The following two iterations incorporated the electrical components that are used in the final design. We operated under the assumption that the tanks would fill at the same speed or faster than they empty. The components and differences between each design are highlighted below in Figure 7.



Iteration 1
1. Dual Tank LEDs
2. 1000 ohm potentiometers
3. Initial test code

Iteration 2
1. Dual Tank + Source Valve LEDs
2. 1000 ohm potentiometers
3. Fertilizer% input (Hard Coded)
4. Implemented Sleep Modes

Iteration 3
1. Test switching of 2 solenoids
2. Float sensors
3. Fertilizer% input (Test Board)
4. Start Implementing Fault Testing

Iteration 4
1. All solenoids
2. Float sensors
3. Fertilizer% input (Test Board)
5. Finalize Fault Testing

Figure 7: All microcontroller prototype iterations

4.3.1 Iteration 1: Design Concept for the Alternation of Tanks

The goal for this iteration was to test the tank switching mechanism through the float sensors with sample code. We operated under the additional assumption that one tank always starts full. The process involved rotating the potentiometers, “filling” and “emptying” the tanks, and having the program recognize when to switch the LEDs from one tank to the other. This design uses four LEDs and two 1000 ohm potentiometers. The four LEDs act as the tank valves and the potentiometers were used in place of the float sensors. The breadboard is divided into a left and a right section, each representing a different tank. The red LEDs resemble the valves located on top of each tank and the yellow LEDs resemble the valves on the bottom. A picture of the first iteration is shown in Figure 8.

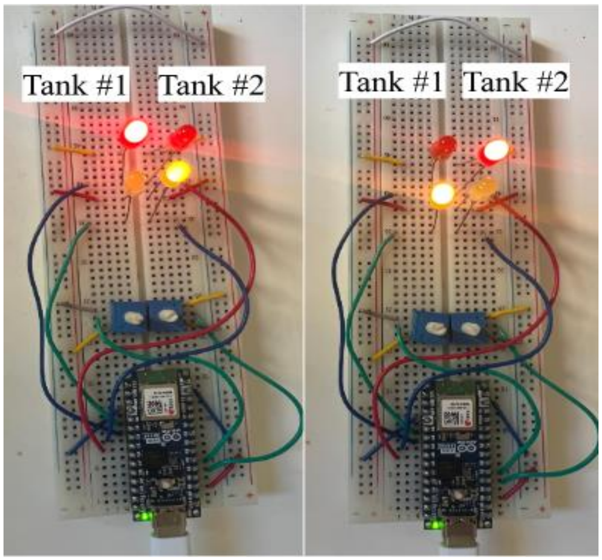


Figure 8: Iteration 1 of the microcontroller prototype.

The picture shows tank 1 filling while tank 2 empties, and the right image shows tank 2 filling while tank 1 empties.

4.3.2 Iteration 2: Source Valve Design Concept

The goal for iteration 2 was to add both the fertilizer source and water source and to introduce sleep modes. For this proof-of-concept prototype, LEDs and potentiometers are used to test the code logic. The value of the percentage of fertilizer in the tank is manually set in the code. When one tank starts to fill, the green LED, representing the fertilizer source, is turned on until the potentiometer is moved past the percentage value set. Once the percentage threshold has been hit, the water source, shown as the added red LED in Figure 9, turns on until the tank is full. For saving power, deep sleep is used when the start/stop bit is low and when the current tank has finished filling. Sleep mode is configured to sleep for 5 seconds until the bit becomes high again.

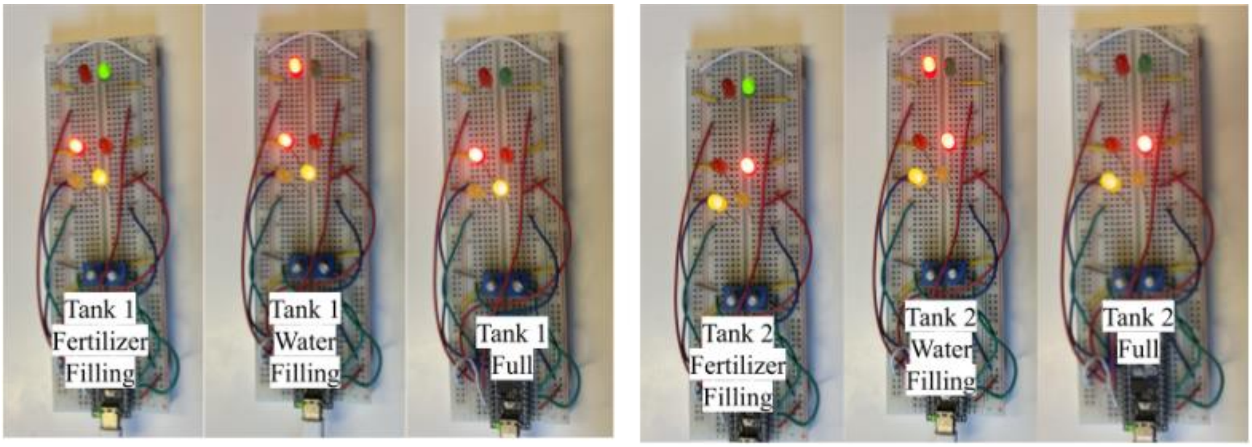


Figure 9: Iteration 2 of the microcontroller prototype.

The left set of images show tank 1 filling. The leftmost image shows the fertilizer source open. The image second from the left shows the water source open. The image third from the left shows tank 1 being full and waiting for tank 2 to empty. The same steps are shown for filling tank 2 on the right set of images.

4.3.3 Iteration 3: Electronic Components Test Prototype

The goal for this iteration was to introduce the electrical components to get two solenoid valves to switch using one logic input and add fault detection. The two added solenoid valves function as the red LEDs which represent the top two valves of the tanks. The physical switching mechanism of the valves was tested using the motor driver that is used in the final design. In addition, the potentiometers were swapped out for float sensors with the correct resistance range, allowing for more accurate testing. This was also the first iteration to communicate with another controller. It receives the fertilizer percentages and the start/stop bit from an Arduino UNO, which is used in place of the SolTag controller. This iteration also includes fault testing which checks to see if the system is running correctly and reports errors to the SolTag controller.

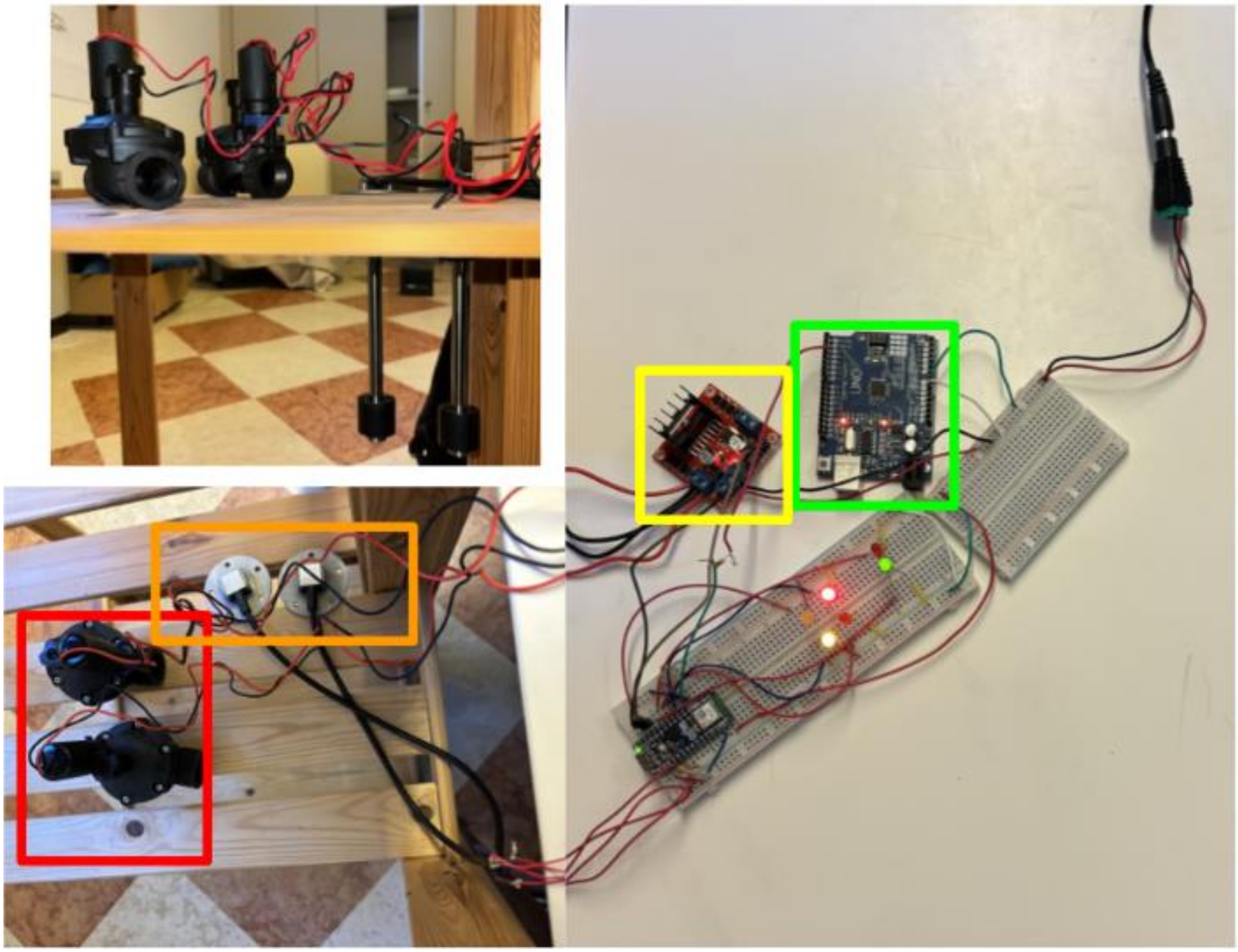


Figure 10: Iteration 3 of the microcontroller prototype.

The green box shows the Arduino Uno mimicking the SolTag controller. The red box shows the two solenoids which are connected to the DC motor driver module shown in the yellow box. The float sensors are highlighted in the orange box and are manually moved up and down to simulate the tanks filling and emptying.

4.3.4 Iteration 4: Final Prototype

The final design completes the entire iterative process and integrates all the components. The LEDs are replaced with solenoid valves and the controller communicates at full capacity. In addition to the digital input pins, it fully incorporates fault testing by sending and receiving a series of voltage pulses over an analog pin. One motor driver is used to control the two source valves, and a second motor driver controls the top set and the bottom set of valves.

4.4 Final Design Product

Figure 11 shows an annotated picture of our final prototype.

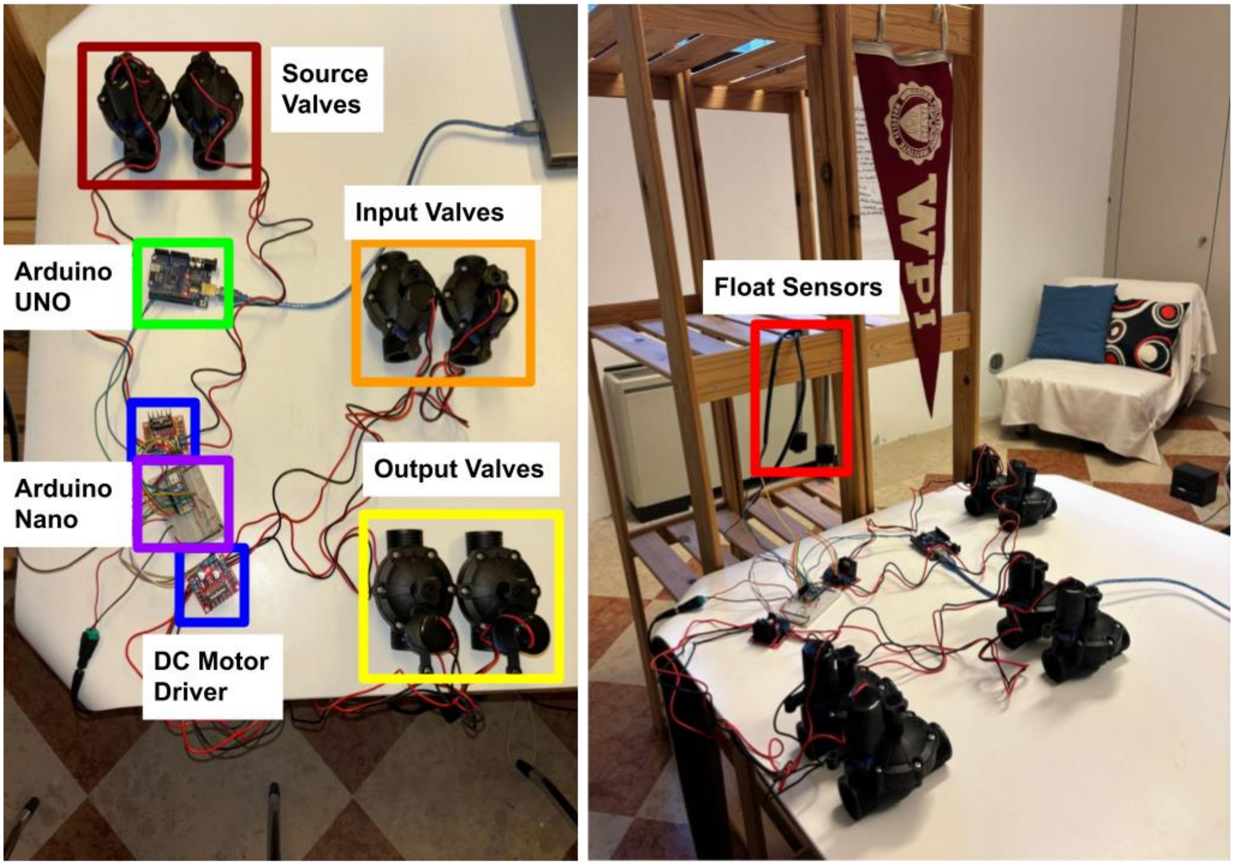


Figure 11: Picture of final prototype.

Left shows a top-down view of the electronics of the system. Right shows an isometric view of the system which also includes the float sensors for both tanks.

The dark red box highlights the two source valves. Left is the water source valve and right is the fertilizer source valve. The orange box highlights the two input valves for the tanks. The opposite color wires are connected between both valves since they are kept in opposite states from each other. The yellow box highlights the two output valves for the tanks. They are wired the same as the input valves but are configured to be in the opposite states so when the tank is filling, the output valve is closed and vice versa. The green box shows the Arduino Uno that acts as the SolTag Controller. The blue boxes show the DC Motor driver modules. The bright red box highlights the float sensors which measure the level of each tank. Finally, the purple box shows the Arduino Nano microcontroller on the breadboard.

4.5 Code Implementation

Figure 12 shows both the overall state diagram of the system (left) and state diagram of the 'ACTIVE' state (right).

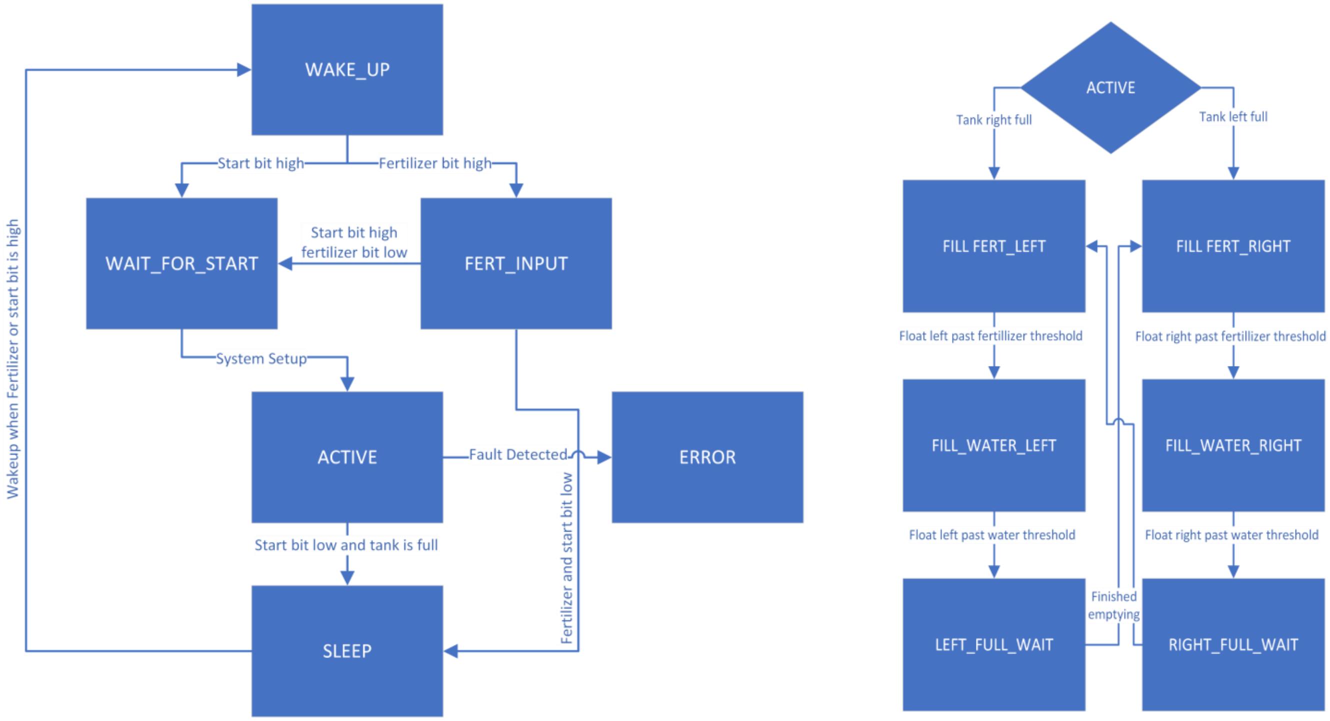


Figure 12: State diagram of code.

The system starts in the ‘WAKE_UP’ state which initiates the main program. If the fertilizer bit is high, the state machine goes into the ‘FERT_INPUT’ state which reads the percentage of fertilizer into the tank. After receiving the percentage, if both the start and fertilizer bits are low, the system goes to sleep and if just the fertilizer bit goes low, it goes into the ‘WAIT_FOR_START’ state. If only the start bit is high during the ‘WAKE_UP’ state, it goes directly into the ‘WAIT_FOR_START’ state which checks the initial setup of the system, and determines which tank is full. When the system is fully set up, it goes into the ‘ACTIVE’ state and starts filling/emptying the tanks. When the start bit is low, the dual tank system will finish filling/emptying the current tanks and then switches to the ‘SLEEP’ state which puts the microcontroller into deep sleep mode. The controller checks for any faults in the system while it is in the ‘ACTIVE’ state. If a fault is found, the system goes into the ‘ERROR’ state and reports the fault back to the SolTag controller. If no errors are found during the ‘ACTIVE’ state, a heartbeat message is sent to the SolTag controller to show that the controller is functioning normally.

4.6 Energy Consumption Calculations

The following equations from Section 3.2.2 (Eq. 4 - Eq. 8) were used to calculate the total power consumption of our finalized prototype.

$$(50mA * 3.3V) + (73.17\mathrm{m}A + 73.17\mathrm{m}A) * 12V) = 1.921\ W$$

$$12h\ *\ 1.921W = 23.05296\ \mathrm{Wh}$$

$$(0.007mA * 3.3\mathrm{V}) + \left((73.17\mathrm{m}A + 73.17\mathrm{m}A) * 12V\right) = 1.7561\ W$$

$$(24 - 12h) *\ 1.7561\ W = 21.073\ Wh$$

$$23.05296\ Wh + 21.073\ Wh\ = 44.1262\ Wh$$

While assuming 12 hours of activity per day, the final power consumption of the prototype came out to 44.1262 Wh.

4.7 Solar Panel System Calculation

The following equations from Section 3.2.3 (Eq. 9 - Eq. 12) were used to calculate the total capacity of the solar panel system and the number of solar panels needed based on the selected model.

$$44.1262\,Wh\ /\ 0.20 = 220.631\,Wh$$
$$220.631\,Wh\ /\ 10.1667h = \ 21.701\,W$$
$$21.701\,W\ /\ 0.80 = 27.1267\,W$$

The final solar system capacity assuming a 20% system efficiency would be 27.1267W.

$$27.1267W\ /\ 30W = Number\ of\ Panels$$

Using a 30W solar panel, the total number of panels would be 0.904. Therefore, only one 30W solar panel is required to power the system.

4.8 Housing

Housing requirements included custom fitting to the microcontroller system for reduction of material and build efficiency, security of all components, reproducibility, and ability to maintain electronic components performance under weather conditions that presented extreme heat and water. In this section we will discuss the results of our housing.

4.8.1 Design and Dimensions

The housing assembly consists of a bottom case and lid, connected by M2.5x10mm screws with holes modeled into both elements of the housing. The collapsed and exploded views of the full housing assembly model, with all necessary component models, are found in Figure

13. Wires have been excluded from the CAD model, but detailed connection schematics are provided in the Iteration 4: Final Design iteration section in 4.3.4.

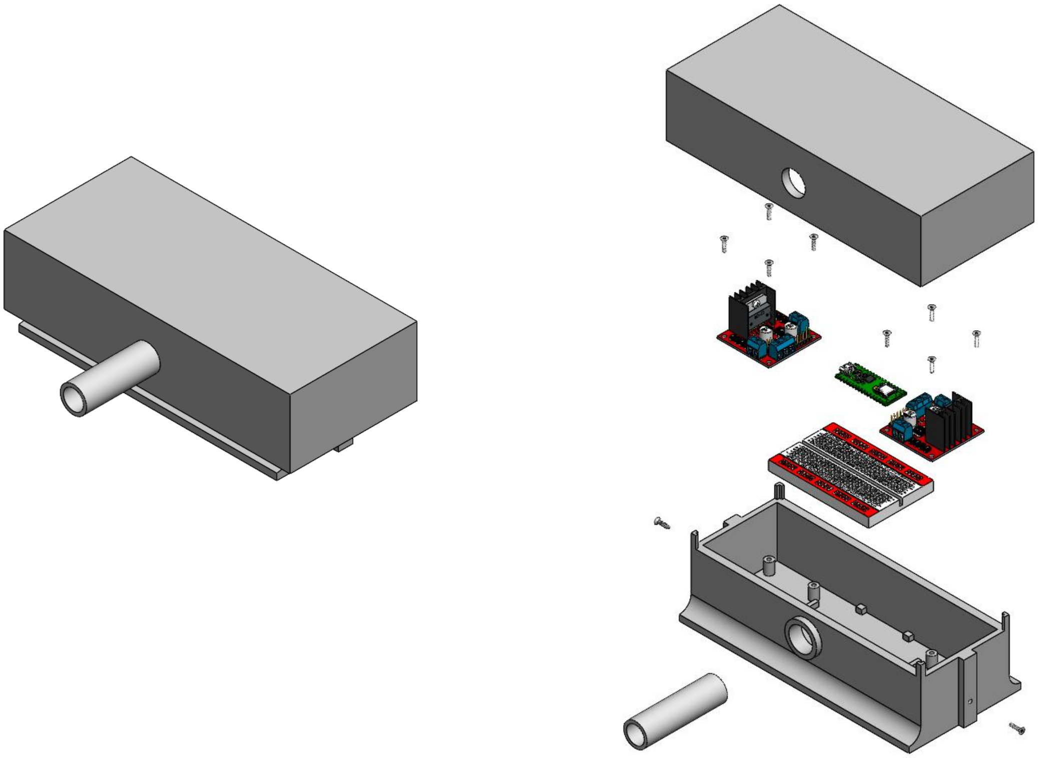


Figure 13: Collapsed (left) and Exploded (right) views of full microcontroller assembly and housing. Arduino Nano: (Finnestrand, Emil.,2024); Mini Breadboard: (T., Alban. ,2013)

The microcontroller system measured 182 mm in length, 55 mm in width, and 37 mm in height. This resulted in housing dimensions of 216 mm in length, 96 mm in width, and 62 mm in height as seen in Figure 14. This resulted in a total housing mass of 0.60 kg in PLA+, and 0.54 kg in ASA. Additional Mass Properties, as well as the model’s material properties and their sources, can be found in Appendix B.

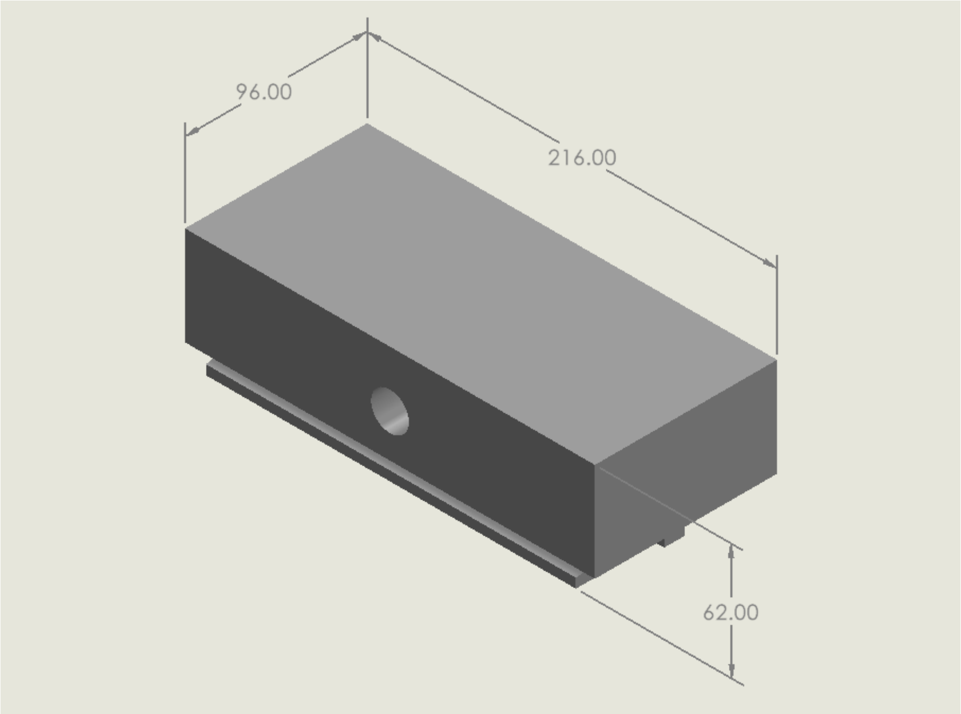


Figure 14: Housing Design Assembly Dimensions.

The components were secured with standoffs and extrusions modeled into the housing. Standoffs restrict movement of the DC motor driver in the x, y, and z directions using M2.5x10 mm screws that secure the board to the standoffs called out in Figure 15. The standoffs have a height of 10mm, providing clearance for all connections between the DC motor driver board and breadboard to be maintained. The extrusions securing the breadboard into the housing are the length and width of the board itself. This allows for the breadboard to drop into place during assembly, and subsequently restricts its movement in the z and x directions. It was not necessary to restrict the breadboard’s movement in the y direction as the use of this system does not require turning the housing upside down. These component securing features and their locations within the context of the full system are found in Figure 15.

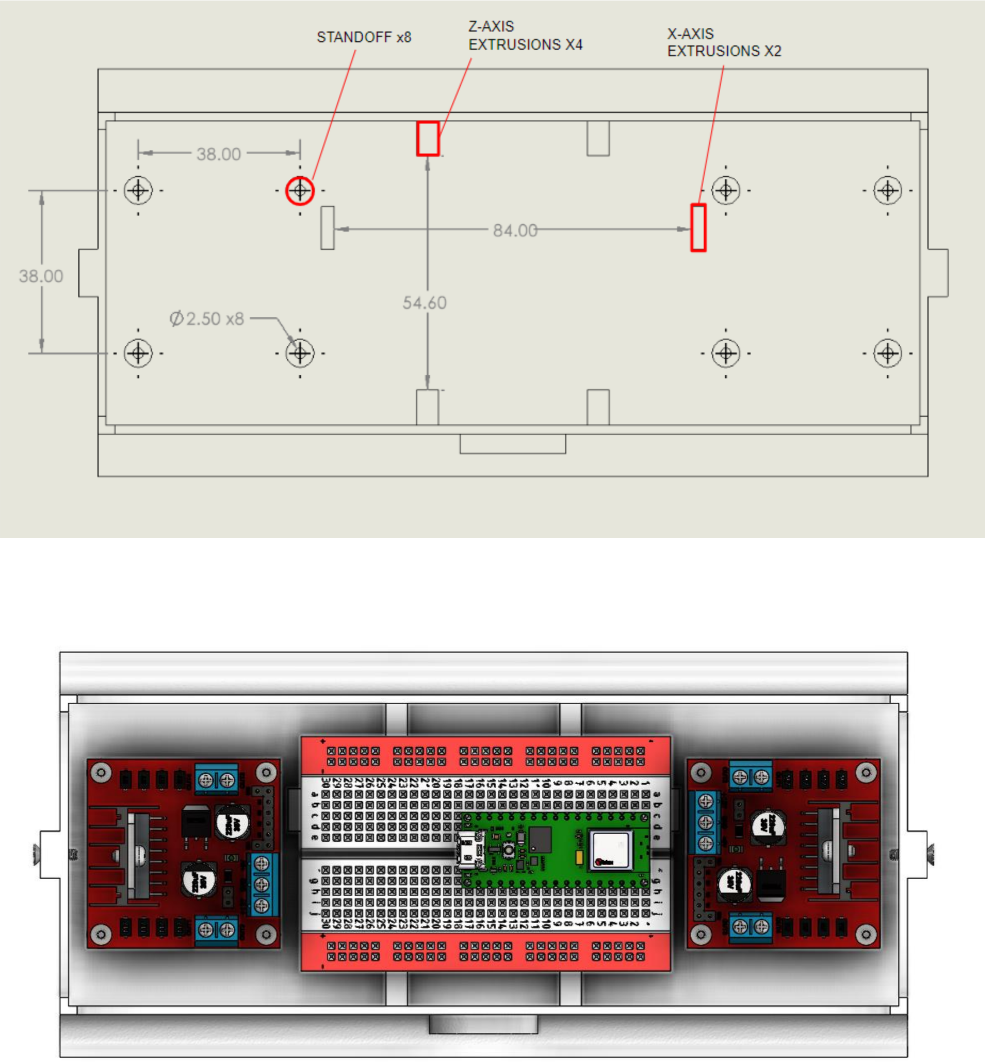
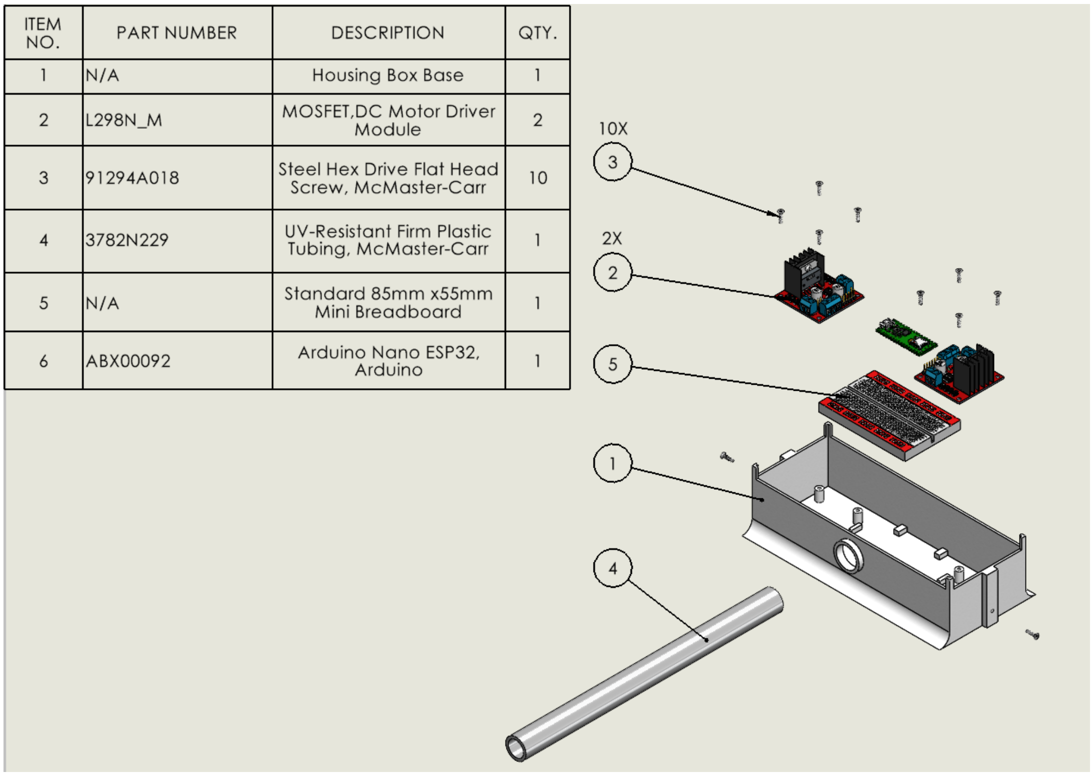


Figure 15: Housing features that secure components.

View 1, top view drawing of the housing base. View 2, components secured by features.

The full assembly parts list can be found in Figure 16, detailing the Bill of Materials including part numbers, descriptions, quantity, and location according to the indication bubbles. The STL zip files for printing the housing assembly are linked in Appendix B.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	N/A	Housing Box Base	1
2	L298N_M	MOSFET,DC Motor Driver Module	2
3	91294A018	Steel Hex Drive Flat Head Screw, McMaster-Carr	10
4	3782N229	UV-Resistant Firm Plastic Tubing, McMaster-Carr	1
5	N/A	Standard 85mm x55mm Mini Breadboard	1
6	ABX00092	Arduino Nano ESP32, Arduino	1

Figure 16: Bill of Materials, including Part Number, Description, and Quantity.

4.8.2 Materials

Heat protection was dictated by the properties of the selected material for which the housing was printed with. This design was printed in Polylactic Acid + (PLA+) as a proof of concept, but Acrylonitrile Styrene Acrylate (ASA) filament has been selected to perform better in long-term extreme heat exposure conditions. PLA+ is an environmentally sustainable filament manufactured from corn, sugarcane, beets, and other plant materials with additional additives such as fillers, nucleating agents, and other thermoplastics for stronger material properties in comparison to standard PLA (Polygenis, 2023). ASA is an acrylic amorphous elastomer created through polymerizing acrylonitrile, styrene and acrylate, with each component of the terpolymer enhancing its versatile material properties (Ventura, 2023). While the glass transition temperature for PLA+ is around 60°C, it can maintain material properties at our defined maximum temperature of 50℃ (Suder et al., 2023). Although PLA+ does meet our requirements, ASA filament has been selected as a preferred material as its glass transition temperature is much higher, with material properties maintained up to a temperature of around 100℃ (Tyson, 2019).

4.8.3 Weather Protection

The design incorporates weather protection characteristics including a ventilation system, shadowed interior base in reference to the overhanging lid, and an extruded wire cover. Heat protection of the microcontroller system is enhanced by the addition of cooling methods for internal electronics. Passive ventilation methods provide airflow into the housing for keeping electronics cool for their proper functioning. As opposed to other ventilation methods, passive ventilation requires no energy input or additional parts. Passive ventilation was incorporated into the design by adding 10 mm apertures where the housing base meets the lid. This was done by modeling extrusions into the housing base that allow the housing lid to press fit into place, as seen in Figure 17.

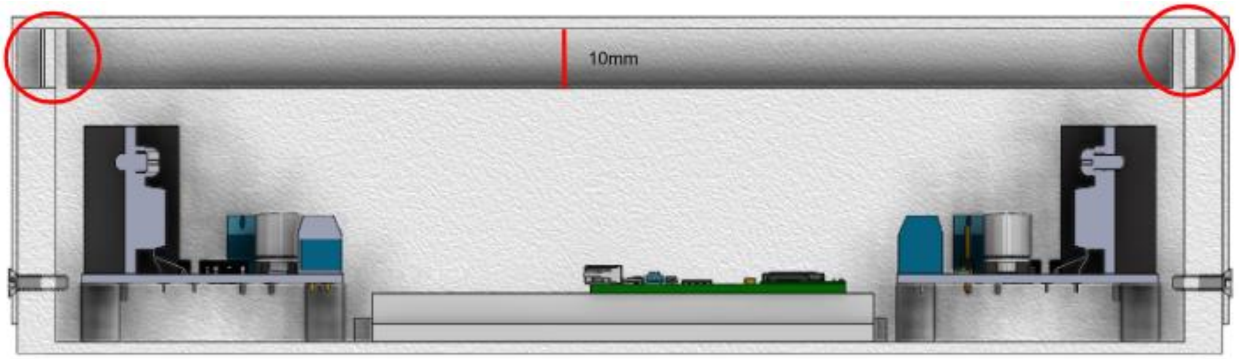


Figure 17: Housing Side View with Ventilation Extrusions called out.

The shadowed interior casing in reference to the lid provides protection against rain without compromising ventilation features. The extruded wire cover provides weather protection by creating an extension from the base of the housing to the housing lid, as seen in Figure 18.

Figure 18: Extruded Wire Cover (highlighted in red) side view.

A UV-protected tube is then inserted through the hole in the housing lid into the extruded wire cover for protection of wires as they are connected to peripheral components. The UV-protected tube has an inner diameter of 15mm, which was selected by adding the individual diameters of each wire connecting to the microcontroller system, including 12 solenoid valve wires, four float sensor wires, two DIO wires, one analog wire, and two power supply wires. Only one hole would be necessary for external connections from the microcontroller system due to the flexibility of the wires. Its location, shown in Figure 19, is equally spaced apart from each of the DC motor driver boards. The extruded wire cover adjoined with the UV-protected tubing eliminates this hole as a point for environmental pressures to have access to the enclosure.

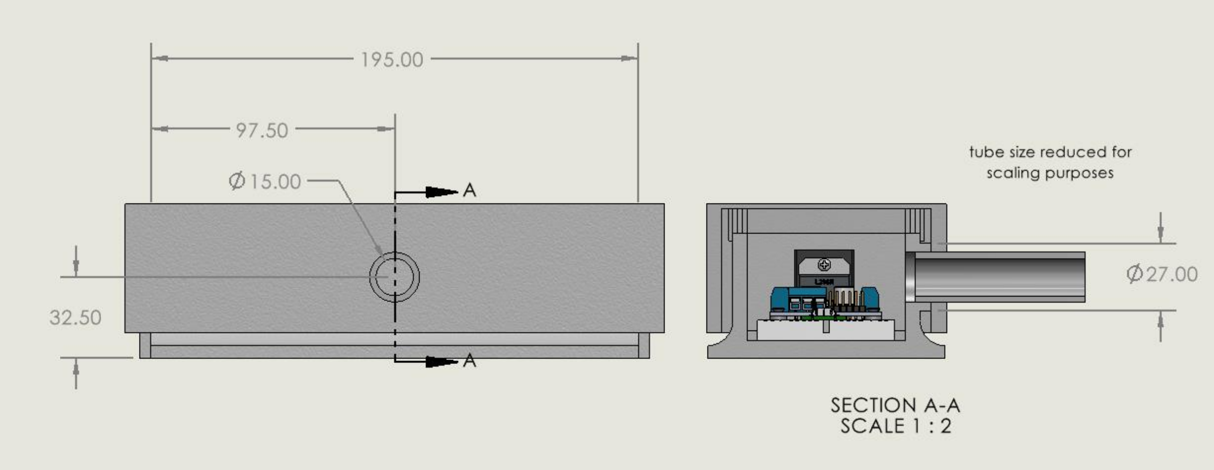


Figure 19: Extruded Hole Cover, front and side views.

Chapter 5: Environmental Performance Assessment

5.1 Definition of Parameters of Impact

In this section, we will discuss the definition of each parameter of impact and their context within the four systems of our Environmental Impact Assessment. Specific scoring can be found in Tables 1-4 of Appendix A.

The Importance of condition (A1) category defines the area of interest for each parameter, ranging from no importance to national/international interests, as seen in Table 2 of Chapter 2. The A1 category is scored consistently as the area of influence of each parameter does not change with the system being evaluated. The Magnitude of change/effect (A2) category that defines the amount of positive or negative effect that each parameter has, compared to the status quo, varies in scores for each system based on the specific functions and designs of the system. These functions and design considerations are specifically defined in the following parameter discussions. All categories under Criteria (B) for each parameter do not change with the system being evaluated. The Permanence (B1) category is defined as how lasting the effects of each parameter are. The Reversibility (B2) category is defined as how reversible the effects of each parameter are. Since this category does not apply to all parameters, we have scored non-applicable systems as no change. The Cumulative (B3) category is defined as how the effects of a parameter may compound with continued practice, ranging from non-cumulative/single effect to cumulative/synergetic effects. As this category does not apply to all parameters, we have scored non-applicable systems as no change. Table 4 shows each of the parameters of impacts used in this RIAM assessment and splits them up into their corresponding categories.

Table 4: Categories considered during RIAM analysis

Physical/Chemical	Biological/Ecological	Sociological/Cultural	Economic/Operational
PC1: Chemical Fertilizer Application PC2: Energy Consumed by the System PC3: Use of Water PC4: Plastic Use	BE1: Effects of Chemical Fertilizer Application BE2: Effects of System's Energy Source BE3: Effects of water usage BE4: Yield Efficiency	SC1: Ease of Education for Operating Machine SC2: Ease of Introduction into Other Systems SC3: Self Sufficiency	EO1: Ease of Assembly EO2: Transportation EO3: Scalability of the System EO4: Cost of System EO5: Versatility of Site Locations

5.2 PC: Physical/Chemical Parameters

5.2.1 PC1: Chemical Fertilizer Application

Chemical fertilizer application is defined as the quantity of chemical fertilizer used in the mixing process. Fertilizer amounts are defined by soil sensor readings in both our improved NESS Fertigation system and the current NESS Fertigation system. System 3, the Manipal University's Automated Fertigation Prototype, similarly uses moisture sensors in the soil to dictate fertilizer quantities. These systems score well in the A2 category of the RIAM as they reduce the overall quantity of fertilizer used in the mixing process when compared to human-input fertilizer amounts. System 4, the FertiOne™ Plus by Netafim, however, requires quantities of fertilizer to be fed into the system manually, leaving greater variability in fertilizer quantities. This may lead to over or under fertilization of plants, which we have scored negatively in the A2 category.

5.2.2 PC2: Energy Consumed by the System

Energy consumed by the system is defined by the quantity of energy needed to properly power the system. Low power consumption modes allow our improved NESS Fertigation system to reduce the overall energy needed to run. Similarly, sleep modes utilized in the current NESS Fertigation system accomplish reduced energy consumption. These systems score well in the A2 category as a result of their reduced power consumption capabilities. On-grid power consumption methods, utilized in System 3, the Manipal University's Automated Fertigation Prototype, and System 4, the FertiOne™ Plus by Netafim, require the constant input of power to sustain system capabilities. This would lead to more energy being consumed by the system, in comparison to Systems 1 and 2, and therefore would score lower in the A2 category.

5.2.3 PC3: Use of Water

Use of water is defined as the efficiency of water usage within the system. As water is increasingly becoming a scarce resource, it is necessary to create a system that effectively uses water provided without waste. This also means that use of water by all systems will score high in the A1 category as this subject aligns with regional and national interests. Specific ratios of water to fertilizer are dictated by sensors in the soil for Systems 1, 2, and 4, and this sum of water is automatically added to the mixing process using automation. This process allows for water to be used more effectively based on crop needs, which reduces the overall amount of water in the mixing process. This makes Systems 1, 2, and 4 score well in the A2 category as these water saving processes are a major positive benefit. System 3, the Manipal University's Automated Fertigation Prototype, similarly uses ratios of water to fertilizer dictated by soil moisture sensors, however, these ratios are manually introduced by the user. This allows room for errors in the amount of water being fed to the system, with water then potentially being over or under used. This inefficiency of water usage makes System 3 score lower in the A2 category, as human error may negatively impact water conservation efforts.

5.2.4 PC4: Plastic Use

Plastic use is defined as the quantity of plastic used in the system. The primary contributor of plastic to many fertilizer mixing systems is the mixing tank itself. System 2, the current NESS Fertigation system, uses one large mixing tank requiring plastic walls with increased thickness for the robustness of its design. This has been modified in System 1, our improved NESS Fertigation system, as the one large mixing tank has been split into two smaller mixing tanks allowing for reduced wall dimensions to maintain similar robustness. Manipal University’s automated fertigation system uses plastic for all of their tanks, including three tanks for fertilizer storage, one for water storage, and another for mixing. The mixing tank will be the only factor taken into consideration due to all systems having tanks that source their water and fertilizer solution. This system has a similar mixing process to NESS Fertigation’s current design and would need the same sized tank in order for it to be compared, therefore, they are both scored equally. The FertiOne™ Plus includes no plastic tanks in the system, therefore, it achieves the highest score out of the four systems.

5.3 BE: Biological Ecological Parameters

5.3.1 BE1: Effects of Chemical Fertilizer Application

Effects of chemical fertilizer application are defined by the damages that the fertilizer causes to the environment around the farm. This includes both soil contamination and the release of nitrous gasses and is directly related to the amount of excess fertilizer used per field. System 1 and 2 score well in the A2 category because the amount of fertilizer is carefully monitored while setting ratios of fertilizer to water. System 2 scores slightly lower in this category because the operator controls how long the system is on and can over fertilize the field if they misuse the machine. The amount of fertilizer used in System 3 is determined by sensors in the soil but is completely manually controlled and therefore scores lower than the previous two systems. For the FertiOne™ Plus, the amount of fertilizer is fed manually into the system, increasing the amount of human error allowed, and scoring the lowest out of the four systems.

5.3.2 BE2: Effects of System's Energy Source

Effects of the system's energy source is defined by the type of energy source used to power the system. Solar power energy is utilized in System 1, our improved NESS Fertigation system, and System 2, the current NESS Fertigation system. Solar powered energy presents less harm on the environment through the reduction of carbon emissions when compared to on-grid electricity systems, allowing it to score well in the A2 category. Regional interests in switching to renewable energy sources have also allowed these systems to score high in the A1 category. On-grid electricity energy sources, as used by System 3 and System 4, may be powered by non-renewable energy sources depending on location.

5.3.3 BE3: Effects of Water Usage

The effects of water usage by the different systems can be defined as the negative byproducts produced due to incorrect use of water throughout each of the systems. Contributions to this parameter include leaching into the soil and bodies of water, adding incorrect amounts of fertilizer mixture into the irrigation lines, and wasting unnecessary amounts of water while using the system. In both our improved NESS Fertigation system and their current system, the negative byproducts are caused by incorrect mixing of the fertilizer in the tanks. In Manipal University's automated fertigation prototype, the main effects are caused by incorrect ratios of each element going into the tank. In this system, the byproducts could be more dangerous due to the presence of nitrogen in one of the tanks. The possibility of nitrogen runoff would be dangerous towards the soil, water sources, and the humans that operate the system. In the case of the FertiOne™ Plus, the system can use fertilizer or acid as a solution to feed the irrigation line. While fertilizer runs in the system, the misuse of water would have a very similar effect to NESS Fertigation's system. However, if enough acid is running through the system, it would cause severe damage towards the soil, water sources, and it would create a hazard for anyone operating the system. It can be concluded that both System 1 and System 2 score the highest in the A2 category, while System 3 and System 4 acquired a much lower score.

5.3.4 BE4: Yield Efficiency

Yield efficiency is defined by the performance of the system in producing a higher yield, proportional to the amount of land in use. System 1 uses a dual tank design that allows for constant flow of the fertilizer mixture into the irrigation line. With the improved precision through our microcontroller, it can produce higher yields than System 2 in any sized field. This is why we confidently scored System 1 as the best of the four in this category. NESS Fertigation's current system and Manipal University's system both acquired the same score as they have a very similar design for mixing fertilizer and injecting it into the irrigation line. Both models include one large mixing tank that mixes fertilizer and water, which is then sent to the irrigation line. System 2 and System 3 are both efficient models for small-scale farms, however, increasing the land size will mean that the tank sizes must be increased as well. This process then becomes inefficient due to long waiting times for the system to empty and fill, which is why System 2 and System 3 were scored equally below System 1. The FertiOne™ Plus by Netafim is a standard fertigation system that can use both fertilizer or acid to feed irrigation lines. This system uses a dosing process that efficiently transfers the solutions into the field, and therefore it is scored equally with System 1.

5.4 SC: Social/Cultural Parameters

5.4.1 SC1: Ease of Education

Ease of education for operating the system is defined by how accessible information for the system's design, usage, and maintenance is. User manuals allow for information on a system to be readily available, allowing for user independence and an aid for educating new users. Similarly, System 4, the FertiOne™ Plus by Netafim, provides an operation and installation manual. Due to their readily available information sources, these systems score well in the Magnitude of effect/change (A2) category as this is a major positive benefit. While System 2, the current NESS Fertigation System, does not provide a design or user's manual, user information on operation and maintenance is readily available through contacting the company. System 2 scores slightly lower than Systems 1 and 4 as their methods of communicating user information is less accessible. System 3, the Manipal University's Automated Fertigation Prototype, does not provide a user manual. This makes System 3 score lower in the A2 category as it has a negative effect on users trying to obtain information about the system.

5.4.2 SC2: Ease of Introduction Into Other Systems

Ease of introduction into other systems is defined by the system's ability to work with pre-existing fertilizer mixing systems. Systems 1, 2, and 4 all score equally in the Magnitude of change/effect (A2) category because they all can be easily implemented into any irrigation system. System 3 does not mention implementation into any system but based on the fact that it has many more components, it would be slightly more difficult than the other three systems.

5.4.3 SC3: Self Sufficiency

Self sufficiency is defined by the system's ability to run on its own without the help of the user. System 1 is the most automated as it requires no inputs from the user while System 3 only requires input for the amount of fertilizer that enters the field. System 2 is partially automated but requires input to start and stop the output of the mixture into the field. System 4 has both manual and partially automated options, giving it the lowest score of the group. System 1 and 2 are both solar powered while System 3 and 4 are powered through on-grid electricity, requiring the energy provided by the user.

5.5 EO: Ecological/Economical Parameters

5.5.1 EO1: Ease of Assembly

Ease of assembly is defined by how easy it is to build and acquire the different components that go into the system. Our improved NESS Fertigation prototype uses components that can be easily acquired through different companies and resellers while not needing any adjustments to cover different sizes of land. In both NESS Fertigation's current system and

Manipal University's automated fertigation system, the components used are also easily acquired. However, the tanks must be switched out depending on the land size, which scores them lower than our improved NESS Fertigation system. The FertiOne™ Plus uses components made by Netafim, and although some of the parts can be found easily, the core components of the system can only be bought directly through Netafim. Therefore, Netafim's FertiOne™ Plus scores the lowest in this A2 category.

5.5.2 EO2: Transportation

Transportation of the systems is defined by how easily a system can be transported based on its size and weight. NESS Fertigation's current system uses a 5000L tank, which has a height of 7.7ft and a radius of 5.7ft. The transportation process for the entire system would be rather inconvenient due to the large size of the tank, and therefore, it scores the lowest out of the four in the A2 category. Manipal University's prototype includes five tanks: three tanks for fertilizer storage, one for water storage and one for mixing. Depending on the size of land that the system will be used for, it will require a different sized tank for both storage and mixing. This means that the system will not necessarily be heavy. However, larger sized fields require tanks similar to the size of NESS Fertigation's current system, which would make transportation very difficult. For that reason, this system will be scored only above NESS Fertigation's current system. Our improved NESS Fertigation System includes two 100L tanks which weigh less than NESS Fertigation's 5000L tank. This means that our improved system would be lighter compared to the two aforementioned, but because of the two tanks, packaging would be relatively large. The FertiOne™ Plus by Netafim weighs 59.5 lbs, has a maximum packed weight of 92.6 lbs, and the dimensions of its package are 26.5/25/39". These dimensions do not include the controller for automation. Transporting the system, whether it be by land or air, is made easy due to it being stored in a single 2x3 ft container. For this reason, even though our improved NESS Fertigation system weighs less, the FertiOne™ Plus has a higher score.

5.5.3 EO3: Scalability of the System

The scalability of the system is defined by the system's ability to perform tasks at different field sizes. Our improved NESS Fertigation system increases the scalability from System 2 by splitting the single tank into dual tanks. The single tank would have to be increased for a larger size field while the dual tanks can stay the same size as it already constantly supplies the water-fertilizer mixture to the irrigation system. System 3 also uses a multi-tank design which would make the scalability better than NESS's current system but with 5 tanks, it would be more difficult to scale than our improved prototype. The Netafim model would outrank all of these in scalability as in addition to a multi-tank design, the model offers adjustable flow rates to increase or decrease the output as needed.

5.5.4 EO4: Cost of System

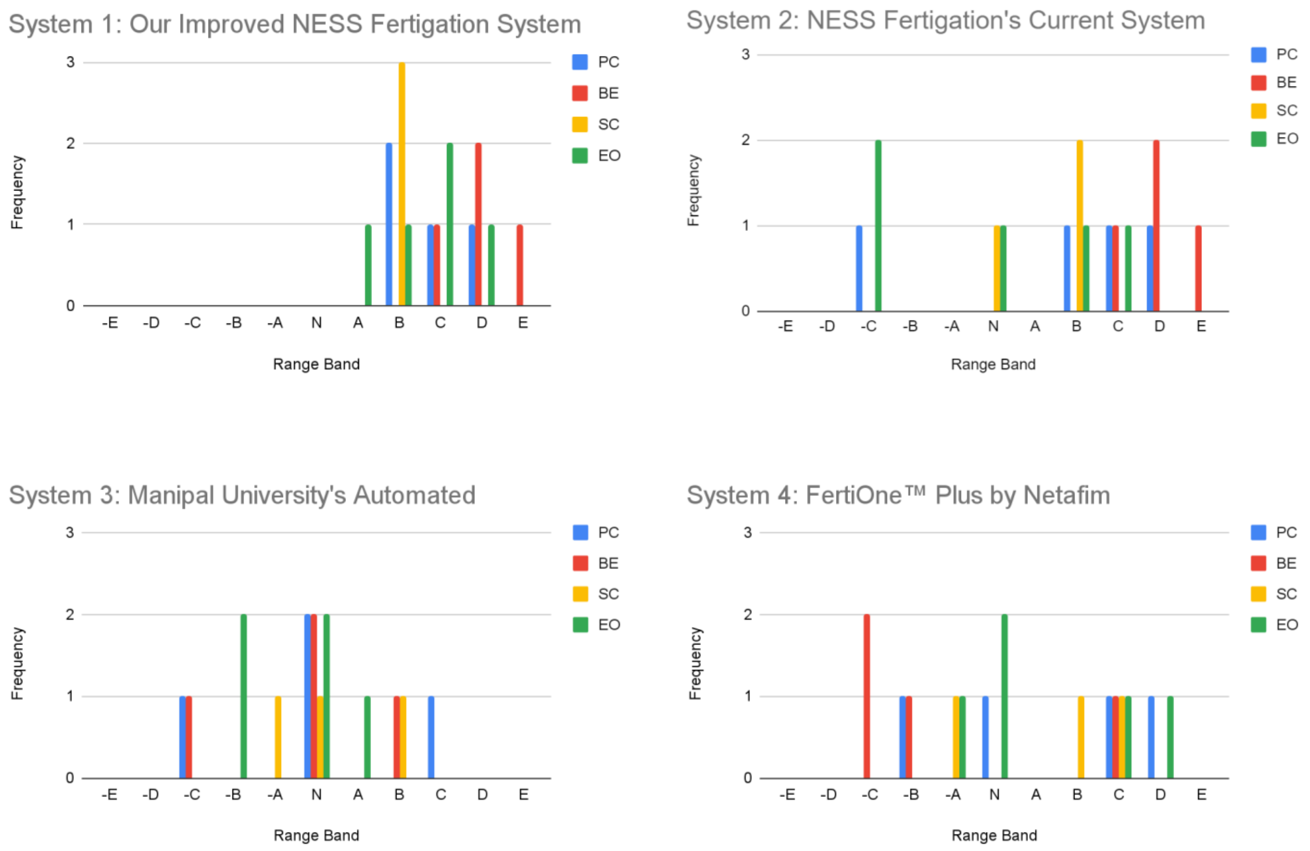
The cost of the entire system is defined as how expensive each system is to create, maintain and install. This price range and cost comparison is important to measure due to the different capabilities of each system and could dictate whether their efficiency and advantages correlate with a higher price. For NESS Fertigation's current system, buying the model and having it installed would cost around $13,000. The advantages of NESS Fertigation's current system are that it is solar powered, and as said on their website, produces 50% more yield than existing solutions and uses 30% less water. In terms of cost, our improved NESS Fertigation system would be in the same range of the current NESS Fertigation system. Some added features of the improved system are that it has increased precision, water and fertilizer efficiency, decreased energy usage, and added full automation. Manipal University's model is presented in its prototype stage, however, scaling the system up to a complete design would cost more than NESS Fertigation's current model. This is due to the increased number of valves and tanks needed to make the system, which would also take more energy to power. As for Netafim's model, it would take around $10,000-$11,000 to buy and have them install the system. Some of the features are its ease of introduction to other irrigation systems, the water and fertilizer efficiency, the durability of its components and its "precise Nutrigation™", as described on their website. However, it is fully manual, and in order to partially automate the FertiOne™ Plus, a 24VAC controller must be bought and paired with it. This type of controller, such as the NMC Pro Controller sold by Netafim, could be bought at an estimated price of $8000, which would increase the total cost of the system to around $18,000-$20,000. With all the information that was provided, it can be concluded that NESS Fertigation's current system and our improved NESS Fertigation system would be scored the highest. The system that would follow close behind them would be Manipal University's automated fertigation system, and lastly the FertiOne™ Plus by Netafim would score as status quo.

5.5.5 EO5: Versatility of Site Locations

The versatility of site locations is defined as the system's ability to perform in locations under different environmental conditions. Different farming locations require flexibility in power methods as well as resistance to different weather conditions. System 3 and 4 can both be placed anywhere there is access to on-grid electricity and are therefore scored the same. System 1 and 2 both run on solar power and can be placed in all off-grid locations with sufficient sun as well as connecting the power source to on-grid electricity. Since both options are available for System 1 and 2, they are scored above System 3 and 4.

5.6 Performance Assessment Results

The following bar graphs show the distribution of the Range Band calculations per system. Figure 20 a-d splits up the parameters by category while figure 21 a-d shows the overall scores for general visualization. The RIAM tables for the assessment of each system along with the specific Environmental Scores can be found in Appendix A Tables 1-4.


System 1: Our Improved NESS Fertigation System

System 2: NESS Fertigation's Current System

System 3: Manipal University's Automated

System 4: FertiOne™ Plus by Netafim

Figure 20: Every system's distribution of Range Band (RB) calculations for each parameter, split up by category.

The figure in the top left (20a) shows System 1, the top right (20b) shows System 2, bottom left (20c) shows System 3, and bottom right (20d) shows System 4.

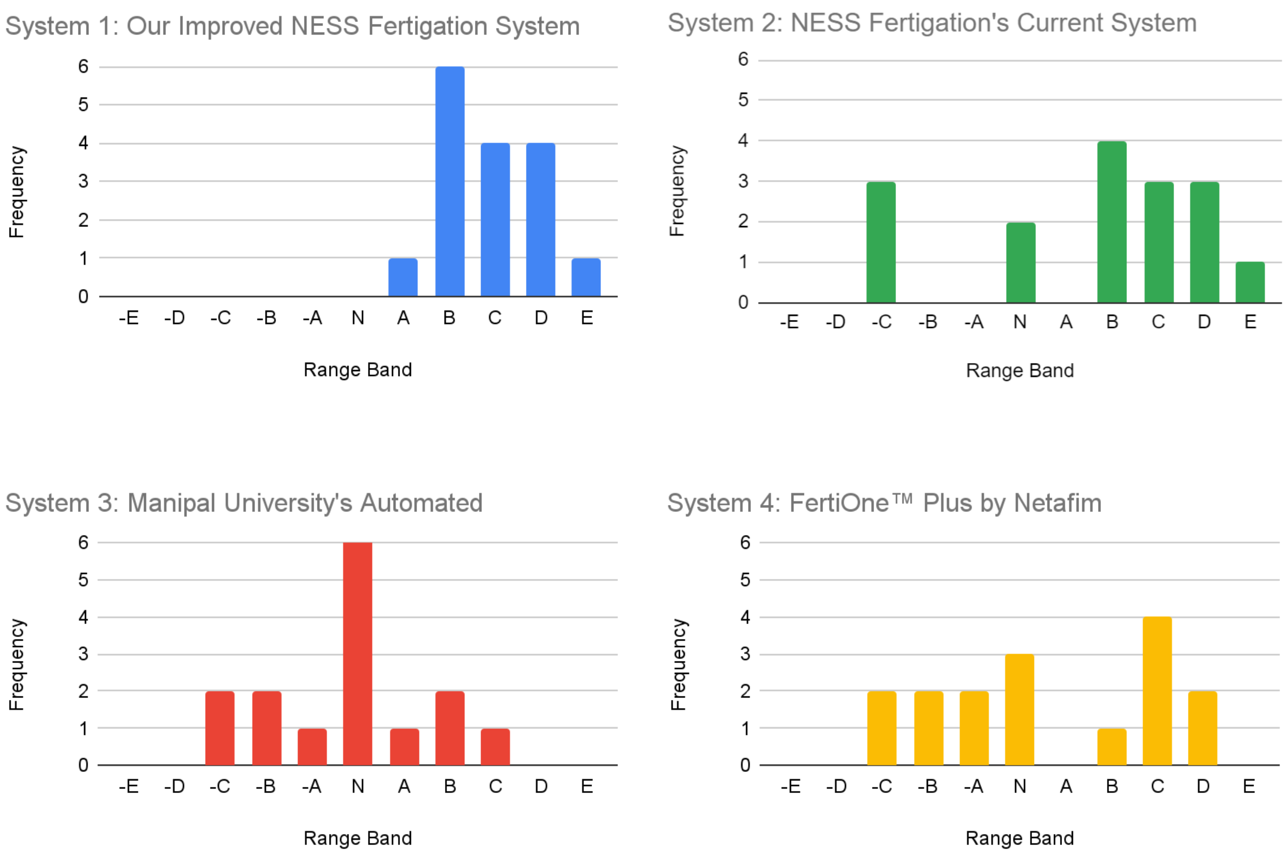


Figure 21: Every system's distribution of Range Band (RB) calculations for every parameter.

The figure in the top left (21a) shows System 1, the top right (21b) shows System 2, bottom left (21c) shows System 3, and bottom right (21d) shows System 4.

5.7 Performance Assessment Discussion

RIAM scores are inherently subjective based on the fact that we are giving qualitative attributes quantitative values. However, even with slightly different value assignments, as long as the table is scored consistently throughout, the general trends between the systems are evident and can be clearly identified.

The performance of each system has been compiled into a Range Band distribution, providing the raw values calculated from the scoring of each Parameter of Impact. In Figure 21a, the distribution of overall Range Bands for System 1, our improved NESS Fertigation prototype, has no negative range band values and scored highest amongst all other systems. System 2, the current NESS Fertigation prototype scored similarly to System 1. System 3 and 4 have scores evenly distributed across all Range Bands without extreme outliers.

Figure 20 a-d shows a more in depth distribution of Range Bands, highlighting the category that each score comes from. Two of the -C scores seen in System 2 are both in the EO category, from the parameters of transportation and scalability of the system (See Appendix A Table 2). The last -C score is in the PC category from the parameter of plastic use (See Appendix A Table 2). The goals for our design included the improvement in all three of these parameters and were addressed in our improved prototype, resulting in the higher scores of System 1.

Manipal University's design, shown in figure 20c, and NESS Fertigation's current system, shown in figure 20b, score negatively in similar categories. System 2 and System 3 both utilize one large mixing tank, recieving equal scores in the parameters of transportation, scalability, and plastic use (See Appendix A Tables 2 & 3).

The amount of fertilizer and water in System 4, Netafim's model, is controlled manually. This resulted in negative environmental scores for the parameters of effects of chemical fertilizer application and effects of water use. Poor operation of the system would result in the excess use of fertilizer and water, which could result in leaching or chemical runoff into bodies of water. (See Appendix A Table 4).

Chapter 6: Recommendations

Further implementations of the project can include more reliable hardware, decrease power consumption, include more resistant housing material, and conduct in-field testing. We were unable to conduct any testing on site as we were relocated from Eilat, Israel to Venice, Italy. The next step to improve the circuit is to create a custom board that includes all the needed system inputs and outputs. This should include extension pins for the microcontroller, power to the board, and all necessary electronic components. The extension pins allow the microcontroller to be mounted securely while also connecting any IO pins in the circuit. Implementing a capacitor circuit would further lower the power usage, by only pulsing to change the state of the solenoids, instead of constantly powering a DC motor driver module. Using internal wiring is more reliable than using a breadboard as all the connections are secured. Any external inputs should be soldered directly to the board or have a latching connection to secure the wires. Lastly, a LoRa module could be added to the system to be able to communicate to the controller remotely.

Additionally, a housing made of ASA instead of PLA+ would make the housing more robust and would increase the amount of farming locations where this project could be implemented. The only filament at the project center that was compatible with the 3d printer we utilized was PLA+. While this material did properly meet the requirements for heat protection (defined in section 3.2.4), due to its material properties, a different filament material, such as ASA, would allow for better heat protection. Additional protection against heat exposure would be done by annealing the 3d printed parts. Annealing parts after a 3d print has shown to increase the Heat Deflection Temperature (HDT), as well as tensile strength and firmness (Kočí, 2019).

Chapter 7: Conclusion

Our project strived to improve the current NESS Fertigation fertilizer mixing prototype by making it more efficient, scalable to any size field, and entirely autonomous. Through these goals, valuable resources may be utilized more effectively in fertigation processes, allowing for their reduced overall use and subsequent environmental impacts. Through a stepwise process, our team designed and built a prototype for an improved system that meets these design goals. This prototype accounts for each design goal by the implementation of a controller, a dual tank design, and by using energy conscious strategies for powering our system. An impact assessment was completed to compare our improved prototype, NESS Fertigation's current prototype, and two other fertigation systems. The distribution of range bands showed that, overall, our improved NESS Fertigation design posed the least amount of negative impact to the environment under the factors assessed. The specifications of this improved prototype were compiled into the design/user's manual for reproducibility by NESS Fertigation. The creation of this improved system will support the development of sustainable agricultural practices around the world.

Works Cited

3D Printing Solutions. (2023, January 16). *What is PLA+?* 3D Printing Solutions. https://www.3dprintingsolutions.com.au/User-Guides/what-is-pla-plus

A beginner's guide to sustainable farming. (2021, June 17). United Nations Environmental Program (UNEP). http://www.unep.org/news-and-stories/story/beginners-guide-sustainable-farming

A Complete Guide on Solar Panel Calculations (2023 Update). (2023, June 12). Anker. https://www.anker.com/blogs/solar/solar-panel-calculation

Agriculture - Worldwide | Statista Market Forecast. (2023, May). Statista. https://www.statista.com/outlook/io/agriculture/worldwide

Azad, N., Behmanesh, J., Rezaverdinejad, V., Abbasi, F., & Navabian, M. (2018). Developing an optimization model in drip fertigation management to consider environmental issues and supply plant requirements. *Agricultural Water Management*, *208*, 344–356. https://doi.org/10.1016/j.agwat.2018.06.030

Bagheri, A., Buj-Corral, I., Ferrer Ballester, M., Magdalena Pastor, M., & Roure Fernandez, F. (2018). Determination of the Elasticity Modulus of 3D-Printed Octet-Truss Structures for Use in Porous Prosthesis Implants. *Materials*, *11*(12), 2420. https://doi.org/10.3390/ma11122420

Burns, J. (2018, March 12). *Organic Foods vs Regular Conventional Food: What is the Difference?* TheDiabetesCouncil.Com. https://www.thediabetescouncil.com/organic-foods-vs-regular-conventional-food-what-is-the-difference/

Cahyadi, W. (2019). *Mechanical Pr Mechanical Properties of 3D Printed Acr ties of 3D Printed Acrylonitrile Styr ylonitrile Styrene Acr ene Acrylate* (p. 27). https://openprairie.sdstate.edu/cgi/viewcontent.cgi?article=4155&context=etd

Callahan, S. (2022, May 16). *USDA ERS - Farmland Ownership and Tenure*. https://www.ers.usda.gov/topics/farm-economy/land-use-land-value-tenure/farmland-ownership-and-tenure/

Cherlinka, V. (2023, May 18). *Fertigation In Agriculture: Benefits, Methods, And Applications*. https://eos.com/blog/fertigation/

Clarion Security Systems. (2022). *IP Ratings Explained | Ingress Protection Rating | IP Codes | Updated 2022*. Clarion UK. https://clarionuk.com/resources/ip-ratings/

Department of Jobs, P. and R. (2023, October 9). *Fertigation - Agriculture* [Text]. Agriculture Victoria. https://agriculture.vic.gov.au/farm-management/water/irrigation/drip-irrigation/fertigation

Diomandé, A. A. (2023, March 22). *Groundwater: How Scientists Study its Pollution and Sustainability*. International Atomic Energy Agency (IAEA). https://www.iaea.org/newscenter/news/pollution-and-sustainability-of-groundwater

Dixon, M., & Liu, G. (n.d.). *The Advantages and Disadvantages of Fertigation*. Ask IFAS - Powered by EDIS. Retrieved January 24, 2024, from https://edis.ifas.ufl.edu/publication/HS1442

Dontigney, E. (2018). *What Are the Effects of Leaching?* Sciencing. https://sciencing.com/effects-leaching-8680465.html

Dubey, A. (2024, February 9). *Sustainable agriculture | Definition, Practices, Methods, Examples, & Facts | Britannica*. https://www.britannica.com/technology/sustainable-agriculture

Encyclopaedia Britannica. (2010, August 9). *Leaching | Soil Chemistry, Nutrient Loss & Pollution | Britannica*. https://www.britannica.com/science/leaching-geochemistry-of-soil

Falivene, S., & Treeby, M. (2011). Fertigation Equipment for Orchards. *Primefact*, *1144*(First Edition). https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/423168/Fertigation-equipment-for-orchards.pdf

Fargo 3d Printing. (2017, October 11). *How Annealing Makes Your 3D Prints Better – Fargo 3D Printing*. https://www.fargo3dprinting.com/annealing-makes-3d-prints-better/

Farm Generators for Agriculture Purposes. (2022, May 24). Woodstock Power. https://woodstockpower.com/blog/farm-generator-for-agriculture-purpose/

Fertilizer 101: The Big 3 - Nitrogen, Phosphorus and Potassium. (2014, May 7). The Fertilizer Institute. https://www.tfi.org/the-feed/fertilizer-101-big-3-nitrogen-phosphorus-and-potassium

FertiOne Plus. (n.d.). Retrieved February 8, 2024, from https://www.netafimusa.com/agriculture/digital-farming/netbeat/fertigation/fertione-plus/

FertiOne^{TM}. (n.d.). Retrieved February 6, 2024, from https://www.netafim.com/en/digital-farming-old/netbeat/Fertigation/fertione/

Finnestrand, E. (2024, February 14). *Free CAD Designs, Files & 3D Models | The GrabCAD Community Library* [CAD database]. Arduino Nano ESP32 3D Model/CAD. https://grabcad.com/library/arduino-nano-esp32-3d-model-cad-1

Frazee, G. (2019, September 23). *4 reasons it's hard to become a sustainable business*. PBS NewsHour. https://www.pbs.org/newshour/economy/making-sense/4-reasons-its-hard-to-become-a-sustainable-business

Gao, G., Xu, F., Xu, J., & Liu, Z. (2022). Study of Material Color Influences on Mechanical Characteristics of Fused Deposition Modeling Parts. *Materials*, *15*(19), 7039. https://doi.org/10.3390/ma15197039

Gaweł, A., Kuciel, S., Liber-Kneć, A., & Mierzwiński, D. (2023). Examination of Low-Cyclic Fatigue Tests and Poisson's Ratio Depending on the Different Infill Density of Polylactide (PLA) Produced by the Fused Deposition Modeling Method. *Polymers*, *15*(7), 1651. https://doi.org/10.3390/polym15071651

Germane, C. (2023, November 14). *Why Are Nitrogen, Phosphorus, and Potassium in Plant Fertilizer?* Better Homes & Gardens. https://www.bhg.com/gardening/yard/garden-care/what-do-nitrogen-phosphorus-and-potassium-do/

Greentumble. (2016, May 2). *Unsustainable Agriculture Techniques | Greentumble*. https://greentumble.com/unsustainable-agriculture-techniques

Greentumble. (2018, May 21). *Pros and Cons of GMOs | Greentumble*. https://greentumble.com/pros-and-cons-of-gmos

Greentumble. (2023, December 14). *Damaging Consequences of Agricultural Runoff | Greentumble*. https://greentumble.com/damaging-consequences-of-agricultural-runoff

Huber. (2021, November 1). *Report: Fertilizer responsible for more than 20 percent of total agricultural emissions*. Food and Environment Reporting Network. https://thefern.org/ag_insider/report-fertilizer-responsible-for-more-than-20-percent-of-total-agricultural-emissions/

Israel | Agriculture & Rural Development | World Bank Development Indicators. (2020, October 28). Trading Economics. https://tradingeconomics.com/israel/indicators-wb-data.html?g=agriculture%2B%26%2Brural%2Bdevelopment

John Hill, McCreary, T., Duerst, M., & Reuter, R. (2019). Growing Food with Fertilizers. In *Hill's Chemistry for Changing Times (Hill and McCreary): Vol. 19.1* (15th ed.). https://chem.libretexts.org/Bookshelves/Introductory_Chemistry/Chemistry_for_Changing_Times_(Hill_and_McCreary)/20%3A_Chemistry_Down_on_the_Farm/20.01%3A_Farming_and_Chemicals-_Fertilizers

Jordan, J. (2023, October 12). PETG vs PLA+: Which Material is Stronger for 3D Printing? *Medium*. https://medium.com/@sunludfilament/petg-vs-pla-which-material-is-stronger-for-3d-printing-3b8dc7a3d60e

Joseph, C., Thirunavuakkarasu, I., Bhaskar, A., & Penujuru, A. (2017). Automated fertigation system for efficient utilization of fertilizer and water. *2017 9th International Conference on Information Technology and Electrical Engineering (ICITEE)*, 1–6. https://doi.org/10.1109/ICITEED.2017.8250474

Kamprad, D. (2021, April 3). *Sustainable vs Unsustainable: What's the Difference? | Impactful Ninja*. Impactful Ninja. https://impactful.ninja/sustainable-vs-unsustainable-differences/

Keena, M., & Meehan, M. (2017, October 31). *Environmental Implications of Excess Fertilizer and Manure on Water Quality | NDSU Agriculture*. https://www.ndsu.edu/agriculture/extension/publications/environmental-implications-excess-fertilizer-and-manure-water-quality

Khosropanah, B. (2016, July 1). *Phosphite containing fertilizers &seed primers on exposure to fire will produce phosphine gas which is deadly poison*. https://www.linkedin.com/pulse/phosphite-containing-fertilizers-seed-primers-fire-gas-khosropanah

Kočí, J. (2019, December 6). *How to improve your 3D prints with annealing*. Original Prusa 3D Printers. https://blog.prusa3d.com/how-to-improve-your-3d-prints-with-annealing_31088/

Korpinen, S., & Bonsdorff, E. (2015). Eutrophication and hypoxia: impacts of nutrient and organic enrichment. In C. L. J. Frid & T. P. Crowe (Eds.), *Marine Ecosystems: Human Impacts on Biodiversity, Functioning and Services* (pp. 202–243). Cambridge University Press. https://doi.org/10.1017/CBO9781139794763.008

Krevh, V., & Dvorski, T. (n.d.). *Determining soil moisture*. Retrieved February 1, 2024, from https://pinova-meteo.com/en_UK/blog/determining-soil-moisture#:~:text=2.-,Gravimetric%20method,recommended%20mostly%20for%20experimental%20work.

Leeper, K. (2022, February 15). *The Differences Between Phosphates and Phosphites*. Heritage Professional Products Group. https://heritageppg.com/blogs/pest-control-blog/the-differences-between-phosphates-and-phosphites

Leffer, L. (2021, April 27). *Why aren't more US farmers using sustainable practices?* Scienceline. https://scienceline.org/2021/04/why-arent-more-us-farmers-using-sustainable-practices/

Lewu, F. B., Volova, T., Thomas, S., & K. R., R. (Eds.). (2020). *Controlled Release Fertilizers for Sustainable Agriculture Book* (1st edition). Academic Press. https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/organic-fertilizer#:~:text=An%20organic%20fertilizer%20is%20a,poultry%20droppings%20and%20domestic%20sewage.

Lindwall, C. (2022, July 21). *Industrial Agricultural Pollution 101*. https://www.nrdc.org/stories/industrial-agricultural-pollution-101

MatterHackers. (2023, June 9). *How To Succeed When 3D Printing With ASA Filament*. MatterHackers. https://www.matterhackers.com/articles/how-to-succeed-when-3d-printing-with-asa-filament

MatWeb, LLC. (2024). *MatWeb - The Online Materials Information Resource*. https://www.matweb.com/errorUser.aspx?msgid=2&ckck=nocheck

Mérida García, A., Gallagher, J., McNabola, A., Camacho Poyato, E., Montesinos Barrios, P., & Rodríguez Díaz, J. A. (2019). Comparing the environmental and economic impacts of on- or off-grid solar photovoltaics with traditional energy sources for rural irrigation systems. *Renewable Energy*, *140*, 895–904. https://doi.org/10.1016/j.renene.2019.03.122

Moridani, M. J., Sadeghi, S. M., Roshan, N. M., Ashouri, M., & Doroudian, H. R. (2023). Effects of Organic and Chemical Fertilizers on Yield and Yield Components of Rice in Different Moisture Stress Conditions. *Gesunde Pflanzen*, *75*(5), 1799–1811. https://doi.org/10.1007/s10343-022-00763-7

NESS FERTIGATION – Absorb fertilizers better. (2023, October 14). NESS FERTIGATION. https://nessfertigation.com/

Nunn, S. (2018, February 5). U.S. Farmers Are Producing Too Much Food. Here's Why They Can't Stop. *Wall Street Journal*. https://www.wsj.com/articles/u-s-farmers-are-producing-too-much-food-heres-why-they-cant-stop-1517842730

Omo-Okoro, P. N., & Pillay, K. (2023). *Phosphorus Fertilizers - an overview | ScienceDirect Topics*. https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/phosphorus-fertilizers

Ongley, E. (1996). Chapter 3: Fertilizers as water pollutants. In *Control of Water Pollution from Agriculture - FAO Irrigation and Drainage Paper 55*. Food and Agriculture Organization of the United Nations Rome. https://www.fao.org/3/w2598e/w2598e06.htm

Orellana Barrasa, J., Ferrández-Montero, A., Ferrari, B., & Pastor, J. Y. (2021). Characterisation and Modelling of PLA Filaments and Evolution with Time. *Polymers*, *13*(17), 2899. https://doi.org/10.3390/polym13172899

Organic Farming and Sustainability. (2023, June 9). Kibbutz Neot Semadar. https://neot-semadar.com/en/organic-farming/

Organic Farming and Sustainability - Kibbutz Neot Semadar. (2023). *Kibbutz Neot Semadar*. https://neot-semadar.com/en/school/about-2__trashed/organic-farming/

Organic vs Conventional. (2019, May 7). Rodale Institute. https://rodaleinstitute.org/why-organic/organic-basics/organic-vs-conventional/

Overview of materials for Acrylonitrile/Styrene/Acrylate (ASA), Unreinforced, Molded. (n.d.). [Materials Database]. MatWeb. Retrieved February 22, 2024, from https://www.matweb.com/search/datasheet.aspx?matguid=24c5655bc30e42c3949df6c53122bd61&ckck=1

Overview of materials for Polylactic Acid (PLA) Biopolymer. (n.d.). [Materials Database]. MatWeb. Retrieved February 22, 2024, from https://www.matweb.com/search/DataSheet.aspx?MatGUID=ab96a4c0655c4018a8785ac4031b9278&ckck=1

Pastakia, C. M. R., & Jensen, A. (1998). The rapid impact assessment matrix (Riam) For eia. *Environmental Impact Assessment Review*, *18*(5), 461–482. https://doi.org/10.1016/S0195-9255(98)00018-3

Pepin, I. (2022, August 30). *What is sustainable agriculture and why is it important?* The Humane League. https://thehumaneleague.org/article/what-is-sustainable-agriculture-and-why-is-it-important

Phosphine: Lung Damaging Agent | NIOSH | CDC. (2023, May 23). https://www.cdc.gov/niosh/ershdb/emergencyresponsecard_29750035.html

PLA Filament Ultimate Printing Guide. (2020, September 2). STANDARD PRINT CO. https://standardprintco.com/read/pla-filament-printing-guide-how-to-succeed-printing-pla-and-troubleshooting-common-problems-step-by-step

Polygenis, T. (2023, October 31). *PLA vs PLA+: A Comprehensive Comparison*. https://www.wevolver.com/article/pla-vs-pla-what-are-the-differences-and-which-fdm-filament-should-you-buy

Polylactic Acid (PLA, Polylactide). (n.d.). Retrieved February 22, 2024, from https://www.makeitfrom.com/material-properties/Polylactic-Acid-PLA-Polylactide

Prasad, K. (2021, September 1). *Sustainable agriculture practices Vs Organic practices*. https://www.cropin.com/blogs/sustainable-agricultural-practices-vs-organic-practices

Protolabs. (2024). *Glass Transition Temperature (Tg) of Polymers*. https://www.protolabs.com/resources/design-tips/glass-transition-temperature-of-polymers/

Ranga.nr. (2023, June 11). Conventional farming: Methods and facts. Farm Practi. (n.d.).

Rashid, M. (2018, September 5). *The main consequences of non-sustainable farming*. Challenge Advisory. https://www.challenge.org/knowledgeitems/the-main-consequences-of-non-sustainable-farming/

Ritchie, H., Rosado, P., & Roser, M. (2024). Emissions by sector: where do greenhouse gases come from? *Our World in Data*. https://ourworldindata.org/emissions-by-sector

Runoff. (2023, October 19). National Geographic. https://education.nationalgeographic.org/resource/runoff

Salih, J. E. M., Adom, A. H., & Shaakaf, A. Y. Md. (2012). Solar Powered Automated Fertigation Control System for Cucumis Melo L. Cultivation in Green House. *APCBEE Procedia*, *4*, 79–87. https://doi.org/10.1016/j.apcbee.2012.11.014

Sealing & Shielding Team. (2017, June 7). *Racetrack Grooves: Can O-Rings be used in Non-Circular Groove Patterns?* Parker. https://blog.parker.com/site/usa/en-US/details-home-page/racetrack-grooves-can-o-rings-be-used-in-non-circular-groove-patterns-us

Semuels, A. (2019, November 27). *"They're Trying to Wipe Us Off the Map." Why Independent Farming in America Is Close to Extinction*. TIME. https://time.com/5736789/small-american-farmers-debt-crisis-extinction/

Smart Motor Devices. (2020). *PLA+ filament 750g - 3D printer material*. https://3dlaboratorio.es/eng/plastic-pla.htm#:~:text=Plastic%20PLA%2B%20is%20an%20environmental,printing%2C%20along%20with%20ABS%20plastic.

Smart Prototyping. (n.d.). *Dual H-Bridge Motor Driver L298N*. Smart Prototyping. Retrieved February 20, 2024, from https://www.smart-prototyping.com/L298N-Dual-H-bridge-Motor-Driver-Board

Subramaniam, S. R., Samykano, M., Selvamani, S. K., Ngui, W. K., Kadirgama, K., Sudhakar, K., & Idris, M. S. (2019). Preliminary investigations of polylactic acid (PLA) properties. *AIP Publishing*, *2059*(1). https://doi.org/https://doi.org/10.1063/1.5085981

Suder, J., Bobovsky, Zdenko, Safar, M., Mlotek, J., Vocetka, M., & Zeman, Z. (2023). EXPERIMENTAL ANALYSIS OF TEMPERATURE RESISTANCE OF 3D PRINTED PLA COMPONENTS. *MM Science Journal*. https://doi.org/10.17973/MMSJ.2021_03_2021004

Sunshine & Daylight Hours in Eilat, Israel Sunlight, Cloud & Day length. (2024). https://www.climate.top/israel/eilat/sunlight/

Sunshine duration and clouds | Copernicus. (2020, April 26). The Copernicus Climate Change Service (C3S). https://climate.copernicus.eu/ESOTC/2019/sunshine-duration-and-clouds#:~:text=The%20average%20value%20for%20Europe,over%20almost%20all%20of%20Europe.

T., A. (2013, March 23). *Free CAD Designs, Files & 3D Models | The GrabCAD Community Library* [CAD database]. Mini Breadboard. https://grabcad.com/library/mini-breadboard--1

The World Bank. (2022, October 5). *Water in Agriculture* [Text/HTML]. World Bank. https://www.worldbank.org/en/topic/water-in-agriculture

Tiseo, I. (2023, December 18). *Agriculture Emissions Worldwide - Statistics and Facts*. Statista. https://www.statista.com/topics/10348/agriculture-emissions-worldwide/

Trafton, A. (2020, May 4). *Technique could enable cheaper fertilizer production*. MIT News | Massachusetts Institute of Technology. https://news.mit.edu/2020/cheaper-fertilizer-production-0504

Tremblay, S. (2021, September 20). *How Does Fertilizer Affect Aquatic Ecosystems?* Sciencing. https://sciencing.com/how-does-fertilizer-affect-aquatic-ecosystems-13425670.html

Trofimov, A., Wang, H., Hassen, A., Tekinalp, H., Kunc, V., Kim, P., & Ozcan, S. (2020). *CHARACTERIZATION ON ANISOTROPIC THERMAL CONDUCTIVITY FOR BIG AREA ADDITIVE MANUFACTURING WITH POLYMERS*. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States). https://www.osti.gov/biblio/1818748

Tsadilas, C. (2021). *Nitrate Handbook: Environmental, Agricultural, and Health Effects* (1st ed.). CRC Press. https://doi.org/10.1201/9780429326806

Tyson, M. (2019, October 23). *Advanced guide to printing ASA Filament*. 3D Printing Solutions. https://www.3dprintingsolutions.com.au/User-Guides/how-to-3d-print-asa-filament

Ultimate 3D Printing Material Properties Table. (n.d.-a). Filament Properties Table. Retrieved February 22, 2024, from https://www.simplify3d.com/resources/materials-guide/properties-table/

Ultimate 3D Printing Material Properties Table. (n.d.-b). Filament Properties Table. Retrieved February 22, 2024, from https://www.simplify3d.com/resources/materials-guide/properties-table/

University of Massachusetts Amherst. (2021, November 19). *Agricultural runoff contributes to global warming - New study helps us figure out how and what we can do about it*. ScienceDaily. https://www.sciencedaily.com/releases/2021/10/211019110540.htm

Unsustainable Agriculture - Community Environmental Legal Defense Fund. (2021, September 26). Community Environmental Legal Defense Fund (CELDF). https://celdf.org/unsustainable-agriculture/

USDA Coexistance Fact Sheets: Conventional Farming. (2015). United States Department of Agriculture (USDA). coexistence-conventional-farming-factsheet.pdf.

Ventura, C. (2023, May 15). *All You Need to Know About ASA for 3D printing*. 3Dnatives. https://www.3dnatives.com/en/asa-3d-printing-170820204/

Vidal, J. (2021, October 18). Factory farms of disease: how industrial chicken production is breeding the next pandemic. *The Guardian*. https://www.theguardian.com/environment/2021/oct/18/factory-farms-of-disease-how-industrial-chicken-production-is-breeding-the-next-pandemic

Wang, Z., Zhang, Z., Li, J., & Li, Y. (2022). Field evaluation of fertigation performance for a drip irrigation system with different lateral layouts under low operation pressures. *Irrigation Science*, *40*(2), 191–201. https://doi.org/10.1007/s00271-021-00760-0

Water Science School. (2018, June 6). *Contamination of Groundwater | U.S. Geological Survey*. United States Geological Survey. https://www.usgs.gov/special-topics/water-science-school/science/contamination-groundwater

World Wildlife Fund. (2023). Impact of sustainable agriculture and farming prac. (n.d.).

Worlddata. (2024, January). *That’s how warm it is in Israel: 26.7 °C on average per year and over 3150 hours of sunshine!* Worlddata.Info. https://www.worlddata.info/asia/israel/climate.php

Appendices

Appendix A

Environmental Assessment Appendix

Table 1: Improved NESS Fertigation Prototype Performance Assessment

Type	Affect	ES	RB	A1	A2	B1	B2	B3
PC1	Chemical Fertilizer Application	24	+C	2	2	2	2	2
PC2	Amount of Energy Consumed by System	18	+B	1	3	2	2	2
PC3	Efficiency of Water Use	63	+D	3	3	2	2	3
PC4	Plastic Use	14	+B	2	1	3	3	1
BE1	Effects of Chemical Fertilizer Application	72	+E	3	3	3	2	3
BE2	Effects of System’s Energy Source	54	+D	3	2	3	3	3
BE3	Effects of Water Usage	54	+D	2	3	3	3	3
BE4	Yield Efficiency	24	+C	2	2	2	2	2
SC1	Ease of Education for Operating Machine	14	+B	1	2	3	3	1
SC2	Ease of Introduction into Other Systems	14	+B	1	2	3	3	1
SC3	Self Sufficiency	18	+B	1	3	3	2	1
EO1	Ease of Assembly	10	+B	1	2	3	1	1
EO2	Transportation	20	+C	2	2	3	1	1
EO3	Scalability of the System	28	+C	2	2	3	3	1
EO4	Cost of System	7	+A	1	1	3	3	1
EO5	Versatility of Site Locations	42	+D	2	3	3	3	1

Table 2: Current NESS Fertigation Prototype Performance Assessment

Type	Affect	ES	RB	A1	A2	B1	B2	B3
PC1	Chemical Fertilizer Application	24	+C	2	2	2	2	2
PC2	Amount of Energy Consumed by System	18	+B	1	3	2	2	2
PC3	Efficiency of Water Use	42	+D	3	2	2	2	3
PC4	Plastic Use	-28	-C	2	-2	3	3	1
BE1	Effects of Chemical Fertilizer Application	72	+E	3	2	3	2	3
BE2	Effects of System's Energy Source	54	+D	3	2	3	3	3
BE3	Effects of Water Usage	54	+D	2	3	3	3	3
BE4	Yield Efficiency	24	+C	2	2	2	2	2
SC1	Ease of Education for Operating Machine	0	N	1	0	3	3	1
SC2	Ease of Introduction into Other Systems	14	+B	1	2	3	3	1
SC3	Self Sufficiency	12	+B	1	1	3	2	1
EO1	Ease of Assembly	0	N	1	0	3	1	1
EO2	Transportation	-20	-C	2	-2	3	1	1
EO3	Scalability of the System	-28	-C	2	-2	3	3	1
EO4	Cost of System	14	+B	1	2	3	3	1
EO5	Versatility of Site Locations	28	+C	2	2	3	3	1

Table 3: Manipal University’s Automated Fertigation Prototype Assessment

Type	Affect	ES	RB	A1	A2	B1	B2	B3
PC1	Chemical Fertilizer Application	24	+C	2	2	2	2	2
PC2	Amount of Energy Consumed by System	0	N	1	0	2	2	2
PC3	Efficiency of Water Use	0	N	3	0	2	2	3
PC4	Plastic Use	-28	-C	2	-2	3	3	1
BE1	Effects of Chemical Fertilizer Application	0	N	3	0	3	2	3
BE2	Effects of System’s Energy Source	-27	-C	3	-1	3	3	3
BE3	Effects of Water Usage	18	+B	2	1	3	3	3
BE4	Yield Efficiency	0	N	2	0	2	2	2
SC1	Ease of Education for Operating Machine	-7	-A	1	-1	3	3	1
SC2	Ease of Introduction into Other Systems	0	N	1	0	3	3	1
SC3	Self Sufficiency	18	+B	1	2	3	2	1
EO1	Ease of Assembly	5	+A	1	1	3	1	1
EO2	Transportation	-10	-B	2	-1	3	1	1
EO3	Scalability of the System	-14	-B	2	-1	3	3	1
EO4	Cost of System	0	N	1	0	3	3	1
EO5	Versatility of Site Locations	0	N	2	0	3	3	1

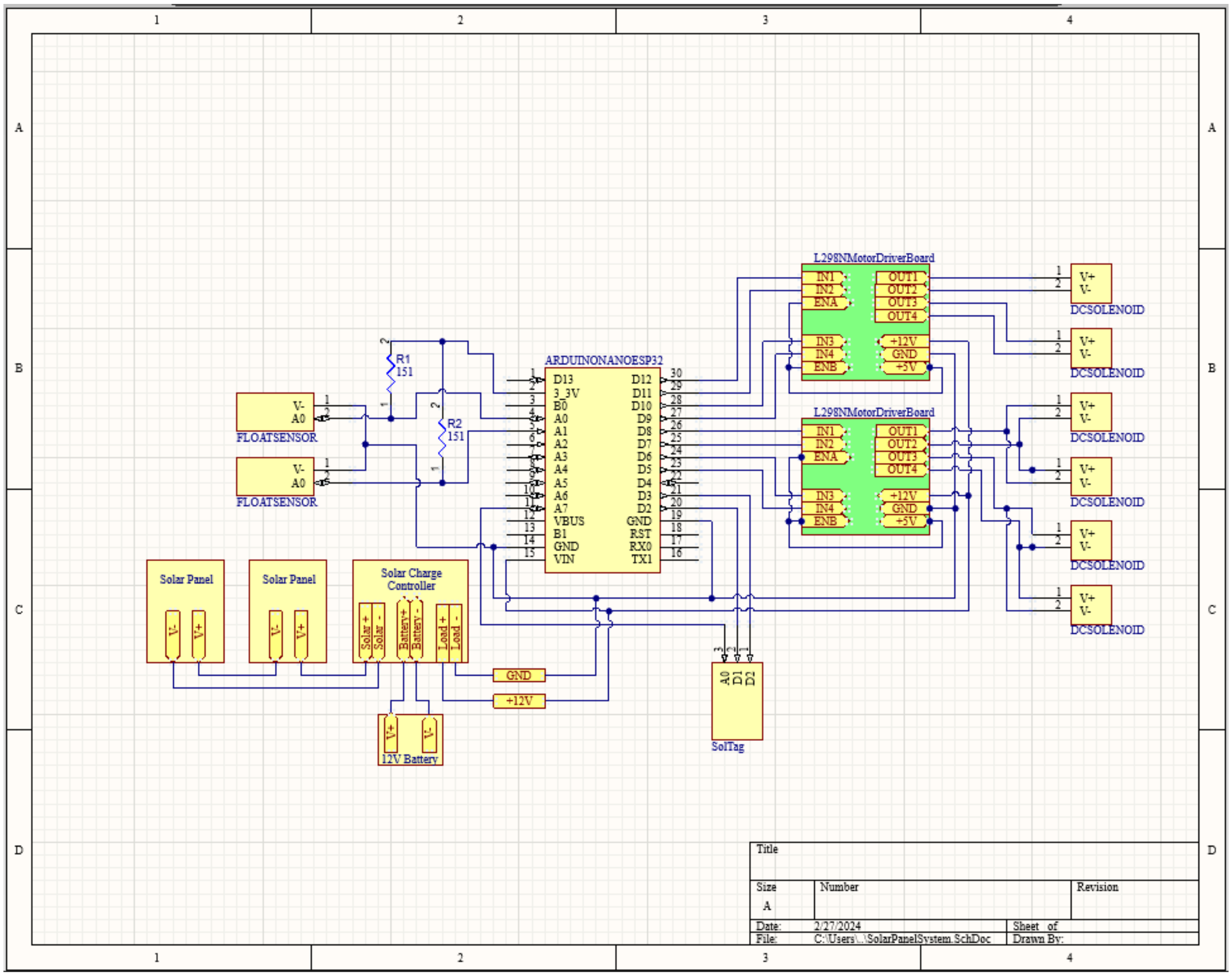
Table 4: FertiOne™ Plus by Netafim Performance Assessment

Type	Affect	ES	RB	A1	A2	B1	B2	B3
PC1	Chemical Fertilizer Application	-12	-B	2	-1	2	2	2
PC2	Amount of Energy Consumed by System	0	N	1	0	2	2	2
PC3	Efficiency of Water Use	21	+C	3	1	2	2	3
PC4	Plastic Use	42	+D	2	3	3	3	1
BE1	Effects of Chemical Fertilizer Application	-24	-C	3	-1	3	2	3
BE2	Effects of System's Energy Source	-27	-C	3	-1	3	3	3
BE3	Effects of Water Usage	-18	-B	2	-1	3	3	3
BE4	Yield Efficiency	24	+C	2	2	2	2	2
SC1	Ease of Education for Operating Machine	21	+C	1	3	3	3	1
SC2	Ease of Introduction into Other Systems	14	+B	1	2	3	3	1
SC3	Self Sufficiency	-6	-A	1	-1	3	2	1
EO1	Ease of Assembly	-5	-A	1	-1	3	1	1
EO2	Transportation	20	+C	2	2	3	1	1
EO3	Scalability of the System	42	+D	2	3	3	3	1
EO4	Cost of System	0	N	1	0	3	3	1
EO5	Versatility of Site Locations	0	N	2	0	3	3	1

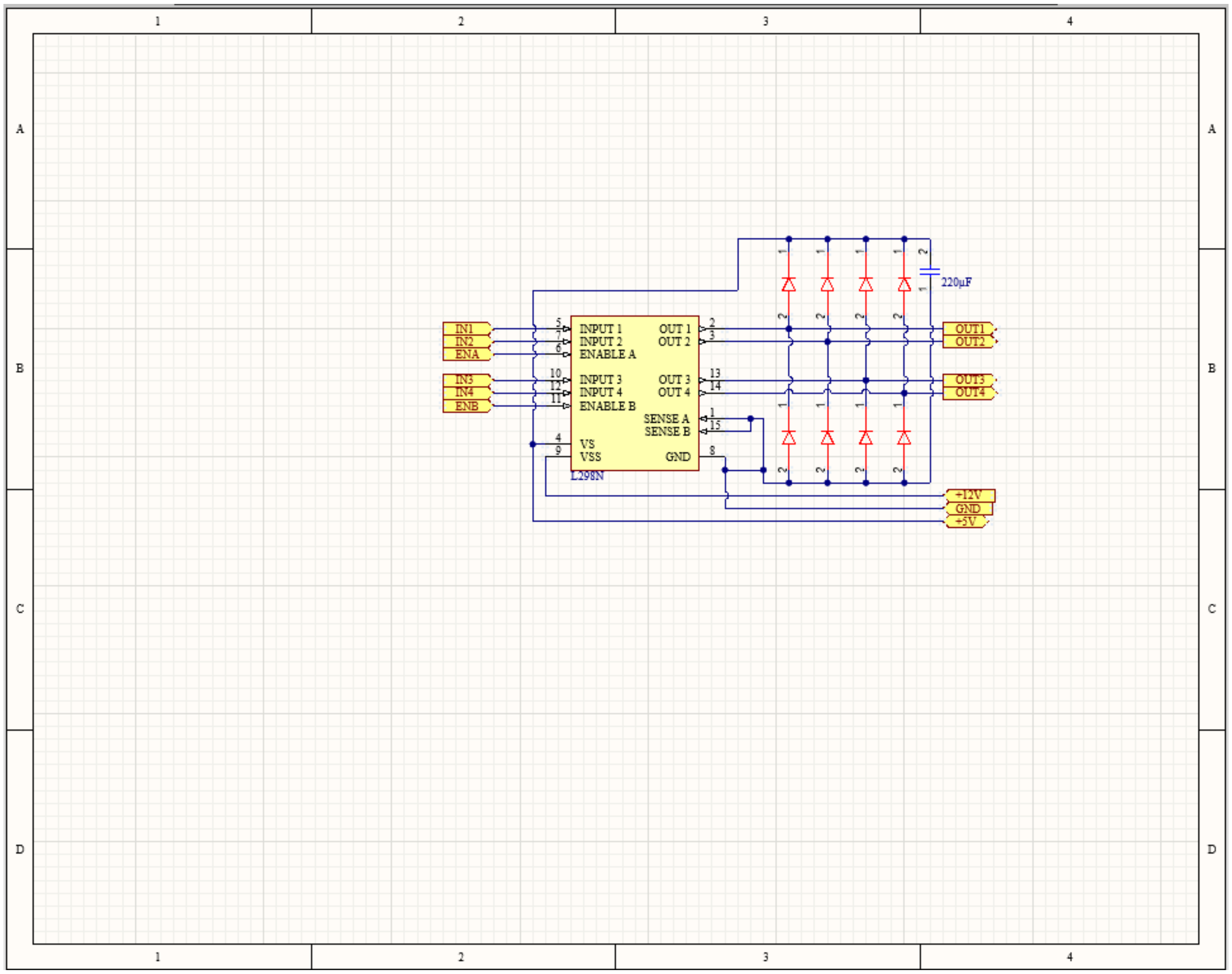
Appendix B

Design Appendix

Full Prototype Schematic



L298N DC Motor Driver Board Schematic



Microcontroller Housing Assembly Link:

[Fertilizer Mixing IQP- Microcontroller System Housing.zip]

Housing Mass Properties (PLA+):

Mass properties of housing3, assem (no components)

Configuration: Default

Coordinate system: -- default --

Mass = 596.29 grams

Volume = 480876.54 cubic millimeters

Surface area = 193253.68 square millimeters

Center of mass: (millimeters)

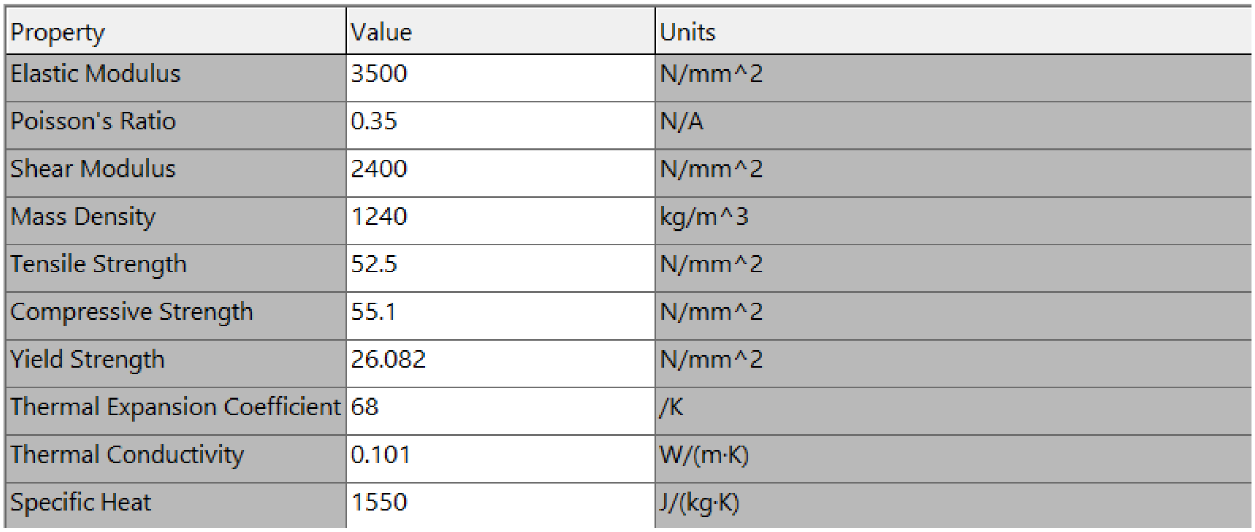
X = 0.00

Y = 21.91

Z = -0.22

PLA+ Material Properties used in Model

(*Ultimate 3D Printing Material Properties Table*, n.d.),(*Polylactic Acid (PLA, Polylactide)*, n.d.),(Trofimov et al., 2020),(*Overview of Materials for Polylactic Acid (PLA) Biopolymer*, n.d.),(Subramaniam et al., 2019),(Gao et al., 2022),(Jordan, 2023),(Orellana Barrasa et al., 2021),(Gaweł et al., 2023),(Bagheri et al., 2018)



Property	Value	Units
Elastic Modulus	3500	N/mm^2
Poisson's Ratio	0.35	N/A
Shear Modulus	2400	N/mm^2
Mass Density	1240	kg/m^3
Tensile Strength	52.5	N/mm^2
Compressive Strength	55.1	N/mm^2
Yield Strength	26.082	N/mm^2
Thermal Expansion Coefficient	68	/K
Thermal Conductivity	0.101	W/(m·K)
Specific Heat	1550	J/(kg·K)

Housing Mass Properties (ASA):

Mass properties of housing3, assem (no components)

Configuration: Default

Coordinate system: -- default --

Mass = 538.58 grams

Volume = 480876.54 cubic millimeters

Surface area = 193253.68 square millimeters

Center of mass: (millimeters)

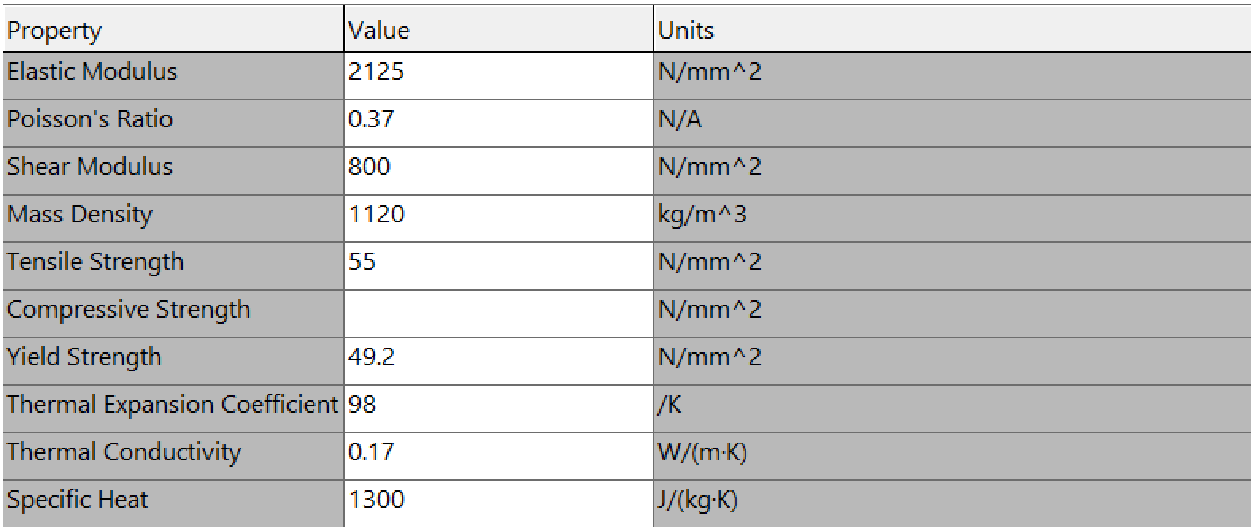
X = 0.00

Y = 21.91

Z = -0.22

ASA Material Properties used in Model

(*Ultimate 3D Printing Material Properties Table*, n.d.),(*Overview of Materials for Acrylonitrile/Styrene/Acrylate (ASA), Unreinforced, Molded*, n.d.),(Cahyadi, 2019)



Property	Value	Units
Elastic Modulus	2125	N/mm^2
Poisson's Ratio	0.37	N/A
Shear Modulus	800	N/mm^2
Mass Density	1120	kg/m^3
Tensile Strength	55	N/mm^2
Compressive Strength		N/mm^2
Yield Strength	49.2	N/mm^2
Thermal Expansion Coefficient	98	/K
Thermal Conductivity	0.17	W/(m·K)
Specific Heat	1300	J/(kg·K)

Housing Front and Side for Center of Mass location: