URBAN VERTICAL FARMING

ME 423 - MACHINE DESIGN: FINAL PROJECT REPORT **TEAM 2: GROOT**

The Mission:

To leverage India's technical prowess, favorable cost of manufacturing, and conducive market to re-imagine the future of agriculture with a *purpose-built, technology-enabled, modular vertical farming* panacea to solve one of the most critical global challenges of our generation: *global food security.*

Executive Summary:

Our global population is growing and getting denser. We will need to grow significantly more food using significantly less land and resources to meet the rising demand for more food, of higher quality, through fragile small landholder systems while also coping with climate change, soil erosion, biodiversity loss, and unpredictability of yield.

We propose an innovative and technology-driven vertical farming solution, which has the potential to revolutionize global food production — it can operate anywhere, virtually invincible against pests, pathogens, and poor weather, and producing local, fresh, high-quality, lower-carbon food year-round with 99% less land and water use.

Food Security: An Impending Global challenge



9.8 Bn	68%	70%
Projected Global Population	Projected Urbanization	Increase in Food Production

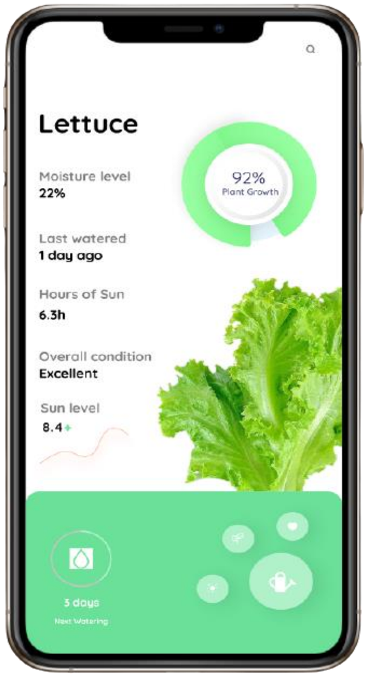
1. By 2050, our global population is projected to reach 9.8 billion. To feed this massive population, we will need to increase our agricultural output by 80% over current levels. Putting this number into perspective, *we will need to grow more food in the next 35 to 40 years than the previous 10,000 years combined.*
2. *About 68% of those 9.8 billion in 2050 will live in urban city centers, compared to the current 56%.* Why is this a problem? People living in rural areas only buy ~40% of their food supply from the market and produce the rest 60%. However, people living in urban areas rely on the market for ~90% of their food supply (twice the rural dependence) => *Market supplies must double every time a person migrates from an agrarian to an urban setting.*
3. Agriculture is exceptionally resource-intensive (Land + Fresh Water + Labour), unpredictable, and heavily influenced by the climate (again, volatile) and soil type (limited human control on soil type). We can't "manufacture" more land or create "more" fresh water to feed this growing population. Arable land is scarce and limited, and so is freshwater. *Only 12% of the world's land can ever be used for farming.* Agriculture is the *single largest consumer of Freshwater, accounting for 70 percent of global usage!*
4. Presently, 80% of food for the developing world is produced by small landholder systems, which are complex, highly heterogeneous, fragile, low in productivity, and dominated by small-scale, poor farmers, precisely the case with the Indian agriculture, which employs 2 in every 5 economically active people.

Thus, not only is our global population becoming bigger, but it's also getting denser. *We will need to grow significantly more food using significantly less land and resources to meet the rising demand for more food, of higher quality, through fragile small landholder systems while also coping with climate change, soil erosion, biodiversity loss, and unpredictable* *output.* Secondary problems like food contamination, nutrient loss in extended supply chains, and chemical fertilizer use also need to be solved.

Modular Vertical Farming: Re-Inventing Food Production

Our product will help current farmers and the urban populace who are interested in gardening to grow crops in underutilized spaces (like abandoned buildings, trucks, balconies, corridors, terraces) in vertically stacked layers (using racking mechanism) with controlled-environment agriculture (humidity, nutrient supply, temperature, light, water), optimizing plant growth (tailored conditions for each crop) with soilless farming techniques such as hydroponics leveraging automation and monitoring systems for enhanced traceability, visibility, and productivity.

1. Essentially, it involves growing food in 3 dimensions => multiplying *10x - 20x yield* on the same 2D piece of land.
2. Since the crops would be grown in a controlled enclosure, it would be *climate-proof / weather agnostic* which would imply:
   a. *Independence from local seasonal variations* / geographical factors and robust *control over environmental factors.*
   b. This will also enable *all-year-round food production* because of reduced dependence on seasons.
   c. No dust, no pests => no usage of chemical pesticides and insecticides needed
3. *Predictable output:* Reduced vulnerability to the mercy of freshwater availability, climate, and soil combined with control and visibility over all factors of production would let us produce predictably, *providing greater flexibility to farmers to vary the yield of different crops according to market conditions to optimize profits*.
4. *Huge savings on Freshwater, fertilizers, and Land use:* By studying the operation of vertical farms, we estimate that we can achieve the exact crop yield with 90-99% Less Water use, 90-99% Less Fertilizer use, 90-99% Less Land use.

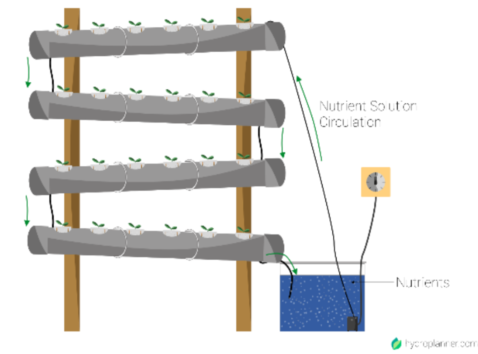


5. *Shortened Agri-Supply Chain:* Usually, the food material is packaged and moved from the farm to the city markets, exchanging multiple hands in 1-2 days, exposing the food to *contamination and destroying nutrient content* by the time it reaches your plates. Growing food in urban areas *enables hyper-local sales, where food reaches your plate from the farm in mere hours.*

Mechanical System Design:

Grow Trays

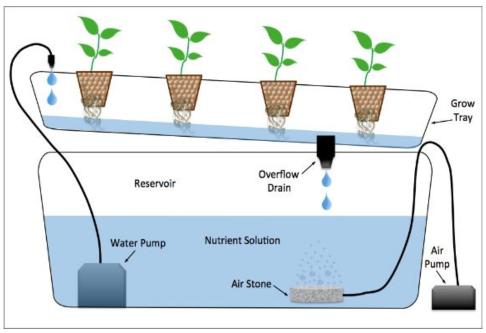
Grow trays are the most integral part of our hydroponic system which physically withholds the plants providing a continuous flow of nutrients and water. We considered the following design options for the grow tray based on market products and concept DIYs.



a) Pipe System:

Pros:
Efficient use of water and nutrients

Cons:
1. Too many failure points (connectors / joints, leakages etc.)
2. Hard maintenance (tough to replace crops, clogging etc.)

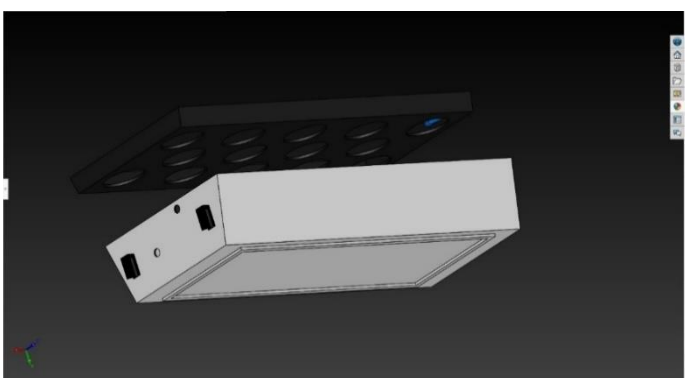


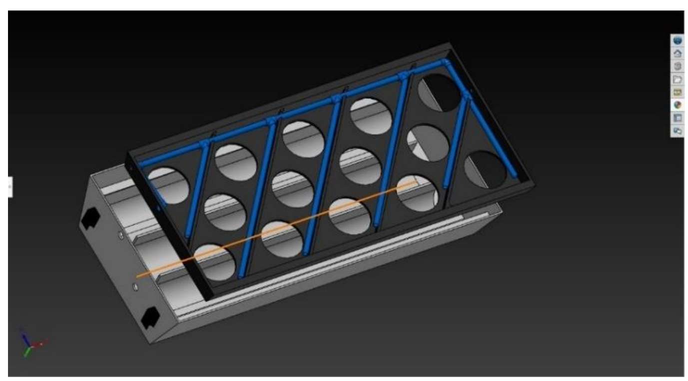
b) Flat-Tray System

Pros:
Aesthetic, Easy to maintain (no connectors/joints, no leakages etc.)

Cons:
Inefficient use of water & nutrients Large space required

Our Design

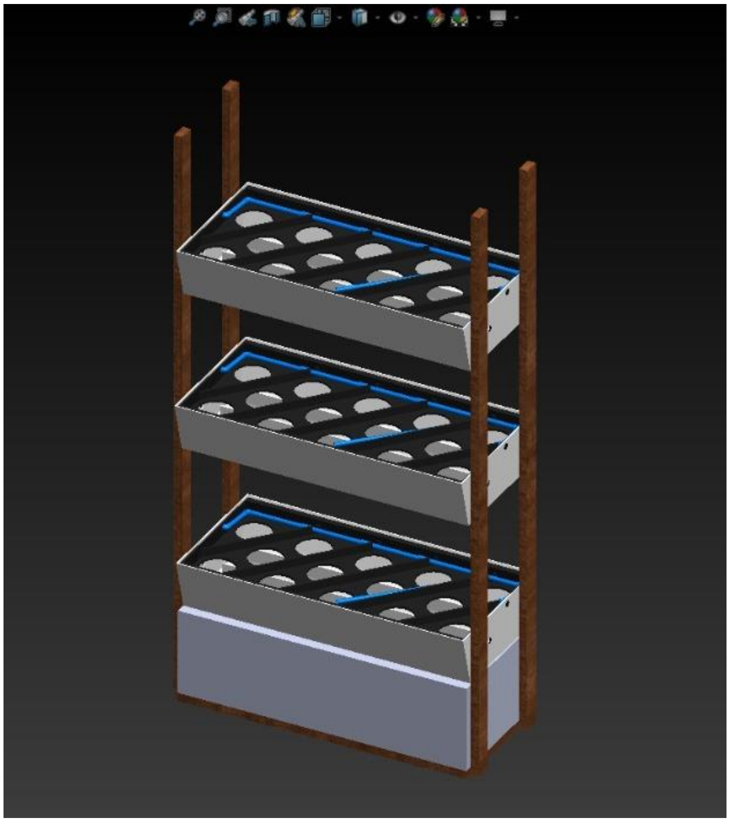




Our design is a hybrid approach of the two. Our tray is made in two components - top & bottom. The top component holds the plants hanging and has a complete drip system laid out in a mesh pattern and thus is extremely efficient with use of water and nutrients. The bottom part meanwhile acts as a local reservoir which accommodates the out-flow of overflow water and also helps maintain humidity and temperature.

Frame & Exoskeleton

Our aim with this design is to build a system that customers can easily assemble on their own and the end assembly would have a very compact and aesthetically pleasing look which looks like a piece of beautiful furniture. The design also provides a flexible modular option to customers allowing them to extend and reduce the number of grow trays and modules and also manage different crops with different environment settings at each tray/module at the same time.
At bottom rests the control unit and main reservoir of our vertical mini-farm. Control unit is also the source of power to lights connected at the bottom of each tray and on the top shelter. Each module/tray can be easily removed and mounted with an advanced clip design mounting.

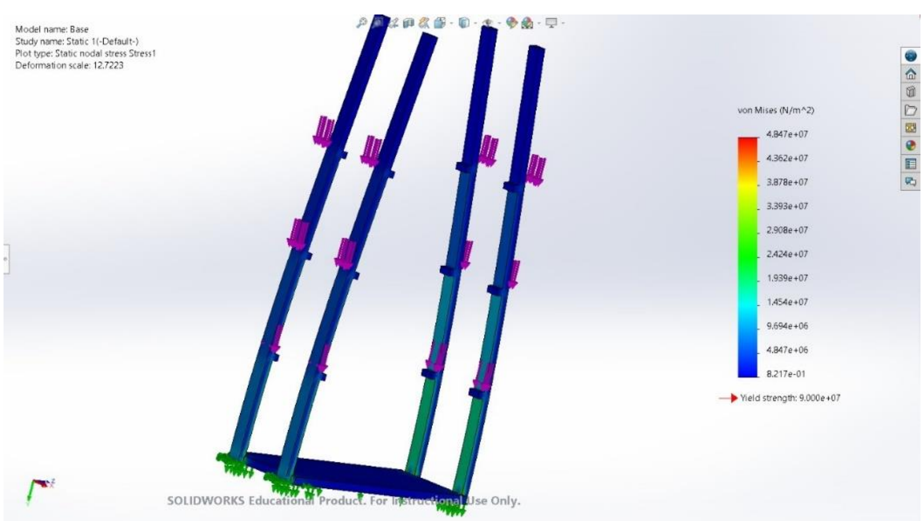


FEA & Material Selection

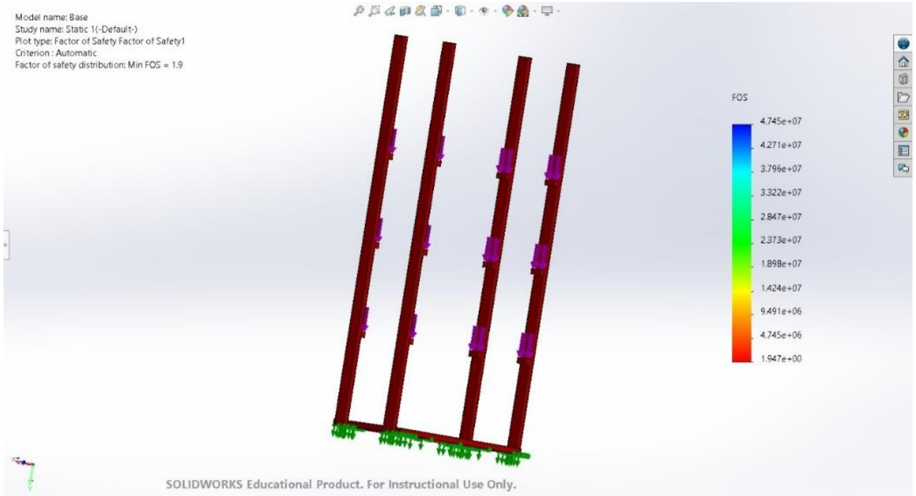
Making the product lightweight, easy-to-assemble & portable are one of our very important USPs and with a target to achieve them at minimal cost we did thorough analysis of our assembly with different materials, thickness and mode of failures which helped us to select the most optimal choice for these parameters. Our product unit being completely static in nature, there were not many parts prone to failure but only the inner frame, which was the most critical component as it was bearing the load of all other components.

To minimize the material, we used structural metal pipes that are hollow with rectangular cross-section to increase sustainability towards buckling. Aluminum 6061 and Stainless Steel were the materials we simulated on with different thickness. The test was performed with normal static loading up to 2 times of our estimated maximum weight. We were able to get safety factor of >1.5 with 2mm of Aluminum & 1mm of Stainless-Steel Structure. Our preference was Aluminum over stainless steel due to cost, weight and ease of manufacturing.

Final Pass Test: Aluminum - 6061T @2mm thickness

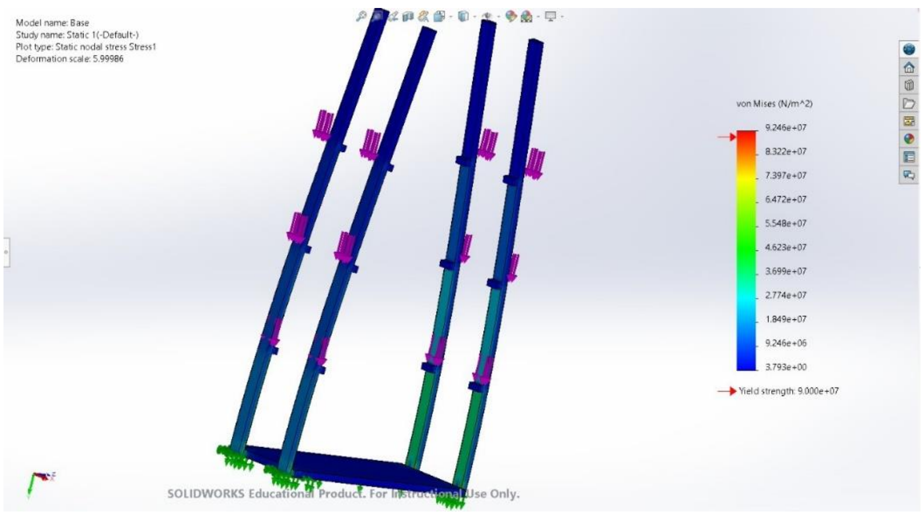


Stress Distribution for Al-6061T at 2mm Thickness & 240kg Load (80kg at each level)



__Factor of Safety (FOS) for Al-6061T at 2mm Thickness & 240kg Load (80kg at each level)__

Initial Fail Test: Aluminum - 6061T @1.5mm thickness



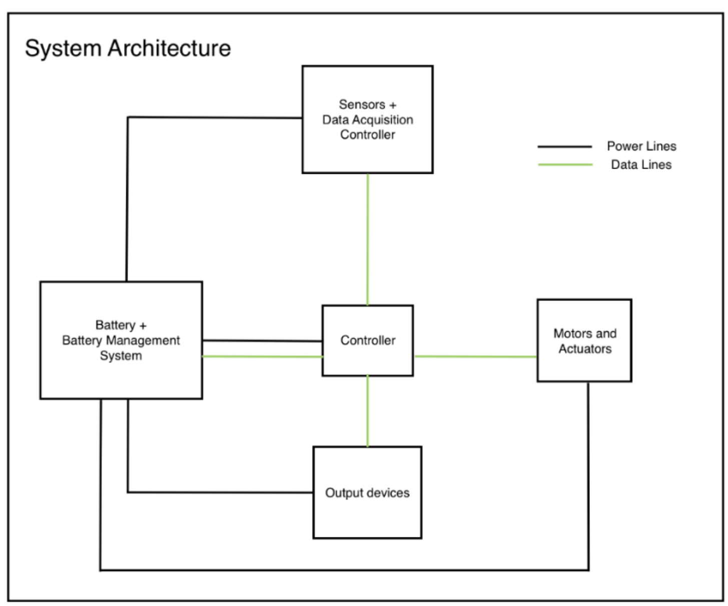
__Stress Distribution for Al-6061T at 1.5mm Thickness & 240kg Load (80kg at each level)__

And thus, Aluminum 6061T pipes with 2mm thickness was most optimal option for us in terms of cost, weight and ease of manufacturing.

System Architecture:

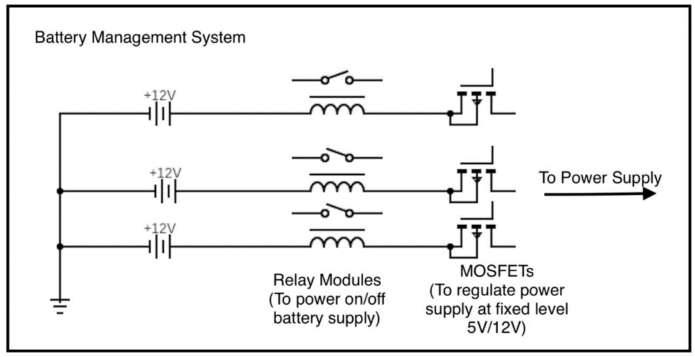
The overall system architecture consists of 5 main components:

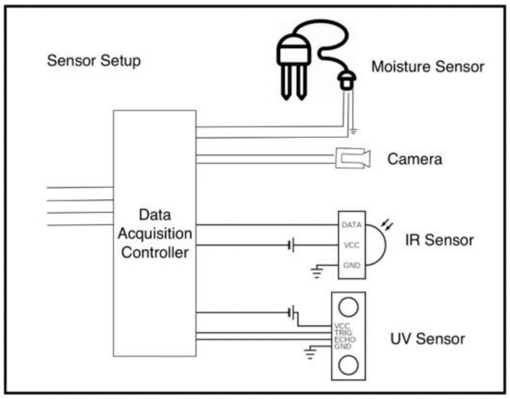
- The controller is the central decision-making component in the system, and controls the various components in the product.
- The battery, along with the Battery management system provides with all the power requirements of the system.
- The sensors and the Data Acquisition Controller, which collects all the information about the system and surroundings.
- Motors and Actuators, which help the controller change the system states and maintain system parameters to desired levels.
- Output devices, which includes LEDs, digital screens, and audio systems



Battery Management System

The battery management system maintains and controls the power circulating in the system. Connected to the microcontroller, it also gives information about the power levels, and creates alerts in case of some malfunctioning. It consists of relay modules, which help in switching between various power sources, and MOSFETs, which help in regulating the power levels to standard values of 12V and 5V.



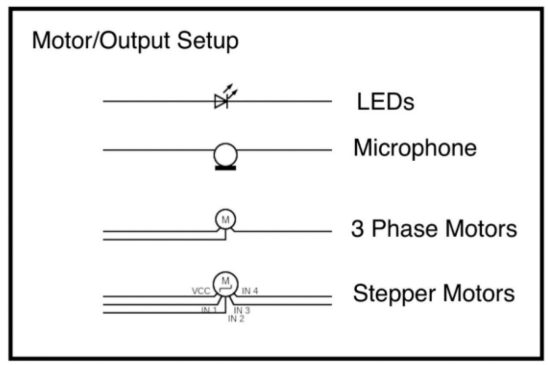


Data Acquisition Controller

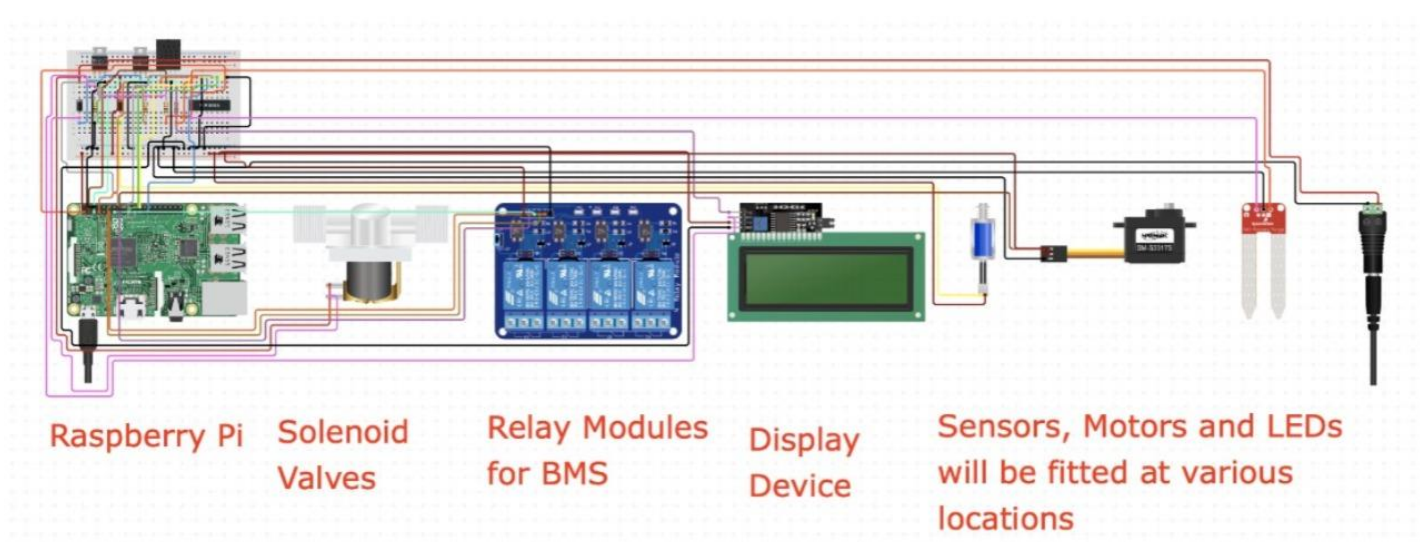
Having multiple sensors, it sometimes becomes very difficult to devote as many I/O pins of the microcontroller to take inputs from every sensor. In such cases, we make use of a Data Acquisition Controller (DAC), which helps us in controller which sensor data we want to read. It helps us in optimizing the requirement of I/O pins required to take in all the sensor data, given the computational limitations of the microcontroller and the utility of all the sensors. By using the DAC, the controller is able to effectively switch between various sensors, calculate its properties, and take appropriate action.

Motors, Actuators, and Output Devices

The controller, after analyzing the surroundings and system properties, takes maintenance and state maneuver activities by using the actuators. These are the "hands" of the system, which perform various actions, like pumping water, nutrients, and waste from one location to another. The controller also provides periodic outputs to the surroundings, to aid the users operating and monitoring the system. These outputs can be in the form of LEDs, microphones, and detailed digital reports of various states and parameters of the system.



Electronic Circuit Schematic



Choice of Microcomputer - Primary Control:

We need a Microcontroller to act as the primary controller of our VF module which integrates and implements the HVAC and humidity control, artificial lighting, crop monitoring, and keeping the user updated about the status.

The following Microcontroller choices were considered.

Arduino – Basic level microcontroller with powerful development platform	
Pros: • Easy to use and develop • Cost effective and small size	**Cons:** • Limited computational power • Limited I/O pins for control
XEP100 - Powerful microcontroller with dozens of I/O pins	
Pros: • Computationally powerful and can handle lots of devices simultaneously • Cost effective and a powerful development environment	**Cons:** • Difficult to code at the hardware level and communicate with peripherals • Lack of availability of powerful libraries to implement image processing and machine learning models
Raspberry Pi - Powerful development environment with dedicated OS and peripherals	
Pros: • Connector slots with inbuilt communication protocols with various peripherals • Very extensive and powerful libraries to communicate and manage complex systems • Cost effective and compact size	**Cons:** • Limited computational powers, • needs extensive optimizations to run complicated machine learning models
Jetson Nano - Very powerful CPU with dedicated peripherals and connector slots	
Pros: • Connector slots with inbuilt communication protocols with various peripherals • Powerful computational power, can help in edge computing and processing of all incoming data	**Cons:** • Very expensive, makes the unit economics weak • Large size, about that of a motherboard, makes it infeasible for small deployments

After carefully evaluating the pros and cons, the module requirements and price considerations, we have settled on Raspberry Pi as our Microcomputer.

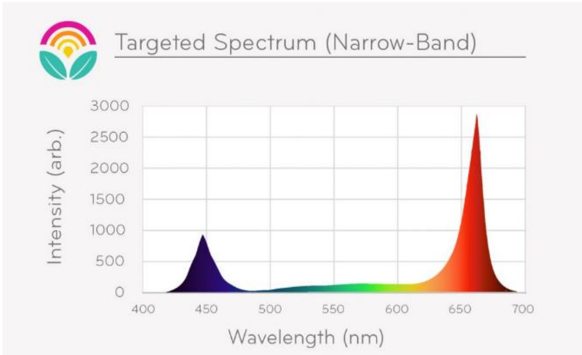
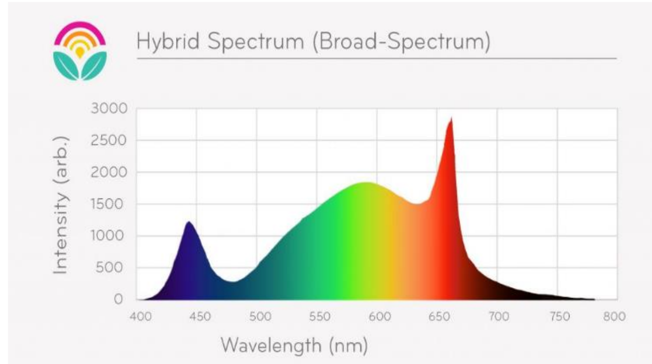
Artificial Lighting:

Objective: Optimize plant growth (tailored to each plant species) with an artificial lighting system with little to no assistance from natural sun-light. Boils down to *increasing high quality biomass yield per unit time* by increasing daylight integral, installing and providing light of a select spectrum and intensity to boost photosynthesis and inducing flowering artificially by controlling photoperiods.

PAR: Photosynthetically active spectral range of solar radiation from 400 to 700 nanometres. The emergence of LEDs made it possible to produce customized spectra. Due to its environmentally friendly, efficiency and long total life advantages, LED lighting is the most revolutionary invention in horticultural lighting in recent decades.

Can we match LED spectrum to the absorption curve of chlorophyll using only red & blue LEDs to max. growth?

In a simplistic way, yes. Only red and blue LED chips are available on the market at relatively low price too. However, maximising photosynthesis is not the only objective. The ratio of energies in the red to far red and UV A to UV B part of the spectrum beyond the PAR range can significantly affect the morphology and metabolism of plants, hence a light source that contains only blue and red is deficient. The development of a perfect growth spectrum takes long experimental research.

Narrow Spectrum LED Lights	Broad Spectrum LED Lights
	
Narrow-spectrum LED grow lights have a pink-purplish hue, are optimized for the blue and red PAR spectrum Ref Link	These lights are white in appearance, the result of a mix of blue, red, and green wavebands. Ref Link

What about light intensity?

Light intensity affects the yield quality in vertical farms. Intensity requirements vary between the developmental stages of the plant. With light intensity the grower can also affect the length of the growth cycle, leaf coloration, total biomass, and dry matter content.

High light intensities can cause substantial heat production, leading to expensive cooling costs. Solution?

The less heat is generated from the light source, the lower the cooling cost, higher lifespan and better the environmental control. LEDs, convert a higher portion of the energy input into light energy therefore permitting lower heat dissipation. Additionally, it is best to choose a LED lighting type with an optimized light spectrum so that lower light intensities can be used. When less light intensity (=> less #lights) in total needs to be installed, it brings savings in hardware, installation, electricity, and cooling costs.

Any other factors to consider?

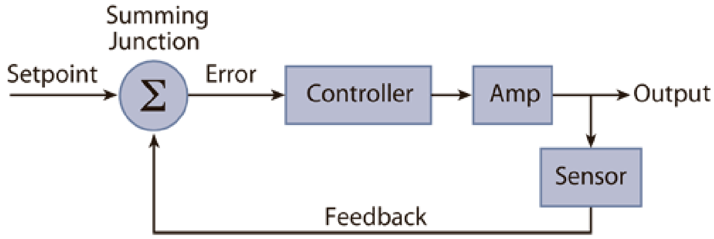
In addition to the correct light spectrum and intensity, it is crucial that *light distribution is uniform* to guarantee a uniform production rate between and within shelves. This must be supplemented with *high sealing effectiveness* of electrical components (IP ratings).

Modern Lighting Technology	Remotely Adjustable, waterproof, Full - Spectrum LED bar lights
Dimensions and Weight	Length : 60 cm, Clearance b/w 2 bar lights : 10 cm, ~ 400 grams per bar
# Bar Lights	Width of tray = 40 cm => given clearance, 40cm/10cm = 4 bars
Spectral Range	400 nm - 700 nm to include PAR, UV A, UV B, and Far-red
Photosynthetic photon flux (PPF)	~ 100 µmol·s-1 per bar (Intensity measured in photon moles per second)
Photosynthetic photon efficacy (PPE)	~ 1.275 µmol·J-1 (Photons moles per joule of energy input)
Desired IP Rating	IP-65 (Protection from water sprays, condensation, dust, etc)
Power Rating and Voltage	~ 100 - 150 Watt, 120 - 240 V
Heat Sinks and Fans	LED bar lights to be manufactured with extruded aluminium to act as heat sinks

Temperature Control:

Our objective is to monitor and control the temperature of our vertical farming enclosure such that the temperature lies in a range which is the most conducive for plant growth.

Phase	Ideal Temperature
Vegetative phase	25 ° Celsius
Flowering phase	28 ° Celsius

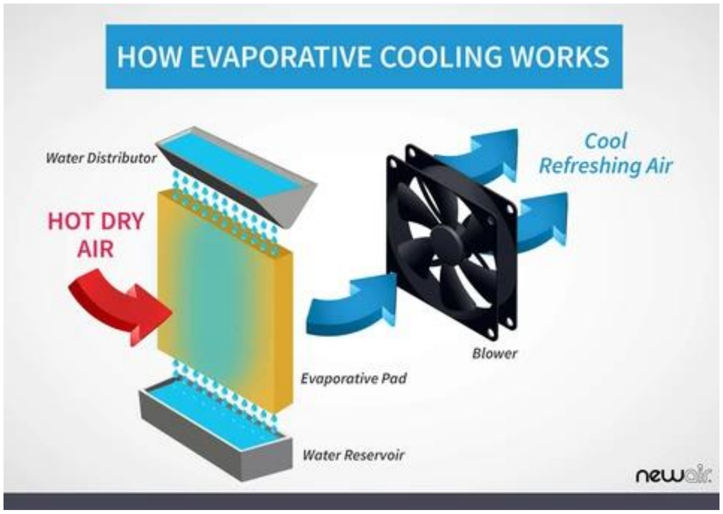


The biochemical process for growth depends on temperatures being kept within ideal range for photosynthesis to occur at optimal rates.

If temperatures are above or below this range, the metabolic and biochemical process will slow down, ultimately slowing down the overall growth of your crop

Since our primary geography would be India, which has a widely varying temperature from extreme hot and cold (45-55 °C to 5-10 °C) we will need a temperature control system that can both heat and cool w.r.t the room temperature.

Solution: Evaporative Cooling (small scale)



Evaporative cooling, which uses the heat in the air to evaporate water from plants and other wetted surfaces can be used to cool the enclosures by as much as *10* °C*.*

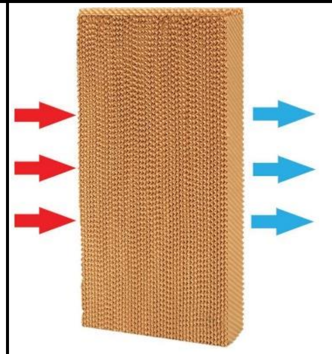
The fan and pad system has been the standard system for evaporative cooling for more than 50 years. In this system, aspen or cellulose pads are mounted in one endwall or sidewall of the enclosure.

They are supplied with water from a pipe above the pads and excess water is collected in a gutter at the bottom.

Air drawn through the wet pads by fans mounted in the opposite endwall or sidewall is saturated and cools the enclosure.
What are evaporative coolers?

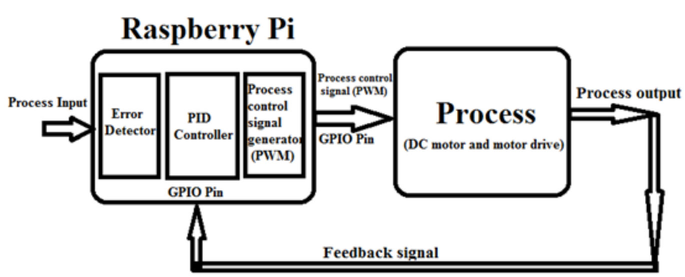
To arrive at parameter specifications of fans and area asbestos sheet required, we followed the guidelines present here: Greenhouse & Floriculture | Center for Agriculture, Food, and the Environment at UMass Amherst
Based on the calculations performed below, we will need 2 fans (the same size as CPU fans)

Parameter	Value
Volume of Vertical Farming unit	0.096 m^3
Volume of air circulation	0.0768 m^3 per min or 2.712 CFM (ft^3 per min)
4'' Cellulose Pad Area required	10.08 cm^2
Water Supply required to nourish the cooling pad	20 L / Hr
Sump Tank Capacity to serve as water reservoir	1 L

CPU Fans	Mini Water Pump	Mini Plastic Tubing	4'' cellulose cooling pad
			
Air Flow : 8 ~ 10 CFM Static Pressure : 0.07 ~ 0.09 inch-H_2O Noise: 24 ~ 30 dB(A) Weight 15.3g Quantity = 2 (1 for inlet, 1 for exhaust) Ref Link	Flow Rate : 80 ~ 120 L/H, Maximum Lift : 40 ~ 110 mm Operating Voltage : 3 ~ 9V Theoretically, 1 motor should suffice, still we will keep 1 more as backup. Ref Link	1 m plastic tubing, Diameter = 0.5 cm Pretty standard, cheap, easy to acquire and install. Ref Link	4 inch cellulose cooling pad Might need a cooling pad of lesser thickness, given that our cooling system has to be miniaturised. Ref Link

HVAC Control system:

Embed this evaporative cooling-based HVAC control system using PID controller (on a R-pi) in conjunction with SSR (power regulator). The temperature can be measured by a 3 wire RTD sensor. A second control system with a simple heating coil can be added with the same sensor and controller to heat the enclosure. We can also check if a miniature space heater exists. The SSR will turn off the power to the cooling fan and pump whenever the temperature of the enclosure reaches below the set point and will turn ON the power when internal temperature exceeds the set point. Similarly for the heating coil.

Block Diagram	Solid State Relay	RTD Sensor
 Ref Link	 Ref Link	 Ref Link

Humidity Control:

Similar to the temperature control system, a humidity control system can also be orchestrated for ensuring that the plants grow at the most optimal moisture content in the air, not too much, not too low humidity is the concentration of water vapour present in the air. Relative humidity, often expressed as a percentage, indicates a present state of absolute humidity relative to a maximum humidity given the same temperature.

Phase	Ideal Moisture Content
Vegetative phase	60-70% Relative Humidity
Flowering phase	40-50% Relative Humidity

Controller: Festnight **XH-W3005 Humidity Controller** Multifunctional Practical High Precision Digital Humidity Controller Hygrometer Switch 0~99% RH Hygrostat **with Sensor** (12V option) Dimensions : 6 x 4.5 x 3.1 cm; 92.82 Grams.
Maximum and minimum Relative humidity limits can be set on the XH-W3005 Humidity controller which then gives a high output if the RH exceeds the maximum limit and low output when it decreases below the minimum limit.

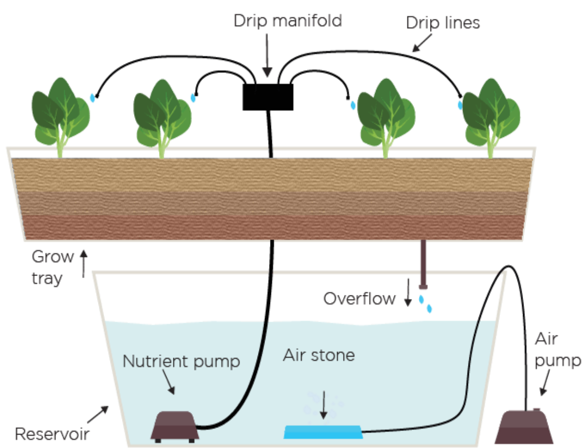
Ref Link1, Ref Link2

Humidifier and Dehumidifier Actuators (Ultrasonic Mist generator Plate):
An ultrasonic mist generator plate (3 W, 16 mm atomizer) can be dipped in water (small 300 ml reservoir) and used to generate mist which can be introduced in the vertical farming enclosure with a small CPU fan (5-10 CFM). This forms the actuator which is connected to the XH-W3005 Humidity controller and sensor.

A simple exhaust fan (small CPU fan 10-20 CFM) can be installed to relay the excessively moisturised air out of the vertical farming enclosure in the same control system of the humidifier.

Water and Nutrient Supply:

Hydroponic drip irrigation systems will be used.
A drip system is an active hydroponic system. This means that it uses a pump to feed your plants with nutrients and water regularly. The system uses small emitters to drip the nutrient solution directly onto your plants.



How does the Drip System Work?

The system usually uses individual pots for plants. Water from the reservoir is connected to the plants by a tubing network. There are two ways to apply pressure to the water supply. It can be a regular water pump or a gravity-based system.

Each individual plant gets at least one dedicated drip emitter. Each emitter has mechanisms that allow it to control the flow of water. This adds to the overall versatility of the system, different flow levels for various plants can be set. The flow to the plants has to be regulated in a drip system. The growing media needs to be given time to breathe in between flows.

All drip systems use a timer system to regulate the flow of water and nutrients to the plants. In typical situations, the pump is operated several times a day to send water to the plants. Once the drip lines are carefully installed, the system can run with minimal assistance.

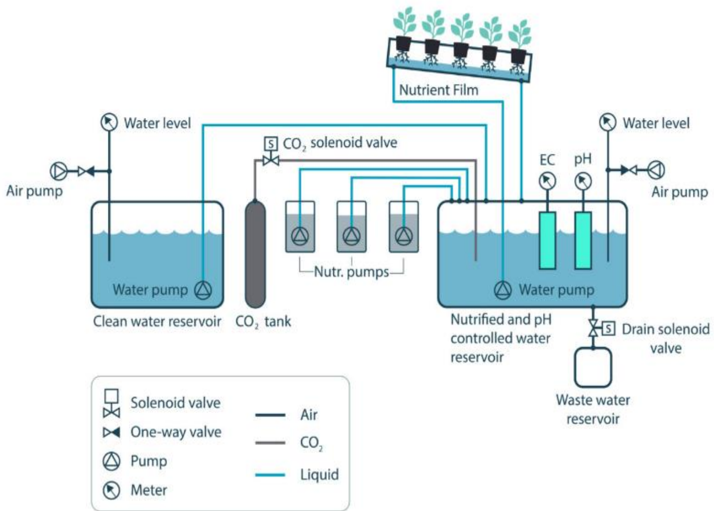
Image Source

Components Used in Setup:

- Drip Emitters: Depending on the number of plants the customer plans to grow, there will be an emitter for each plant.
- Thin Tubing: Spaghetti tubing will be used for a drip emitter.
- PVC Tubing: These will be the main lines that carry the water and nutrients from the reservoir pump to the emitters. For smaller home-based setups, two-inch tubes are enough.
- Water Pump: A regular submersible pump of capacity 120-300 gallons per minute should suffice for smaller setups.
- A Tray: In smaller recirculating setups, best results will be gained by having all the pots drain into a common tray. This is a simpler option than having separate run-off tubes from each pot to the reservoir.
- A Large Bucket/Bin: This will act as the reservoir. Size of between 10-20 gallons volume depending on the size of setup.
- A Garden timer for the pump and Aquarium grade silicone sealant: Reference

Controlling pH Level: Why pH is Important in Hydroponic Systems?

The right pH level is crucial because it affects nutrient availability for growing plants. Hydroponically grown plants need different pH levels than plants grown in soil. Without soil, plants do not benefit from microorganisms, organic matter, and interactions between water and minerals that regulate pH levels. The optimal pH range for hydroponically grown crops is generally **between 5.5 and 6**.



Parameter	Ideal Range
Sensor type	Combination electrode
Measurement range	0~14pH
Temperature of operation	16~30ºC
Zero electric potential	7±0.25p
Response time	<1min
Internal resistance	≤250MΩ
Repeatability	0.017
PTS	>98.5
Noise	<0.5mV
Alkali error	15mV
Reader accuracy	up to 0.01

Sensors:

- Ultrasonic sensor (HC - SR04) to detect the height value of the nutrient solution in hydroponic plants by the parameter of the high of water (in Cm)
- The sensor (LM-35) to detect the temperature in units of °C range
- CX20 Conductivity Controller: it plays a crucial role in the quantitative estimation of various salts
- ARM Cortex-M4 microcontroller: it plays a key role in the automation of the overall process of supply of nutrients as well as water: References1 Reference2

Nutrient	Utility
Nitrogen (Nitrate form)	Helps foliage grow strong and with chlorophyll production
Phosphorus	Helps with root & flower growth while helping plants withstand environmental stressors.
Potassium	Strengthens plants, especially during early growth, and helps them retain water.
Magnesium	Plays a key role in giving plants their green colour.
Sulphur	Helps plants resist diseases, to grow seeds, create amino acids, enzymes, and vitamins
Calcium	Aids in the growth and development of cell walls, to prevent diseases and enables nitrate absorption

Monitoring Systems

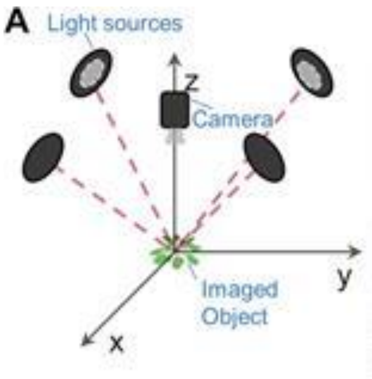
Growth Monitoring

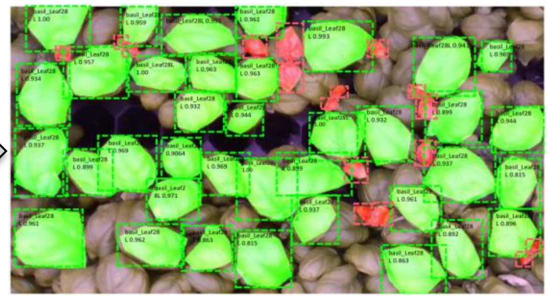
We have set up cameras to watch over each tray of the farming module. These cameras help us monitor the health and growth of the produce, as well as provide the user the ability to access a live feed of their crop right from the comfort of their phone via our mobile application.
At periodic intervals, frames from this feed will be analyzed using Image Processing and AI techniques for various objectives:

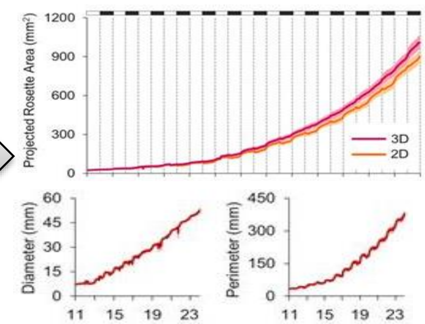
1. Computer Vision techniques can be leveraged to perform image segmentation of frames to be analyzed and detect the leaves in these frames. This will allow us to track leaf count and size during the growth cycle of the crops. This data can also be compared with expected data for the particular crop in question, and the user can be informed in case of any major defects or deviation that needs to be rectified

2. Segmentation will also allow early detection of spots, patches or discoloration on the leaves due to disease, thus ensuring that timely actions can be taken for healthy yield of crop
3. RGB-D sensors can be incorporated in later versions, which will allow better tracking of leaf size, along with predicting plant height and weight. This data can be employed to give the user an accurate image of the crop growth status, along with a predictive analysis of the harvest date and harvest amount

A concise and up-to-date report of the growth-monitoring system will also be accessible to the user at all times through the analytics dashboard on the mobile application.







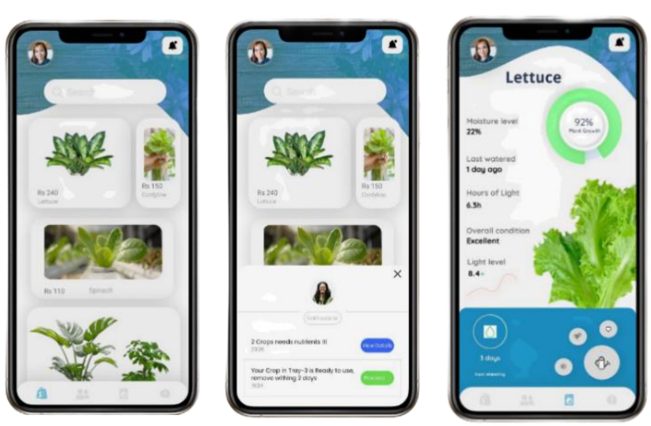
Example leaf segmentation (Source)

Nutrient Monitoring

We have sensors monitoring various quantities of interest in the hydroponic solution like its temperature, pH level, nutrient content, etc. The data collected by these sensors can help in monitoring the hydroponic solution composition, to ensure that all parameters remain within the specified ranges based on the particular crop being grown in a certain tray. This can be done by employing the following techniques:

1. The time-series data stream from these sensors can be mapped on relevant control charts with upper and lower limits based on the particular crop that is currently growing in a certain tray. This can be used to alert the user when the process is out of control and appropriate actions can be recommended to bring it back in control. These control charts are also viewable by the user via the analytics dashboard
2. Time series forecasting techniques can be used to perform predictive analyses like:
    a. Predicting whether the process is likely to go out of control well before it can happen
    b. Estimating when the next nutrient intake will be needed in the hydroponic solution of a certain tray

Product and UI

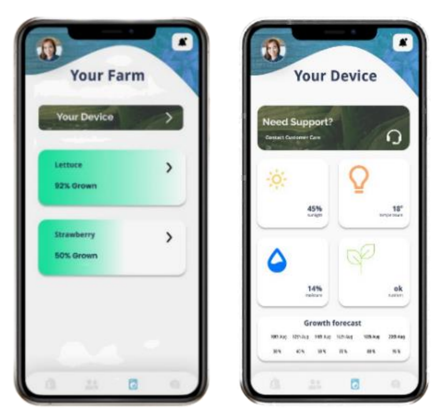


Marketplace: Built-in marketplace to shop a wide variety of seeds and nutrients required for farming certified & compatible for the device.

Notifications & Reminders: Most handy feature is to put Reminders and notifications directly to the customer to update on the availability and crops' status

Crops: One-stop for all the crops, from tracking the status of the plant growths, to automatically/manual feeding with required things

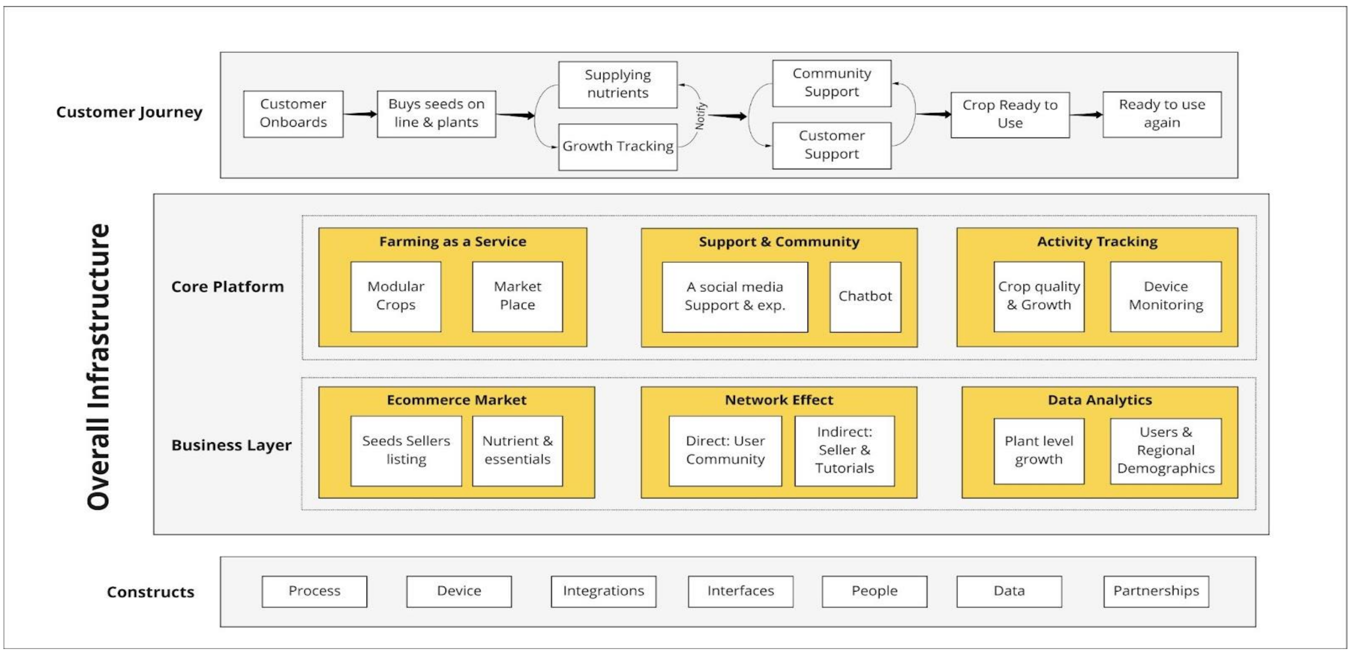
Device: Track the performance of the machine, status, and control



Community: Share the experience, discuss about anything with the available community to get yourself equipped with the latest news

Groot: 24x7 available chatbot to help the user in discovery of all the required assist. From requesting repair support to suggest trending crops, it will remind users to unplug the grown crops from the module, remind to buy necessary nutrients.

Service Architecture:



The overall infrastructure consists of 2 main layers, the core, and business layer, with all the customer side facing core layer, will provide the best-in-class performance to the users, whereas Business layer is something that will keep on improving the value & quality of the core platform.

The onboarding of more and, more users/sellers on the platform will increase the value of the platform. And as more and more data is collected, advanced & well-trained Machine learning models will improve & adapt to how the user interacts with the device and take the user experience to the next level.

Total Addressable Market Calculation

Urban, Tech-savvy households that are health conscious form our primary customer base, along with high-end restaurants and hotels that want to serve freshly harvested, juicy herbs and greens to their customers.

Estimating Number of Target Urban Households		
The population of India as of 2019	1366	Million
Percentage of Population Living in Urban Centres	35%	
The average size of an Indian Urban Household	4	
Number of Urban Households in India	119.525	Million
Since our Product costs, ~ 10 k INR => affordable only to Upper Middle Class and Rich households		

% of Households who can afford the product (% Upper Middle + %Rich)	15%	
% of Households that have underutilized space at home	20%	
% of Households who are health-conscious	80%	
% of Households who are Tech Savvy	50%	
Total Household Addressable Market Size	**1.4343**	**Million**
Estimating Number of Target Hotels and Restaurants		
Number of Restaurants in Urban India	7	Million
% of High End, fine dining restaurants	10%	
Number of Hotels in Urban India	0.053	Million
% of 4 and 5-star Hotels	5%	
Total Addressable Market Size from Hotels and Restaurants	**0.70265**	**Million**
Grand Total Market size in #Vertical Farming Units (assuming 1 unit per entity)	**2.13695**	**Million**

Cost Analysis and pricing:

Based on Raw Materials (aluminum, glass, PVC), electronic devices (sensors, actuators, lighting, circuitry), HVAC (aquaponics system), and climate control, cost estimations will be about INR 5000 – 7,000 (estimated in the engineering requirements table). Let's take the average cost of Raw Materials and sub-assemblies INR 6000.

Assuming a manufacturing and operational cost per unit of 25%, and an added cost of value-added services like data servers for the application, customer support, discounted maintenance, delivery, and end-point installation costs as an extra 25%.

Therefore, the total variable cost of manufacturing and delivering a unit, including the cost of providing other value-added services during the product lifetime, would be INR 9000. Assuming a 10% profit margin on the above-estimated cost per unit, the product's final price: INR 10,000.

Financial Forecast and Break-Even Analysis:

Driving Assumption: We will be able to tap into 25% of the total addressable market estimated above, i.e., sell ~0.5 Million units in the next ten years through 2 factories. Note that the cost of Research and Development is included in setting up, and marketing costs are included in overheads.

Parameter	Value	Units
Cost of Constructing 1 Factory	100	Million INR
Factory Production Capacity	1000	units per week
# Operational weeks excluding downtime	40	weeks per year per factory
Annual Production Capacity	40000	units per factory
Price per unit	10000	INR
COGS (Cost of RM + Manufacturing)	9000	INR
Overheads	15	Million INR per year per factory

10 Year Financial Forecast										
Year	1	2	3	4	5	6	7	8	9	10
# Factories	1	1	1	1	1	2	2	2	2	2
Annual Capacity in Units	40000	40000	40000	40000	40000	80000	80000	80000	80000	80000
Factory Utilization	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%

Production per year	32000	32000	32000	32000	32000	64000	64000	64000	64000	64000
Revenue per year (Mil)	320	320	320	320	320	640	640	640	640	640
COGS	288	288	288	288	288	576	576	576	576	576
Operational Profit (Mil)	32	32	32	32	32	64	64	64	64	64
Cost of Setting-up Factory (Mil)	100	0	0	0	0	100	0	0	0	0
Overhead Costs	15	15	15	15	15	30	30	30	30	30
Net Profit	-83	17	17	17	17	-66	34	34	34	34
Cumulative Profit	-83	-66	-49	-32	-15	-81	-47	-13	21	55

Empirical Research and Data Based Design Optimization

Currently all the control systems, lighting, temperature control, irrigation system, humidity control, camera module, are designed independently and their overall effect together in optimization of complete setup is unknown. Also, all the existing research papers only have the independent design optimization not the particular combination needed for our modular farming setup. For optimizing the plant growth, we need to collect data from all of the control systems working together.

What to optimize?

- Plant Growth (Biomass Yield per unit time)
- Resource Consumption (Electricity, water, nutrients over the plant lifecycle)
- Temperature and Humidity control (These 2 control systems might be at odds with each other)
- Total Energy Consumption (per month, per year, per plant lifecycle)
- Total Cost (per month, per year, per plant lifecycle)

Detailed breakdown of systems to be optimized in future (Read Appendix B)

Conclusion

- Due to the high cost of the initial investment in setting up a factory, the payback period is extended, i.e., we break even in the 9th year (Positive Cumulative Profit as highlighted in green in the forecast) after starting production.
- In addition, Urban India gave us a 2.5 Million x 10,000 INR = 25 Billion INR addressable market. The venture also broke even in the 9th year and became profitable too!
- Our product sustainably solves one of the most critical global challenges of our generation, food security, with judicious use of modern science, technology, and manufacturing by saving land, water, labor, and fertilizers and also limits the susceptibility of food production on varying environmental factors to provide a steady source of high quality, organically grown food throughout the year.

Further Discussion

General Challenges to Vertical Farming:

- Highly Energy-intensive as 24x7 artificial lighting and climate control systems need to operate round the clock.
- High Maintenance cost due to the requirement of esoteric technical skills to find and fix problems.
- High Initial investment capital is required to set up a large farm, hence has a long payback period.
- Basic technical training is required to operate the farm; an uninitiated farmer will not be able to operate it.

APPENDIX A

The Team – Roles and Responsibilities:

We all work as a team and support each other in all kinds of tasks. However, based on interests, skills, and explicit instructions from Prof. and TAs, we assign roles for each of us.

Name	Role	Function
Abhishek Soni	Product	Responsible for managing the viability and applications of the technology for real-world use-cases. Innovation, business, and development of the product.
Anuj Agarwal	Product	Responsible for managing the viability and applications of the technology for real-world use-cases. Innovation, business, and development of the product.
Aryan Chirania	Operations	Responsible for the development and implementation of growth strategies and processes, while also ensuring the delivery of results on a week-to-week basis.
Harshit Garg	Design	Responsible for overseeing all design and innovation aspects of the product and services including product design, computational design and industrial design.
Rishab Dodeja	Design	Responsible for overseeing all design and innovation aspects of the product and services including product design, computational design and industrial design.
Shaswat Gupta	Director	Responsible for brainstorming, setting vision, planning, delegation, execution, product research, editing, pitching & presentation. Assists in all other functions.
Shubham Lohiya	Director	Responsible for brainstorming, setting vision, planning, delegation, execution, product research, editing, pitching & presentation. Assists in all other functions.

APPENDIX B

What to optimize?

- Plant Growth (Biomass Yield per unit time)
- Resource Consumption (Electricity, water, nutrients over the plant lifecycle)
- Temperature and Humidity control (These 2 control systems might be at odds with each other)
- Total Energy Consumption (per month, per year, per plant lifecycle)
- Total Cost (per month, per year, per plant lifecycle)

How can they be optimized in the future:

- Plant Growth
    - Plant growth is one of the most important things to monitor and optimize. The goal is to achieve the desired growth of a plant in minimum time without affecting its natural properties.
    - Few parameters can be measured for plant growth tracking:
        - Biomass yield measurement and its rate
        - Stem length and its growth rate variation
        - Total number of leaves and rate of area expansion, rate increase in #leaves

- Irrigation System
    - Irrigation system consists of the pumping system and nutrients/fertilizer supplying system. Optimization of the both of them working together is very important as these are used frequently and most required for a farming setup.
    - Parameter to track:
        - Number of refills (litres/day or litres/week)
        - Amount of nutrients/fertilizers (gm/day or kg/week)

- Temperature and Humidity control
    - As the plants require optimal temperature and humidity, it is very critical to maintain those in their optimum range.
    - Temperature can be increased using the existing lighting system but that combined with the water from irrigation can increase the humidity and that can create an extra load on the dehumidifier and will consume more energy. Thus, optimizing these together will be a difficult and important task that we have to achieve in future.

- Energy Consumption
    - Optimizing the energy consumption can reduce the overall cost for the system.
    - Data for energy consumption can be collected over a weekly or monthly basis.
    - The overall energy consumed depends on the several individual components and can be optimized by optimizing their individual consumption.
    - Some of the components are:
        - The overall lightning system
        - Pumping system
        - The camera module
        - Electricity used for other actuators

- Total Cost
    - Optimizing cost is one thing required in a product and it will be much better for the consumer if the usage cost is minimum.
    - Total cost will include cost of
        - Seed
        - Water

        - Nutrients
        - Electricity
        - Maintenance (twice a year)

How to measure the parameters mentioned above?

- Plant growth:
    - Stem length can be measured using the camera module in addition to computer vision.
    - Biomass yield can be measured using a weight sensor. It can be calculated as weight per tray.
- Irrigation and Nutrients:
    - These will be measured by the user input: Volume of tank x No. of refills
- Electricity:
    - Overall Units
    - No. of charge x Total capacity of battery used

The data obtained from all the sensors will be plotted in real time and using them the correlation of different components will be obtained.

Some patterns to be obtained after getting enough data:

- Temperature v/s plant growth
- Amount of water required v/s plant growth
- Amount of nutrient required v/s plant growth
- Energy consumed v/s plant growth

From all the patterns and data obtained after a significant time, overall correlation will be made and the optimum values for each parameter obtained will be used in future systems.

APPENDIX C

Converting Product Requirements to Engineering Features:

The following is a translation of our customer requirements and product features into quantifiable engineering requirements.

Category	Parameter	Customer need	Engineering Requirements / Goals
Geometry	Size	A single unit should fit into small spaces, should be about the size of a washing machine	Main Hull (Base Module) of about 60cm*40cm*40cm
			Plantation modules of area 60cm*40cm*10cm
			Height with 4 modules + Base = 100cm - 120cm
	Weight	Portable: Easy to move around and, if required, transportable	Up to 40kg (complete assembly in a dry state), and movable by rolling on wheels
Material Considerations	Base Module	Sufficiently strong to hold pumps and backup batteries	Aluminum with a Transparent Polycarbonate Lid
	Frame	Inexpensive and Tough	Aluminum
	Plantation Tray	Non-corrosive, lightweight, reasonably strong	Polycarbonate with Aluminum frame & mounting points
HVAC	Heating, Ventilation, and Air-Conditioning	Automatic Climate Control; Remote Control by the user over the internal environment; Avoid weeds and unpleasant smells	Air conditioning 1) Small-space humidifier + dehumidifier 2) Temperature control mechanism (small scale evaporative mechanisms) Capability to modify HVAC remotely using IoT
Automation	Climate schedules; Nutrient supply; automatic updates	Ability to grow required items with negligible intervention once started, with periodic status updates	Controlled umbrella (Gelatin hood) for mini-greenhouse effect
			Programmable Night lighting (with Spectrum adjustment) for different crops and stages
			Controlled/Programmable Periodic Sprinkling for temperature/humidity control
Energy	Electricity	Low power consumption; Run by AC to DC adapter: 12V 10A	Micro-controller System & Sensors: ~20W
			Water Pump: 50W
			LED lights: ~30W
			Total Gross: 100W
	Backup Power	Provisions to cruise through uncertain Power-cuts (Up to 24hr backup)	Lead Acid Batteries (cheap and safer than Li-po/Li-ion)
			24000mAh, 12V 10A
Nutrients	Plant health, growth, and yield rate	Effective Germination	Coco-Pit (Base Soil)
		Good quality, healthy yield with short lead times.	DAP & Urea (Regular Input - Nitrogen and oxides supplements)
			Sulfur (Supplement - for initial branching and greenery)

			Sterameal (Supplement - Organic Food for accelerated growth and flowering)
Production	Yield	High yield/space ratio	Varies for every crop (50 gm - 2 kg per tray)
Maintenance	Cost	Low yearly maintenance costs to achieve product longevity	INR 500-1000; Filter cleaning, sensors/motors replacements, nozzles cleaning, etc.
	Time	Lower frequency of maintenance visits preferred	every six months (recommended) for a general checkup, professional cleaning, and HVAC maintenance.
User	Risks	No health or safety risks, or risk to machine components	Carrying/moving & Assembly/Disassembly involves the risk of handling damages to delicate sensors.
			Using Calcium-rich/Hard water as input may decrease the service life of motors/nozzles
	Standard operating procedure	Easy to operate, clean, and maintain	Mobile App Controlled System: needs to be connected over a standard Wi-Fi
			Set up your crop growth plan by feeding hour-wise temperature/humidity ranges, lighting options, water levels, etc.
			OR choose from many preloaded programs by selecting crop name and age
			Different Program/Setting for each module or plantation tray
	Cleanliness and waste disposal	Easy access for cleaning the internal area of the module Minimal waste generation and safe disposal	1) Detachable inner structure components allowing for easy and regular cleaning 2) Sanitizer mist spray after manual cleaning in mist mode of the module to ensure isolated env without contamination 3) Safe disposal of the minimal waste generation
Economic	Unit cost	As inexpensive as possible without compromising the revolutionary modular design	Estimated 7k per module for hydroponics; 10k per module for aquaponics
	Monthly power consumption		90-120 KWh, equivalent to a moderately sized refrigerator consumption
	Supplements costs		750-1000 rupees per month (for starter seeds/material, maintenance, material to aid growth, 1.5-2x the cost of purchasing similar mass-produced stuff from the market, the equivalent price to buying organic)

APPENDIX D

Monitoring Crop Growth:

We need to closely monitor the growth cycle of crops, and take actions recommended by the monitoring system to provide an automated farming experience. We plan to use camera modules coupled with Image Processing and Machine Learning algorithms to monitor the crop growth, detect any possible defects at an early stage, and prompt the user to take swift appropriate action. The following camera modules have been considered:

Image Source

Google Coral Camera	**Raspberry Pi Camera Module V2**	**Omnivision 5647 Camera Module**
Pros: 5MP**,** Autofocus and Exposure, black-level calibration **Cons:** Expensive, redundant features	**Pros:** 8MP, 1080P30 video **Cons:** Fixed Focus, expensive	**Pros:** 5MP, light weight(3g), inexpensive **Cons:** Relatively lower image quality

After careful consideration, we have decided to go with the **Omnivision 5647 Camera Module** as it is very cheap compared to the other options, and allows us to include multiple cameras for monitoring without affecting module cost too much. It has all the features we need at this stage, and the lower image quality compared to the other options is not really an issue as our tasks are not heavily influenced by that level of difference in quality.

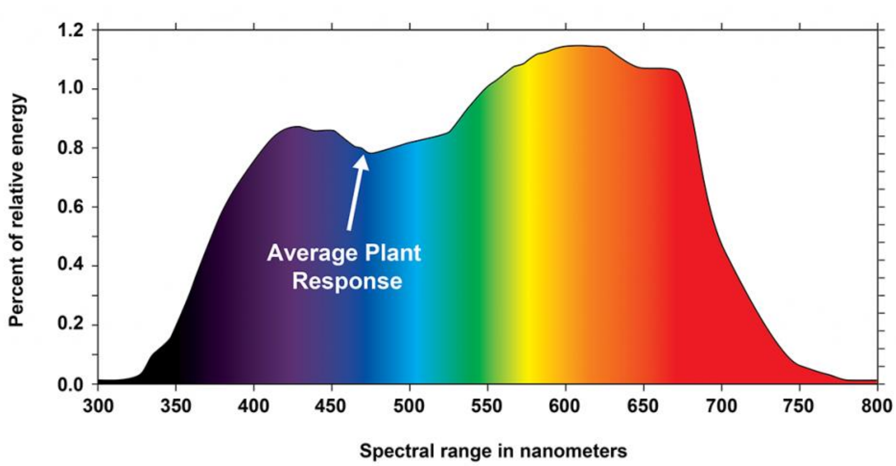
Artificial Lighting for Modular Vertical Farming

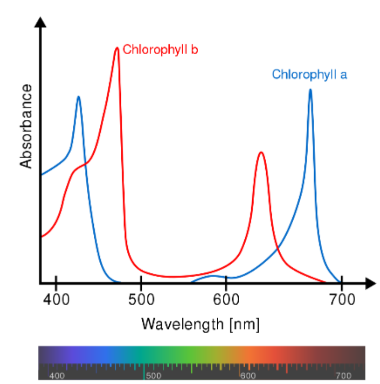
Optimize plant growth (tailored to each plant species) with an artificial lighting system with little to no assistance from natural sun-light. Boils down to *increasing high quality biomass yield per unit time* by increasing daylight integral, installing and providing light of a select spectrum and intensity to boost photosynthesis and inducing flowering artificially by controlling photoperiods.

Target Crops: Lettuce, aromatic plants, and culinary condiments, microgreens, sprouts and baby vegetables.

Primer: *Chlorophyll* is a green-colored plant pigment found inside intracellular chloroplasts that absorb photon-energy in the form of the sun's electromagnetic spectrum and use it to synthesize complex organic molecules and induce/regulate flowering induction, seed development, stem elongation and leaf expansion. Photosynthesis is not very efficient since only 4-6% of the energy available in the radiation is converted into biomass.

PAR : Photosynthetically active spectral range of solar radiation from 400 to 700 nanometers that plants use for photosynthesis.





Ref of graph #1 : McCree Curve

Ref for graph #2 : Active Region

The McCree Curve represents the average photosynthetic response of plants to light energy. There are two main types of chlorophyll : chlorophyll a and b, which differ from each other in their light absorption curves, allowing them to capture more of the sunlight spectrum.

Spectrum	Role
UV (100 - 400 nm)	UV-A (315-400 nm), UV-B (280-315 nm), and UV-C (100-280 nm) have beneficial effects on color, nutritional value, taste, and aroma.
Blue Light (400 - 500 nm)	Enhances biomass quality – especially in leafy crops, promotes the stomatal opening – allowing more CO2 to enter, drives peak chlorophyll absorption during photosynthesis
Green Light (500 - 600 nm)	Less important. Low absorption. But cannot be neglected completely.
Red Light (600 - 700 nm)	Most effective light spectrum to encourage photosynthesis, encourages stem, leaf and general vegetative growth. Initiates seed germination and root development.
Far red Light (700 - 850 nm)	Initiates a shade-avoidance response, promotes flowering and increases yields.

High-pressure sodium (HPS) lamps (used in green-houses) irradiate mainly in the yellow and red area, while *fluorescent lights* (used in growth chambers) have more blue light in their spectrum.

Based on their photoperiod (light vs dark period) characteristics, plants can be categorized into:

- Short-day plants (require dark period ~12h to induce flowering) like chrysanthemums, strawberry, beans, camellias and primroses.
- *Long-day plants (6-18h light, shorter dark period) like lettuces, spinach, and other leafy greens.*
- Day-neutral plants (flower regardless of photoperiod) like cucumber and peas.

Other important design considerations:

Wires & connectors:

Wires and connectors come in various sizes and insulations, and each component requires a different set based on the requirements. The considerations required are mainly:

- **Power** - High power peripherals (like the BMS) require large connectors and thick wires, and need to be properly connected to cooling systems to ensure the heat does not affect the electrical circuit
- **Distance** - Heavy power transmission wires must be kept as far away from circuit boards and communication wires to minimize the disturbance caused due to fluctuations in the power supply from the battery.
- **Insulation** - Wires come with a variety of insulation materials, and proper choices are to be made to balance heating effects along with reducing disturbances one part of the circuit causes to the other parts.

Sensors:

Communication protocol - Analog sensors can be easily integrated into any microcontroller, giving very specific information about the attribute of the environment. However, complex sensors, like camera, use a complicated communication protocol to transmit data to the microcontroller, which further requires processing the get insights about the data

Power consumption - Different sensors require different wattages of power, and all of these requirements have to be taken into consideration before building the circuit elements of the system.

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