Revolutionizing Vertical Farming:

Tower Garden Commander

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Table of Contents

Executive Summary

Vertical hydroponic farming, or aeroponics, is the future of efficient, healthy agriculture, making it critical to address any problems currently facing this innovative new technology. The most significant aeroponic farming problem centers around the time and effort required to measure water health data, consisting of measuring the water's pH, EC, depth, and temperature for use in Tower Gardens, a popular vertical farming product with a bright future in the industry. The selected engineering solution is a wireless smart sensing device capable of measuring the four metrics for water health data and seamlessly connecting to the user's phone, displaying water health data in an integrated application while being designed to interface into existing Tower Garden products' operation and infrastructure. Successful implementation will make impactful waves in the agricultural industry by automating farming processes, significantly reducing time and labor, ranging from farms with 1,000+ Tower Gardens to single unit residential applications.

At the unit level, key challenges include selecting sensors that operate accurately without interference, waterproofing the electronics and preventing moisture buildup, and maintaining a cost-effective product for farmers. At the system level, challenges include managing large-scale data aggregation, optimizing wireless communication across hundreds of units, and integrating variable-interval monitoring with local/cloud storage.

The design process includes sensor selection, packaging design, PCB fabrication, firmware programming, application integration, and manufacturability analysis. This is guided by conceptual design tools such as a HOQ, function tree, morphological chart, prototyping, and testing. Key performance specifications include accurate sensor measurements, automated wireless data collection, user-friendliness, and affordability. Initial research through the design process and ideation yields the selected design concept to be Concept Beta which optimally matches the client's requirements, boasting high-performing functionality especially for highly desired specifications. The manufacturing and testing of the first prototype of Concept Beta proves functionality in its water-tight packaging, accurate sensor readings, and quick on-demand data visibility. The initial prototype helped identify successes and improvement areas, giving insight into future actions and next prototype designs. A successful proof of concept final prototype is created, demonstrating a design that meets nearly all customer requirements.

Nomenclature and Glossary

1.1 Aeroponic Farming – method of growing plants suspended in the air (rather than soil) by raining, and recycling, nutrient-rich water over the suspended roots.
1.2 Tower Garden – Company that manufactures vertical gardens and accompanying products, main product is called a Tower Garden, with a variety of models.
1.3 pH – potential of Hydrogen: The quantitative measure of the acidity or basicity of aqueous or other liquid solutions, logarithmic unit on a scale from 0-14 with 7 being neutral (water).
1.4 EC – Electrical Conductivity: The measure of a material's ability to conduct electric current, units of microSiemens per centimeter [μ S/cm]
1.5 Temperature – units of degrees Fahrenheit [F] or degrees Celcius [C] depending on user-specified preference
1.6 Water health – defined as the pH, EC, temperature, and water level within the Tower Garden's basin, reflecting important metrics into the nutrient concentration and quality of the water.
1.7 GUI – Graphical User Interface: A system of interactive visual components for a computer or system software.
1.8 PCB – Printed Circuit Board: A structure for assembling electronic components and their connections into a unified circuit that allows electrical current to pass between components.
1.9 Cost for Consumer: The overall cost of the product to the consumer. This includes the cost of sensors, electronics, wiring, manufacturing and assembly, as well as ~20% margin for the company.
1.10 Lead-time: The amount of time it takes to manufacture the product.
1.11 Assembly-time: The amount of time it takes to assemble the product and make it consumer-ready. This includes assembling individual components as well as integrating hardware and software.

1. Introduction and Background

Tower Garden provides both industrial farmers and homeowners with a convenient way to grow fresh produce using an aeroponic gardening system. The Tower Garden product can grow an assortment of plants three times faster with 98% less water usage than traditional farming methods [1]. The regulation of the tower's water health is essential to produce healthy, thriving harvests, ensuring a balanced mixture of nutrient solution and water is maintained during operation when water is recycled by trickling down through the plants. While these towers effectively support plant growth autonomously, they require consistent manual monitoring to ensure ideal nutrient concentration and water health. Although monitoring a single tower may be manageable for individuals, farmers overseeing dozens or even hundreds of Tower Gardens face a time-consuming challenge in manually measuring pH, EC, water temperature, and water depth, which all make up metrics defining the water health of the system.

To address this challenge, the team is developing an advanced sensing unit that enables both farmers and individual users to monitor and manage their Tower Garden remotely via a mobile application. This unit will integrate multiple sensors to detect the pH, EC, temperature, and water depth. These sensors will provide immediate transparency on the water health data within the tower's basin, ensuring that the nutrient-rich water being pumped and recycled throughout the system remains optimal for plant growth. The device is connected within a network of other Tower Commanders within a facility to record and upload all Tower Garden data to a central application. The data is reported to the gardener at scheduled intervals or on-demand, and alerts will be provided for data points that indicate problems with the system. By automating the monitoring process, the device nearly eliminates the need for manual checks/maintenance, enhances efficiency, and promotes healthier, more consistent crop yields.

The product is designed with user experience and customization in mind, allowing farmers and individual consumers to easily understand and tailor their monitoring experience to best suit their needs. Through the mobile application, users can set preferences for the frequency of updates they receive throughout the day, the precision of threshold alerts, and overall parameters that define their ideal Tower Garden operation. The sensing unit operates accordingly, providing immediate updates at the user's chosen intervals, and sends notifications when critical parameters, such as water depth or pH levels, do not meet the farmer's standards. Additionally, the application is designed to offer intelligent insights and recommendations to assist users in maintaining optimal growing conditions. This proactive approach not only minimizes the risk of plant health issues but also streamlines the farming process, ensuring a more efficient and automated experience for both large-scale farmers and home growers alike.

To guarantee the successful and safe growth of produce, the device must adhere to strict safety standards and best practices. This includes maintaining clean water quality, implementing watertight seals to prevent leaks and water damage, ensuring proper ventilation to regulate system conditions, and preventing cross-contamination that could compromise plant health. An initial prototype is developed to evaluate current performance metrics through direct testing proving that the device is watertight, interfaces with the tower garden, and wirelessly sends water health data at the user’s discretion.

Throughout the remainder of this document, the ideation, development, and critical considerations involved in creating this innovative sensing unit will be outlined. This includes an in-depth look at design choices, technological implementations, and the steps taken to meet industry standards while enhancing efficiency and usability for all growers.

2. Existing Products, Prior Art, and Applicable Patents

Commercially, this Tower Commander device is designed to integrate specifically into the existing Tower Garden infrastructure to solve one of the Tower Garden farmers’ most frustrating problems: the significant manual labor commitment that is required to monitor the Towers frequently enough to produce maximally healthy crops. However, water sensing and monitoring technology has the untapped potential to benefit consumers in a diverse set of applications. Pools, aquariums, and agricultural research may all utilize the Tower Commander’s functions to advance user knowledge of water diagnostics. Through creative design of the device enclosure, this Tower Commander product can serve Tower Gardens while also competitively impacting other markets with water sensing requirements.

It is critical that the team understand how the Tower Commander will fit into the commercial market space, both technically and legally. One patent, KR101819416B1, resembles a function that the team is working towards developing. The patent specifically protects the idea of “an intelligent water quality measuring apparatus equipped with a self-diagnosis function for each water quality measuring” [2]. The focus of the patent is on the self-diagnosis of accuracy shortcomings for the sensors, which is an ability that the Tower Commander could implement for enhanced functionality but is not required. The patent also covers that the device cannot "generate an alarm for calibrating the sensor or requesting replacement of the sensor." This directly interferes with the Tower Commander's required function to indicate to users when the sensors may need replacement or recalibration. A second patent, KR101135697B1, more generally claims having "water quality measuring instruments, and more particularly, having a plurality of sensors in one tank, so that various characteristics of the water quality can be measured in one water tank to minimize the size of the water quality measuring instrument" [3]. The patent additionally refers to ultrasonic cleaning of the sensors and sensor self-diagnosis resembling the first patent's coverage. This patent potentially limits the teams' placement of sensors which constrains potential design ideas.

In addition to these patents, similar products exist on the market mirroring several desired functions of the Tower Commander. Two examples of such products are a pool water monitor by Qivine and a manual hydroponic measuring device by AC Infinity, shown in the figures 1-2 below.

Figure 1: Qivine Pool Sensing Device [4]

Figure 2: AC Infinity Hydroponic Meter Kit [5]

Figure 1 showcases a $53.69 automated, floating pool thermometer that senses the pool water's pH, EC, and temperature by Qivine. This device also uploads the recorded data to a compatible mobile app via Wi-Fi connection. It is specifically designed for floating applications such as a pool, hot tub, spa, or aquarium. Figure 2 presents a hydroponic meter pro kit gardening application that the sponsor's desired design problem covers; however, it requires manual operation to record the pH, EC, and water temperature data. This $149 product is reasonably representative of what the largest Tower Garden farms currently utilize for their water health measurements. The device's sensor probe is highly accurate and interchangeable. An important addition to these design references is the sponsor's own initial prototype, shown in Figure 3.

Figure 3: Sponsor's Prototype

The sponsor for this project desires the team to innovate upon his prototype, named Tower Commander Alpha, to specifically fix issues of unstable connectivity, sensing errors, water ingress, and battery life. Similar products' solutions for these problems are crucial to reinventing the prototype.

Analyzing these patents and products significantly impacts decision-making and ideation stages of the design process. The patents constrain the possible solution since they cover some of the intelligence and physical water-sensing features, such as sensor self-diagnosis and placement that the Tower Commander product needs to have. The products found on Amazon both constrain and inspire the solution by providing product designs that offer solutions to similar problems such as automated water sensing in pools and hot tubs or manual sensing of hydroponic garden reservoirs. While the former is not designed to fit a Tower Garden, it is possible that a Tower Garden consumer has purchased one of these or other similar products and outfitted it to their Tower Garden in the past.

Considering this, addressing issues specific to the context of the project sponsor's work that still cannot be confronted by existing products, such as product size/shape compatibility with Tower Garden Architecture, extended battery life/alternate powering solutions, and network communication for multiple connected devices are emphasized as differentiating factors for the prototype. Additionally, innovations that further enrich the product design and make it competitive with the existing products are implemented to rise above the current art. The hydroponic meter kit's accuracy and ratings to establish a target quality can be drawn upon, but automated operation, transferring and uploading data, and lower total cost must be achieved in prototype to make it a viable product. On the other hand, the pool sensing device can provide inspiration for an inexpensive sensor which can link with mobile devices but is missing crucial functionality including water depth data, integration with the Tower Garden's infrastructure, and ability to collect data from hundreds of devices at once. These observations help directly shape the product specifications, functions, and design choices that are crucial to design an effective prototype.

3. Codes and Standards

To ensure safe operation and healthy produce, the device must comply with key regulatory standards preventing contamination, maintaining water quality, and upholding food safety.

The FDA Food Code (21 CFR Part 110) - Current Good Manufacturing Practice (CGMP) [6] mandates that all equipment in food production environments, including the sensors and enclosures, be hygienic and non-toxic. As a result, the design uses food-safe materials resistant to microbial growth and degradation. Similarly, NSF/ANSI 61 - Drinking Water System Components - Health Effects [7] ensures that submerged materials do not leach harmful substances into the water supply, maintaining water purity.

To protect against environmental exposure, the IEC 60529 - Degrees of Protection Provided by Enclosures (IP Code) [8] requires the device to meet an IP68 rating, ensuring it remains fully functional and watertight during continuous submersion. Additionally, the ISO 22000 - Food Safety Management Systems standard [9] ensures the design maintains watertight integrity to prevent contamination. These watertight standards will be tested rigorously in preparation for the design and implementation of the final prototype.

Our system must also comply with Hazard Analysis and Critical Control Points (HACCP) [10] to prevent contamination risks in food production. All sensors and enclosures will be validated for hygiene and safe operation. The 3-A Sanitary Standards for Equipment [11] further ensure that the device is easy to clean, minimizes bacterial buildup, and prevents cross-contamination. These standards are most prevalent in the prototyping process during the sensor and material selection stage. While the first prototype bypassed some material and food safety considerations in pursuit of an efficient and effective design, testing, and improvement process, these compliances will be prioritized in the final prototype and deliverable to the project sponsor.

Lastly, the EPA Clean Water Act (CWA) - Water Discharge Standards [12] ensures that any water discharged from the system meets environmental safety regulations, preventing contamination of local water bodies.

By adhering to these standards, the final product will be food-safe, environmentally responsible, and user-friendly, ensuring optimal operation for both commercial and residential customers.

4. Customer Requirements and Engineering Design Specifications

The key stakeholders in this project include Clint Crowe (Sweetwater Farms), the Tower Gardens Company, and various Tower Garden clients. Clint Crowe, as the product sponsor, holds the highest influence (10) and plays a critical role in supporting and driving the project's success. The Tower Gardens Company, which supplies and manufactures tower farms, is another major stakeholder with significant importance (7) and moderate influence (5), as its support is crucial for scalability and market adoption. Large farms clients represent the biggest potential market and are highly important (6), though they have a lower influence (2). Mid-sized farm clients and residential farm customers, while also stakeholders, have relatively lower importance (4 and 2, respectively) and influence, as they contribute to expanding the product's reach but are not primary drivers of its adoption. The stakeholder matrix highlights the varying degrees of impact and influence each group has on the project's direction and success.

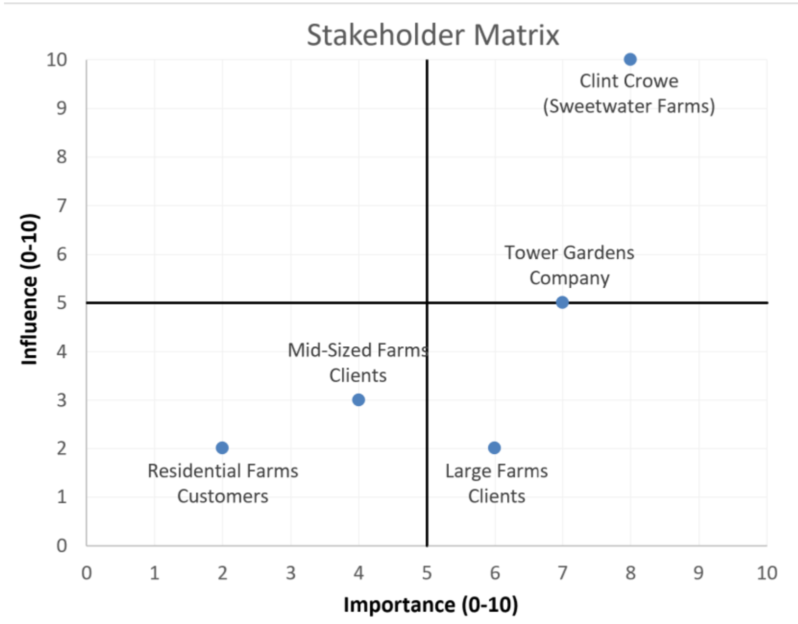


Figure 4: Stakeholder Matrix outlining the parties that have influence on, and give importance to, a Tower Garden Tower Commander product

The customer requirements for this project are categorized into *Demands* and *Wants* to distinguish essential features from desirable inclusions. Key demands include compatibility with existing Tower Gardens infrastructure, a rechargeable or replaceable battery, wireless data transmission, and replaceable sensors, particularly for pH measurements. The system must also be waterproof, affordable, user-friendly, safe, and CE-rated to ensure compliance with industry standards. Easy recalibration and troubleshooting are also crucial to ensure long-term usability. On the other hand, the wants focus on additional functionality such as CO_2, lighting, humidity, and air quality sensors, multiple daily data recordings, and highly accurate readings. While not essential, these features would enhance performance and user experience, making the system even more robust and efficient. A specification sheet, shown in Table 1, is utilized to specify the design functionality, accounting for each one of the customer requirements.

Table 1: Specification Sheet

No.	Date	Demand/ Want	**For:** Tower Commander & System **Specification**	**Issued:**	**Page:1**
			Requirements	**Respons.**	**Source**
1	2/1/25	D	Minimum Connected Devices (System), 40	Siddharth Singh	Sweetwater Farms
2	2/1/25	D	Retail Price, $99 (Homeowners); <$99 (Farmers)	Kyle Ralyea	Sweetwater Farms
3	2/1/25	W	Compatible with existing GUI	Viraj Pahwa	Sweetwater Farms & Sproutify
4	2/1/25	D	Compatible with Tower Garden Reservoir Cap	Kyle Ralyea	Sweetwater Farms
5	2/1/25	W	Sensor Precision Below 2% of Maximum Reading	Ben Starkey	Team
6	2/1/25	W	5 Minute Setup Time	Siddharth Singh	Sweetwater Farms & Sproutify
7	2/1/25	W	Sized Within 5x8x12 inches	Brody Oliver	Tower Farm Design
8	2/1/25	D	Sensors record to a depth within 3 inches of empty	Brody Oliver	Tower Farm Design
9	2/1/25	D	FDA Approved Materials	Brody Olver	Standards & Codes (discussed previously)
Electrical					
10	2/1/25	W	Time to full charge, 4 hours	Rachel Ha	Tower Commande r (Alpha) Setup Guide
11	2/1/25	W	Holds charge for minimum 30 days	Rachel Ha	TC_errata
12	2/1/25	D	Frequency of Data Collection, every 10 mins	Siddharth Singh	Tower Commande r (Alpha) Setup Guide
13	2/1/25	W	Wireless Communication Between Devices	Rachel Ha	Sproutify

14	2/1/25	W	Re-calibration Protocol to Base Condition, <30s	Siddharth Singh	Sproutify
15	2/1/25	D	pH Sensor, 0-14	Viraj Pahwa	Tower Commander (Alpha) Setup Guide
16	2/1/25	D	EC Sensor, 0-75,000 u/cm	Viraj Pahwa	Seedgistics Tower Commander Overview
17	2/1/25	D	Water Depth Sensor, 0.25-1ft	Ben Starkey	Seedgistics Tower Commander Overview
18	2/1/25	D	Temperature Sensor, 50-120F	Ben Starkey	Seedgistics Tower Commander Overview
19	2/1/25	W	CO2 Sensor, 0-50,000 ppm	Viraj Pahwa	Sweetwater Farms
20	2/1/25	W	Lighting Sensor, 0-50,000 lux	Viraj Pahwa	Sweetwater Farms
21	2/1/25	W	Humidity Sensor, 0%-100% RH	Ben Starkey	Sweetwater Farms
22	2/1/25	W	Air Quality Sensor, 0-5,000 ppm	Ben Starkey	Sweetwater Farms
23	2/1/25	D	Max 1% Sensor Offset Drift	Viraj Pahwa	Sproutify
24	2/1/25	D	Water Tight, IP68 [8]	Brody Oliver	Tower Commander (Alpha) Setup Guide
25	2/1/25	D	Battery Temperature, 50-120F	Brody Oliver	Standards & Codes
26	2/1/25	W	Replaceable pH Sensor (< 1 min total per device)	Brody Oliver	Sweetwater Farms
27	2/1/25	W	Mass Manufacturable	Brody Oliver	Sweetwater Farms

These engineering requirements and corresponding engineering specifications are designed to specifically address all customer requirements, shown in the House of Quality (HOQ) in Figure 5.

The HOQ shows this relationship directly, with strong correlation markings shown down the diagonal, linking customer and engineering requirements together.

Category	Weight	Engineering Requirements Customer Requirements (Explicit and Implicit)
General	9	System can communicate with multiple units
	7	Affordable
	4	Compatible App/GUI that Displays Data
	1	Aesthetic
User Operation	4	User-friendly
	10	User and Garden Safe
Electrical	7	Rechargable (type-c)/Replaceable Battery
	6	Battery lasts for about a month
	7	Data collected/recorded multiple times per day
	10	Relays sensor data & battery level wirelessly
	4	Easy re-calibration of sensors/troubleshooting
Sensors	10	pH, EC, Temp, & Depth sensors
	3	CO2, Lighting, Humidity & Air Quality Sensor
	9	Accurate Readings
Mechanical	8	Water Proof
	3	Heat Resistant
	10	Compatible with Tower Garden infrastructure
	6	Replaceable Sensors (especially pH)
	8	Easily Manufacturable

Figure 5.a: HOQ – Customer Requirements

Column #	Direction of Improvement	Customer Requirements (Explicit and Implicit) / Engineering Requirements	Specification	Max Relationship	Target	Max Relationship
1	▶	Several Connected Devices	> 40 devices	9	124	8%
2	◀	Retail Price	< $99	9	63	4%
3	◇	Data Throughput	process 10 sensors/second	9	12	1%
4	▶	Tower Compatability	Should match Tower Reservoir Cap	9	90	6%
5	▶	Sensor Precision	within 2% of Maximum Reading	9	94	6%
6	◀	Setup Time	5 Minutes	9	87	5%
7	◇	Size	5" x 8" x 24"	9	99	6%
8	◇	Safe Materials	FDA Approved Materials	9	138	9%
9	◀	Time to Full Charge	4 hours	9	90	6%
10	▶	Battery Life	30 days	9	95	6%
11	◇	Frequency of Data Collection	Every 10 minutes	9	99	6%
12	◇	Wireless Communication	Communication in >5 Minutes	9	138	9%
13	◇	Automated Readings	< 1 Human Intervention per Week	9	171	11%
14	◇	Recalibration Accessibility	Less than 5 minutes	9	126	8%
15	▶	Operating Range	Based on Standard Farming conditions	3	39	2%
16	◀	Sensor Accuracy	Maximum 1% Sensor Offset drift	9	138	9%
17	◇	Water Tight	IP68 Standard	9	72	4%
18	◇	Operating Temperatures	65-120 F	9	27	2%
19	▶	No. of Parts (Manufacturability)	≤ 50 unique components	9	82	5%

Figure 5b: Engineering Requirements and Specification

. Available: http://www.schrodingersghost.com/?cat=54.

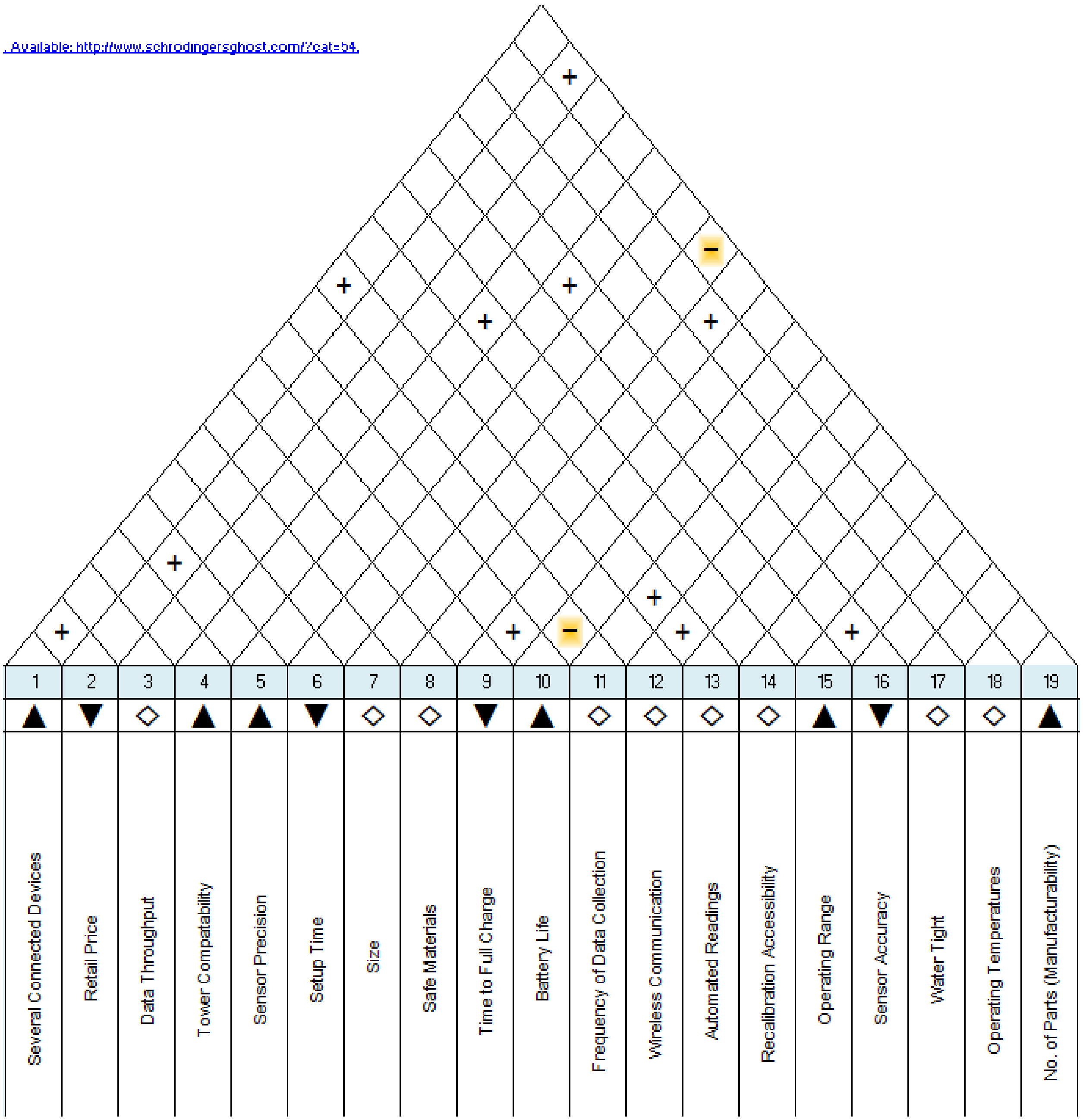


Figure 5.c: HOQ – Engineering Requirements Inter-Correlation

Category	Weight	Customer Requirements (Explicit and Implicit) \ Engineering Requirements	Several Connected Devices	Retail Price	Data Throughput	Tower Compatability	Sensor Precision	Setup Time	Size	Safe Materials	Time to Full Charge	Battery Life	Frequency of Data Collection	Wireless Communication	Automated Readings	Recalibration Accessibility	Operating Range	Sensor Accuracy	Water Tight	Operating Temperatures	No. of Parts (Manufacturability)
General	9	System can communicate with multiple units	●								▽	▽		○	▽	▽					
	7	Affordable	▽	●						▽											
	4	Compatible App/GUI that Displays Data	●		○																
	1	Aesthetic							○												
User Operation	4	User-friendly						●	▽			▽									
	10	User and Garden Safe						▽	○	●											
Electrical	7	Rechargable (type-c)/Replaceable Battery						▽			●	○									
	6	Battery lasts for about a month									○	●	▽								
	7	Data collected/recorded multiple times per day										▽	●	○	●						
	10	Relays sensor data & battery level wirelessly											○	●	●						
	4	Easy re-calibration of sensors/troubleshooting						▽								●					
Sensors	10	pH, EC, Temp, & Depth sensors					▽										○	○			
	3	CO2, Lighting, Humidity & Air Quality Sensor					▽										○	○			
	9	Accurate Readings					●								▽	○		●			
Mechanical	8	Water Proof								○									●		
	3	Heat Resistant								○										●	
	10	Compatible with Tower Garden infrastructure				●		○													▽
	6	Replaceable Sensors (especially pH)							●							●		○			
	8	Easily Manufacturable							▽	▽											●

Figure 5.d: HOQ – Correlation Matrix

	> 40 devices	< $99	process 10 sensors/second	Should match Tower Reservoir Cap	within 2% of Maximum Reading	5 Minutes	5" x 8" x 24"	FDA Approved Materials	4 hours	30 days	Every 10 minutes	Communication in >5 Minutes	< 1 Human Intervention per Week	Less than 5 minutes	Based on Standard Farming conditions	Maximum 1% Sensor Offset drift	IP68 Standard	65-120 F	≤ 50 unique components
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9	9	3	9	9	9	9
Target	124	63	12	90	94	87	99	138	90	95	99	138	171	126	39	138	72	27	82
Max Relationship	8%	4%	1%	6%	6%	5%	6%	9%	6%	6%	6%	9%	11%	8%	2%	9%	4%	2%	5%
Technical Importance Rating																			
Relative Weight	5	4	5	4	5	4	5	3	5	4	5	4	4	4	5	5	5	4	5
Weight Chart	5	5	3	4	4	4	0	3	4	4	3	3	3	3	2	4	4	4	3
Our Product	4	2	5	4	3	3	3	4	3	3	4	3	4	3	4	5	4	5	3
Competitor #1: Qivine Pool Thermometer Wirelesss	2	5	4	3	4	3	2	1	1	5	4	3	5	0	3	5	4	0	3
Competitor #2: INKBIRD WiFi Gateway and Wireless Pool Thermometer	4	3	4	4	4	4	2	4	2	3	4	3	0	0	4	5	3	0	1
Competitor #3: Raddy PT-3 Smart Pool Thermometer with 2 Additional R	2	4	4	3	4	3	2	0	5	5	4	2	0	0	4	5	4	0	4
Competitor #4: AC Infinity Hydroponic Meter PRO Kit, High Precision Digi	3	1	2	5	3	4	4	3	2	1	2	3	5	2	5	5	3	3	4

Figure 5.e: HOQ – Engineering Requirement Weightage

Our Product	Competitor #1: Orvine Pool Thermometer Wireless	Competitor #2: INKBIRD WiFi Gateway and Wireless Pool Thermom	Competitor #3: Raddy PT-3 Smart Pool Thermometer with 2 Addition	Competitor #4: AC Infinity Hydroponic Meter PRO Kit, High Precisio	Row #
4	2	4	2	3	20
2	5	3	4	1	19
5	4	4	4	2	18
4	3	4	3	5	17
3	4	4	4	3	16
3	3	4	3	4	15
4	1	4	0	3	13
3	1	2	5	2	12
3	5	3	5	1	11
4	4	4	4	2	10
3	3	3	2	3	9
4	5	0	0	5	8
3	0	0	0	2	7
4	3	4	4	5	6
5	5	5	5	5	5
4	4	3	4	3	4
5	0	0	0	3	3
3	3	0	4	4	2
2	4	3	4	3	1

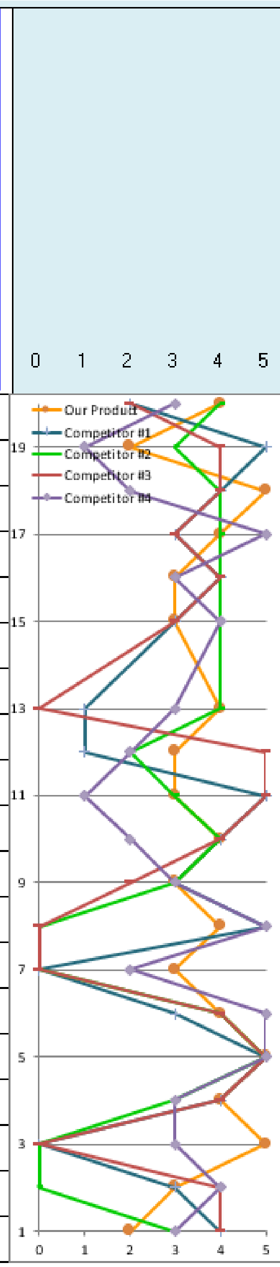


Figure 5.f: HOQ – Competition Evaluation

The HOQ helps reveal the more important, heavily weighted engineering requirements and their associated specifications detailing how well the device must perform at each requirement. From the HOQ shown, the top six engineering requirements (with weights) are Automated Readings (11%), Wireless Communication (9%), Sensor Accuracy (9%), Safe Materials (9%), Several Connected Devices (8%), and Recalibration Accessibility (8%). These are all crucial requirements of the product, helping design a unique, yet impactful device. It is a top priority to Automate Readings, as this is what will cut down the extensive labor effort and time taken to check water health currently. Similarly, this communication must be done wirelessly to again ensure minimal effort from farmers. Sensor Accuracy is important to ensure that the water health measurements are dialed in, providing not only a surviving, but thriving environment for produce to grow. These top engineering requirements are clearly non-negotiables, as they enable the product to successfully solve the labor intensive and time consuming, manual task of measuring Tower Garden water health.

The corresponding engineering specifications define how well the device must perform each of these functions quantitatively, which is key to designing and selecting an optimal final solution. According to the specifications, to achieve Automated Readings, the device must require less than one human interaction/week, all encompassing, to help drive down the manual labor time associated with manual water data collection. Wireless Communication is successful if the product can communicate/upload the water health data in less than five minutes, again helping reduce the need for manual labor and time commitment. Sensor accuracy is specified to be within 1% of the reading, for all sensors, such that the water health is accurately recorded to ensure thriving produce. For Safe Materials, the device must be compatible with FDA standards/codes ensuring garden safety. The specification for having Several Connected Devices is ensuring a minimum of 40 connectable devices, for immediate implementation into the Sponsor's farms. Finally, the sixth specification is for Recalibration Accessibility, where the goal is to limit recalibration time to less than five minutes. These top engineering specifications, and the remainder, will be physically tested after the production of the first prototype.

The product must also fall within a hardware and software constraint. This product must be compatible with the existing Tower Garden infrastructure so it can be sold as an accessory. This includes engineering specifications such as FDA approved materials and waterproofing the product to ensure ample safety for both the garden as well as users. Similarly, the sponsor is in the process of helping develop a mobile app to easily check and report the water health of each tower, so another constraint is ensuring effective communication through the existing and in-progress software and application protocols.

5. Market Research/Potential Impact

Due to the incredible production benefits, Tower Gardening is a rapidly increasing market space, with around 3,500 aeroponic crop farming businesses in the United States, boasting a 4.2%

increase from 2023 [13]. To outline the market size of the Tower Commander solution, the team determined that the desired product is limited in use and should first be designed directly for Tower Garden users. However, it is worth exploring diversified applications for such a product once the Tower Garden solution meets sponsor's expectations.

For the focused application to Tower Gardens, the team has and will continue to consult with the sponsor for this project, Clint Crowe, an owner and farmer of over 40 Tower Gardens in both farm and residential settings. Most Tower Garden farms range from employing 10-100 units, though for solutions that encompass much larger farms, the team will look to contact and conduct research into the Tower Garden experience in larger applications of up to 1200-tower farms, for example Scissortail Farms in Tulsa, Oklahoma [14]. Research will be conducted to determine the most reliable and cost-effective sensing solutions.

A drawback of the Tower Garden and vertical farming market is the high initial cost to set up farms, running around $700 per tower [1]. Therefore, a market cost of $99 was determined to be an appropriate cost for the sensing device to ensure it is affordable for large commercial farms where it can have the most impact. Tower Gardens was first launched in 2012, and in 2024, Tower Gardens served 11 markets with prices ranging from $670 to $725 for the basic tower garden units. Accessories range from $12 to $325, consisting of wheel adapters for ease of mobility, replaceable pumps, LED lighting fixtures and more. Indoor Tower Garden farms tend to use LED lighting fixtures for lighting in lieu of the sun. This increases electrical cost for each tower quite significantly, from around $1 to $5 monthly [15]. As a result, the device should conserve as much electrical power, and in turn reduce electrical cost as possible. In general, the tower garden hardware, infrastructure, and products are expensive, which is a deterrent for farmers considering entering the market [16]. It is crucial that this accessory sensing device has a targeted, reasonable price, balanced with the benefits provided to farmers. The device is planned to be marketed as a Tower Garden accessory/extension product, sold on their website. As mentioned previously, products do exist that gather water health data and report back to the user, but these are designed for use in pools, not specifically for Tower Garden applications. The specified target sales price for the product is $99 to encompass a balanced price for larger commercial farms and residential farmers alike. Each Tower Garden is reported to produce $50-$100 monthly depending on market prices and specific produce, so farmers can quickly and feasibly pay off the investment.

Not only will the Tower Garden efficiently pay off the cost in around 1-2 months, but large commercial farms will benefit massively from the device, saving about 5 minutes/tower/day, which at larger existing farms could be $500,000 yearly. Measuring water health takes roughly 5 minutes/tower/day for a skilled farmer and is the single most important differentiator between producing thriving, rather than simply surviving, produce. Scaling up to larger farms, using the 1,200-tower farm in Tulsa as an example, is 80+ labor hours daily equating to $750,000 yearly, all just for manually checking the water health. Successful implementation of a device that fulfills the $99 engineering specification would have a high initial cost of around $120,000, but would significantly reduce manual labor and time, saving $500,000 per year directly at the farm in Tulsa. The product could even help farmers take multiple measurements a day to ensure their water health is at thriving levels.

6. Design Concept Ideation

Several potential design solutions are formulated using distinctive solutions from a list of broad potential ideas, allowing for analysis and comparison of various product functionality. The designs must fulfill a variety of functions at both the unit and the system level. At the unit level, the essential functions of the device include the measuring of water pH, depth, temperature, and EC, along with communicating this information to the user autonomously/automatically with the least amount of human intervention possible. The autonomous/automatic functionality of the device is re-emphasized to the reader. At the system level, the primary functions include large-scale data aggregation, coordination and optimization of wireless communication between multiple sensor units, and integration of data display and unit control within the existing graphical user interface (GUI). These are viewed as primary functions as these are most crucial for automating the process and operating at a reasonable scale.

Figure 6 includes a detailed depiction of the function tree developed for the device. It is worth mentioning that the function tree includes both customer requirements and design functions, providing a detailed understanding of the system's needs and guiding solution-oriented thinking. For instance, while protecting internal components from moisture is crucial from a technical standpoint, it doesn’t directly address a particular customer need. This distinction helps in balancing user-centric features with necessary design considerations.

As discussed earlier, the tree highlights a variety of essential functions of both the device and system. On the device level, sensing is a central feature. An important note on sensing is to do with precision and accuracy. Engineering specifications discussed in Section 4 highlight that these must be within 1% of true reading. An obvious concern is that these must be balanced with further engineering specification related to cost, which stipulates that this must be kept below $99. Furthermore, functions that are children to the transmission and receiving of data wirelessly and automatically are crucial to ensuring that sensor data is sent to the system/server and appropriate controls from the server are received. At this level, managing power is also a critical design step function, as the implementation of the correct sleep mode protocols will heavily dictate the level of power consumption, thereby potentially affecting expected battery size and the battery life of a single charge of the system, addressing an important engineering requirement of lasting more than 30 days on a single charge. At the system level, functions primarily address design steps rather than direct customer requirements. The automatic operation of the system level without the need for consumer intervention is emphasized to the reader. Coordinating multiple sensor units is a crucial design function to address important engineering requirements related to scalability and minimum number of connected devices. Additionally, communicating over the network efficiently by managing bandwidth consumption and regulating costs is critical in keeping the device impactful while leaving a low footprint to the consumer. Given that the device will be operating at a consumer level, it is also essential that there is infrastructure for troubleshooting the device, as for operations at scale, single-unit functionality cannot be reliably controlled in any other way. This relates to the engineering requirement stipulating that the device must meet less than one human intervention per week on average, as this accounts for charging and troubleshooting as necessary.

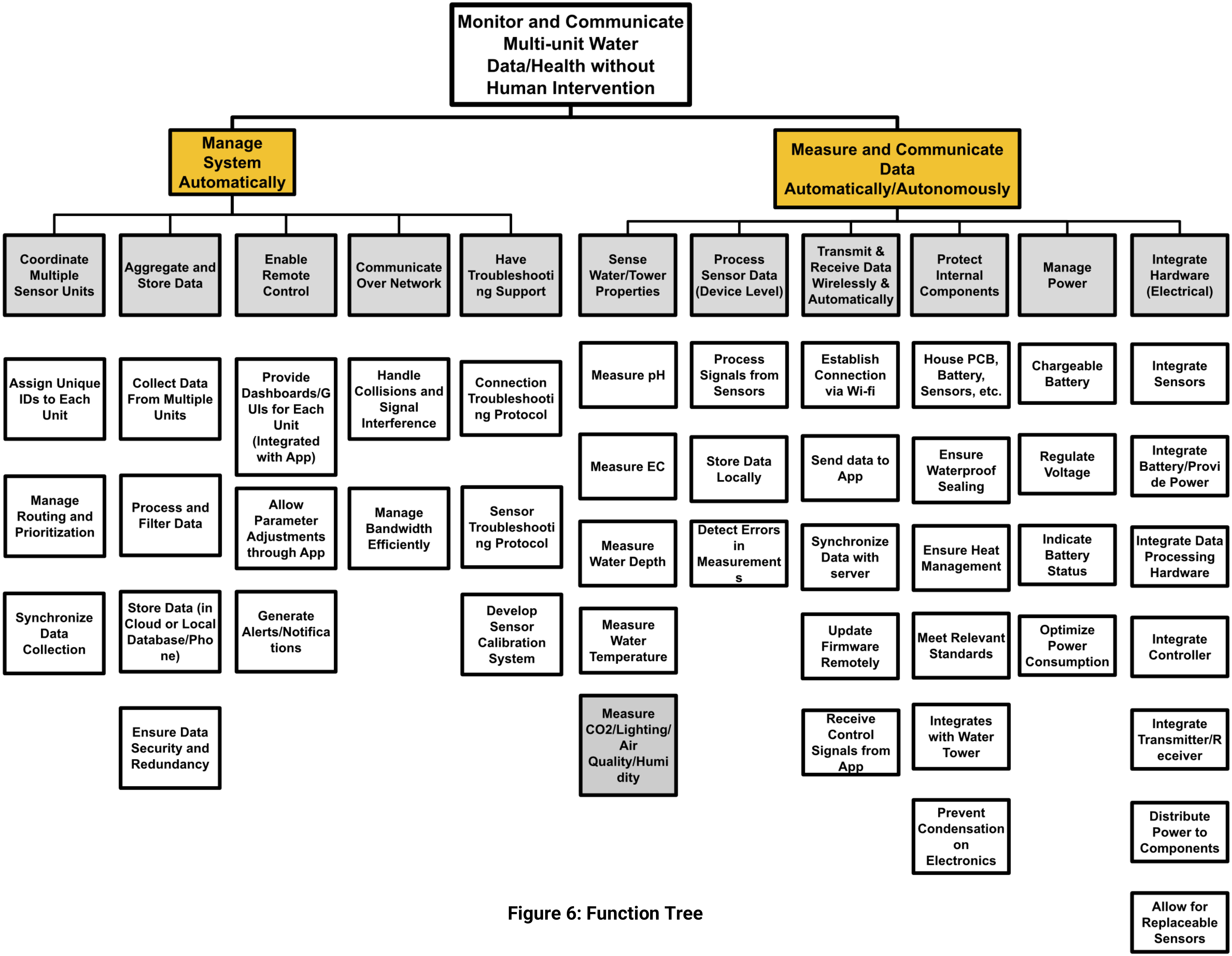


Figure 6: Function Tree

Table 2 below depicts the developed morphological chart highlighting potential solutions for each function above. The chart is broken down into device level and system level solutions. Each function is further classified into realm/infrastructure, namely sensors, electrical, packaging, communication, app, and troubleshooting.

Sensor selection is central to the development of the device, directly impacting decisions relating to the further sub-categories of electronics, packaging, communications, the user application, and troubleshooting. The various types of each sensor are presented as solutions in the below morphological chart. This is because the mechanism behind the sensor function is crucial to understand in order to ensure device crosstalk does not occur. For example, an EC sensor that heats up the water locally that is placed right next to the temperature sensor would result in false or inaccurate temperature readings. Additionally, sensors are primary drivers of cost for the system, as these can vary from high-end lab-grade sensors to inexpensive budget ones. Power consumption is also important in sensor selection, as choosing sensor types that draw similar power would simplify the power distribution board and reduce the number of parts. Additionally, the data collection electrical interface of these sensors also drives the PCB architecture and has the ability to increase or decrease the number of parts. Finally, the sensor size also dictates the shape and size of the overall packaging, along with the obvious PCB system.

An important decision revolving power is also made within the chart, where using a wired source is ruled out completely. There are some things to note here. Firstly, this decision is made upon sponsor request, where powering the device with wall power would necessitate thousands of additional sockets/extenders at large scale farms, making implementation impractical. Secondly, integrating the device with the existing power drawn from the pump within the Tower Garden is also ruled out completely, as this would require the re-design of the tower gardens. It is emphasized to the reader that the scope of the project involves the development of an additional supporting product rather than an integrated system of the tower gardens. A wall-powered solution would also drastically increase the number of components on the PCB board, complicating manufacturing and increasing unit costs. This drives the decision of a battery powered solution. Solutions relating to battery and optimizing power consumption are seen as crucial to meet the battery life requirement of more than 30 days. Battery types are presented as solutions, where the decision of lithium-ion, alkaline AA/AAA, or NiMH AA/AAA is decided. Alkaline AA or NiMH AA/AAA are only feasible options given rigorous power optimization strategies, as 6-batteries of any standard size would last less than 30 hours at constant power. Lithium-ion provides potential for simple rechargeability, reducing battery cost and waste, along with the obvious benefits of high-power density/longer single charge life.

Decisions regarding connection establishment significantly impact both the device's capabilities and overall cost. While Bluetooth and wired connections may be feasible for smaller-scale farms, they are impractical for larger deployments. Cellular connectivity, though viable, introduces recurring costs for users and requires additional hardware integration. Wi-Fi is identified as the most practical option, though it does impact user bandwidth and may introduce some associated costs. Data storage is another key consideration. Local storage via an SD card would require a waterproof access slot, adding complexity to the design. Storing data directly on a user's device minimizes cost but can become inconvenient at scale. Cloud storage offers seamless integration allowing users to access sensor data from anywhere with an internet connection, though it introduces ongoing costs for both users and the development team.

Functions along the communication section focus on assigning uniqueness for incoming data and synchronization of data. Uniqueness can be ensured using MAC addresses or other unique IDs. This is done to ensure that incoming data is sorted correctly, and users are aware of sensor-tower pairings. Synchronization involves various communication protocols to minimize bandwidth use as well as power consumption. Certain functions such as handling collision, managing routing, and bandwidth management, are crucial, as they ensure scalability as discussed earlier. The solutions list common communication protocols that are often used for these purposes; however, it is important to note that depending on the decision of higher-layer communication systems, these may fall outside control/scope.

The chart also lists mechanical packaging as its own section, reflecting its importance in the overall design. Key functions include housing the PCB, battery, sensors, and other components, ensuring waterproofing and compliance with relevant standards, and integrating seamlessly with the existing Tower Garden system. As discussed later, fitting into the existing access port within the tower is determined to be the only feasible option. Additionally, the packaging will likely be developed using a single solution, namely injection molded with virgin plastic, as this is the only material that meets all necessary standards.

Table 2: Morphological Chart

No.	System/ Device	Category	Function	Solution				
				1	2	3	4	5
1	Device	Sensors	Measure pH	pH Electrode	Optode pH Sensor	ISFET	Gell Polymer Material	pH Paper
2	Device	Sensors	Measure Electrical Conductivity (EC)	Electrode	Optical	Inductive	MEMS	Resonance-based
3	Device	Sensors	Measure Water Depth	Pressure Sensor at Bottom of Basin	Waterproof Ultrasonic Distance Sensor	Bathymetric LiDAR Sensor	eTape Liquid Level Sensor	Infra-red liquid contact sensor
4	Device	Sensors	Measure Water Temperature	Thermocouple	RTDs	Thermistors	Semi-conductor Based	Mercury/ Alcohol Thermometer
5	Device	Electrical	Process Signals from Sensors	Analog-Digital Converter	Digital Signal Processor	Kalman Filter	Edge AI Chip	Op-Amps
6	Device	Electrical	Store Data Locally	MicroSD Card Module	Flash Memory	Circular Buffer in RAM	Solid State Drive	MySQL (local database)
7	Device	Electrical	Detect Errors in Measurements	Redundant Sensors	ML Anomaly Detection	Threshold Based Error Detection	Self-Calibration Algorithm	AI Model
8	Device	Electrical	Establish Connection	Easy wi-fi Connect (local AP)	Bluetooth	LoRa	Cellular	Wired Connection
9	Device	Electrical	Send Data to app	MQTT Protocol	HTTP REST API	BLE Notifications	FTP/SFTP	CoAP

10	Device	Electrical	Synchronize Data	Cloud Based	Delta Updates	Data Batching and Periodic Syncing	Push Notifications	Merge Strategies
11	Device	Electrical	Update Firmware Remotely (Receive Control)	Over the Air	GitHub w/ auto-downloader	MQTT-Based Firmware	AWS IoT	Remote SSH updates
12	Device	Electrical	Receive Control Signals from App	MQTT w/ JSON Commands	HTTP POST Requests	BLE GATT Service for Mobile Apps	CAN Bus for Industrial Applications	Cellular Networks
13	Device	Packaging	House PCB, Battery, Sensors, and Components	Injection Molding using food-grade virgin plastic	SLA 3D printing	FDM printing	Machined/CNCed aluminum	Vacuum Forming
14	Device	Packaging	Ensure Water Proofing	Rubber O-rings	Conformal Coatings	Potting	Gaskets and silicon sealant	Dielectric Grease
15	Device	Packaging	Ensure Heat Management	Thermal Fins/Heat Sink	Cooling Fans	Liquid Cooling/Heat Pipes	Reflective Coating	External Attachments
16	Device	Packaging	Meet Relevant Standards	Ensure Water-Tight System	Ensure no Hazards	Follow Water Safety	3A Sensor Guidelines	Clean Water Act
17	Device	Packaging	Integrate with Water Tower	Fit into Pre-existing Access Port	Float on Water in Basin	Sit on Floor of Basin	Attach to Sides of Basin	Design Nook for Device
18	Device	Electrical	Chargeable Battery	Lithium-Ion (Li-Ion)	Alkaline	Nickel-Metal-Hydride (NiMH)	Lithium Iron Phosphate (LiFe-PO4)	Nickel-Zinc (NiZn)

19	Device	Electrical	Regulate Voltage	Low Dropout Regulator	Switching Regulator	Zener Diode Voltage Regulator	Capacitor Decoupling	Buck Converters
20	Device	Communication	Indicate Battery Status	App sorts by lowest charge	LED Indicator	Audible Alerts	OLED Screen	Visual Cues
21	Device	Electrical	Optimize Power Consumption	Sleep Mode	Adaptive Power Scaling	Solar Energy Harvesting	PWM Control	Charge Controllers
22	Device	Electrical	Integrate Sensors	Integrate All Required Sensors	Integrate Non-required Sensors	Voltage/Current Norming	Interference Elimination	
23	Device	Electrical	Integrate Battery	Lithium-Ion Battery Pack	Modular Battery System	Solid State Batteries	NiMH Battery Packs	Sodium Ion Batteries
24	Device	Electrical	Integrate Data Processing Hardware	Microcontroller	Single Board Computer	Remote Server Processor	IC	ASICs
25	Device	Electrical	Integrate Controller	Arduino	ESP32	Custom PCB	STM32	Arm MBED
26	Device	Electrical	Integrate Transmitter/ Receiver	Bluetooth Module	LoRa Module	Wi-Fi Module	RF Transceiver	LPWAN
27	Device	Electrical	Distribute Power to Components	Power Management IC	PCB Power Rails	Current Sensing/Protection Circuit	Bus System	Outlet Plug
28	Device	Packaging	Allow replaceable sensors and compatibility	Use watertight mounting/ fastening	Recalibration Alerts	Accessible Sensor Placement	Water Detection Identification	Water Detection Protocols

29	System	Communication	Assign Unique IDs to each unit	MAC Addresses	UUID (Universally unique identifier)	Device Serial Number	Custom Unique ID	IP Addressing
30	System	Communication	Manage Routing and Prioritization	Round-Robin Scheduling	Priority-based	Time-based	Queueing	Shortest First
31	System	Communication	Synchronize Data Collection	Time-stamping	Scheduled polling	PTP	Clock Sync	BLE Synchronization
32	System	Communication	Collect Data from Multiple Units	Central-server (Phone)	Central Server (Computer)	Servers Placed Throughout Towers	Manual	Computer-to-Phone
33	System	App	Process and Filter Data	Hardware filtering	Filtering on phone/ app	Filtering on separate server/ computer	DSP	Capacitive Filtering
34	System	App	Store Data	Cloud	Local on Phone	On device SD Card	On device USB Drive	On separate desktop that has hard drive
35	System	App	Ensure Data Security & Redundancy	Encryption	Backup Servers	Authentication	Masking	Session Expirations
36	System	App	Provide Dashboards/GUIs for each unit (Integrate)	REST API	MQTT	WebSockets	Push Notifications	Data Caching
37	System	App	Allow parameter Adjustment Through App	Value Input	Slide Bar	Revert to Previous Settings	Recommendations for Parameters	Time-Based Scheduling

38	System	App	Generate Alerts/Notifications	Push notifications on app	SMS	Email Alerts	Display Alerts on Device	Email Updates
39	System	Communication	Handle Collisions and Signal Interference	CSMA/CD	Frequency Hopping	Error-correction	Capacitor for Oscillation	LoS/NLos Accountability
40	System	Communication	Manage Bandwidth Efficiently	Data compression	Adaptive sampling rate/ updates	Event-driven updates	Data-aggregation	Queueing
41	System	Troubleshooting	Connection Troubleshooting Protocol	Auto-reconnect	Diagnostic Logs	Wi-fi strength indicator (in-app)	Customer Call Line	Help Manuals
42	System	Troubleshooting	Sensor Troubleshooting Protocol	Self-test routines	Error-codes	Recalibration Prompts	Accounting for Battery Level	Water Damage Protocols
43	System	Troubleshooting	Develop Sensor Calibration System	Manual-calibration interface (through app)	Auto-calibration?	Calibration Reminders	Calibration Wizard (tutorial)	Customer Call Line
44	System	Communication	Export Data Functionality	Export to .xls	Export to .csv	Cloud export	PDF-chatGPT report	PDF-template based report

The above morphological chart allowed for the development of various concepts, primarily on the device level, as presented in the following sub-sections.

Concept 1: Beta Concept

This concept continues the design philosophy of the initial prototype (Tower Commander Alpha) while upgrading the hardware and improving the packaging. This includes redesigning the PCB board, replacing the sensors and modifying the method of fitting the detachable pipes to the main body, while keeping the overall packaging the same.

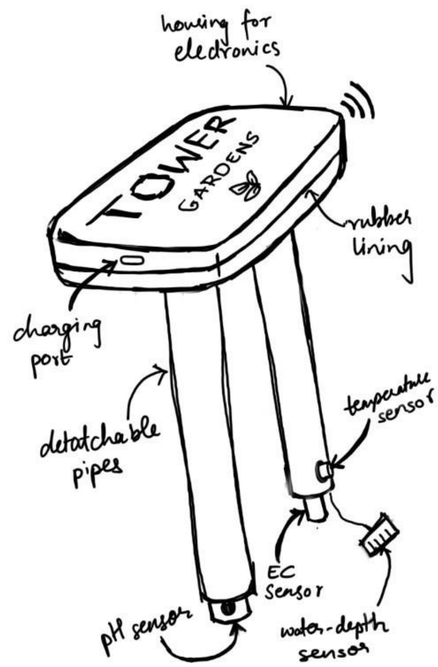


Figure 7: The Beta Concept

The upgraded sensor package will make this device more accurate and reliable. The interface chosen for these sensors (predominantly I2C, with the exception being pH sensor which is analog) is also compatible with each other. With the help of better fittings, recalibration and sensor replacement could be easier and more intuitive for the user, which allows for less manual labor. The simplicity of the external packaging makes this design extremely suitable for mass production, which is a key factor in the decision to carry forward the overall design. Finally, the inclusion of a rubber lining also makes it a better fit on the access panel when opening the tower garden.

While this concept does improve on some of the engineering requirements of sensor accuracy, recalibration accessibility and wireless communication, it does have issues that should be highlighted. As there are two pipes in contact with water, the device is highly susceptible to water-entry. The moisture that enters through these ports could damage electronics. There is also a lot of downtime that comes when the device needs to charge, as the Lithium-ion battery is not removable. This makes removing the whole device out of the reservoir for charging necessary, which is inconvenient.

Concept 2: The ExoSense Concept

This concept focuses on maximizing the operating-life of the device. The device uses a pump attached to a syphon tube to transport the water from the reservoir of the Tower Garden into an external temporary compartment, where the water health is detected. The data is collected using externally mounted, lab grade sensors and transmits data over Wi-Fi to the application on the consumer's phone. The cost for consumers is estimated to be $149.

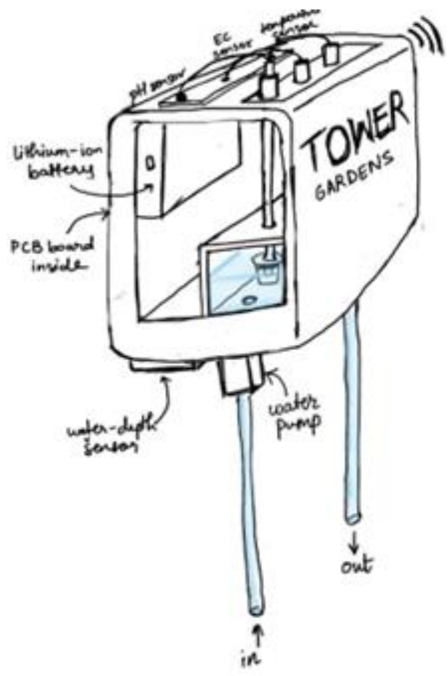


Figure 8: The ExoSense Concept

This method of sensing is useful as (1) all the electronics are now overboard which decreases the chances of damage due to moisture, (2) the sensors are easily accessible for calibration and replacement, and (3) the sensors are not always immersed in water and so increase sensor-life longevity.

The water level sensor is a non-contact, signal based detector that is packaged at the bottom of the device inside the reservoir. It follows IP68 standard for waterproofing [8] and so would not get damaged when in a damp and moisture-dense environment for extended periods of time. The device also works on a Lithium-ion battery, which boasts a long battery life.

While these pose considerable advantages, this concept does perform poorly in some engineering requirements. The new methodology of the sensing process will lead to a time delay in readings. This is because the external reservoir will have to fill to a certain level before it can provide accurate sensor readings. This also includes added components like the pump, syphon tube, and external compartment which will drastically increase the cost of the product. Furthermore, due to the complexity of the design, it would be difficult to ensure the design is suitable for large scale manufacturability, which is a long-term goal.

Concept 3: The Sensible Concept

To meet every farmer's needs, the need for the Sensible concept arose. This revolves around minimizing costs on every level, from sensors, to packaging to manufacturing. The cost for consumers is estimated to be $50.

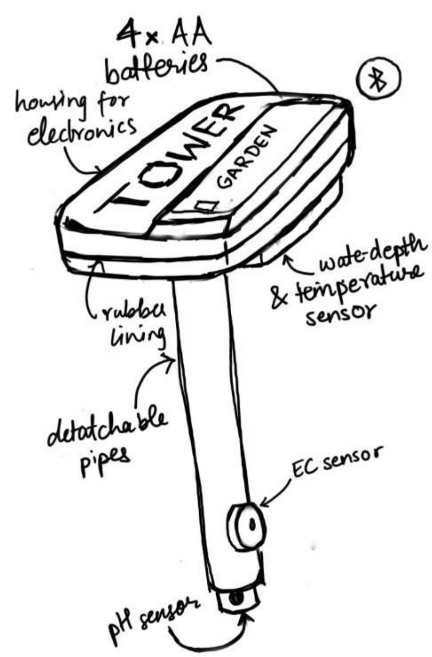


Figure 9: The 'Sensible' Concept

The sensors selected for this device are chosen based on cost rather than accuracy. The use of a dual water-level and temperature sensor, which works without contact with water, allows for cost savings and simplified packaging. With the pH electrode and EC sensor housed in the same detachable pipe, it reduces the number of parts that need to be manufactured as compared to Concept Beta, decreasing overall lead-time and assembly-time. However, the pH sensor and EC sensor are packaged too close to each other and so will lead to sensor interference and disrupt the accuracy of the readings.

The use of 4 AA batteries also makes it very cheap compared to Lithium-ion batteries, but compromises on battery life. It also uses Bluetooth instead of Wi-Fi to decrease the total cost of the device, while compromising on the range in which this device can transmit information to the user.

Concept 4: The Beltline; Justification of access panel-based concepts

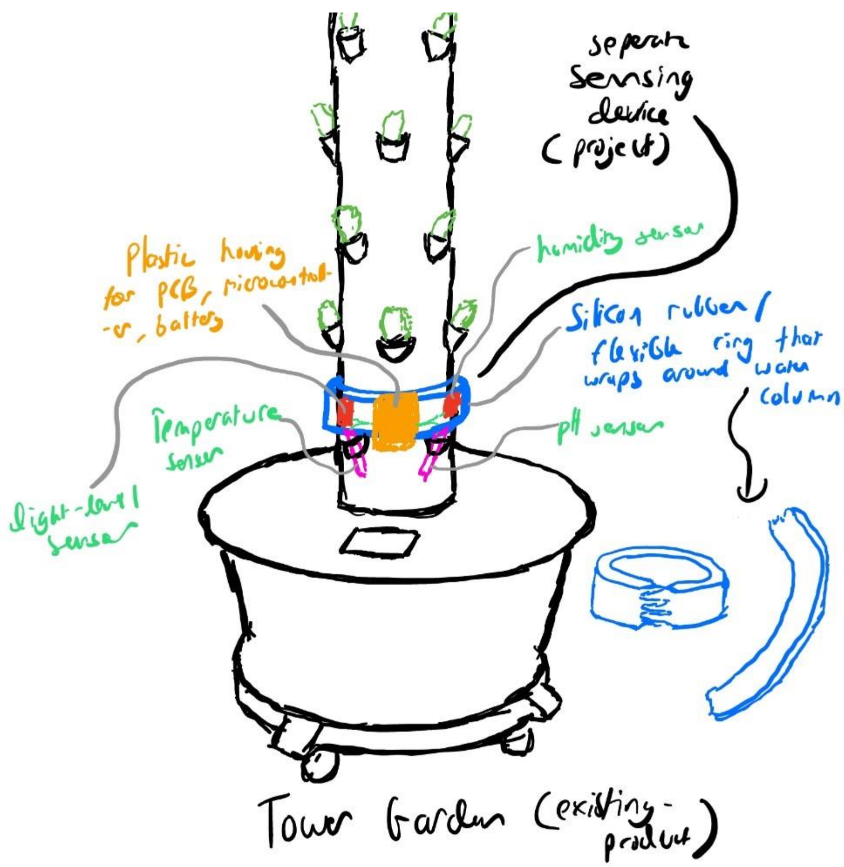


Figure 10: The Beltline Concept

This concept was primarily developed to highlight the advantages of utilizing the access panel as the mounting location for the device. The Beltline approach involves a flexible belt with release buckles, where sensors are mounted to fit within the existing plant holes, occupying an entire row of the tower. However, there are several reasons why this concept is unfeasible. Firstly, it cannot accommodate all required water health sensors, such as EC, depth, and accurate pH measurement, as these sensors must be submerged in the liquid reservoir to function properly. This reinforces why any mounting location other than in or around the access panel is not a viable solution. Extending the sensor length to reach the reservoir would significantly increase the device's size, making it difficult to set up and maintain. Secondly, this concept sacrifices an entire row of revenue-producing crops, which, on certain tower gardens, can reduce revenue by more than 8%. Given these fundamental issues, this concept does not require further consideration.

In fact, devices that are not mounted on to the tower garden will require manual human labor for the sensing of water health properties, meaning the base level requirement of automaticity is not met, while any other mounting location, such as long the column, or on the top of the column where the water sprouts, will result in a reduced sensor suite due to the lack of available submersible water. Other mounting locations, including any sort of drilling or retrofitting, will certainly have similar issues while also causing longer set-up times and permanent damage to the tower gardens. This addresses and justifies the chosen access-panel based on conceptual development and is why the team will be moving forward with this choice.

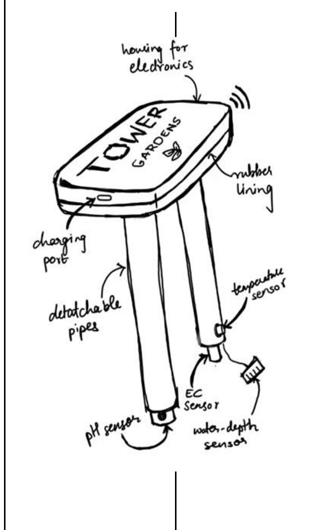
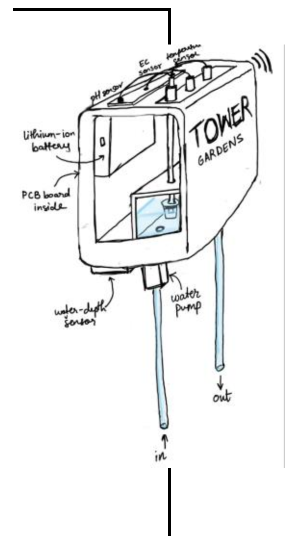
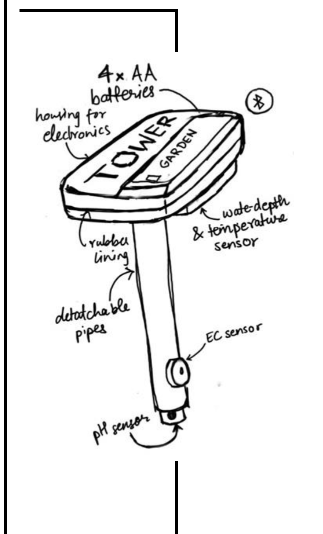
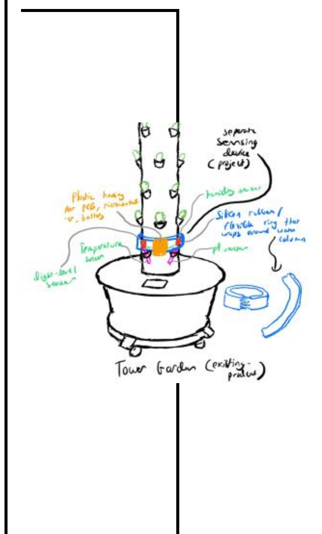
7. Concept Selection and Justification

Evaluation Matrix

Based on the Evaluation Matrix, the chosen design is the Beta concept. This is because this is the only concept that has a low spread in its unweighted score for the engineering requirements, averaging an 8. This shows that while the alternatives do perform well in certain criteria, Beta consistently scores high, especially in highly weighted criteria, making this design the best approach to addressing the engineering specifications. For example, Beta scores a 9 in the largest weighted engineering specification, Automated Readings (11%), scoring at least 2 points over the other potential designs. Similarly, Beta scores higher than all other alternatives in Wireless Communication (9%) with a score of 8, boasting its advantages in the highest weighted engineering specifications. However, Beta scores one point lower than ExoSense in the Sensor

Accuracy (9%) criteria, scoring 9 versus ExoSense's 10, as ExoSense boasts lab-grade sensors. Beta still scored much higher than the other two alternatives in the Sensor Accuracy criteria, as both solutions scored a 5. Not only did Beta score highly in the highly weighted criteria, but it also lacks superior scores in lower weighted criteria. For example, Beta scores a 3, the lowest of any design, in the Operating Temperatures (2%) criteria, which does not hinder the final score as compared to the other designs that score higher, since it is a lower weighted engineering requirement. Similarly, Beta scores a 7 in Watertight (4%), which is again the lowest of any design, though also a relatively low weight compared to other engineering requirements. This demonstrates how the best product design is Concept Beta, as it most closely matches the most important engineering requirements while sacrificing the lower ranking requirements. Concept Beta scores highest among all designs particularly in the highest rated engineering requirements, and the criteria it scores lower in are weighted less, such that Concept Beta is the best design to move forward with.

Table 3: Evaluation Matrix

	Criteria	Weight	Concept Score							
										
			Beta		ExoSense		Sensible		Beltline	
			Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted	Unweighted	Weighted
1	Minimum Connected Devices	8	8	64	7	56	4	32	5	40
2	Retail Price	4	8	32	2	8	10	40	5	20
3	Data Throughput	1	5	5	9	9	7	7	8	8
4	Tower Compatibility	6	9	54	6	36	8	48	5	30
5	Sensor Precision	6	8	48	8	48	6	36	3	18

6	Setup Time	5	8	40	5	25	9	45	3	15
7	Size	6	8	48	5	30	8	48	5	30
8	Material Safety	9	8	72	9	81	5	45	2	18
9	Time to Full Charge	6	9	54	7	42	10	60	5	30
10	Battery Life	6	9	54	9	54	5	30	4	24
11	Frequency of Data Collection	6	8	48	7	42	8	48	8	48
12	Wireless Communication	9	8	72	7	63	7	63	7	63
13	Automated Readings	11	9	99	7	77	6	66	6	66
14	Recalibration Accessibility	8	8	64	10	80	7	56	2	16
15	Operating Range	2	8	16	9	18	9	18	6	12
16	Sensor Accuracy	9	9	81	10	90	5	45	5	45
17	Water Tight	4	7	28	10	40	8	32	9	36
18	Operating Temperatures	2	3	6	8	16	9	18	6	12
19	No. of Parts (Manufacturability)	5	5	25	2	10	10	50	3	15
				910		825		787		546

Selected Concept Feasibility Review

Beta Concept provides a consumer friendly, manufacturable answer to the problem at hand, which can perform all defined functions and meets all the engineering requirements to ensure optimum water health for the tower garden farmers. Due to the similarity in size of the device in length and breadth to that of the access panel, it is very intuitive to understand the setup procedure for this device- just replaces the access panel on the reservoir, connects to the device through the application via Wi-Fi and the device is ready for use. No additional tasks need to be performed to get this device set up, making this product easy to work with.

The key driving factors for this design were its emphasis on sensor accuracy, battery life and parts manufacturability. These sensors are now packaged in a way to decrease interference, especially between the pH sensor and EC sensor as both require emitting signals into the water to capture readings. Now placed far away from each other, these do increase the validity of the data received from the sensors. By upgrading to more accurate sensors compared to those in the initial prototype, we can sense the water health to within 1% of the true value, which makes this a successful design concept. By using a Lithium-ion battery, we also increase the battery life of the device in use. Assuming the four sensors need to activate twice a day, each sensor activation lasts one minute and draws 50mA, the microcontroller uses 80mA, the system uses 1mA during sleep mode and the Lithium-Ion battery capacity is 2000mAh, the device can last up to ~60 days with one full charge. This is double the current requirement of a 30-day battery life (View Appendix A for calculation). When looking from a manufacturing perspective, the device can be split into three components, the main body, and the two detachable pipes. Each of these parts can be easily manufactured due to their standard shapes and would each have existing permanent molds that could be used for this manufacturing process. With injection molding, it would take 2-3 weeks to [17] mass produce the product, as well as finishing and packaging, which is on the lower end of the average lead-times for consumer products.

Risks and Countermeasures

Several risks have been identified for the selected Beta Concept. When compared with the other concepts, the watertightness of the design proved to be a potential risk factor due to its proximity to the water in the basin and its sealing method. Since the cap is recommended to be removed bi-monthly for nutrient input, placing sensors on the bottom of the cap should not pose a significant inconvenience to users, however, routine cleaning introduces risks of physical damage and water ingress into the circuitry. Other options to supplement the usage of a rubber lining for sealing against water intrusion are being explored, including sealing the tops of the pipes with rubber or epoxy. The operating temperature was also an area of concern. Because the greenhouses in which the product is expected to operate can reach extreme heats, there exists a risk that the product may not work as expected in real world conditions. Further testing will be required to determine if this proves to be a problem, and which cooling system will be best to address it. The larger number of parts when compared to the other designs was another issue with the Beta Concept. However, this problem is made up for by its superior useability and simplicity of setup. Finally, the incorporation of multiple sensors into the device will increase the risk of signal interference, calibration drifting, and potential failures due to environmental exposure. To counteract these issues, robust sensor calibration protocols will need to be implemented, and redundancy should be considered to ensure data reliability even if some sensors degrade over time. By implementing these countermeasures, we can ensure the device remains durable, reliable, and user-friendly, even in the demanding conditions of the Tower Garden environment.

CAD Model

To analyze the physical dimensions/tolerances, part compatibility, and overall sizing of the device a CAD model is created. This also helps with the prototyping process as five parts, the lid, enclosure, two pipe fittings, and the pH attachment piece, are planned to be printed using ABS and PLA plastics. The labeled CAD model is shown in Figure 11 below.

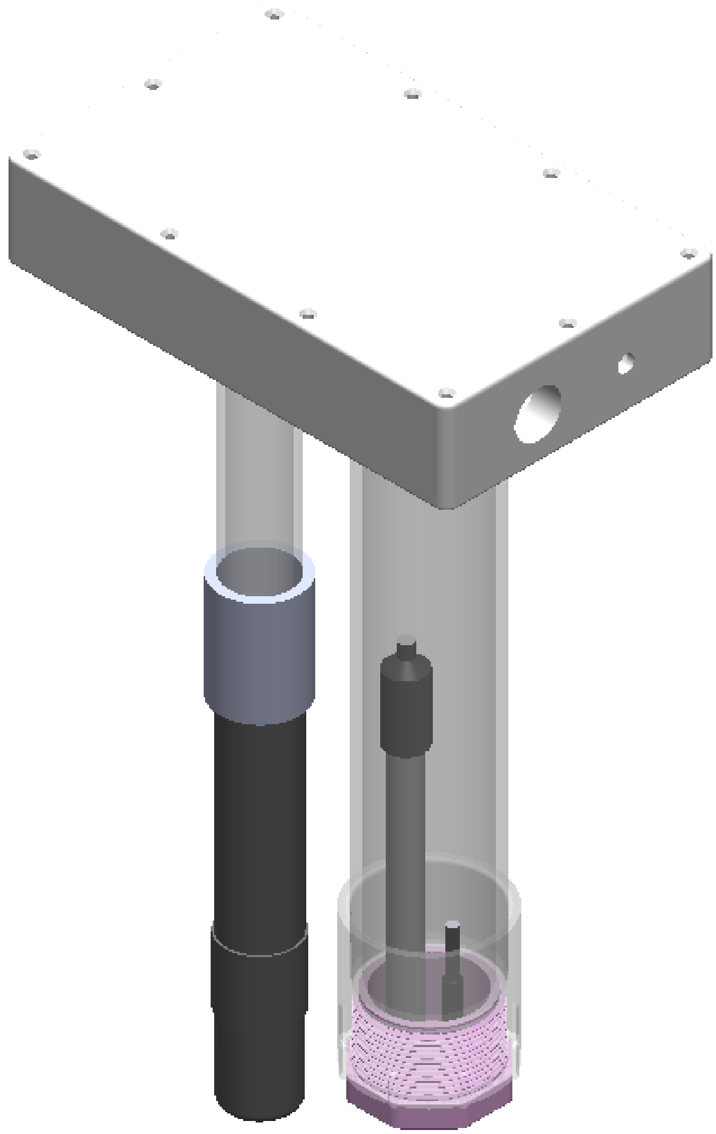


Figure 11a: Isometric View of Prototype 1 Cad Model

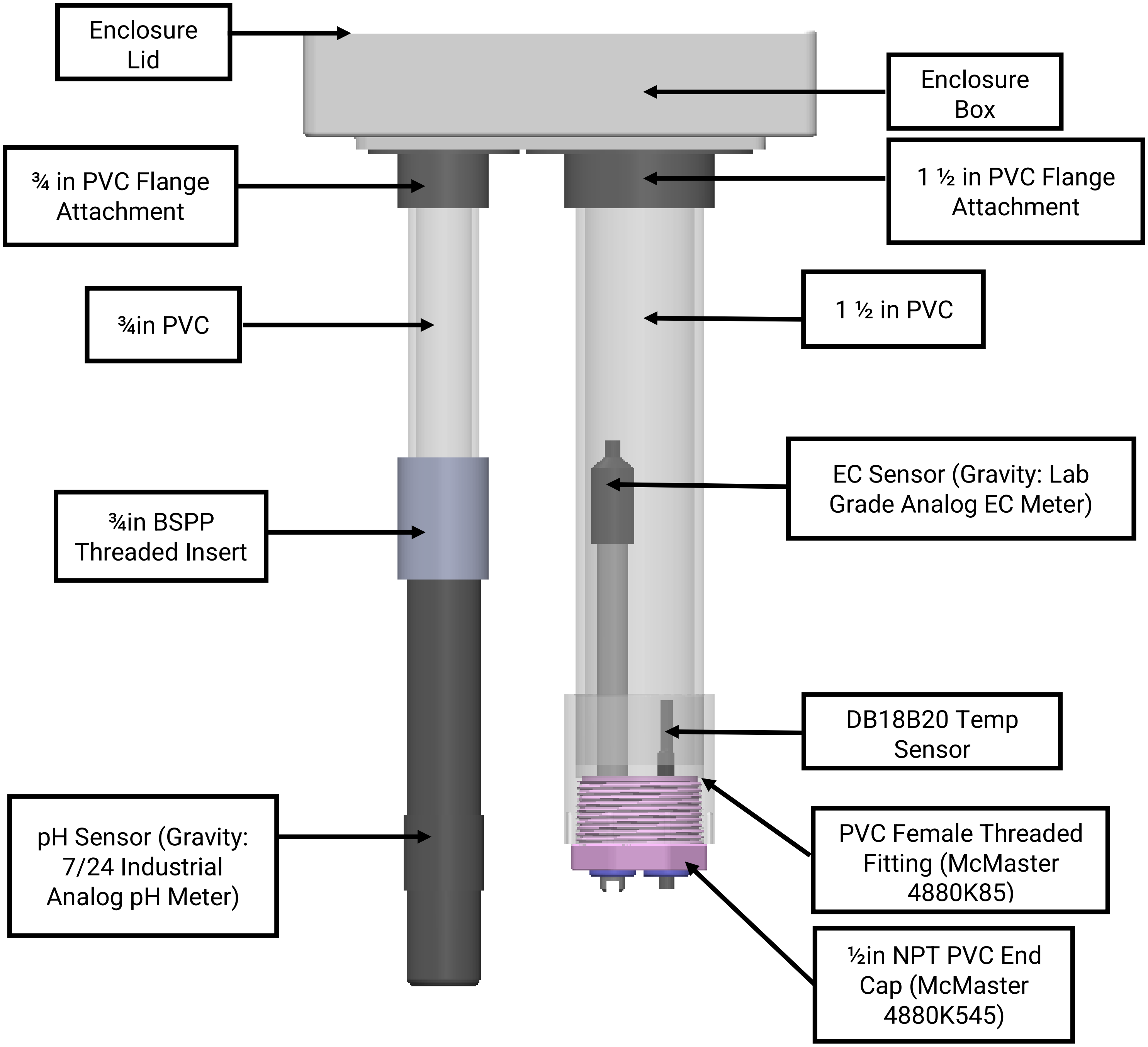


Figure 11b: Labeled View of Prototype 1 CAD Model

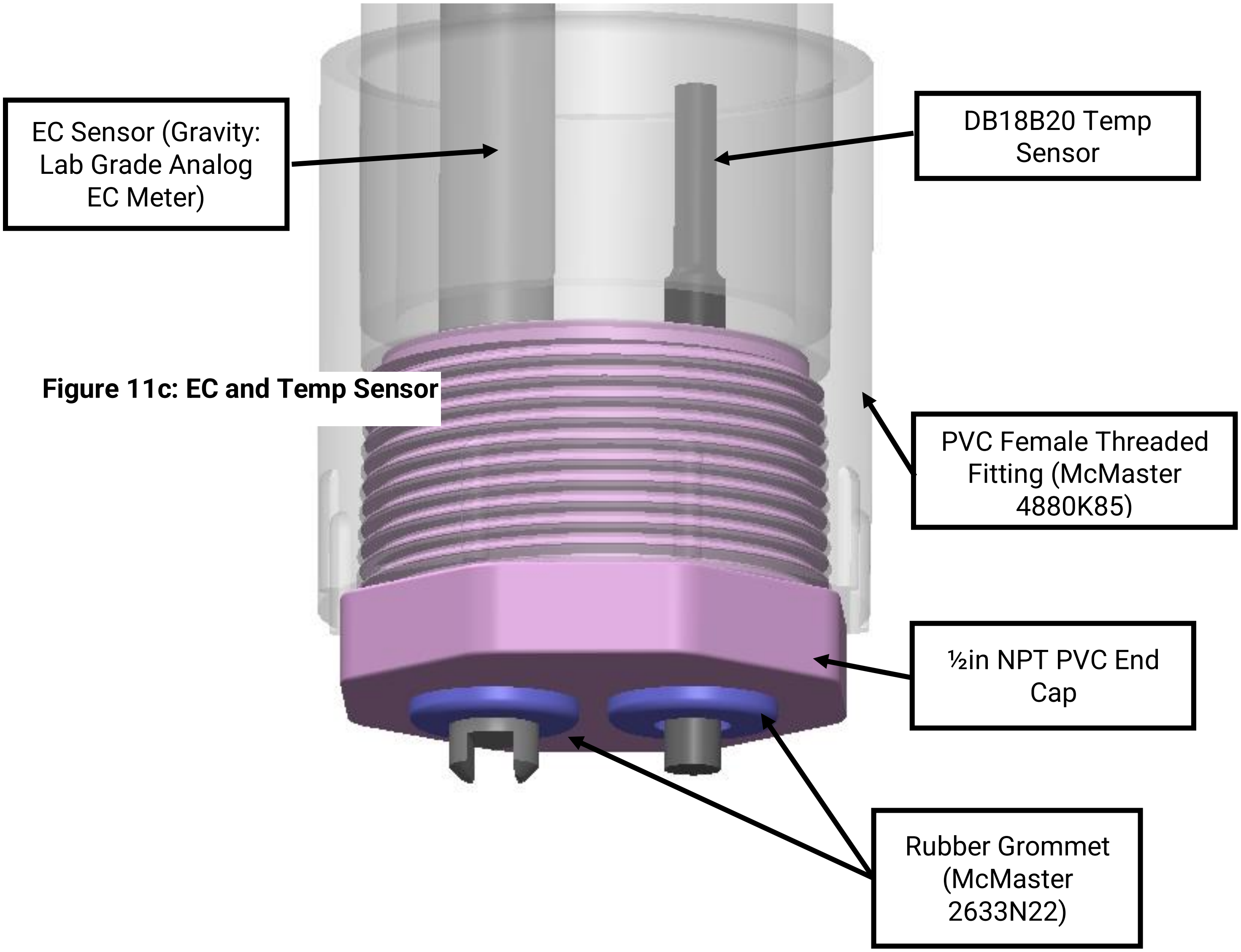


Figure 11c: Labeled View of EC and Temperature Tube Cad Model

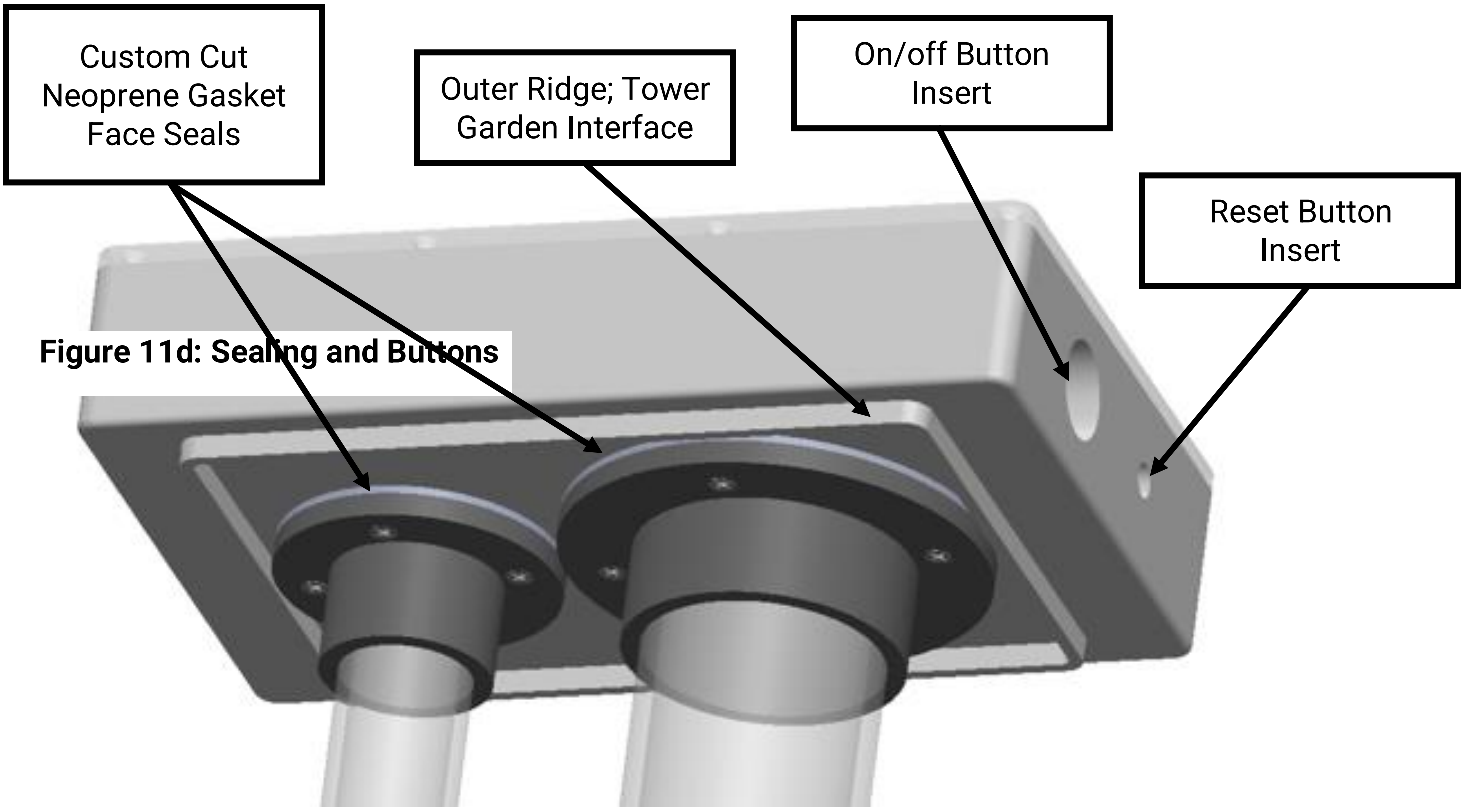


Figure 11d: Labeled View of Prototype 1 Enclosure Cad Model

8. Industrial Design

The sensing device's scope does not focus on significant interaction with humans. In fact, the device's value lies in limiting user interactions with the Tower Garden products. Factors such as the ease of access to the device's measurements, customizability for users' testing preferences, and intuitive installation are all details that were considered when designing the connections between farmers and the device technology. The current product design subtly calls upon visual hierarchy theory to draw users' eyes to elements of the device that promote ease of installation and use. An example of this usage of hierarchy is the prominence of the ridge that fits seamlessly into the existing Tower Garden infrastructure or the geometric buttons protruding from the otherwise smooth enclosure. Both of these elements subtly streamline the operator's experience. After brief consideration of device branding, the team arrived upon the graphic depicted in Figure 12 uniting the team behind a gardening focused ethos.

The device itself is named a "Tower Garden Commander" to highlight its specific collaboration with the Tower Garden product. The Tower Commander consists of smooth food-safe materials and will be primarily colored white to match the Tower Garden aesthetic. Other considerations for texture and color are environmental resistance and appealing to the contemporary technology-invested customer demographic of Tower Gardens. The following branding markets the device with an emphasis on its shape and ethos.

Figure 12: Tower Commander Product Branding

9. Engineering Analyses and Calculations

Power Consumption Analysis

To ensure the device can hold charge for the desired period of over 30 days as documented in engineering specifications, a current-driven power consumption analysis is used. Through direct experimentation of the prototype's ESP32 and all sensors, current values are recorded for both the active, meaning sensors are actively sensing water data, and inactive, meaning the sensors are not sensing water data but the device is still on and connected to Wi-Fi in a form of sleep mode. Results from testing yielded active current draw of $150\ mA$ while sleep mode current draw is around $20\ mA$.

Calculations are performed to indicate how long the prototype can hold charge for. Using the charge of the selected battery of $3000\ mAh$, calculations are shown in Appendix A.1 demonstrating the prototype can hold charge for approximately six days (5.92 days). This is planned to be optimized in the next prototype, where deep sleep will be used, and sensors will turn off in downtime. This optimization does not change the active sensing current draw but significantly decreases the sleep current draw, from $20mA$ in modem sleep to $0.1mA$ in deep sleep, meaning the device can hold charge for a much longer time. The optimization calculations are shown in Appendix A.2, where the device can hold charge for 32.5 days, increasing from the 6-day period in the current prototype and exceeding the 30-day desired engineering specification. This optimization will happen purely in software. The process means that the user can get real time readings any time of the operational work day, but the device goes to sleep during unusual work hours, meaning no readings during this time. Future work involves successfully integrating deep sleep functionality including researching the practicality of using solar cells to omit the need for regularly scheduled charging. The possibility of utilizing solar cells to help charge the device idly will rely heavily on direct testing in an actual tower garden farming environment, with lots of variability in various parameters of the space to consider.

Mechanical Analysis

When analyzing the mechanical packaging to ensure the device will not deform or break, several failure modes are analyzed to determine the factor of safety for multiple points on the device. Through direct measurement of the prototype, the weight of the device is found to be 1.89 lbs. (856 grams). For analysis, the device is analyzed as having an additional 10 lbs. applied axially to the bottom, if perhaps something is stacked on top of the device during operation or the user is pushing on the device. For the vast majority of the device, the force applied will only be applied from the device's own weight as it sits in the tower garden's basin. By accounting for an extra force five times larger than the nominal weight force, the analysis can be considered a reasonable worst-case scenario. With this in mind, several failure points and detailed calculations are shown in Appendix B, all demonstrating extremely high safety factors on the order of 100. This is not due to the device being overdesigned, but rather that applied loads on the device are relatively small compared to the materials, fasteners, and cement used. The lowest safety factor of 17 is found to be at the interface between the PVC pipe fitting and PVC endcap, which is important to consider as it is significantly lower than the other safety factors, but still large enough to instill confidence in the packaging of the device.

10. Prototyping and Experimentation

Mechanical Packaging and Waterproofing

The initial design for the prototype consists of an enclosure to house the electronics and two tubes to house sensors. The enclosure is designed to sit on top of the tower garden basin whereas the tubes are designed to extend the sensors down to a sufficient water level inside the basin. The initial prototype is intended to test the fit of the components and determine any problem areas in the design to be addressed in future prototypes.

A ¾ inch PVC pipe is used in the design for the pH sensor tube, and ABS 3D printed parts are intended to be used as the pipe attachment to the enclosure and the adapter for the threads on the pH sensor. Oatey ABS to PVC Green Transition Cement is used to create a watertight seal between the ABS parts and PVC pipe. A water resistant, FDA approved neoprene rubber sheet is used between the pipe attachment and the enclosure as a gasket to help waterproof the device. Additionally, the threads used for the adapter between the pH sensor and the pipe are British Standard Pipe Parallel (BSPP) threads, ensuring the water tightness of that joint.

A 1-½ inch PVC pipe is used for the tube housing the EC and temperature sensors. The same strategy is used as in the pH tube where an ABS 3D printed pipe adapter with a neoprene face seal gasket connects to the enclosure, and ABS to PVC transition cement connects it to the pipe. The design features an off the shelf PVC NPT fitting and NPT endcap to install onto the bottom of the EC pipe using Oatey Purple Primer and Oatey Regular Clear PVC Cement on the pipe to fitting joint. Two holes are drilled on the endcap such that the EC and temperature sensor fit into cut-to-size SBR grommets to prevent water intrusion past the initial ends of the probe which stick into the water.

Finally, both the enclosure and the lid are PLA 3D printed pieces. All screws fastening lid and pipe attachments to the enclosure bottomed out in heat set inserts inserted into the enclosure itself in the prototype design. A neoprene rubber gasket is once again used as the face seal between the enclosure and the lid.

Prototype 1 was completed largely according to plan from a mechanical standpoint. One issue identified was tolerancing between the internal diameters of the printed ABS parts and the external diameters of the PVC part. For this reason, the parts were left as friction fitted together without cement being used between them. The threaded insert holes on the enclosure were also printed too small, leading to a failure to install many of them. Finally, the gasket manufacture proved to be more challenging than expected, and therefore the first prototype was left without neoprene gaskets.

For the next prototype, the 3D tolerancing issues are addressed, allowing for ABS to PVC cement to be used to make waterproof seals between the relevant parts, and the gasket manufacturing process will be refined by printing pieces and then cutting gasket. Waterproof testing of the device showed a mostly working device, with small intrusion into the EC grommet. As a result, the final design uses a larger grommet, discussed in section 11.

For the production of the final market-ready product, the intent is to manufacture all the plastic parts with Tower Gardens' proprietary food-safe, FDA approved proprietary plastic, and to combine the pipe attachments and adapters/fittings into just two parts. While the neoprene gaskets, BSPP, and NPT threaded waterproofing measures will be included in the final design, the need for the PVC to PVC and ABS to PVC cemented joints will be eliminated.

Sensor Calibration, Testing, and Data Transfer

To confirm functional sensors and accurate data collection, all three sensors are tested in solutions/water with known properties. The pH sensor is calibrated using a linear equation relating the voltage output to the pH using three different buffer solutions with known pH levels, i.e. pH 4.0, 7.0, & 10.0. An example resulting voltage-pH relation is as follows:

$$pH(v) = -6.74129v \ + 16.14568$$

The selected pH sensor claims to need calibration every month to ensure accurate readings and avoid sensor drift. Future testing on the pH sensor will validate the pH sensor calibration and help inform the standard procedure for re-calibration in the final product device. Similarly, the EC sensor is tested using buffer solutions provided from the vendor, where a two-point linear model is created relating voltage to EC, utilizing 1413 μS/cm and 12.88 mS/cm buffer solutions. An example resulting voltage-EC relation is as follows:

$$EC(v) = \frac{7122.3603v + 845.2112}{1000} \ \frac{mS}{cm}$$

Temperature correction factors have not been determined for EC measurements. Finally, the temperature sensor is calibrated using water at ambient temperature to relate the output voltage to the temperature values. Sensors are all tested after calibration using solutions of known quantities to ensure the correct procedure which resulted in accurate values to all significant figures.

To facilitate quick, real-time data transmission to the user's mobile application, Supabase, a backend-as-a-service (BaaS) platform that provides a scalable and serverless database with a structured table format is utilized. Supabase automatically generates a RESTful API for seamless integration, requiring an API key for authentication.

The data acquisition process begins with the external sensor modules which measure the pH, EC, and temperature of the water, processing their respective signals before transmission. The EC sensor output is used to infer water depth, as a reading of 0V implies that the sensor is no longer submerged in liquid. In this case, the water depth is said to be LOW, and otherwise HIGH. This also means that the height of the EC sensor is controlled.

Data Collection and Transmission

The sensor data is collected through respective GPIO pins on an ESP32 microcontroller. The ESP32 first generates a local Access Point (AP), which the user connects to. The user then provides the network SSIN and password to allow for the ESP32 to connect to the local Wi-fi and access the internet for data transmission. Once connected to the internet, the ESP32 begins its data collection. Once collected, the sensor data is structured into a JSON payload, ensuring a consistent data format for transmission. The data schema is as follows:

- pH (float)
- EC or Electrical Conductivity (float)
- Temperature (float)
- Water Depth (string: "HIGH" or "LOW")

The structured JSON payload is then transmitted to Supabase using an HTTP POST request. Upon receipt, Supabase stores and organizes the data into predefined table columns based on the schema. The stored dataset includes timestamped entries, allowing for historical tracking and real-time monitoring. It is also trivial to generate unique IDs given each device's MAC address and add this to the data payload, making this an easily scalable solution that can differentiate between various devices. This implementation ensures efficient, scalable, and structured data logging for remote monitoring applications, providing real-time insights into environmental conditions.

Future prototyping will include a slightly different infrastructure for data transmission, where the data will first be sent to an N8N in a standard payload format. The hosted N8N will make use of a webhook that will parse the data in a particular format and upload this data onto Supabase. The backend of the sponsor's application will read off of this Supabase server in order to present this data to the user.

PCB Design and Modules

To safely house all electrical components within the enclosure outlined in the mechanical section, designing a compact PCB is essential. Before moving to PCB design, the circuit is first implemented and tested on a breadboard to verify functionality. EAGLE software is used for schematic and board design, as well as generating Gerber files for fabrication. This allowed for the creation and integration of necessary libraries for each sensor module to be embedded onto the board.

The PCB design begins with the battery, which mounts onto the board via a JST PH 2-pin connector. The battery connects to both the ground and a trace leading to the on/off switch, which is also mounted on the PCB via a JST PH 2-pin connector. The on/off switch then feeds into the voltage input (Vin) pin of an AMS1117 voltage regulator, which ensures that the 3.7V battery output is stepped down to a stable 3.3V for the ESP-32 processor. The AMS1117 chip also includes a ground and a voltage output (V_{out}) pin, which supplies power to the ESP-32, as well as the pH sensor module, EC sensor module, and temperature sensor module. Each module is grounded and has a dedicated signal pin routed to a corresponding GPIO pin on the ESP-32, GPIO32, GPIO33, and GPIO5, respectively.

Additionally, a reset button is implemented on the enclosure, mounted onto the PCB using a JST PH 2-pin connector. One pin is grounded, while the other connects to the EN pin on the ESP-32, enabling easy device resets and troubleshooting capabilities.

A key consideration in PCB development is spacing, as dimensions are limited to 125mm by 75mm to ensure all components fit within the enclosure. To optimize space, modules are mounted using non-conductive standoffs. Stacking the PCB with the modules maximizes space efficiency while ensuring proper wire feed-in to the pipes housing the sensors. As a result, mounting holes for the modules are strategically placed on the PCB, as shown in Figure 13.

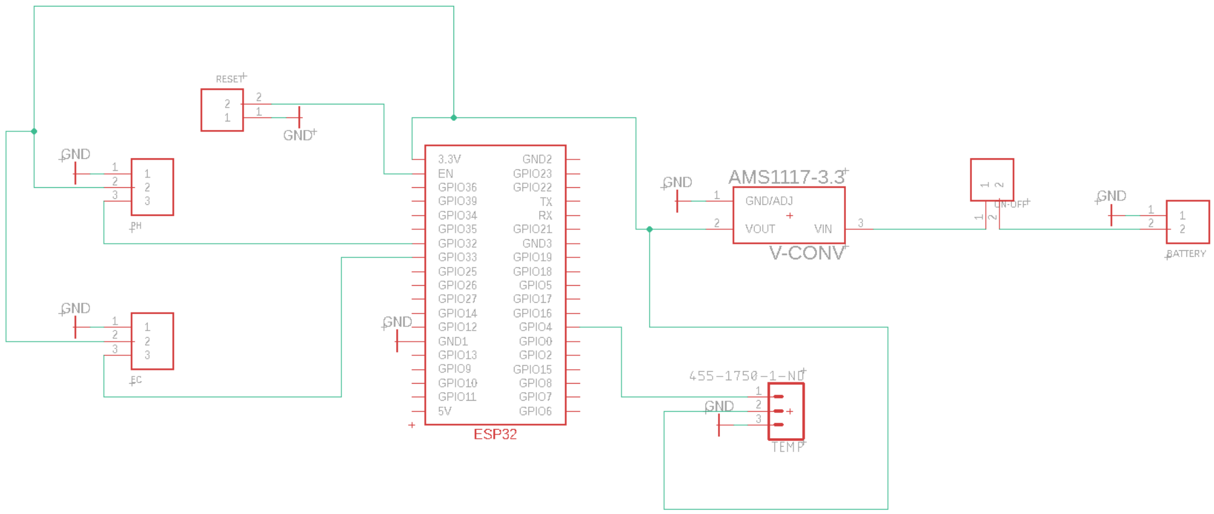


Figure 13a: Prototype 1 PCB Schematic Layout

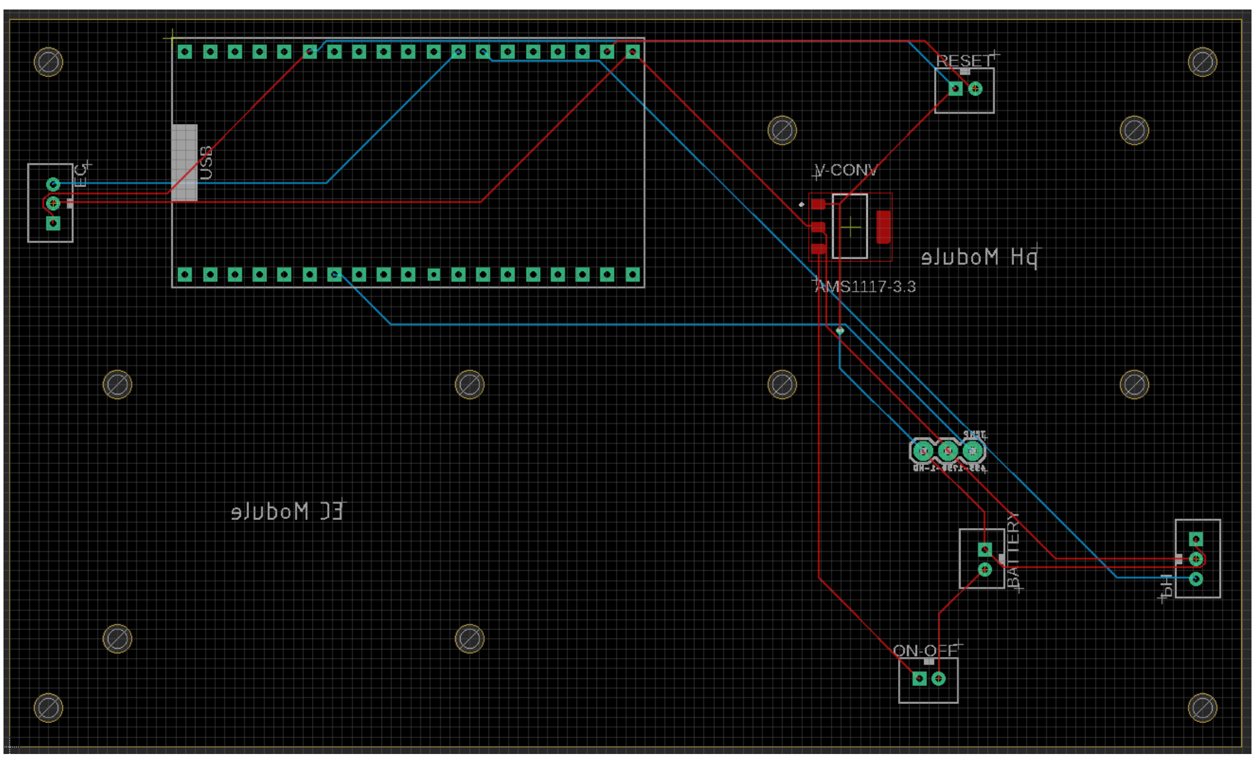


Figure 13b: Prototype 1 PCB Board Design

After finalizing the board design and generating the necessary files, the PCB is ordered. Once delivered, soldering of all components onto the board allows for testing of the PCB to confirm functionality. Although the PCB was unable to succeed prior to presentation day, a trace test the following day was performed which pinpointed the issue. The problem was not with the PCB itself but rather simple engineering oversight as we had neglected to properly attach the on/off switch, preventing the battery from supplying power to the components. Once this was corrected, the ESP-32 successfully established communication and verified connectivity.

From this PCB prototyping, the next steps include integrating the various modules, including the ESP32, pH, EC, and temperature module, into the PCB itself. This will drastically reduce the height footprint of the board and allow for a cleaner and more compact enclosure design. Also, extra buttons, indicator lights, and a more convenient charging method will be added to the exterior of the enclosure/lid to allow for increased user interfacing. Buttons include adding a wake-up function, lights will include an indicator light when on or when battery gets low, and a charging port will be added such that the user does not have to disassemble the device to charge. Adding the buttons and charging port also adds complexity to the water proofing of the device.

11. Final Design

The final design can be grouped into three separated categories: mechanical packaging, electronics, and software. Each of these categories provides for a group of specified customer requirements, ensuring necessary design elements. A detailed bill of materials is shown below in Figure 14, detailing necessary parts to create the final prototype design.

Part Name	Vendor	Vendor Part Number	Unit Price	Quantity	Price
Enclosure Box				1	
Enclosure Lid				1	
pH pipe attachment				1	
EC/temp pipe attachement				1	
pH sensor adapter				1	
3/4" PVC pipe*	Home Depot	224411	$2.79	1	$2.79
1-1/2" PVC pipe*	Home Depot	PVC071120200HA	$4.98	1	$4.98
Oatey Purple Primer*	Home Depot	3075633	$9.27	1	$9.27
Oatey Regular PVC Cement*	Home Depot	310133	$7.96	1	$7.96
Oatey ABS to PVC Transition Cement*	Home Depot	309003	$9.29	1	$9.29
Neoprene Rubber Sheet (Gasket Material)*	Grainger	1MXC8	$12.44	1	$12.44
#4-40 Heat-Set Insert*	Grainger	1GML6	$15.42/pack of 100	1	$15.42
#4-40 x 3/8" Long Stainless Steel Screw*	McMaster-Carr	91771A108	$6.56/pack of 100	1	$6.56
Cut-to-Size Grommets*	McMaster-Carr	2633N22	$9.04/pack of 10	1	$9.04
Cut-to-Size Grommets*	McMaster-Carr	9307K884	$9.83/pack of 10	1	$9.83
1-1/2" PVC NPT Pipe Fitting	McMaster-Carr	4880K85	$1.64	1	$1.64
1-1/2" PVC NPT Plug	McMaster-Carr	4880K545	$2.83	1	$2.83
On/Off Round Rocker Switches*	Amazon	B07S1MV462	$6.99/pack of 5	1	$6.99
Momentary Push Button*	Amazon	B083JWJPW5	$7.99/pack of 12	1	$7.99
PCB v2	In House			1	
Gravity: 7/24 Industrial Analog pH Meter Kit	DFRobot	SEN0169-V2	$64.90	1	$64.90
Gravity Analog Electrical Conductivity Sensor Meter V2 K=1	DFRobot	DFR0300	$69.90	1	$69.90
DS18B20 Temperature Sensor Module Kit 1m*	Amazon	B0924NBNZP	$14.99/pack of 4	1	$14.99
AMS1117-3.3V Low Voltage Regulator*	Amazon	B0881X2YGB	$6.99/pack of 10	1	$6.99
3.7V Lipo Battery 2000mAh Rechargeable	Amazon	B0CNLPK1F8	$9.99	1	$9.99
LED	In House			1	
LED Besel	Digikey	L65DR12L-ND	$3.71	1	$3.71
Type C Female Charge Port Waterproof	Amazon	13494ST-1	$4.99	1	$4.99
HiLetgo Type-c USB 5V Battery Charger Module*	Amazon	B07PKND8KG	$5.99/pack of 3	1	$5.99
JST PH Connector Kit 580PCs*	Amazon	B0BHT1FQGY	$9.99/pack of 580	1	$9.99
HiLetgo ESP-WROOM-32 Development Board	Amazon	B0718T232Z	$9.99	1	$9.99
				Total:	**$308.47**

Figure 14: Bill of Materials for Final Prototype

Mechanical Packaging

For the mechanical packaging, a key focus is on waterproofing the packaging to promote safety in long term water conditions, as well as a modular design giving the ability to troubleshoot and replace sensors, improving maintainability. In terms of the packaging, only a few changes are made from the first prototype: larger tolerances on the ABS printed parts allow for the PVC cement to be used between joining parts preventing any water ingress, larger sizing on the heat set insert holes allow for significantly easier and stronger connections between the enclosure and pipe holder parts, and finally a larger grommet is used along the EC sensor's shaft, as testing showed initial water ingress in the prototype grommet. Despite these changes, the bulk of the packaging is rather similar to the first prototype. These fixes are shown in the final physical design shown in Figure 15.

Figure 15: Final Device Prototype Packaging

These packaging changes help ensure the customer requirements, keeping maintenance and troubleshooting capabilities through a modular design, but also balancing a tight design to prevent water damage to all sensors and electronics contained inside the device. As seen from the bill of materials above, the sensors take up a large portion of the total cost of the device, so it is paramount to keeping them safe and operational.

Electronics

The electronics are fundamental to the functionality of the device. The custom-designed PCB integrates all the necessary circuitry for amplifying, filtering, and processing signals from the three sensors, shown in Figure 16. Each sensor is supported by its own dedicated circuitry to ensure reliable communication with the ESP32 processor. Two major components of the circuitry center around the pH and EC sensor interfaces. The pH sensing circuit uses a pair of cascaded operational amplifiers to condition the signal before feeding it into the ESP32. Additionally, the EC sensor relies on an oscillator chip working in conjunction with an operational amplifier to generate and condition the signal, while a series of three additional operational amplifiers provide stable grounding for the sensor.

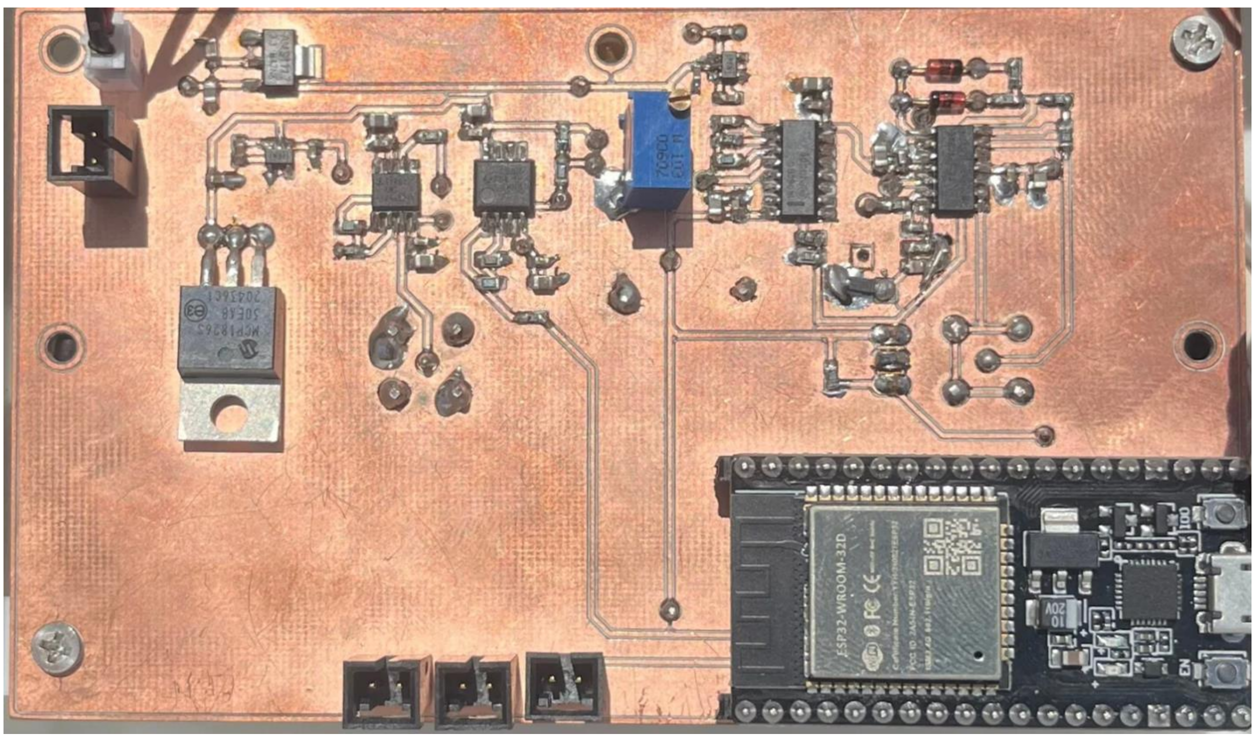


Figure 16: Final PCB Design

Throughout the first and second prototyping phases, an iterative design and testing process was crucial. For each subsystem: voltage control, pH, EC, temperature, battery, and charging, the workflow involved research, circuit design, breadboarding, testing, and refinement. This repeated until the circuits produced consistent, accurate, and intended results. Although creating a custom PCB added significant complexity, it was a requirement from the project sponsor to ensure the design was manufacturable, consistent, and robust.

The PCB also incorporates interactive components for user control, as shown in Figure 17. A physical on/off switch allows users to power the device manually, while a reset button enables readings to be taken at arbitrary times. Another button is dedicated to calibration: a single press activates calibration mode and captures the first reference value, while a double press records the second. An onboard LED provides real-time device status indicators, with distinct colors, flash patterns, and behaviors indicating distinct events such as power on/off, active sensor readings, sensor errors, low battery, and the need for sensor recalibration.

Figure 17: Final Device Buttons and Operations

Overall, the electronics serve as the critical bridge between the mechanical and software elements of the device, ensuring seamless operation and reliable performance.

Software

The software for the Tower Commander was crucial to ensuring data collection, processing and user interaction. The software architecture was split into three components: the microcontroller driving code, the backend automation workflows, and the user-facing frontend application.

On the device side, the ESP32 microcontroller was programmed to minimize power consumption. This was done by using the default sleep modes that are available through online libraries. To maximize battery life, we took the advantage of the “deep sleep mode” as compared to the regular “sleep mode” to ensure minimal power consumption when not in operation. Upon waking, it would connect to Wi-Fi, take sensor readings (pH, Electrical Conductivity and temperature), compute the raw voltage values into a JSON payload, and transmit it to the backend via a webhook before returning to deep sleep. This approach maximized battery life while also reporting data; thus, ensuring that customer requirement of a 30-day battery life is met.

For the backend processing, we implemented workflows using “n8n”, with the schematic shown in Figure 18. Incoming data from the ESP was captured by the n8n webhook and then structured for entry into the “Supabase” database, another service available for remote data storage. Data in Supabase was divided into multiple tables corresponding to sensor types to allow for efficient storage and retrieval. Separate tables are also used for calibration to allow for storing data temporarily until both calibration points are retrieved for linear interpolation. This can be used to then calculate the slope and intercept, which is later used by n8n for converting raw voltages into sensible values.

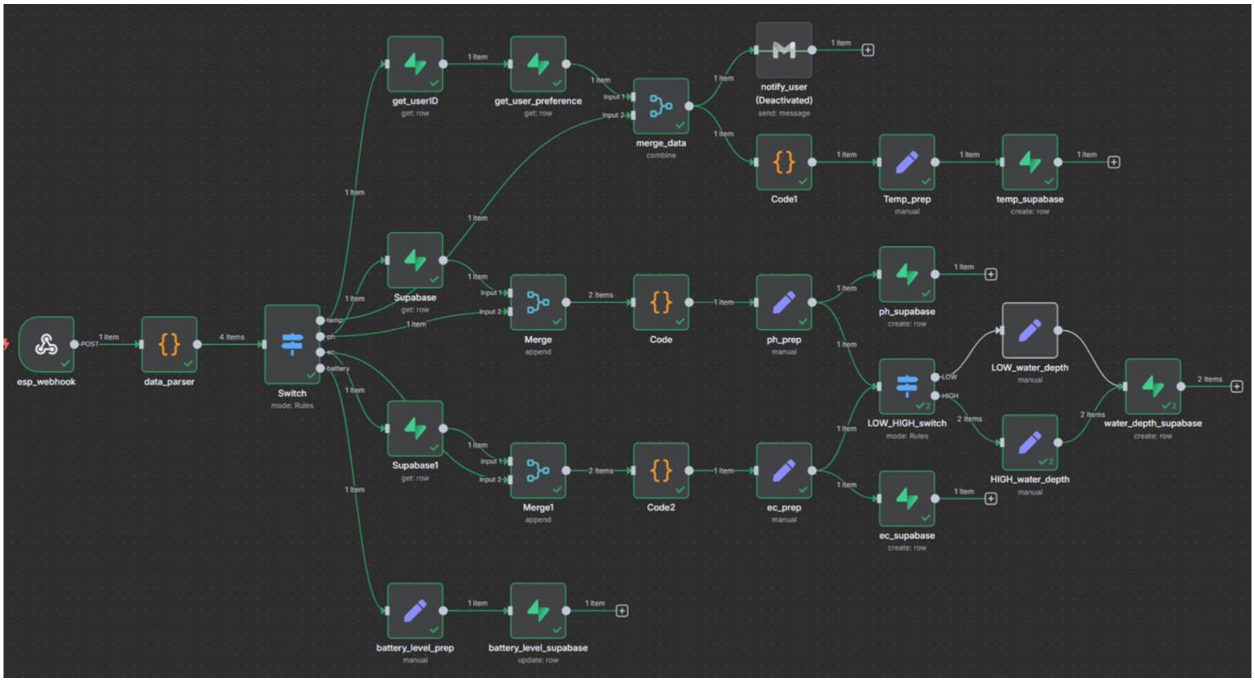


Figure 18: N8N Webhook Flow

The frontend application was developed using FlutterFlow, providing users with a friendly and easy-to-use interface, as shown in Figure 19. The homepage displays a list of registered Tower Commander devices for a particular user. On clicking on a particular device, a detailed device page shows up that displays real-time sensor data based on past readings. On this page, the user has a recalibration button to manually set the values of calibration solutions that the user is using. Also, a “view history” button also exists on this page which navigates to a page showing a line graph of the past data of each sensor to track how the water property in that tower garden is evolving with time. It also shows the date when the sensor was last calibrated to ensure that the sensor does not go out of its calibration range.

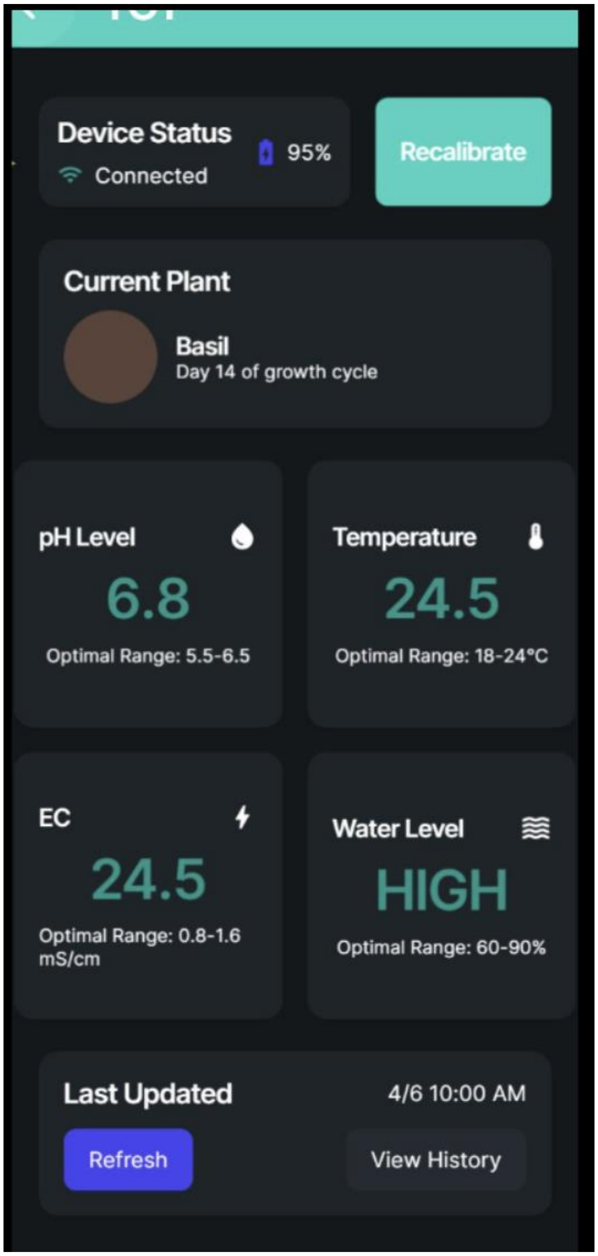


Figure 19: Mobile Application for Analyzing User's Tower Garden Water Health

This software architecture successfully enables wireless data capture, storage, and display while maintaining low power operation and user-friendly recalibration, all critical to meeting critical customer requirements. This implemented system also allows Tower farmers to remotely monitor their plant health and keep track of trends that could later be harmful. These features truly compliments to the successful design and implementation of the product.

12. Manufacturing

In general, the previously discussed final design is a prototype demonstrating a strong and functional proof of concept, and such is not the market ready device. Production details for this prototypical final design can be found in the fabrication package, though the future goal is to manufacture the device on a much larger, industrial scale. Mass manufacturing of the device is vastly simplified by using single piece, injection molded, proprietary, food safe, antimicrobial Tower Garden plastic over the prototype's PVC pipes and 3D printed parts. Although parts still are modular to ensure maintainability, this change in the manufacturing process ensures a food safe device, an incredibly important customer requirement. Since the plan is to have this device sold as a product through Tower Garden, using the patented plastic is a reasonable specification. Similarly, processes need to be put into place to mass manufacture the custom PCB which integrates the sensor modules and ESP onto the board, also done by the Tower Garden company. Overall, the target market cost for a final device is targeted at $99, which seems reasonable given the changes and bulk purchasing from mass manufacturing. However, custom sensors is a next step that can significantly decrease the sensor cost of the device, since in general the bulk of the cost comes from the waterproof sensing units. As a result, simpler or custom designed sensors could be used to better match the desired requirements and specifications of the product, helping to reduce overall cost as well.

13. Societal, Environmental, and Sustainability Considerations

To evaluate the social impact of implementing a wireless smart sensing device in Tower Gardens, it is important to define the device's function. The Tower Commander measures water health data and integrates with a mobile application to automate monitoring. The functional unit is one water diagnostics measuring device per Tower Garden.

The product has four lifecycle stages that should be considered: in production, raw material extraction, the manufacturing of sensors and electronic components, and device assembly. During processing, the consumer installs the device in a Tower Garden and integrates the device wirelessly with associated software. Day-to-day farming operations and monitoring by users occur during the operation stage before finally the end of life for the device is the disposal or recycling that occurs when its quality has decayed beyond usefulness.

Stakeholder groups, social impact categories, and key indicators of the product's inventory analysis are listed in Table 4.

Table 4: Stakeholder Groups and Social Impact Categories

Lifecycle Stage	Stakeholder Group	Social Impact Category	Indicators
Production	**Workers** (Manufacturing and assembly employees)	Fair salary, Safe working conditions, Working hours	Wages compared to industry standard, accident rates, average working hours
Processing	**Consumers** (Farmers and individual users)	Access to technology, Product safety	Device affordability, ease of use, compliance with food safety regulations
Operation	**Consumers** (Farmers and individual users) **Local Community** (Communities around production sites)	Employment opportunities, Environmental impact	% of local hiring, pollution from manufacturing processes
End of Life	**Society** (Wider agricultural sector) **Value-Chain Actors** (Supply	Contribution to sustainable farming, Economic impact, Recycling/sustainability	Reduction in water usage, increased crop yield efficiency

	Chain - Recycled Parts Users)		

An interpretation of the lifecycle stages, stakeholder groups, and social impacts yield both positive and negative projected effects. For workers, this device could lead to potential job creation through the implementation of mass manufacturing. To farmers and consumers, the device promotes increased efficiency, less manual labor, improved crop yield, and healthier, thriving food production. In local communities, positive impacts could include economic growth through a more cost-efficient farming sector. To value-chain actors, benefits could include encouragement of sustainable material sourcing and ethical supply chain management. One of the most important benefits is the reduced water waste and increased contribution to environmentally friendly agricultural practices in society.

It is also important to take note of and consider mitigation measures for the potential negative impacts that widespread adoption of the product could have on various groups. With increased manufacturing, it is important to promote fair wages and safe working conditions by sourcing from certified ethical manufacturers. Unless proper recycling programs are implemented, device disposal can negatively impact communities. Finally, there is the potential introduction of an affordability gap between small and large farms. The device could widen the gap between the quantity and quality of crops that are produced by large farms relative to smaller businesses. Understanding these societal, environmental and sustainability considerations is critical to the team's design ideas and the device's ethical success.

14. Risk Assessment, Safety, and Liability

Potential risks of the device are listed in Table 5 below, where each hazard has an associated severity and probability. As seen in the table, the total risk score is calculated as the product between severity and probability, with a minimum score of 1 and maximum score of 100. From this, the risk scores for all potential risks are low, with the top scores coming from potential water infiltration (20) and battery failure (10). These score highest due solely from the hazards being very severe for the device with the potential to harm the user, tower garden, or produce if the event occurs. The probabilities are very low scoring, as analysis in the report and appendices support, resulting in total risk scores that are significantly lower than the maximum or even halfway point, demonstrating very low risk when using this device. It is clear to see from this that there are no major risks to the user when operating this device. The designed device does not pose any serious concerns or potential damages to any person (user or otherwise) or the facilities, including tower gardens and surrounding environment.

Table 5: Risk Assessment of Potential Device Hazards

Hazard	Severity	Probability	Risk Score
Water Infiltration	10	2	20
Tube breaks	5	1	5
Sensor Drift	1	3	3
Battery Failure	10	1	10
Poor User Calibration	1	4	4
Plant Interference	1	4	4

15. Patent Claims and Commercialization

The Tower Commander's patentability is focused on its unique and novel features. Some specific innovations and design elements that distinguish the Tower Commander product from existing patents are the specific integration with Tower Garden access panel as well as the slightly less novel features such as method for data upload, modularity, energy-efficient "Deep Sleep" power management, and calibration, specifically through the lens of aeroponic sensing applications. The body of the claim and its dependents could be similar to the following:

"An apparatus comprising:

- a waterproof enclosure configured to mount into an access panel of a vertical hydroponic farming system;
- a plurality of sensors positioned within the enclosure, the sensors configured to measure at least pH, electrical conductivity (EC), water temperature, and water depth;
- wherein the enclosure is constructed from food-safe, water-resistant materials; and
- wherein the apparatus interfaces with the hydroponic system without requiring modification to the structure of the hydroponic farming tower."

The apparatus of Claim 1,
wherein sensor data is transmitted wirelessly via Wi-Fi to a mobile application;
wherein the apparatus is configured to aggregate and synchronize data from multiple hydroponic towers.

The apparatus of Claim 1,

further comprising modular sensor housings detachably coupled to the enclosure;

wherein each sensor housing is individually waterproof, user-replaceable, and serviceable without full disassembly of the apparatus.

The apparatus of Claim 1,
further comprising a power management system configured to:

- place the apparatus into a low-power deep sleep mode during inactive periods, and
- wake the apparatus for scheduled data collection intervals or on-demand queries, wherein the apparatus operates for more than 30 consecutive days on a single rechargeable battery charge.

The apparatus of Claim 1,
further comprising a calibration prompting system configured to:

- generate user notifications for optional sensor recalibration based on elapsed time or predefined usage cycles,
- without automatic internal fault diagnosis or autonomous calibration alarms."

In addition to the device's patentability, the Tower Commander is positioned for direct commercialization as an accessory product for Tower Garden systems. The device's marketing would focus on Tower Garden farmers' and residential growers' major pain point: labor-intensive manual water monitoring. With a target retail price of $99, it offers a fast return on investment with an estimated value return period of three to four months regardless of the farm's scale.

The commercialization strategy includes the target market, sales channels, product scaling, expansion opportunities, and future product development in addition to the aforementioned intellectual property strategy. The primary market is new and existing Tower Garden users at any scale. A focus can be placed on farms managing more than 25 towers, as this is where labor savings are most impactful because it takes one person more than two hours of labor each day to manually monitor the water in 25 Tower Gardens. The optimal channel for Tower Garden sales is through direct partnership with the Tower Garden company for co-marketing, sales via the Tower Garden website as an accessory, and outreach to large Tower Garden customers. Manufacturing the product at scale makes up the majority of the future work. Mass manufacturing can be achieved by leveraging injection-mold fabrication rather than 3D-printed assembly of components which makes production scaling feasible with low lead-times. Additional future work is the design developments that can be made to build beyond just Tower Garden integration. The device could be adapted for broader hydroponic, aquarium, and pool monitoring markets through minor physical interface redesigns. Finally, additional features like further sensing, lighting and humidity monitoring, and solar-powered charging are under consideration to expand the product line and offer premium models.

16. Team Member Contributions

Every team member has played an integral role in the project's development, contributing extensively to ideation, concept refinement, design, component research, report writing, and revisions. Each member has actively participated in discussions, offering valuable insights and technical expertise to shape a well-rounded and feasible solution.

Viraj, Sid, and Ben have been focused on ensuring that every aspect of the project remains within scope while prioritizing feasibility. Their efforts are geared toward developing an optimal and practical solution that meets the needs of Tower Commander owners. By evaluating constraints and refining the overall system architecture, they help ensure that the final product is both functional and efficient.

Rachel, as the electrical lead, has been ensuring all components are compatible. This includes researching individual components, analyzing datasheets, and cross-referencing specifications to guarantee seamless, or at least hassle-free, integration of all electrical elements. She was lead designer of the circuitry and PCB, though she had help from Viraj and Sid.

Brody and Kyle, serving as Technical and Design leaders, have played an instrumental role in ensuring the prompt execution of critical development tasks. Kyle helped significantly with the CAD drawings. Brody was the lead mechanical designer, spending time ensuring a waterproof design, who led the development and assembly of the packaging of the prototype.

Ben, Sid and Viraj, in addition to their contributions overall, took the lead in creating the Week 5 presentation slides, effectively synthesizing complex technical details into a clear and engaging format. Brody and Viraj’s presentation provided a professional overview of the project’s progress, key challenges, and next steps, helping to keep the team aligned and informed. Ben was the primary editor of the report and ensured everyone contributed their respective strengths and knowledge to the report.

Viraj and the team have been instrumental in facilitating seamless communication and coordination among themselves, as well as between the team and external stakeholders, including the sponsor and advisor. The team's efforts in organizing meetings and maintaining project alignment have been crucial in ensuring steady progress.

Collectively, the team has invested significant time and effort in refining concepts, troubleshooting design challenges, keeping the project on track, and making progress with the prototype design, assembly, and redesign. Through continuous collaboration, research, and iteration, we are steadily progressing toward developing a fully functional and optimized solution.

17. Conclusions and Future Work

Through a rigorous evaluation of the initial concepts against customer requirements and engineering specifications, the Beta Concept is selected, designed, and prototyped. This design demonstrates clear advantages over alternative concepts in terms of feasibility, cost-effectiveness, and real-world applicability, making it the most practical choice for both farmers and homeowners. Through direct engineering analyses, calculations, and initial experiments, a final prototype is developed which gives significant insight into future steps to transform the prototype into a final product. The physical assembly process that makes up the prototype consists of 3D-printed pieces, store-bought PVC pipes, fasteners, and waterproofing cement. In the finished product, this assembly can be replaced with a single injection-molded product made of the proprietary food-grade plastic that is employed in Tower Garden products. The design of this product will correspond to the design laid out in the *Fabrication Package*, with minor edits to accommodate for injection-mold fabrication requirements. Along with the shift to injection-molding processes, the finished product should undergo mass manufacturing to optimize the cost of each component of the product build. This may also decrease the costs of sensor components in the product. To further decrease sensor costs, research and development should be conducted to design cost-optimized substitutes of the relevant sensors. An example avenue for cost optimization is in the electrical conductivity sensor. The market-bought sensor can potentially be replicated with a two-wire system that measures the drop in voltage due to the water's resistance. The voltage drop can be used to calculate the water's electrical conductivity.

The precision of the prototype's sensors is two significant figures. The prototyping process also confirmed the electronics and coding functionality through successful sensor readings and instant data transfer when hooked up to the breadboard, even when powered by the chosen battery. The chosen battery and calculations proved that using the deep sleep approach will drastically increase the battery life, though the tradeoff comes at the expense of user-specified data collection at any time. The final battery life comes in at about 32.5 days when optimized with the three-phase battery settings. Next steps could include looking into a solar cell solution to help improve the battery life and promote on-demand water health readings. An optimized solar-powered battery would require minimal attention or upkeep from farmers. Pertaining to the device's electronics, the PCB with integrated modules could be further innovated to promote advanced functionality. Additional software improvements could also be made to add app and alert customization for users. The final prototype is complete, functional and demonstrates a proof-of-concept device that meets nearly all customer requirements, with further effort needed to refine the mass manufacturability and cost optimization aspects of the product.

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Appendices

Appendix A: Power Consumption Analysis and Calculations

A.1 – Prototype Charge Calculations

Known values:

Current consumed when actively sensing $= 150\ mA$

Time when actively sensing $= 4\min * 3\ sensors = \frac{12}{60}hr$ (estimated as most readings at 4 readings per day taking 1 minute for each of the 3 sensors)

Current consumed when not actively sensing (light sleep) $= 20mA$

Time when inactive $= 24\ hr - \frac{12}{60}hr = 23.8\ hr$

Battery Capacity $= 3000\ mAh$

Calculations:

Energy used per day when active $= 150 \times \frac{12}{60} = 30\frac{mAh}{day}$

Energy used per day when not active $= 20mA \times 23.8hr = 476\frac{mAh}{day}$

Total daily consumption $= 30\frac{mAh}{day} + 476\frac{mAh}{day} = 506\frac{mAh}{day}$

Total consumption over 30 days $= 506\frac{mAh}{day} \times 30\ days = 15{,}180\ mAh$

∴ Battery Life $= \frac{3000\ mAh}{15{,}180\ mAh} \times 30\ days = 5.93\ days \sim 6\ days$

A.2 – Improved Device Charge Calculations

Known values:

Active: 3 sensors activate 4x per day (60s each)

- Sensing & transmitting on WiFi **150 mA**

Sleep: ESP32 WiFi-on modem sleep **20 mA**
Deep Sleep: Disconnects from WiFi **0.1 mA**
Battery Capacity $= 3000\ mAh$

Calculations:

For 1 Day: (150mA * 0.2hr) + (20mA * 3.0hr) + (0.1 mA * 20.8hr)

= (30 + 60 + 2.08) mAh = 92.08 mAh

∴ Battery Life $= \frac{3000\ mAh}{92.08\ mAh} \times 30\ days = 32.5\ days\ > 30\ days$

Appendix B: Mechanical Design Analysis and Calculations

B.1 – Prototype 3D Printed ABS pH Sensor Threads

pH Sensor Thread Size: BSPP G3/4 gives $D_{smin} = 1.041\ in, E_{nmax} = 0.995\ in, n = 14, L_e = 0.773\ in$ [ ]

3D printed ABS material strength $S_{ABS} = 3060\ psi$ (0.6 of the ultimate tensile strength) [ ]

Shear area $A_{ts} = \pi n L_e D_{smin} * \left[\frac{1}{2n} + 0.57735(D_{smin} - E_{nmax})\right] = \pi(14)(0.773)(1.041) * [\frac{1}{2(14)} + 0.57735(1.041 - 0.995) = 2.199\ in^2$

Therefore maximum force is $F_{max} = S_{ABS} * A_{ts} = 3060\ psi * 2.199\ in^2 = 6728\ lb$

Safety Factor of this part is $FOS = \frac{F}{F_{app}} = \frac{6728}{12} =$ 560.7, meaning the part will not break.

B.2 – Prototype PVC to ABS Joints

The Lap Shear Strength (LSS) of the Oatey green PVC to ABS transition cement is read directly off the product as $LSS_{green} = 600\ psi$

The pH PVC tube to pH ABS sensor holder area is found via the CAD model, $A_{bond} = 2.69\ in^2$

This means the safety factor for this part is $FOS = \frac{LSS_{green}}{F_{app}/A_{bond}} = \frac{600}{12/2.69} = 134.5$

The pH PVC tube to pH enclosure area is found via the CAD model, $A_{bond} = 3.308\ in^2$

This means the safety factor for this part is $FOS = \frac{LSS_{green}}{F_{app}/A_{bond}} = \frac{600}{12/3.308} = 165.4$

The EC PVC tube to EC ABS enclosure area is found via the CAD model, $A_{bond} = 6.009\ in^2$

This means the safety factor for this part is $FOS = \frac{LSS_{green}}{F_{app}/A_{bond}} = \frac{600}{12/6.009} = 300.5$

B.3 – Prototype PVC to PVC Joints

The Lap Shear Strength (LSS) of the Oatey clear PVC to PVC transition cement is read directly off the product as $LSS_{clear} = 250\ psi$

The EC PVC tube to pipe fitting area is found via the CAD model, $A_{bond} = 6.997\ in^2$

This means the safety factor for this part is $FOS = \frac{LSS_{clear}}{F_{app}/A_{bond}} = \frac{250}{12/6.997} = 145.8$

The PVC pipe fitting to PVC Endcap area is found via the CAD model, $A_{bond} = 1.363\ in^2$

This means the safety factor for this part is $FOS = \frac{LSS_{clear}}{F_{app}/A_{bond}} = \frac{250}{12/1.363} = 18.7$