DESIGN AND IMPLEMENTATION OF AN INDOOR HYDROPONIC SYSTEM FOR ENHANCED CROP PRODUCTION

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A Final Year Design Project (FYDP) submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering (BSEEE)

Declaration:

It is hereby declared that

1. The Final Year Design Project (FYDP) submitted is my/our own original work while completing a degree at Brac University.
2. The Final Year Design Project (FYDP) does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The Final Year Design Project (FYDP) does not contain material that has been accepted or submitted for any other degree or diploma at a university or other institution.
4. I/We have acknowledged all main sources of help.

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Approval:

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Ethics Statement

We, therefore, confirm and affirm that this Final Year Design Project document here in on "Design and Implementation of an Indoor Hydroponic System for Enhanced Crop Production" meets all the standards set by the BRAC University Authority and the Department of Electrical and Electronic Engineering of BRAC University on Final Year Design Project as a partial fulfillment of the requirement for the award of the degree of Bachelor of Science (B.Sc.) in Electrical and Electronic Engineering. Accordingly, this project report has been prepared with the assistance of all members of the group, including the findings of our surveys and investigations, our designs, and details of the test results of our prototype. Every single source and literature review contains proper references as advised by our ATC Panel.

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Abstract/Executive Summary

Urban agriculture in densely populated regions, which faces severe constraints due to limited arable land, soil degradation, and water scarcity, requires efficient and space-saving cultivation solutions. This project introduces an automated Indoor Vertical Hydroponic System specifically designed for space-constrained urban environments. By incorporating IoT sensors that monitor TDS, turbidity, water level, temperature, and humidity, the system allows for precise environmental tracking to automate nutrient delivery and optimize crop health. The system operates largely independently of outdoor weather by utilizing spectrum-controlled LED lighting and a camera module for real-time visual monitoring, ensuring year-round production. The use of automated water and oxygen pumps guarantees efficient resource circulation, significantly minimizing water waste compared to traditional soil-based farming. Moreover, the system is designed as a scalable, ready-made agricultural product, providing a user-friendly solution that maximizes yield per square foot. By addressing both space constraints and resource efficiency, this project not only improves the competitiveness of the agricultural sector but also promotes sustainable food security in Bangladesh's land-scarce markets.

Keywords: Indoor vertical farming; IoT; Hydroponics; Smart monitoring and control; Water conservation; Sustainable agriculture

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Chapter 1: Introduction - [CO1, CO2, CO10]

1.1 Introduction

The world is experiencing a transition of agricultural practices because of the environmental constraints and the increasing demand of food. Conventional farming based on soil is finding it hard to produce reliable harvests as climatic unpredictability, soil erosion, and water unavailability present a great limit to large-scale crop cultivation. Simultaneously, the population increase and urbanization are placing increased pressure on the quality and nutritional value of food, which can be otherwise be met only through the innovative farming systems that can generate more food using less.

Hydroponic agriculture has also come out as a promising alternative to the traditional agriculture practices where soil-less farming can be done in carefully regulated solution of nutrients in water. This method can accurately control factors of plant growth including nutrient level, temperature, humidity and light intensity that results in shorter growth periods and more production per acre. Hydroponics is not dependent on soil, so it is adapted to urban and indoor settings where there is a scarcity of land. Also, the vertical hydroponic towers and modular enable further space-efficiency by enabling crops to be stacked in place of being spread out horizontally.

In addition to conserving space, hydroponic systems are also involved in conserving resources because they minimize waste of water and conserving fertilizers by recycling nutrients. The indoor hydroponics will also eliminate the reliance on pesticides, environmental conditions, and allow year-round production, which is not based on climatic conditions and season. These features render hydroponic farming a suitable solution to regions with agricultural limitation as well as to communities that are interested in localized and sustainable food production patterns.

Nevertheless, there are numerous shortcomings of the current hydroponic systems, as most of them are constrained by poor monitoring, excessive energy usage and due to frequent manual treatment. The nutrient balance, incorrect light, inappropriate oxygen supply, or un-optimal environmental conditions can deteriorate within a short period of time the crops in terms of their quality and quantity. These issues highlight the fact that further unified, automated, and smart hydroponic systems that could resourcefully manage the conditions of growth of plants, as well as promote scaleability in urban and rural environments, are necessary.

With the increasing popularity of sustainable agriculture and the technological improvements it offers, the creation of an inexpensive, modular, and information-driven indoor hydroponic system is a significant prospect to innovate the modern agricultural processes and provide the world with food resilience in the future.

1.1.1 Problem Statement

Climate change, soil degradation and water scarcity are critical problems to the agricultural industry of the whole world. Conventional agricultural practice uses about 70 percent of the freshwater in the world [1] drastically depleting most parts of the world. Moreover, there is an estimated 70 percent increase of food demand in the world by the year 2050 [2], which would further pressure the agricultural systems. One of the promising alternatives is hydroponic farming that has the ability to reduce water consumption by up to 90 percent relative to soil-based farming [3]. Most of the current systems of hydroponics, however, lack efficiency in monitoring and control resulting to inefficient growth of crops and utilization of resources. Research has shown that more than 30 percent of losses incurred in controlled environment agriculture are caused by poor monitoring of the nutrients, temperature, and humidity [4]. Also, the use of grid electricity to power hydroponic systems has an adverse effect on both the operation cost and carbon footprint, which is another obstacle to sustainable farming practices. These issues define the necessity of better monitoring and management of resources to increase efficiency and sustainability in controlled environment agriculture.

1.1.2 Background Study

Increasing water stress, soil erosion and declining agricultural areas are rooting limitations to traditional agriculture. In fact, almost 70 percent of the freshwater resources in the world are used in agriculture alone, hence efficient utilization is necessary [1]. Meanwhile, the population growth is expected to grow rapidly by the middle of the century [2]. Controlled-environment agriculture (CEA) has thus worked out as a tactic avenue toward stabilizing output and reducing input footprints and post-harvest losses [4]. Indoor hydroponics is a facilitating technology which is driven by these macro trends to produce resilient food.

Hydroponics substitutes the soil with nutrient-enriched solutions, which provide water and ions to the roots. NASA and related research confirm huge water savings in comparison with field agriculture due to recycling solution in closed loops, whereas keeping the EC/TDS and pH under strict control to improve the uptake of nutrients [3]. Such recirculating systems can greatly cut down on water use and also reduce nutrient waste in resource constrained settings.

The prototyping of other critical building blocks has been previously recorded in the scholarly literature such as compact PP buildings, recirculation pumps of varying sizes by equilibrium head and friction losses, LED photosynthetic lighting with set points in photoperiods, and dosing nutrients using peristaltic pumps connected to stage-specific EC/pH points [5], [8]. Other studies have also affirmed ranges that have empirically validated ranges that have already been included in this design like keeping pH at 5.5 to 6.5, dissolved oxygen levels at 5-6 mg/L and the correct amount of solutions to add to the plant per day.

Digital control and sensing also increase the reliability of the system. The IoT-based greenhouses show how cheap EC, pH, temperature, humidity, flow, and oxygen sensor networks, with microcontrollers and cloud dashboards are able to stabilize microclimates and alleviate the load on operators [9]. The latter is directly applicable to the control measures that have been suggested in this paper, namely PWM-based outflow of light, oxygenation by pump, and solenoid vs. peristaltic delivery of nutrients. Constant monitoring of parameters and recording of the past data is the key to the attainment of constant performance in controlled environments. Moreover, the suggested system will include an application-based control interface, which enables the user to monitor and manipulate the major parameters like the lighting cycles, dosing of the nutrients and the oxygenation directly on a smartphone or a computer. This is an application-based control that increases user-friendliness, minimizes human intervention, and makes the vertical hydroponic system more feasible to the small and large-scale applications.

It is also important in the selection of crop portfolio. The argument on the basis of diversity of crops in hydroponics is that it is best to plant species and varieties that will get the highest nutritional yield per unit area and energy [10]. This helps in staggered planting of year round supply. Meanwhile, plant-health surveillance is an area where computer vision is becoming involved, and the implementation of a disease-detection workflow based on Efficient NetB4 is in line with current trends in dataset-based diagnosis of fungal and bacterial stress in leafy crops [4], [10]. Through these ways, early intervention can be done and hence minimizing losses.

The compilation of these sources can be said to be the practical engineering envelopes that will guide this build. The sizing of hydraulic flow is based on lift plus friction head with oxygen requirements of 6-9mg/L (leafy greens) and low-single digit watt pump power (compact towers) [3], [8]. Lighting plans are of 12-16-hour photoperiods and LED-based fixtures are set 12-36 inches over the canopy with the intensity varied depending on the growth stage of the plants to provide sufficient photosynthesis and cost-effective lighting [3], [5], [8]. Stage-dependent dosing of macro and micro elements, automated peristaltic delivery and periodic solution refresh is necessary in nutrient management to eliminate ionic drift [3], [5], [8]. Energy budgets validate that lighting dominates the daily consumption, pumps and controllers rely on relatively small amounts of power, which confirms the necessity of the efficiency-based approach to the scheduling of LEDs [5], [8], [9].

Hydroponics is sustainable and policy wise, it fits into the global goals of water conservation and low agrochemical runoff as pointed out in the FAO guidelines [1], [4]. These systems have the ability to achieve this by facilitating the realization of production in urban and peri-urban areas, thereby cutting down on the use of degraded soils and reducing supply chains. With the demand expansion conditions [2], hydroponics can serve local food security due to predictability of the yields and uniform quality.

To conclude, the literature is in favor of the system specification adopted in this project. Hydroponics will directly solve the issue of water and land shortages [1]-[4], substrate methods are more advantageous to yield of specific crops, IoT sensing and control contribute to stability [9], and diversification of crops and detection of diseases will make crops more resilient [10]. In addition, a combination of an application-based control system guarantees the vertical hydroponic system is technically stable as well as user friendly, scalable and accessible to the users and, therefore, a viable solution to the current agriculture. Empirically proven ranges of structural, hydraulic, dosing, lighting, and monitoring options in this work are within the recent prototype and research prototypes and studies.

1.1.3 Literature Gap

The literature has established that hydroponic farming has potential as an alternative to the traditional soil-based farming, which consumes resources. Earlier researchers focus on water conservation and state that hydroponics can help conserve by nearly 90 percent of water levels in comparison to field agriculture [3]. On the same note, estimates of food demands across the globe underscore the dire need to incorporate more innovative agricultural systems that will facilitate the issue of population growth in the future [2]. Although these works provide solid motivation, the majority of the literature revolves around general performance gains instead of integration of the automation process, data-driven monitoring, and plant health intelligence on the level of the system.

Also, controlled environment agriculture (CEA) studies point out that almost 30 percent of crop losses are associated with lack of enough monitoring of nutrient levels, temperature, humidity and pH [4], although current systems reported in literature do not have closed-loop feedback that would automatically change operating conditions based on sensor data. Research concentrating on design of hydroponic systems has almost universally considered nutrient delivery or lighting subsystems independently of each other, without considering reliance on each other as lighting, oxygenation and nutrient regulation subsystems.

Moreover, even though IoT-based agricultural platforms have attracted attention towards real-time monitoring, the literature demonstrates a gap in the research relating to implementing machine learning or a computer vision algorithm into hydroponic systems to assist in the detection of early-onset diseases and the health of the vegetables. The proposal proposal background research cites computer vision, as well as EfficientNet-based models to help detect diseases [10]; nevertheless, these are unexplored in the context of compact indoor hydroponic systems that are to operate in urban environments. Lastly, there is no sufficient literature that highlights modularity, scalability, energy savings, or user-friendliness as there is on the benefits of hydroponic performance and sustainability. The majority of commercial hydroponic systems are based on the extensive use of grid electricity that raises the cost of operation and ecological footprint, a phenomenon that is not adequately discussed in the scholarly literature. As such, there is a gap in the process of creating integrated, automated, resource-efficient, and user-friendly indoor hydroponic systems that include sensing, control, machine intelligence, and a little bit of manual intervention.

1.1.4 Relevance to current and future Industry

Economically, there is a major technological change in agriculture which is fuelled by urbanization, sustainability issues and the demand to produce food throughout the year. In the modern production environment, the hydroponic and controlled-environment systems are fast growing as plausible alternatives to soil-based production since they can maximize the use of space, save water and provide predictable production regardless of climatic situations. These attributes can serve the world priorities in food security, resource efficiency, and urban sustainability programs, and as such, hydroponics is becoming more a viable option in commercial agriculture, greenhouse, and urban agriculture markets.

Indoor hydroponics is also being integrated with sensing, automation, data analytics to further position it in the new realms of technological development like smart farming, precision agriculture, and agri-tech. Indoor hydroponics uses Internet-of-Things (IoT) sensors, automated nutrient dispensers, and LED grow light to cut the labor expense and enhance crop quality. Supermarkets, hotels, and restaurant supply chains are also being served by vertical farming systems, containerized farms, and rooftop greenhouses being implemented by companies in North America, Europe, the Gulf region, and southeast Asia. This shows that intelligent hydroponic platforms are ceasing to be an exclusive feature of a research setting and are becoming a scalable commercial project.

Considering the future trends in the industry, there will be an increase in the demand of localized food production because of the increased logistics cost and climate disturbances and supply chain weaknesses. Another alternative that is resilient is hydroponic systems that facilitate decentralized and distributed agriculture around consumption hubs. Renewable powered hydroponics, AI-based crop decision systems, automated harvesting systems, and disease detection using computer vision are also among the future trends that will make processes less complex and more productive. These developments point to smart hydroponic systems to be a key component of the future of agricultural infrastructure specifically in land-limited megacities and climate-stressful areas.

Thus, the creation of small, miniaturized, and automated hydroponic systems is directly correlated with the demands of the present-day industry, as well as future tendencies in the industry. Such systems will help define the future of agriculture by enhancing its efficiency, sustainability, and technological advancement as a process that will no longer be field-based, but will be controlled, data-driven, and environmentally-conscious farming systems.

1.2.1 Objectives

The expected outcomes of this project might be stated as objectives. The project's objectives are:

- Develop and implement advanced control and monitoring systems to optimize water, nutrient, and energy usage in indoor hydroponic farming systems.
- Utilize data analytics and monitor the systems to control environmental factors such as temperature, humidity, and nutrient levels with accuracy for enhanced crop growth.
- Minimize water wastage by developing hydroponic systems that use less water compared to traditional farming methods.
- Encourage sustainable farming practices by improving the efficiency of hydroponic systems, reducing the need for chemical inputs, and minimizing resource waste.
- Develop guidelines to make hydroponic farming more sustainable, ensuring it can meet the growing global food demand while minimizing environmental impact.

1.2.2 Scopes

It is within the scope of the project to design a small and modular prototype that can be used in an indoor environment, especially in the indoor farming. It will be designed to be cost effective, user friendly and with minimal water wastage, the building will include components of low consumption of power like LED lights and low power air/water pumps. There will also be an entry-level user interface or alert system, where the user checks the status of the system and notifications are made when any critical thresholds are exceeded. The other important area is the comparison of the performance of the system against the traditional systems, in the context of saving water, health, and growth rate of crops. The particular focus regarding the TDS and turbidity monitoring implementation to refine the nutrient solution control and mitigate the risk of root diseases or algae formation will be given.

Finally, the project can serve as a scalable educational and research hub, advancing sustainable urban agriculture, and engaging more people in the adoption of smart hydroponic systems in the areas that may be limited by land, water, or climatic issues. The resulting system can be a starting point of the further development of the fully IoT-enabled or renewably powered agricultural technologies.

1.2.3 Requirements

Table 01: Functional and Non-Functional Requirements

SI	Functional	Non-Functional
01	PVC Structure	Power Source
02	Uniform illumination of light for Photosynthesis	Record Crop Past Data
03	Water Flow Control	
04	Nutrition and pH Management	
05	Oxygenator	
06	Temperature and Humidity adjustment	
07	Monitoring of the system	

1.2.4 Specifications

PVC structure: In a vertical hydroponic system, a 2.5 to 6-ft (30 to 72-inch) long PVC structure is suitable for an indoor setup. For a 2.8-feet-long system with a 1.31-feet (0.40m) diameter, a plant spacing of 3-6 inches is needed, whereas, for a larger setup, this spacing would be 20-25 inches. In a 2.8-foot-long system, there will be 6 rows of plants, with 5 plants in each row, yielding a total of 15 to 30 plants.

Lighting: LED needed **12-16 hours/day**. The amount of light energy plants need (measured in lumens) can vary from **6,000 to 43,200 lumens** per square meter per second, depending on the plant species and its growth stage (seedling, vegetative, or flowering/fruiting). Therefore,

Blue Light: Supports vegetative growth, leaf development, and root systems. As per the requirement, **5-15 watts**.

Red Light: Encourages flowering and fruiting, contributing significantly to overall growth. As per the requirement, **10-25 watts**.

White Light: Combines the benefits of all wavelengths, making it ideal for supporting entire photosynthesis processes. Typically, **10-60 watts** can cover the ranges needed for the various stages of growth.

Keep the lights about **12-36 inches (30-90 cm)** above the plants, depending on the light intensity and type of plants.

Water Flow Control: Lettuce requires **2-3 liters**, strawberries **3-4 liters**, cucumbers **5-8 liters**, tomatoes **5-8 liters**, and cabbage **3-4 liters** of nutrient solution per plant per day in hydroponic systems. Along with this, TDS (Total Dissolved Solids) **500-2000 mg/L** water quality has to be maintained over the entire plant.

Nutrition and pH Management: In a hydroponic system, nutrient concentrations are adjusted based on the growth stage, with **1-2 teaspoons** per gallon (3.79 liters) for seedlings, **2-3 teaspoons** for vegetative growth, and **3-4 teaspoons** for flowering/fruiting. The pH levels should range from **5.5 to 6.5** for effective nutrient absorption.

Oxygenator: An Oxygen Concentration of **5-8 mg/L** has to be maintained for root respiration.

Temperature and Humidity Adjustment: A temperature of **22-26°C** during the day and **18-22°C** at night has to be maintained for proper metabolism and nutrient intake. Humidity of **50%-70%** Relative Humidity is used to avoid transpiration and maintain proper water intake by the plants, and a humidifier is used to maintain the required humidity.

Power Source: The total energy consumed by one setup in a 3 to 6-foot vertical hydroponic system per day is between **0.5 kWh and 0.7 kWh** without a grow light.

1.3.1 Applicable standards and codes (CO2)

Table 02: Applicable Standards and Codes

IEEE Standards	Description	Application in the project
IEEE 1680-2009	Environmental performance standards for sustainable materials and energy efficiency.	It focuses on the environmental performance of electronic products and would apply to the energy efficiency and sustainability of materials like PP.
IEEE 1451.0-2024	Standard for smart transducer interface for sensors and actuators.	Supports sensor integration for water flow, pH management, nutrition, and environmental controls.
IEEE 802.15.4-2020	Standard for Low-Rate Wireless Networks	Facilitates wireless communication for remote monitoring and real-time control of system components.
IEEE 1888	The standard for sensor network communication.	Supports data collection and communication from various environmental sensors in the hydroponic system.
IEEE 1680.2-2024	Energy efficiency standards for IT equipment, including lighting systems.	Ensures energy-efficient lighting for plant growth
IEEE 11073-10472-2023	For medical device communication, including remote monitoring.	Facilitates remote monitoring and control of the plants in hydroponic systems, similar to health-related IoT devices.
IEEE 1471	Standard for software engineering, focusing on data storage and system management.	Applies to the storage and management of crop data and system performance records over time.
IEEE 11073-20601	For the security and privacy of IoT devices	Ensure safe remote monitoring and control

1.4 Conclusion

The project is a new practice of hydroponic farming to create an innovative solution to the modernization and introduction of the control and monitoring of processes to meet the current problematic issues in agriculture, including the influence of climate change, the increasing food demand across the planet, and the shortage of water resources. In spite of the fact that our project is at its initial stage, we have in mind the vision of the system that will contribute to the productivity of crops, as well as reduce the cost of operations and waste to a minimum. Through technology, we would like to develop a sustainable agriculture system that would avoid excessive pollution of the environment and maximize resource utilization. Although there are some challenges associated with the project including, the initial cost of setting it up is high and it needs a consistent power supply, the same is not difficult. It is made in a manner that allows the solution to be scalable, energy saving, and flexible enough so that it can be adapted to satisfy the increasing request in sustainable food production over time. We feel that this project with further growth and refinements will be critical in the development of hydroponic farming methods, making them more affordable yet accessible and environmentally manageable in the coming years.

Chapter 2: Project Design Approach - [CO5, CO6]

2.1 Introduction

In this part we explore the available engineering approaches which can be used in order to overcome the constraints of urban agriculture in space limited settings. Since an efficient indoor farming needs a strong control of the environment, we are cognizant of our main approach that involves applying vertical architecture to achieve as much yield as possible on a very small footprint, which is highlighted in this chapter. In this case, we also describe the work of the whole IoT-based environment and describe how a network of sensors that measure TDS, turbidity, and climate is connected with automated pumps and LEDs that are controlled by a spectrum. This summary makes a full grasp of how vertical design, sensor fusion, and automation can be integrated to address the water shortage and land scarcity issues in a proper manner.

2.2 Core System Block Diagram

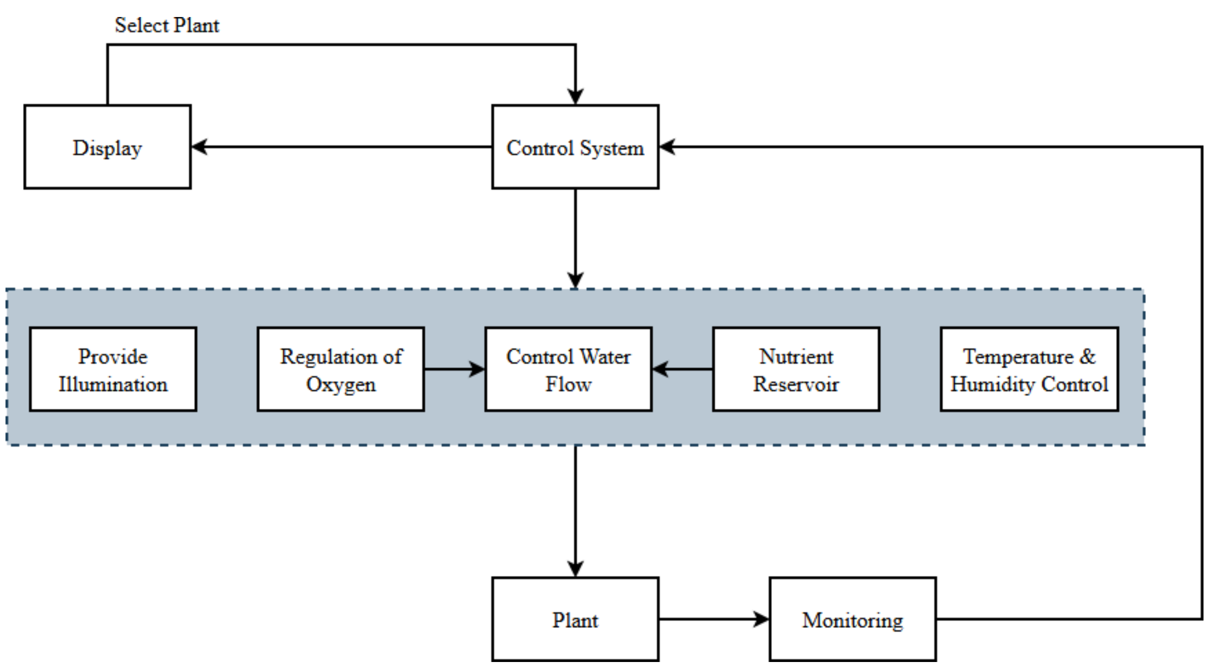


Figure-01: Core System Block Diagram of Vertical Hydroponic System

2.3 Identify the Multiple Design Approaches

There are two design methodologies that were created to execute the suggested system. Approach 01 Design Design Approach 01 employs a peristaltic pump to deliver the nutrients in a precise manner and has a rotating camera with a servo-controlled rotation that enables dynamic monitoring. Moreover, this method uses a ResNet model that is trained in leaf data to identify disease in plants. Conversely, Design Approach 02 has a solenoid-based pumping design and a multi-camera system to provide an all-encompassing surveillance. In the case of disease detection, a MobileNet architecture is implemented. As well, both design incorporates an easy to use mobile interface, allowing remote control and monitoring.

2.3.1 Design Approach-01

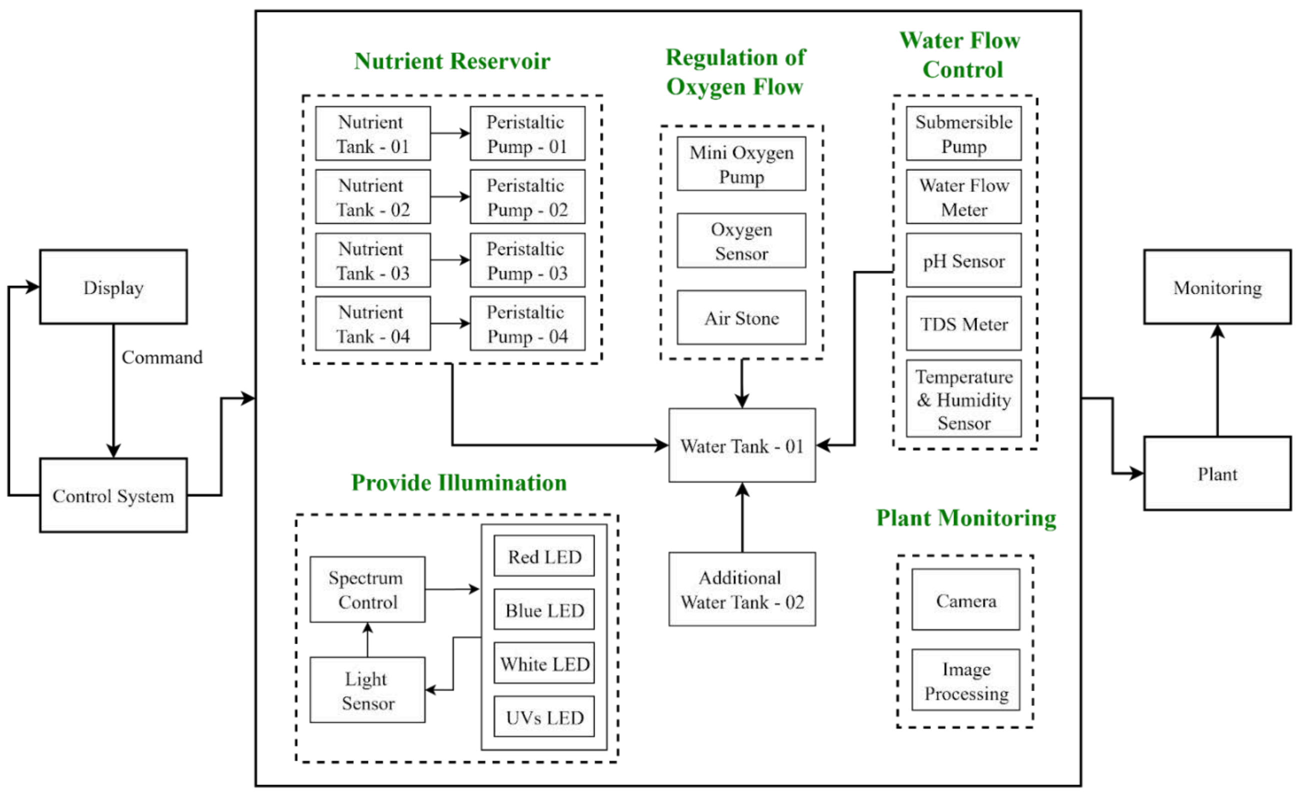


Figure-02: Block Diagram of Vertical Hydroponic System Design Approach-01

Figure 02 presents the block diagram of vertical hydroponic system de Approach 1ch-1 that will provide the optimal plant growth by controlled automated nutrients, water, oxygen, light, and environmental conditions. It is controlled by a central point of control that takes real time readings on pH, TDS, water temperature, oxygen concentration, humidity, light intensity and then modulates the sub systems accordingly. Water pumps are used to circulate water and nutrient tanks provide nutrient solution in exact quantities by using peristaltic and nutrient pumps respectively. Water pumps help in circulation and nutrient solution is supplied by nutrient tanks respectively and monitored by a flow meter. A mini oxygen pump, air stones and oxygen sensors are used to sustain dissolved oxygen which aids in healthy root respiration. The spectrum control of red, blue, white, and UV LED lights is used to set the intensity depending on the growth phase of the plants, and light sensors guarantee an adequate distribution and homogeneity. An image processing (EfficientNetB4) camera is used to track the health of plants and identify stress or illness. The display will offer real time system information to its users who can easily monitor. This mix of pumps, sensors, LEDs, and monitoring devices is a feedback loop and therefore the control system can continually optimize operations, so that there is efficient automated and controlled growth and minimum wasting of resources and maximization of yield.

2.3.2 Design Approach-02

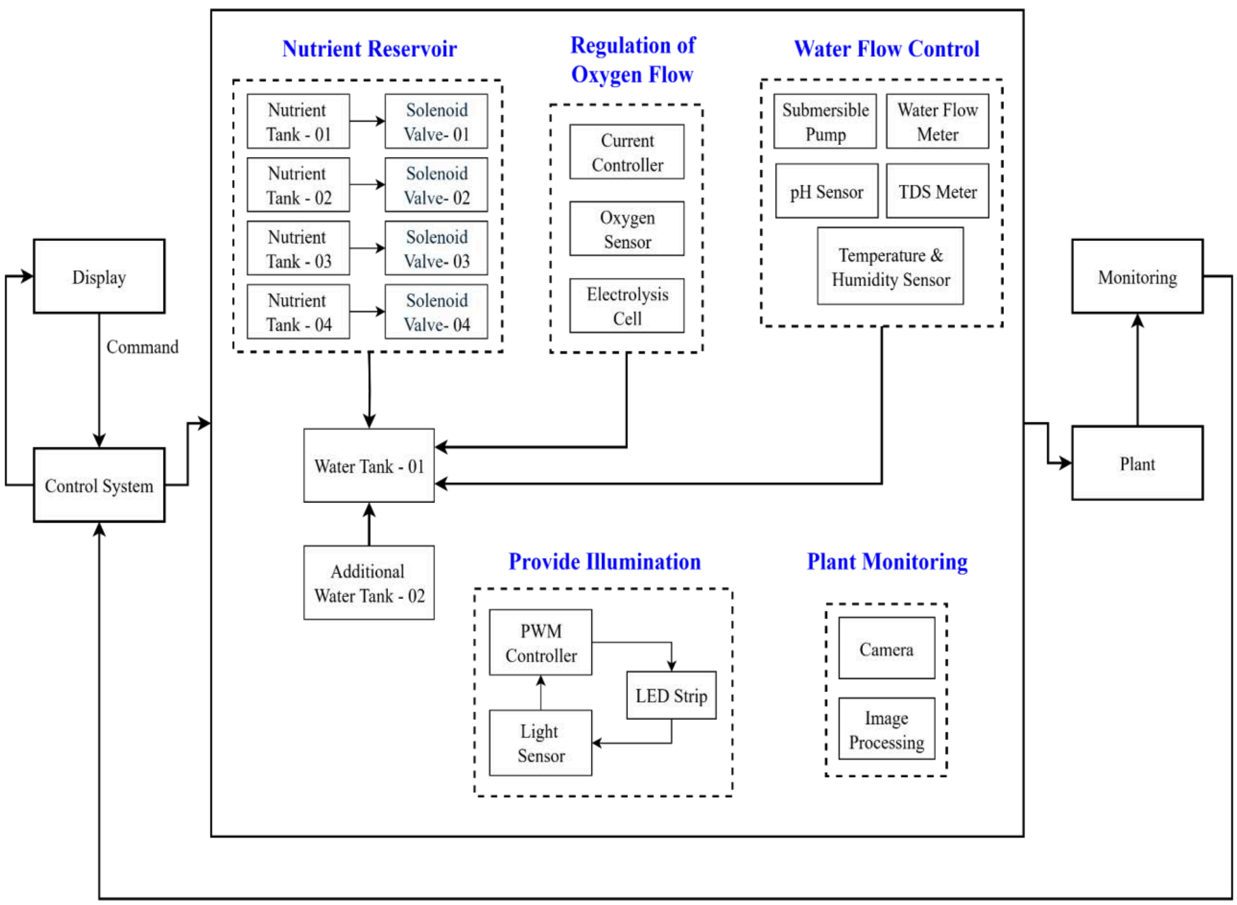


Figure-03: Block Diagram of Vertical Hydroponic System Design Approach-02

The block diagram of vertical hydroponic system design Approach 2 illustrated in Figure 03 has the automated control system at the centre. The system controls the flow of nutrients into the system through four nutrient tanks using solenoid valves and water is circulated with submersible pumps and checked using flow meters. A continuous measurement of the environmental conditions (pH, total dissolved solids, temperature, humidity and dissolved oxygen) is made using sensors. Oxygen is provided on the water using an electrolysis cell. Lighting is done through LED strips that are regulated through PWM controllers and light sensors to give the best illumination during the different growth stages. A camera equipped with image processing is used to monitor the health of the plants and provides information looped back to the control system to make appropriate adjustments. A display gives real time information and users are able to monitor the performance of the system. All these elements constitute a closed-loop system that manages the nutrient, water, oxygen, and light most effectively to achieve efficient, automated, and controlled growth of the plants.

2.4 Analysis of multiple design approaches

2.4.1 LED Control

When we have Vertical Hydroponic System, there is a need to provide adequate light distribution to facilitate maximum photosynthesis by the growing plants. Different plant species require different levels of light and therefore, the light distribution system should be such that it provides the correct spectrum and intensity of light to each vegetation. The following table outlines the suggested light distribution in the variety of plant species:

Table 03: The optimal light distribution parameters for various plant types.

Plant Type	Total Lumens Needed	Red LED (%)	Blue LED (%)	White LED (%)	Distribution (Lumens)	Light Distance from Plant
Lettuce	6,000-10,000	30%	40%	30%	R: 2,000-3,000 B: 2,400-4,000 W: 1,800-3,000	20-25 cm
Spinach	9,000-12,000	30%	40%	30%	R: 2,700-3,600 B: 4,000-5,400 W: 2,300-3,000	20-30 cm
Coriander	6,000-10,000	30%	40%	30%	R: 2,000-3,000 B: 2,400-4,000 W: 1,800-3,000	20-25 cm
Red Amaranth	8,000-12,000	35%	40%	25%	R: 2,800-4,200 B: 3,200-4,800 W: 2,000-3,000	20-30 cm
Strawberry	12,000-20,000	45%	30%	25%	R: 5,400-9,000 B: 3,600-6,000 W: 3,000-5,000	30-40 cm
Cherry Tomato	20,000–30,000	50%	30%	18%	R: 10,000-15,000 B: 6,000-9,000 W: 3,600-5,400	35-45 cm

LED System Design Approach-01

Simulate how the light-controlling sub-system will work for design approaches-01. A Proteus simulation is given below

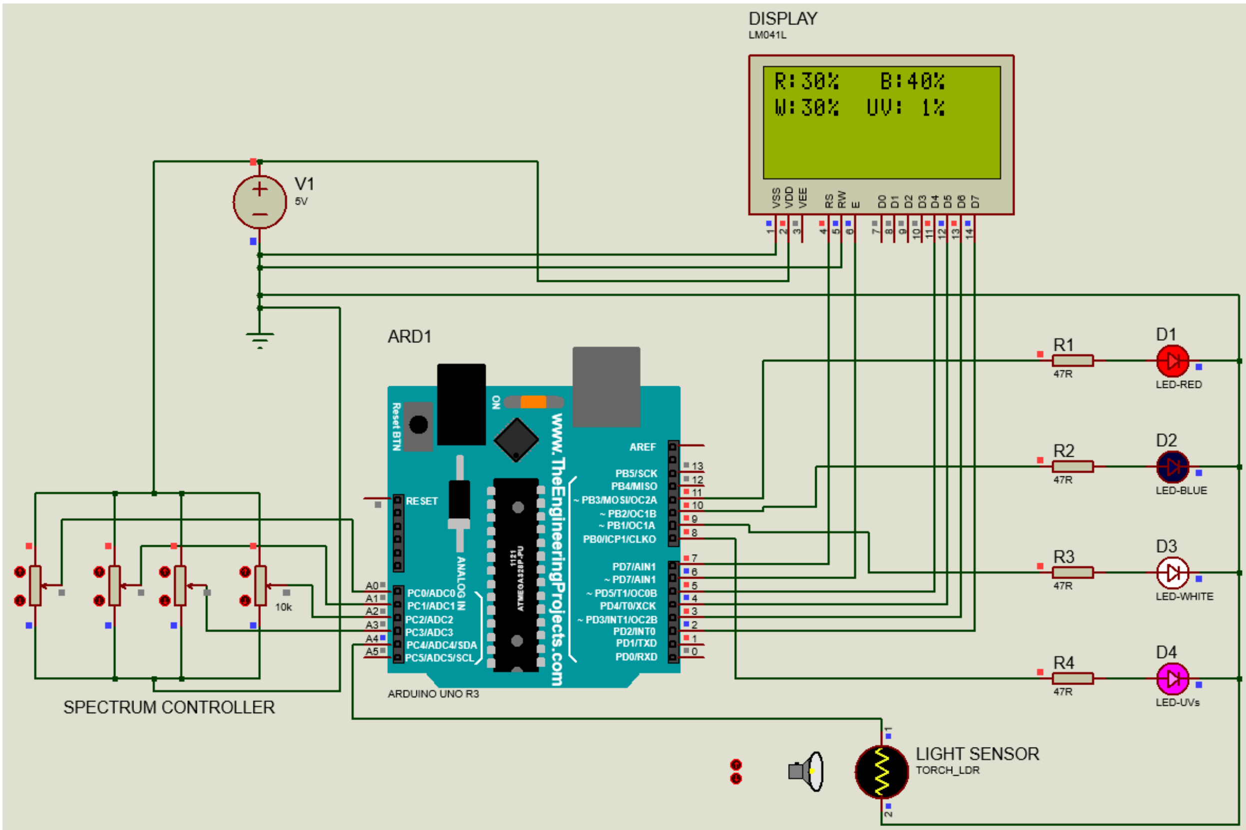


Fig. 04: Proteus Simulation for LED control using the Spectrum Controller

This Arduino system is capable of maximizing growth of the plant by dynamically controlling the output of LED spectral development through real-time ambient light readings supplied by a built-in LDR sensor. The microcontroller is keeping a certain ratio of Spectral 40% Blue to vegetative development, 30% Red to photosynthetic efficiency, 30% White to large scale coverage and 1% UV to secondary metabolite production. The system compensates automatically the variations of natural light to maintain a constant Photosynthetic Photon Flux Density (PPFD) and energy-efficiency and shows the real-time status through an LCD interface.

LED System Design Approach-02

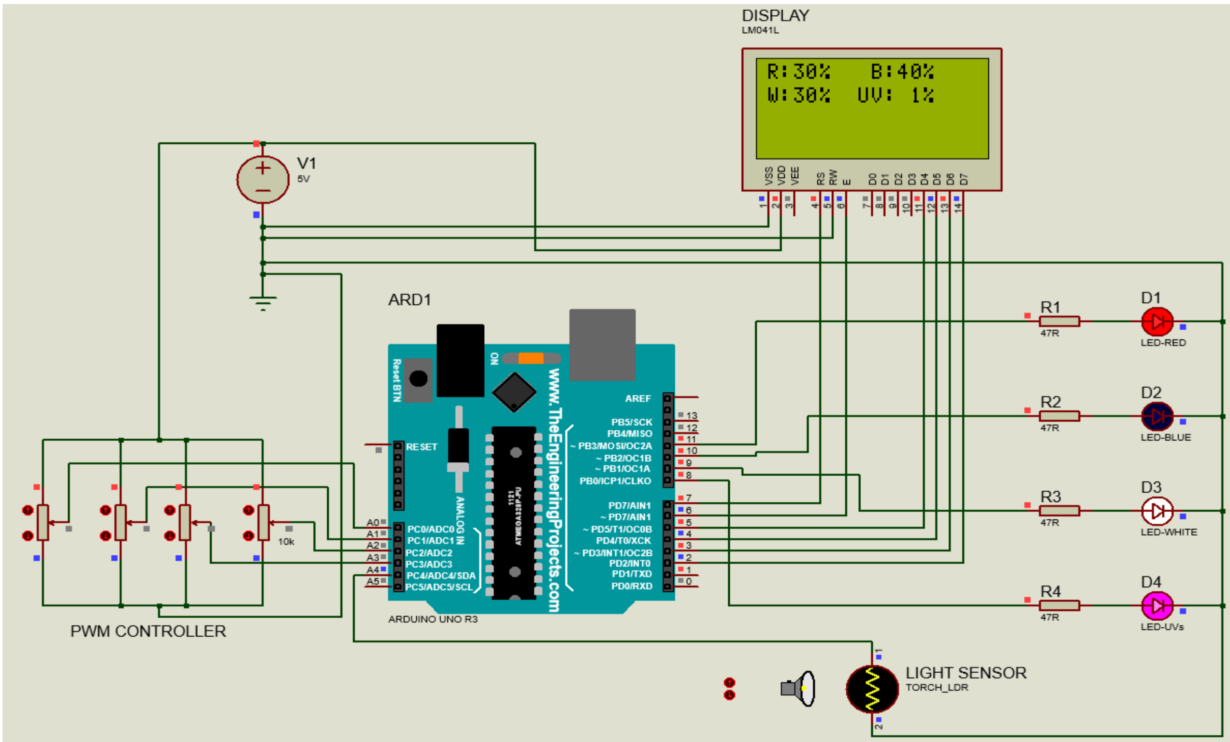


Fig. 05: Proteus Simulation for LED control using PWM Controller

This Arduino-based LED plant growth controller automatically manages optimal lighting conditions for vegetative plant cultivation through a smart feedback control system. The light sensor (LDR) continuously monitors ambient light levels and sends data to the Arduino Uno R3, which processes this information along with user inputs from the controller panel to determine precise LED output requirements. The microcontroller uses PWM signals to control four LED channels at specific intensities: red at 30% for photosynthesis, blue at 40% for vegetative growth, white at 30% for full-spectrum support, and UV at 1% for plant quality enhancement. The system operates in a continuous loop where the light sensor measures current conditions, Arduino calculates required adjustments, PWM signals regulate LED brightness through 47Ω current-limiting resistors, and the LCD shows real-time percentages. This automated approach ensures energy-efficient operation while providing optimal light spectrum for enhanced lettuce growth, automatically compensating for changing natural light conditions throughout the day to maintain consistent growing conditions.

Theoretical Calculations:

From Table-01, we choose the maximum and minimum of each lumen range, photoperiod H = 16 h/day, typical LED luminous efficacy 100 lm/W (conservative), and 15% system losses (driver/reflection/wiring).

Calculation for Lettuce Plant:

<u>Red LED:</u>

Maximum Lumens 3000 and minimum 2000 lumens

Maximum Electrical Power required, $P_{max\ red} = \frac{Total\ Lumens}{Lumenous\ Efficacy} = \frac{3000}{100} = 30\ W$

Minimum Electrical Power required, $P_{min\ red} = \frac{Total\ Lumens}{Lumenous\ Efficacy} = \frac{2000}{100} = 20\ W$

Maximum Energy required per day, $E_{max\ red} = \frac{P_{max} \times H}{1000} = \frac{30\times16}{1000} = 0.48\ kWh/day$

Minimum Energy required per day, $E_{min\ red} = \frac{P_{min} \times H}{1000} = \frac{20\times16}{1000} = 0.32\ kWh/day$

<u>Blue LED:</u>

Maximum Lumens 4000 and minimum 2400 lumens

Maximum Electrical Power required, $P_{max\ blue} = \frac{Total\ Lumens}{Lumenous\ Efficacy} = \frac{4000}{100} = 40\ W$

Minimum Electrical Power required, $P_{min\ blue} = \frac{Total\ Lumens}{Lumenous\ Efficacy} = \frac{2400}{100} = 24\ W$

Maximum Energy required per day, $E_{max\ blue} = \frac{P_{max} \times H}{1000} = \frac{40\times16}{1000} = 0.64\ kWh/day$

Minimum Energy required per day, $E_{min\ blue} = \frac{P_{min} \times H}{1000} = \frac{24\times16}{1000} = 0.384\ kWh/day$

<u>White LED:</u>

Maximum Lumens 3000 and minimum 1800 lumens

Maximum Electrical Power required, $P_{max\ white} = \frac{Total\ Lumens}{Lumenous\ Efficacy} = \frac{3000}{100} = 30\ W$

Minimum Electrical Power required, $P_{min\ white} = \frac{Total\ Lumens}{Lumenous\ Efficacy} = \frac{1800}{100} = 18\ W$

Maximum Energy required per day, $E_{max\ white} = \frac{P_{max} \times H}{1000} = \frac{30 \times 16}{1000} = 0.48\ kWh/day$

Minimum Energy required per day, $E_{min\ white} = \frac{P_{min} \times H}{1000} = \frac{18 \times 16}{1000} = 0.288\ kWh/day$

The same calculation logic is similarly applied to optimize lighting for other plant varieties.

Summary of calculation for all plants:

Table. 04: Necessary Requirements for Energy and Power from Matlab.

=== PLANT LED REQUIREMENTS SUMMARY ===

Plant	Lumens_Min	Lumens_Max	Power_Min(W)	Power_Max(W)	Energy_Min (kWh/day)	Energy_Max (kWh/day)
Lettuce	6300	10150	74.1	119.4	1.186	1.912
Spinach	9150	12200	107.7	143.5	1.722	2.294
Coriander	6300	10150	74.1	119.4	1.186	1.910
Red Amaranth	8120	12200	95.5	143.5	1.530	2.300
Strawberry	12200	20300	143.5	238.8	2.300	3.820
Cherry Tomato	19900	29800	234.1	350.6	3.750	5.610

Note: Power values include 15% system losses
Operating hours: 16 hours per day
LED efficacy assumed: 100 lumens/watt

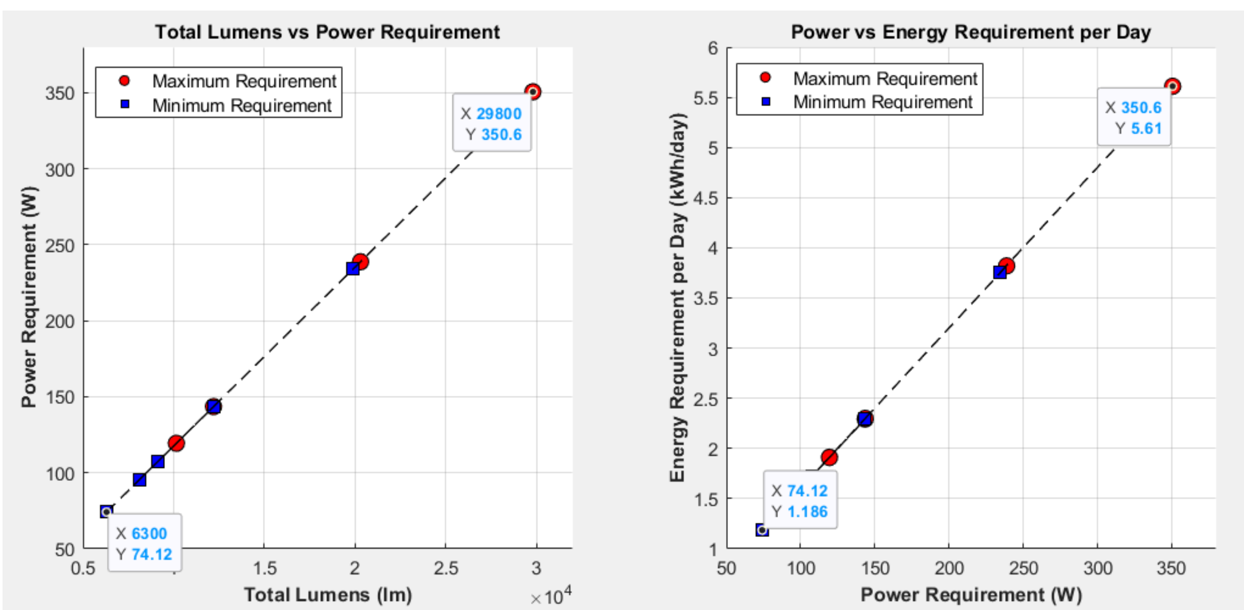


Fig. 06: (i) Lumens vs Power Requirement **(ii)** Power vs Energy Requirement

Fig. 06 graphs indicate the basic correlation between, lighting needs, power needs, power consumption in our hydroponic growing systems that are vertically located. It shows the linear dependence between total lumens required and power needed with the smallest point of low-demand crops and plants that need low electrical energy of 6,300 lumens and 74 watts and the highest spot of high-intensity crops and plants that require up to 29,800 lumens and 350.6 watts. The red circles indicate maximum requirements and the blue squares are minimum requirements and the dotted lines joining the operation ranges of each type of plant. Such linearity shows that the efficiency of the LED systems is constant over the whole range of plant requirements, thus, it is easy to estimate energy demands given desired levels of light output. These power needs are converted into real life daily energy needs with Fig.06 graph, which illustrates how electrical power is converted to operational costs during a standard 16-hour growing cycle.

The energy needs are proportional to between 1.2 kWh per day of minimum lighting systems and 5.61 kWh per day of high growing systems. This linear scaling testament of power versus energy consumption is a result of consistent schedule of operation and effectiveness of the system whereby growers are able to forecast reliably the extent of electrical infrastructure and the current operating cost. The linear characteristics of the two relationships simplify the system design decisions in that doubling the light intensity requirements will be accurately predicted to increase the power consumption and the daily energy expenses, which are easy to compute the economic effect of increasing the plant varieties or the production volume.

From Table 02, we take the minimum distances from plants as d = 20 cm and the maximum as d= 45 cm. So, Light Energy Efficiency,

$$\eta_{max} = k \times e^{-(0.0258\times d)} = 143.65 \times e^{-(0.0258\times 20)} = 85.75\%$$

$$\eta_{min} = k \times e^{-(0.0258\times d)} = 143.65 \times e^{-(0.0258\times 45)} = 44.98\%$$

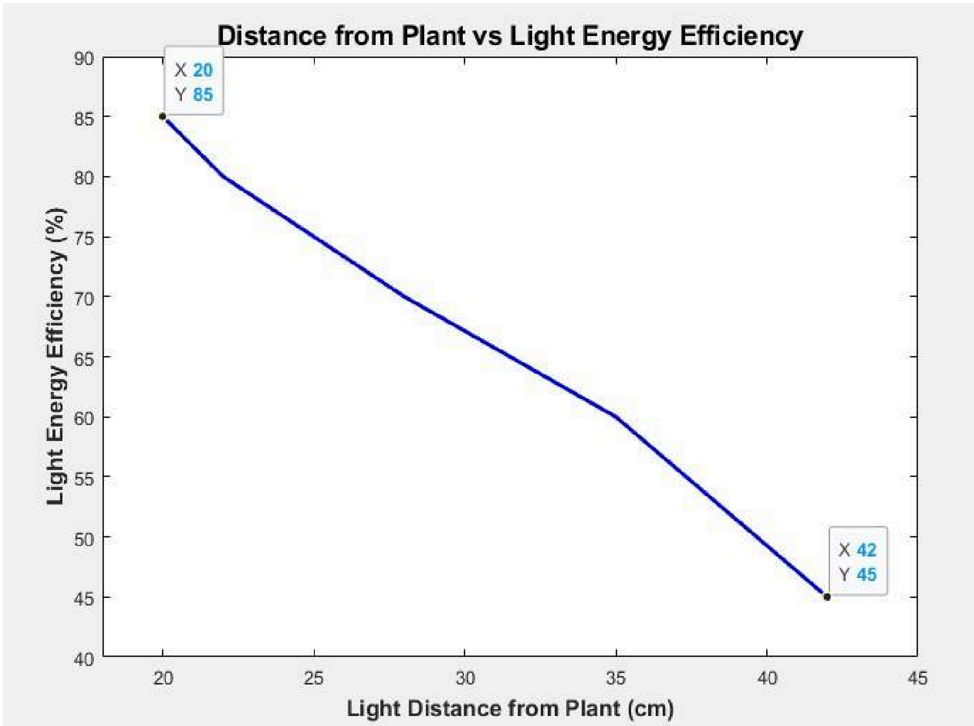


Fig. 07: Graph for Light Energy Efficiency

Fig.07 graph shows the negative correlation between the distance of the lights used in hydroponic and energy efficiency. The efficiency decreases linearly with a distance of 85 percent at 20cm distance and 45 percent at 42cm distance, indicating that a location of light is a major driving force in influencing the system performance. This decreasing tendency is the laws of physics in which the intensity of light diminishes with distance and therefore, greater electrical power is needed to produce the same amount of useful light to the plants as the distance increases. The linear drop in efficiency loss of about 1.8 percent centimeter increase in distance indicates that the closer the LEDs are to plants, the more energy efficiency and the lower operating expense.

2.4.2 Nutrient Supply

To ensure proper nutrient supply, we must determine the exact amount of nutrients each plant requires per day, and simultaneously calculate how these nutrients will be efficiently delivered to the plants. The detailed calculations provided below demonstrate the precise nutrient requirements and delivery mechanisms needed for optimal plant growth in our system.

Table 05: Necessary Nutrient Requirements for Plants.

Plant	$Ca(NO_3)$ (ml/L)	KNO_3 (ml/L)	$MgSO_4$ (ml/L)	Micronutrients (ml/L)
Lettuce	1.2	0.6	0.5	0.1
Spinach	1.4	0.7	0.6	0.1
Coriander	1	0.5	0.5	0.1
Red Amaranth	1.1	0.5	0.5	0.1
Strawberry	0.47	0.48	0.26	0.1
Cherry Tomato	0.79	0.6	0.44	0.1

Nutrient Calculation for Lettuce Plants
1 plant needs 1.5L of water per day [3]. So, 12 plants need = (12 × 1.5) = **18**L/day

Calcium Nitrate[$Ca(NO_3)$]:
1 L of water requires $Ca(NO_3)$ = 1.2 ml
1.5L of water requires = (1.2 × 1.5) = 1.8 ml
So, $Ca(NO_3)$ needed for 12 plants = (1.8 × 12) = **21.6** ml/day

Potassium Nitrate (KNO_3):
1 L of water requires KNO_3 = 0.6 ml
1.5L of water requires = (0.6 × 1.5) = 0.9 ml
So, KNO_3 is needed for 12 plants = (0.9 × 12) = **10.8** ml/day

Magnesium Sulfate ($MgSO_4$):
1 L of water requires KNO_3 = 0.5 ml
1.5L of water requires = (0.5 × 1.5) = 0.75 ml
So, $MgSO_4$ is needed for 12 plants = (0.75 × 12) = **9** ml/day

Micronutrients:
1 L of water requires = 0.1 ml
1.5L of water requires 0.1 × 1.5 = 0.15 ml
Micronutrients needed for 12 plants = (0.15 × 12) = **1.8** ml/day
Total Nutrient = (21.6 + 10.8 + 9 + 1.8)ml/day = **43.2** ml/day

The Total Nutrient Tank needed 4, and Each Tank Size is 250 mL.

Nutrients need to change after $= \frac{250}{43.2} = 5.78$ *or* **5** *Day***s**

Peristaltic Pump Rating Calculation:

Assume the pump-01 running time is for Calcium Nitrate($CaNO_3$), $t = 2 minutes.$

Nutrient Flow Rate, $Q = \frac{V_s}{t} = \frac{21.6}{2} = 10.8\ ml/min$

Pump-02 running time is for Potassium Nitrate. $t = \frac{V_s}{Q} = \frac{10.8}{10.8} = 1\ minute.$

Pump-03 running time is for Magnesium Sul. ate, $t = \frac{V_s}{Q} = \frac{9}{10.8} = 0.833\ minute.$

Pump-04 running time is for Micronutri. $t = \frac{V_s}{Q} = \frac{1.8}{10.8} = 0.167\ minute.$

So, we need a 12V adjustable peristaltic pump (flow 10–80 mL/min)

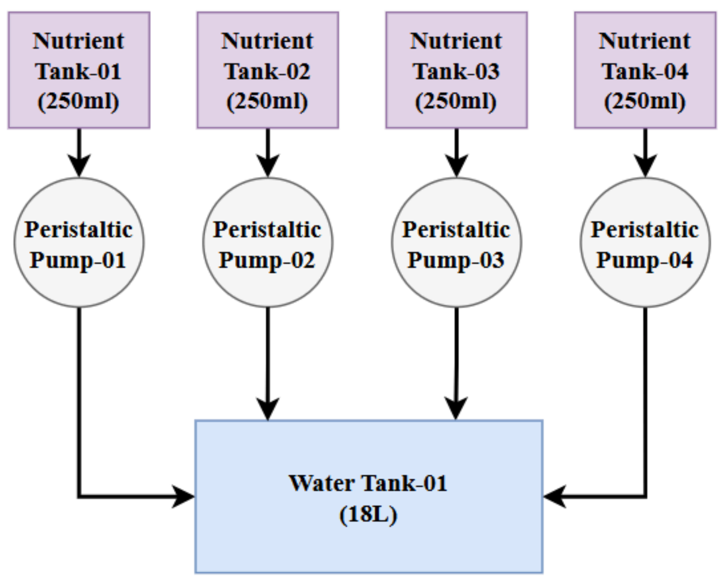


Fig. 08: Automated Nutrient Mixing System into the Water.

The system uses four 250 ml nutrient tanks, each connected to a dedicated peristaltic pump. By running the pumps for controlled durations, precise amounts of each nutrient are dispensed into a central 18-liter water tank, where they mix to form the final solution. This setup enables accurate nutrient ratio control and ensures consistent automated mixing without manual measurement.

Here are the calculations for other plants' daily nutrient and time requirements:

Table. 06: Necessary Nutrient Requirements, Peristaltic Pump requires time, Refill days for all the Plants from MATLAB.

PLANT TYPE	WATER (L)	Ca(NO3) (ml/L)	KNO3	MgSO4	Micro	DAILY NUTRIENTS (ml) Ca	KNO3	MgSO4	Micro	PUMP TIMES (min) P1	P2	P3	P4	TOTAL (ml)	REFILL (days)
Lettuce	18	1.2	0.6	0.5	0.1	21.6	10.8	9.0	1.8	2.00	1.00	0.83	0.167	43.2	5.8
Spinach	18	1.4	0.7	0.6	0.1	25.2	12.6	10.8	1.8	2.00	1.00	0.86	0.143	50.4	5.0
Coriander	18	1.0	0.5	0.5	0.1	18.0	9.0	9.0	1.8	2.00	1.00	1.00	0.200	37.8	6.6
Red Amaranth	18	1.1	0.5	0.5	0.1	19.8	9.0	9.0	1.8	2.00	0.91	0.91	0.182	39.6	6.3
Strawberry	18	0.5	0.5	0.3	0.1	8.5	8.6	4.7	1.8	2.00	2.04	1.11	0.426	23.6	10.6
Cherry Tomato	18	0.8	0.6	0.4	0.1	14.2	10.8	7.9	1.8	2.00	1.52	1.11	0.253	34.7	7.2

Here, we generate a graph to easily understand how nutrient demand increases proportionally with the number of plants, and also, pump running time rises with plant count to meet nutrient requirements.

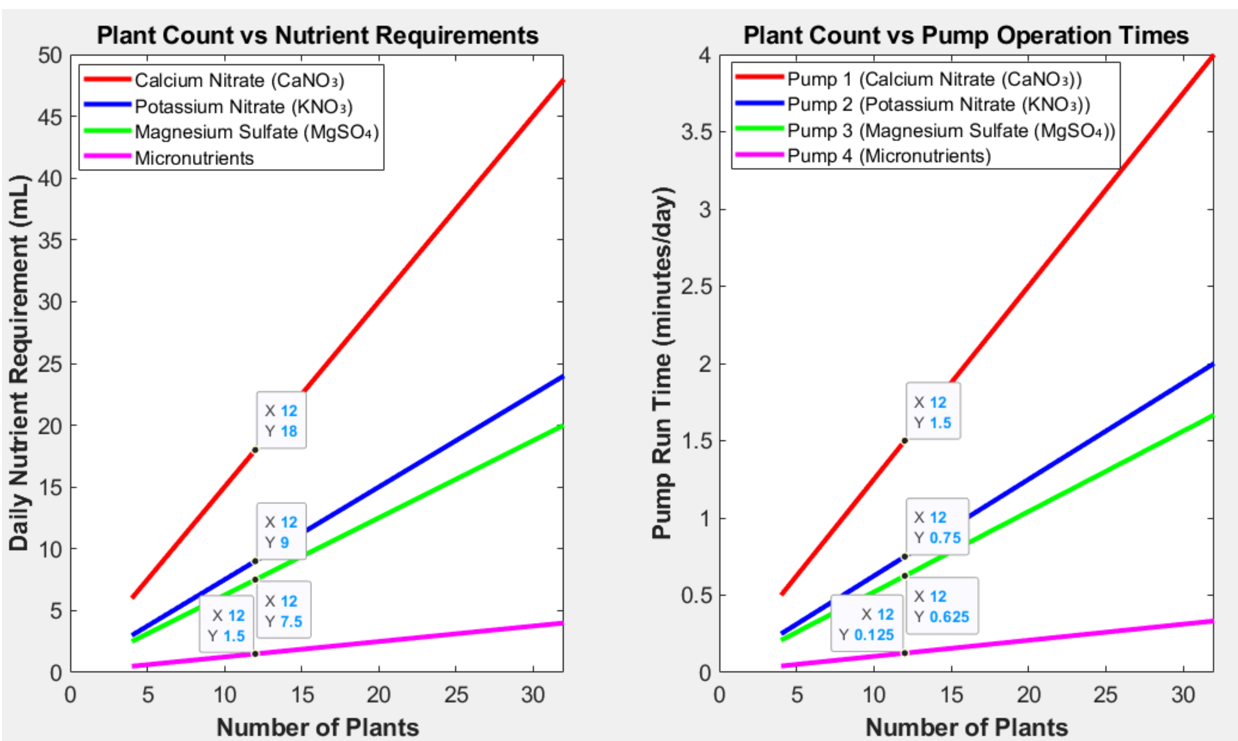


Fig.09: (i) Plant Count vs Nutrient Requirement (ii) Plant Count vs Pump Run Time

These graphs illustrate how nutrient requirements and pump operation times scale with the number of plants in the system. Figure 10(i) shows the daily nutrient requirements (in milliliters) for four different nutrients. For example, Calcium Nitrate (red line) requires approximately 18 mL for 9 plants, while Potassium Nitrate (blue line) and Magnesium Sulfate (green line) require about 24 mL and 7.5 mL, respectively. Micronutrients (pink line) have the lowest demand, at only around 1.5 mL.

Figure 10(ii) translates these nutrient requirements into pump operation times. Pump 1, which supplies Calcium Nitrate, operates for nearly 1.5 minutes per day when supporting 12 plants, whereas the micronutrient pump runs for less than 0.2 seconds. Both graphs indicate a clear linear trend-when the number of plants doubles, the corresponding nutrient requirements and pump operation times also double proportionally.

We can apply two approaches to supply nutrients in our system. One is using a peristaltic pump, and another is using a Solenoid Valve. To simulate how the Nutrient Supply sub-system will work, for both design approaches, a Proteus simulation is given below:

<u>Nutrient Supply Approach-01:</u>

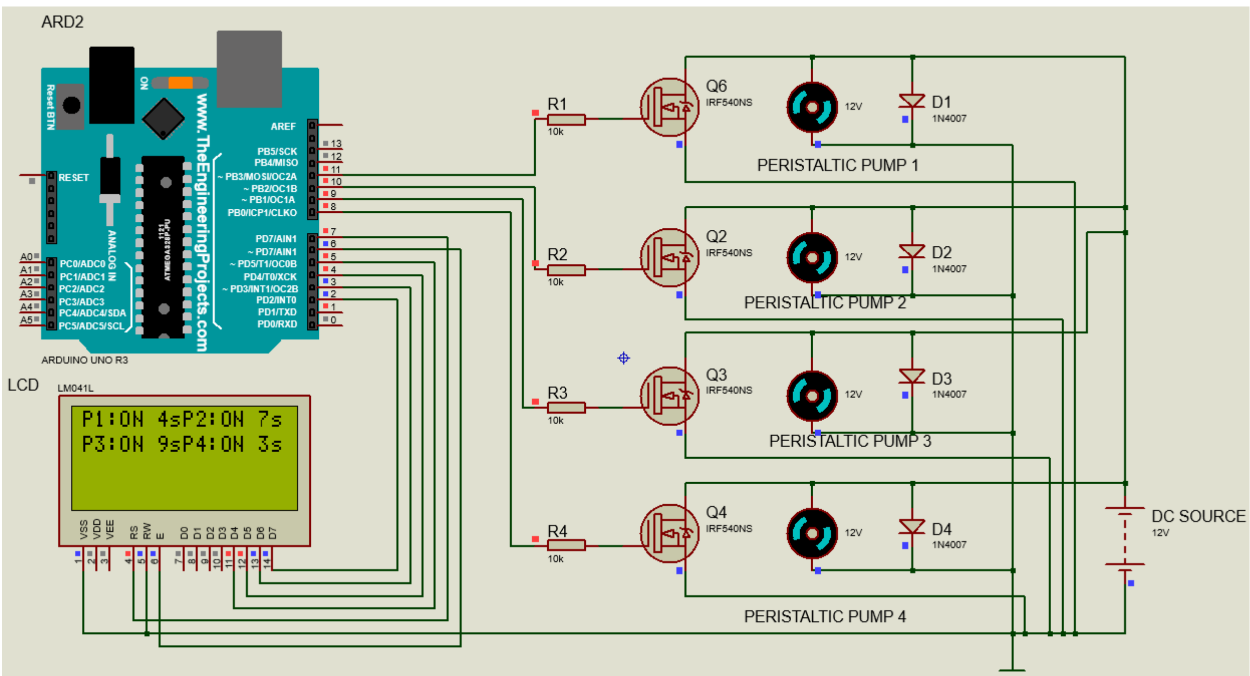


Fig. 10: Proteus Simulation for Nutrient Flow Control using Peristaltic Pump.

This circuit illustrates an automated hydroponic feeding system controlled by an Arduino. It operates four peristaltic pumps through MOSFET switches to deliver precise amounts of liquid nutrients. An LCD screen shows pump status and timing, such as “P1: ON 4s.” Each pump dispenses nutrients according to plant requirements, ensuring accurate dosing without manual watering. Plants receive essential macronutrients ($Ca(NO_3)_2$, KNO_3, $MgSO_4$) and micronutrients (Fe, Mn, B, Zn, Cu), with specific ratios summarized in Table 04. Automated timing improves growth efficiency, reduces nutrient waste, and minimizes environmental impact by preventing runoff.

Nutrient Supply Approach-02:

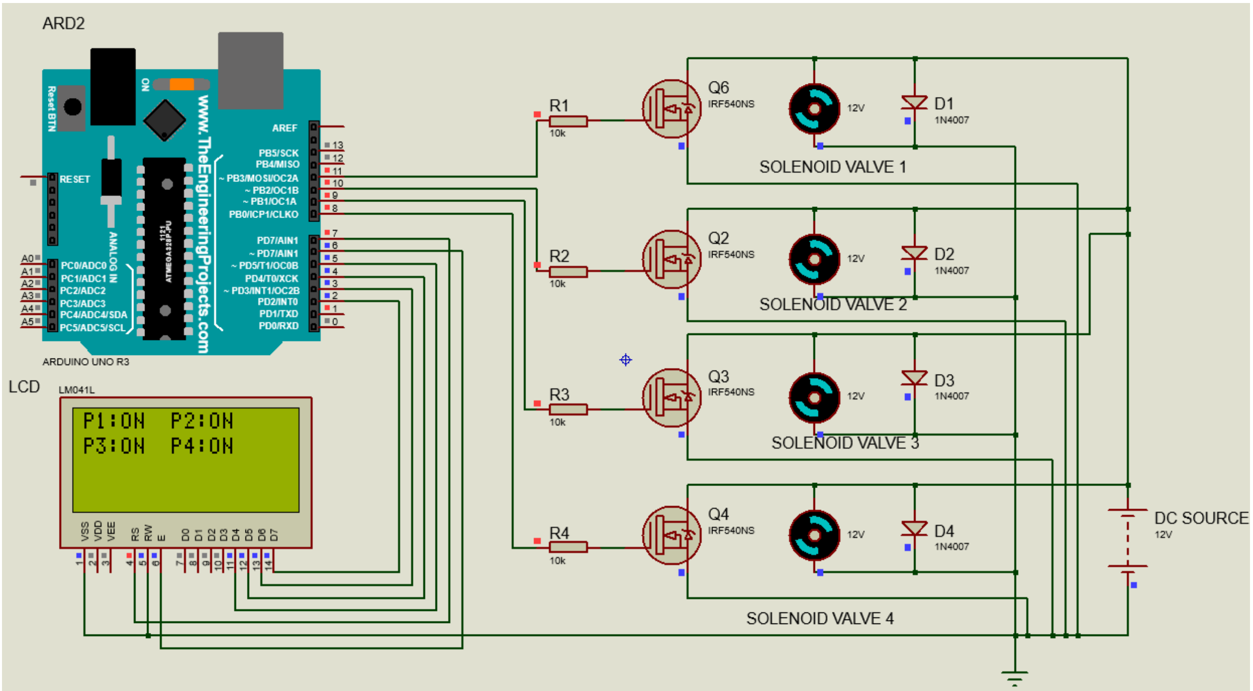


Fig. 11: Proteus Simulation for Nutrient Flow Control using Solenoid Valve.

In this circuit, an automated system of controlling the solenoid valve that delivers nutrients is demonstrated. The Arduino microcontroller is the brain, which controls four solenoid valves rather than the peristaltic pumps that are indicated in the prior design. All the valve circuits consist of a 10k resistor, and IRF540NS MOSFET switch, and a 1N4007 protection diode to operate the 12V solenoid valves safely on 5V Arduino signals. The LCD displays the status of the four valves P1:ON, P2:ON, P3:ON, and P4:ON indicating which lines of nutrients are being used to flow now. The major distinction of the pump-based system is that solenoid valves are on/off switches which are not responsible of moving the liquid as the pumps but of controlling the flow of pre-pressurized nutrient solutions. This design needs a pressure external source e.g. gravity fed tanks or pressurized reservoir to force the nutrients to flow through the valves as they open. The system enables the accurate time management of the timing of the flow of each type of nutrient to the plants, however the flow rate is determined by the pressure difference and size of the valve opening as opposed to the speed of the pump. This method is usually more predictable in terms of longer-term activities because solenoid valves contain fewer moving parts than pumps are more likely to be mechanically stable and kept in constantly expanding operations.

2.4.3 Water Flow Control

For healthy plant growth in our vertical hydroponic system, it is essential to supply water continuously and properly to each plant. To achieve this, we need to precisely calculate the required water flow. The following section presents the calculations for water flow control:

System Structure Calculation:

Geometry & Plant Count

- Plants per column = $\frac{122}{25} = 4.88 \sim 4$
- Circumference for 4 plants/row, $C = (3 \times 20) + 20 + (3 \times 5.08) = 95.24cm$
- Pipe diameter: $D = \frac{C}{\Pi} = \frac{95.24}{3.1416} \approx 30.31\ cm$
- Total plants per pipe: $Row \times Plants\ per\ Column = 3 \times 4 = 12\ Plants.$

Water Usage & Tank Size

- Daily water use: $12 \times 1.5L = 18\ L/Day$
- Recommended tank: 18+22 (Additional tank) = 40 L

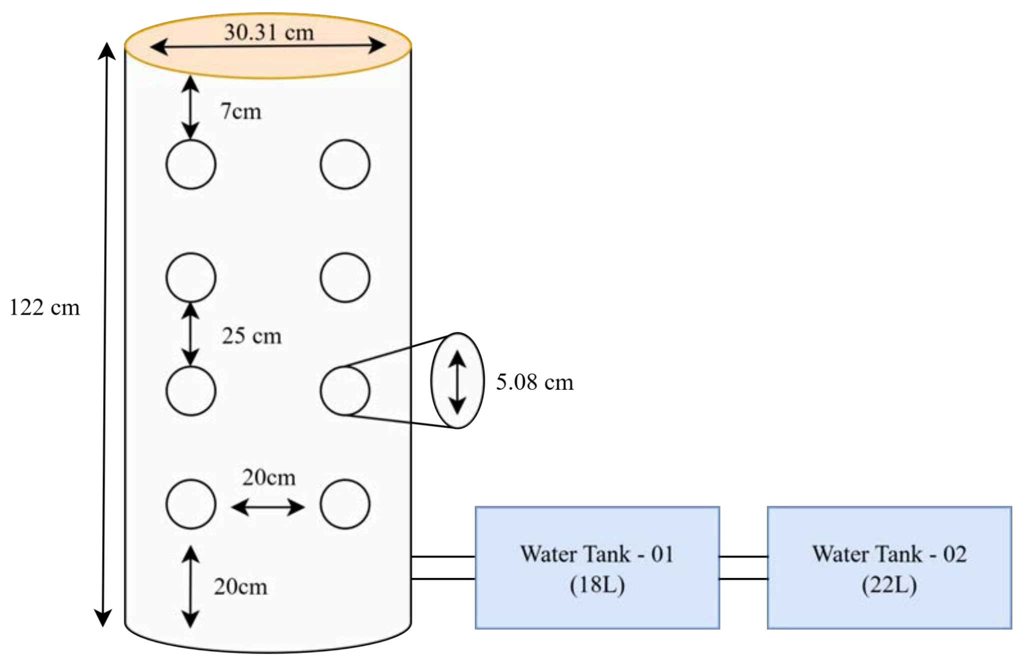


Fig.12: Vertical Hydroponic Tower Structure.

Calculation for Water Pump:

Daily water consumption for 12 plants is **18L/day.** For a hydroponic system, we need a 7.57 L/hr water flow rate to keep the root moisture for almost all hydroponic plants. [8]

Now,

Pump Head, $H = H_s + F_L$

For Static Head (Hs):

Vertical lift = 122 cm = 1.22 m

Friction Loss, $F_L = 0.5\, m$ $[using, F_L = \frac{f\, x\, (\frac{L}{D})}{(\frac{V_2}{2g})}]$

Total Head Required, $H = 1.22 + 0.5 = 1.72\, m$

Now,

ρ = 1000 kg/m³ (water density)

g = 9.81 m/s²

Q = 0.00021 m3/sec

H = 1.72 m

Hydraulic Power, $P = \rho g Q H = 1000 \times 9.81 \times 0.00021 \times 1.72 = 3.54\, Watts$

Motor Power (accounting for efficiency ~75%):

Moto Power, $P_{motor} = (3.54 \div 0.75) = 4.72\, Watts\, (input)$

Recommended pump rating is 5W.

Here, we can create a graph to better understand how hydraulic power and pump rating change according to the water flow rate. This graphical representation helps visualize the direct relationship between flow rate and pump performance. By analyzing the trend, we can determine the most efficient operating point for the pump and avoid undersizing or over-sizing. Such analysis ensures optimal energy use and reliable water delivery in the system.

The following Fig. 13 represents Water Flow Rate & Pump Rating Estimation: These graphs show how pump power requirements increase with flow rate in hydroponic systems. The left graph displays the direct relationship between flow rate and hydraulic power needed, where increasing from 1 L/hr to 15 L/hr requires proportionally more power from 0.47 W to 7.01 W.

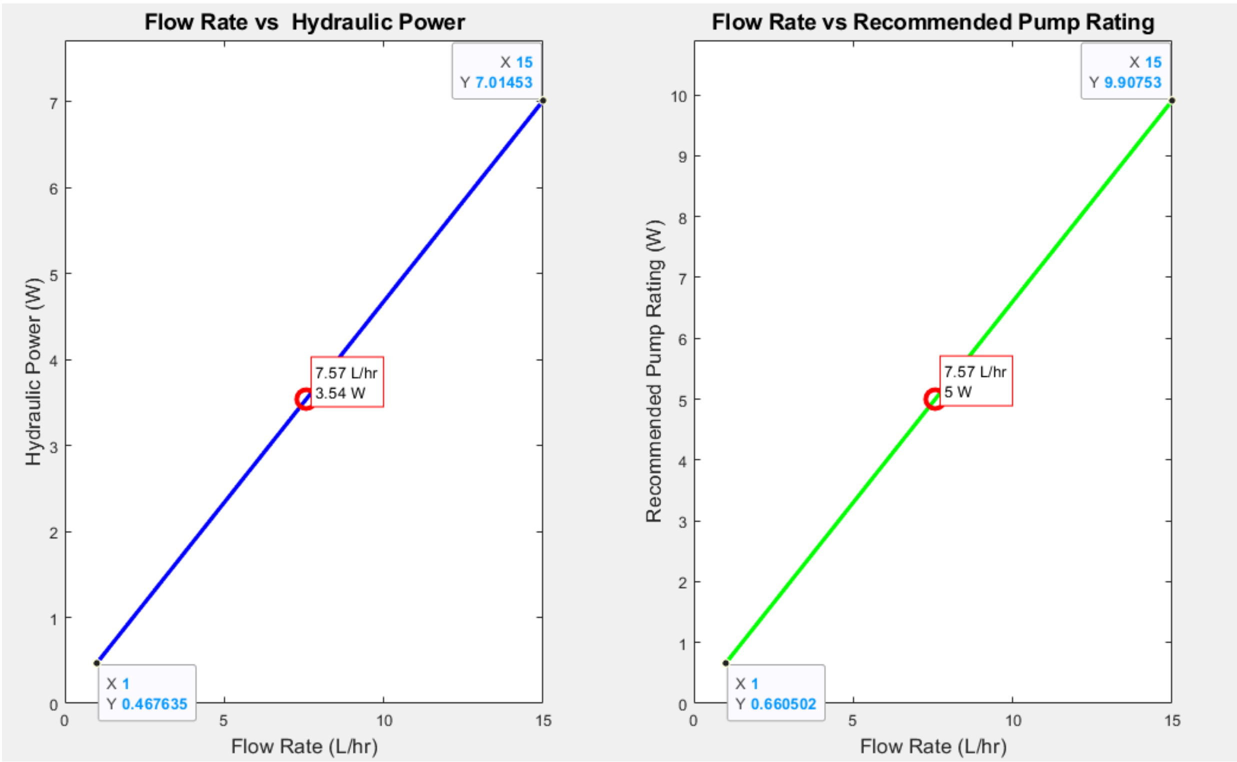


Fig. 13: Water Flow Rate & Pump Rating Estimation

The highlighted fact indicates that 3.54W of hydraulic power is required to generate a flow rate of 7.57 L/hr. Right graph indicates the recommended pump rating at each rate of flow which is always more than the hydraulic power to consider pump inefficiencies and safety margins. At the same 7.57 L/hr flow rate we would have the 5W-rated pump which will offer over and above the requirement of 3.54W the theoretical value of the pump. The two relationships are linear to a perfect extent i.e. doubling the flow rate doubles the power requirement. This aids the system designers in the calculation of the pump specifications without issues. When we require a flow rate of 10 L/hr, interpolating will give us that roughly we require 4.7W of hydraulic (power) and we should choose a pump with a rated power of 6.6W. The difference between hydraulic power and pump rating is the practical variables which includes efficiency of the motor, resistance and friction, and the need of steady operation at the long term. This information is critical in the process of choosing the pumps of the right size that is able to produce the necessary flow rates of water without being overpowered or overly large.

We must also monitor the water condition depending on the flow rate of the water. These factors are also employed to make sure that the plant is in good health just as pH value, temperature, humidity and total dissolved solids. We attempt to determine the values of the temperature (day and night), humidity, pH value, as well as the total dissolved solids of various types of plants. The Table. 06 containing the required parameter values is presented below:

Table 07: Required Parameters (pH, Temperature, Humidity, TDS) for Different Types of Plants

Plant	pH Range	Day Temp (°C)	Night Temp (°C)	Humidity	TDS (ppm) Range
Lettuce	5.5 – 6.5	18-24	12-16	50-70	560 – 840
Spinach	6.0 – 7.0	15-22	10-15	50-70	1260 – 1610
Coriander	6.2 – 6.8	20-25	12-16	50-60	980 – 1260
Red Amaranth	6.0 – 7.0	20-28	15-18	50-70	1050 – 1400
Strawberry	5.5 – 6.2	20-25	10-15	60-80	840 – 1050
Cherry Tomato	5.8 – 6.5	22-28	16-20	60-70	1400 – 3500

Water Supply System Design Approach 1 and 2

Here, Proteus Simulation is used to better understand our Water Control System for Approaches 1 and 2.

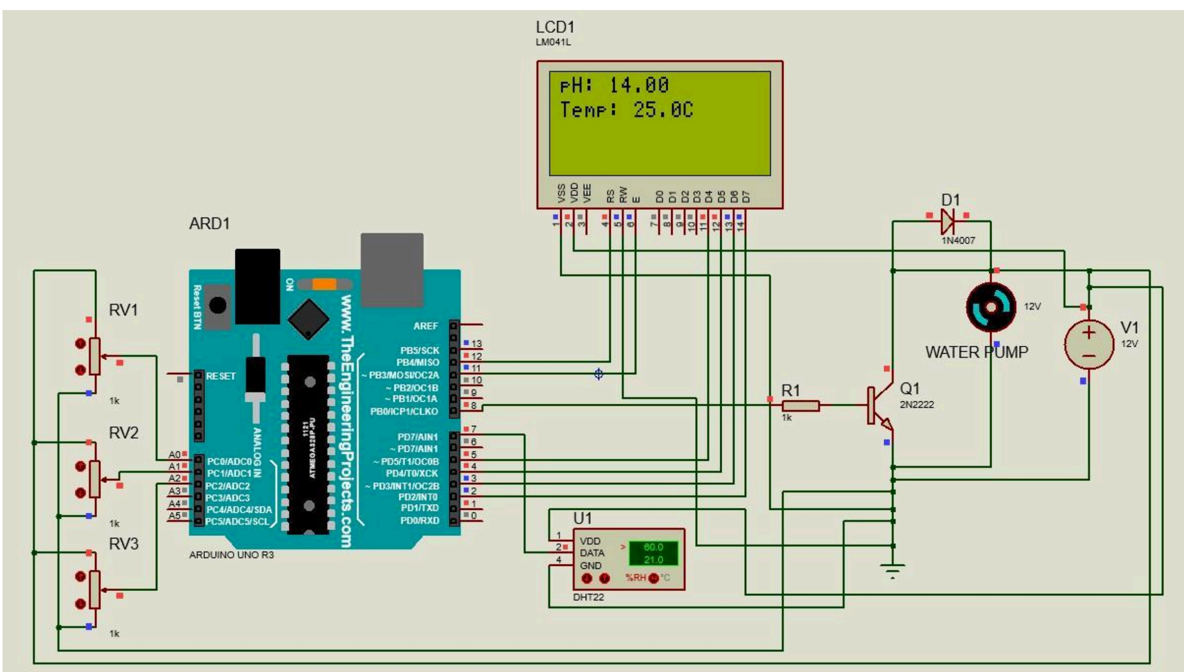


Fig.14: Simulation for Water Flow Control Showing pH and Temperature Value on Display

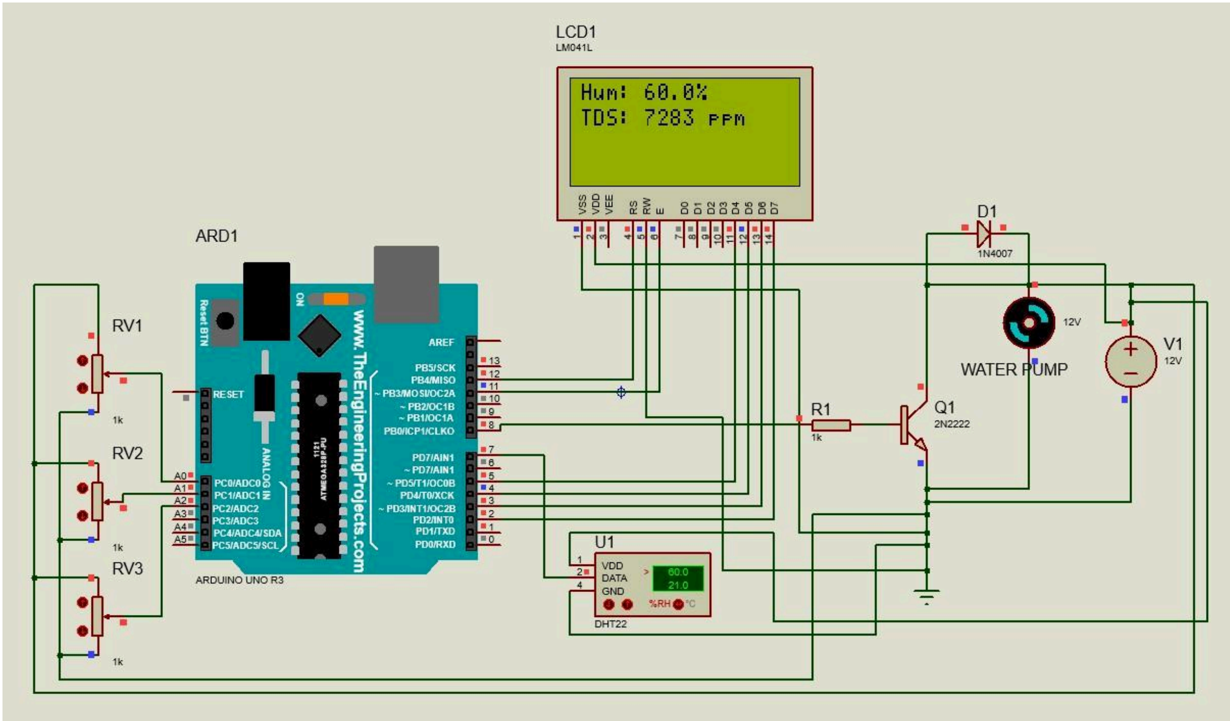


Fig.15: Simulation for Water Flow Control Showing Humidity and TDS value on Display

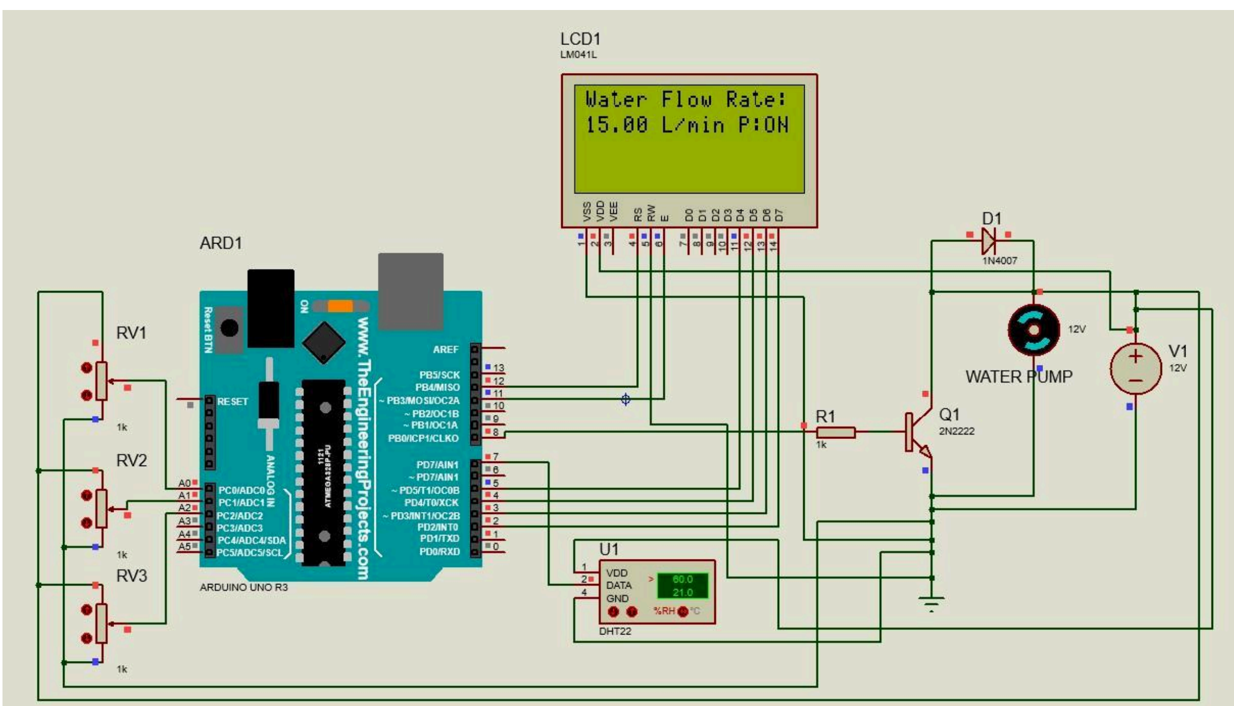


Fig.16: Simulation for Water Flow Control Showing Water Flow Rate and Pump Status.

Figure 14 pH and Temperature Monitoring System: The system is used to show water quality parameters that are important in the health of the plant in hydroponics. Various types of sensors are used to measure the value of the required parameters. The LCD displays the following: pH: 14.00 and Temp: 25.0, which means that the system has an indicator of both acidity levels and water temperature. The sensor data are processed by the Arduino to make the nutrient solution have the optimum PH level (5.5-6.5 most plants thrive in this range) and temperature to maximize the amount of nutrients it absorbs. Water pump may be programmed to circulate the solution in case the readings are out of acceptable limits.

Figure 15 Humidity and TDS Monitoring System: It is a set up that is used to monitor the environment and nutrient concentration factors. The results of the display indicate that the relative humidity and Total Dissolved Solids are Hum: 60.8% and TDS: 728 ppm respectively, thus reflecting the concentration of nutrients in the water. TDS measurements assist in the determination whether the nutrient solution is either too dilute or too strong whereas humidity control aids in maintenance of proper growing conditions. The reading of 728ppm indicates that it is a moderately concentrated nutrient solution that can be used as hydroponic crops.

Figure 16 Water Flow Rate and Pump Control System: The design is dedicated to fluid dynamics control, and it represents the Water Flow Rate: 15.00 L/min and the pump status indicators. The system tracks the amount of water and nutrient solution that passes across the irrigation lines so that the plants receive adequate water and nutrients. The flow rate of 15.00 L/min is adjustable depending on the size of the plant and the size of the system. This flow monitoring in real time will help to avoid under-watering and over-watering which are key elements in the success of hydroponics.

2.4.4 Oxygen Supply

Oxygen Rate per Liter of Water 5 mg/L is considered the minimum safe level. 6-9 mg/L is ideal for most hydroponic crops. [8] Total Oxygen (mL/min) = Water Volume (L) × Oxygen Rate (mL/min per L)

Based on this, we simulate a graph here,

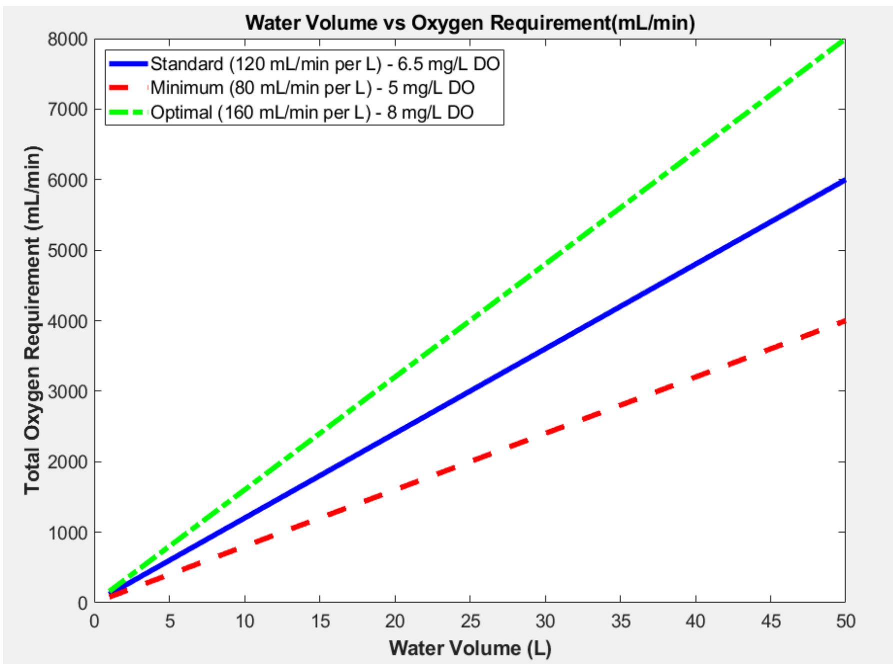


Fig.17: Water Volume vs Oxygen Requirement Graph.

This graph shows the linear relationship that exists between water volume and oxygen requirements within hydroponic systems where there are three different operational situations that depend on desired dissolved oxygen (DO) levels. The three parallel lines reflect some of the oxygenation strategies. The blue solid line indicates normal functioning at 120 mL/min per liter to retain 6.5 mg/L of dissolved oxygen to sustain basic respiratory requirements of the plant. The red dashed line shows the minimum viable operation at 80 mL/min per liter with 5mg/L DO - this is the bare minimum to allow root suffocation and anaerobic conditions. The green dotted line denotes the case at the optimum 160 mL/min per liter and 8 mg/L DO to produce the maximum root health and nutrient uptake efficiency.

Here is the Proteus Simulation,

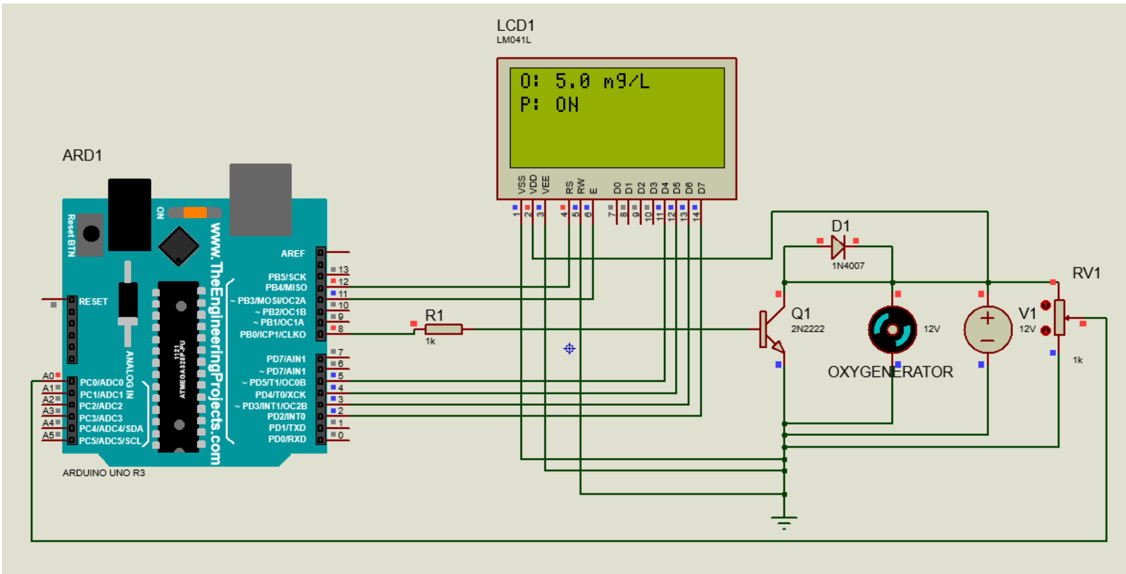


Fig.18: Oxygen Supply into the Water using Oxygen Pump

Fig.18 below is a circuit diagram of an oxygen monitoring and control system that we would be using in our hydroponic applications. The dissolved oxygen content is read by the Arduino microcontroller and O: 5.0 mg/L is shown in the LCD, which shows the concentration of oxygen in the water at the moment. The P: ON is also displayed which indicates that the oxygen pump is in operation. The circuit uses a 2N2222 transistor switch to operate an oxygen generator, in which case 1k resistor will be applied to regulate the flow of current and 1N4007 will be applied to reduce the voltage surges. Once the dissolved oxygen concentration falls below the set point, the Arduino triggers the 12V oxygen generator to be able to continue optimal oxygen levels to allow healthy root growth. This is an automated system that maintains dissolved oxygen in the desired range (5-8mg/L) that we have already discussed in the analysis of oxygen requirements. Lastly, Finally, Design Approach-01 and Approach-02 simulation of Design Approach to our Vertical Hydroponic System.

Oxygen Supply Design Approach 01

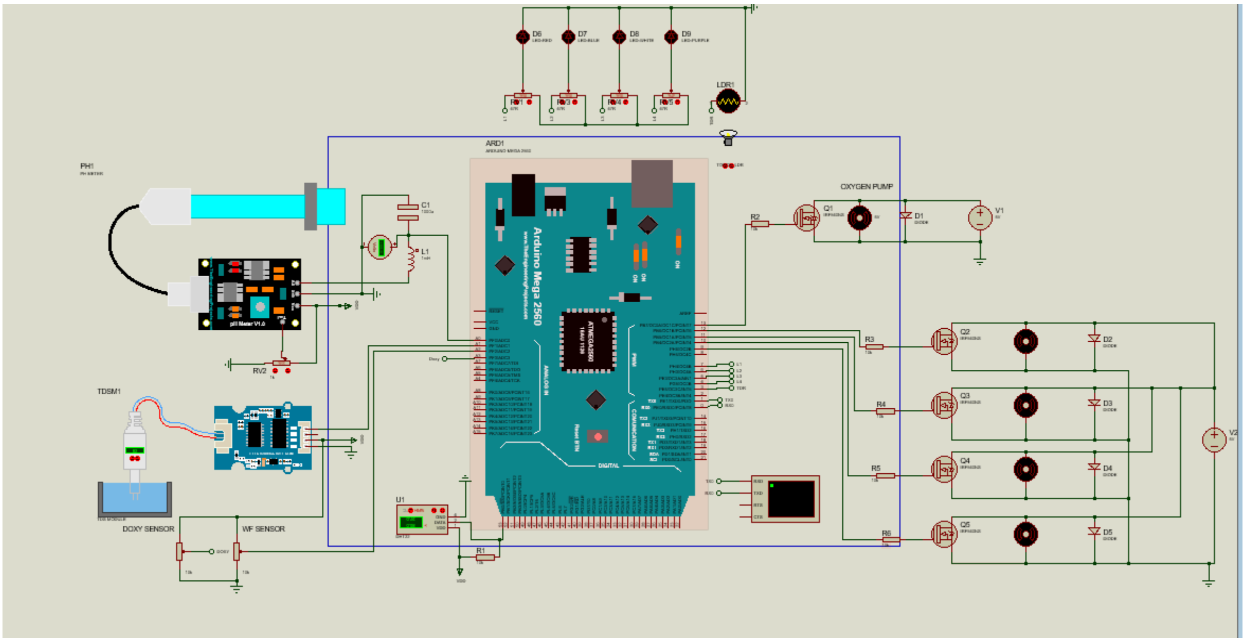


Fig.19: Simulation for Design Approach-01 for Vertical Hydroponic System

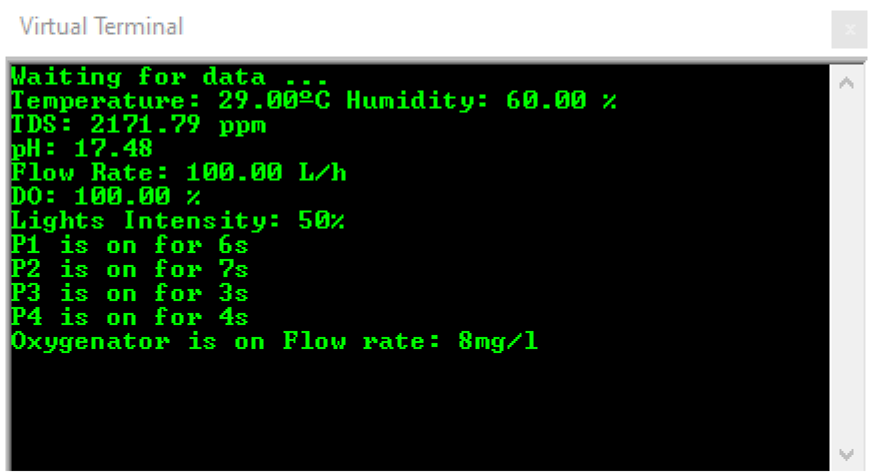


Fig.20: Output in Virtual Terminal for Design Approach-01

The simulation of our automated vertical hydroponic system (Design Approach-01) is represented by these figures: it will operate on a microcontroller based circuit that will control several sensors, pumps, and valves. It works based on sequential loading of four nutrient peristaltic pumps of a certain duration after which there is a break of 24 hours and key parameters of the environment like temperature, humidity, pH, TDS and the flow rate are monitored all the time. The terminal output demonstrates the completely automated delivery cycle of nutrients in the system as well as real-time control of the necessary conditions of growth.

Oxygen Supply Design Approach -02

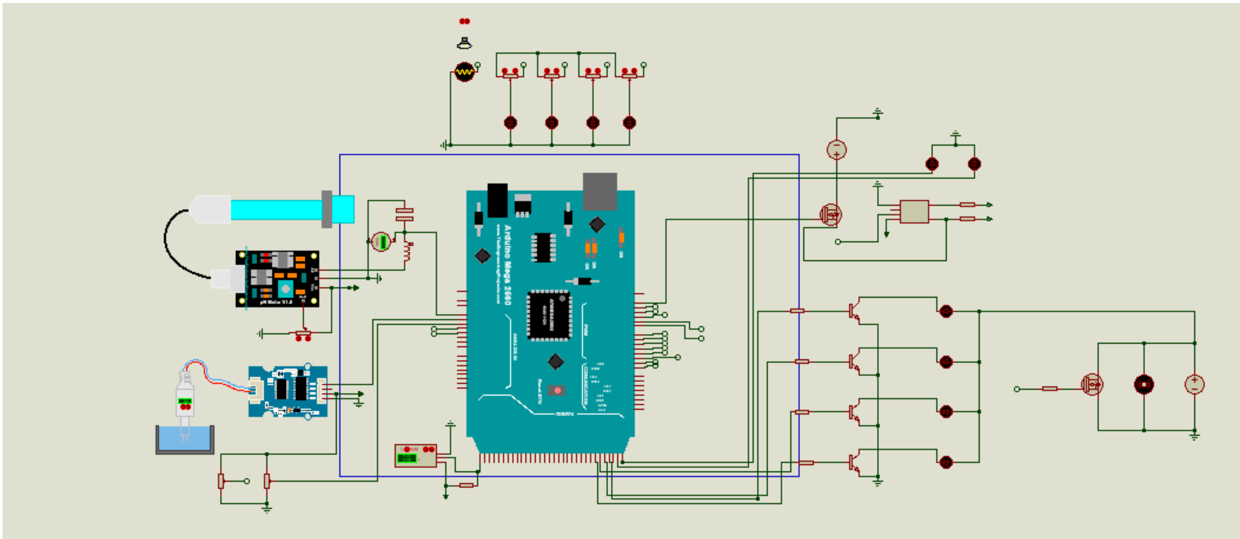


Fig.21: Simulation for Design Approach-02 for Vertical Hydroponic System

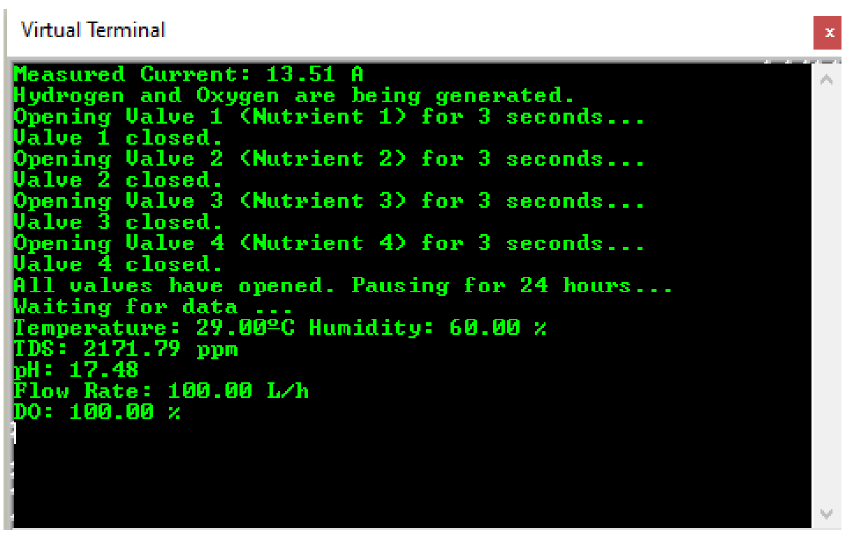


Fig.22: Output in Virtual Terminal for Design Approach-02

These are the simulation of our automated vertical hydroponic system (Design Approach-02) using a microcontroller based control circuit controlling a number of sensors, pumps and valves. This system opens 4 nutrient valves at various intervals, and then rests after 24 hours, continuously maintaining the parameters of the environmental conditions, such as temperature, humidity, pH, TDS and flow rate. The terminal output will show the system of automated work process on the delivery of nutrients and real-time monitoring the critical growing conditions.

2.4.5 Plant Health

Design Approach - 01 (ResNet)

Machine Learning Model: The model applied is ResNet, which is a form of Convolutional Neural Network (CNN). The CNNs recognize image features such as edges, textures and patterns by convolutional and pooling layers with automatic identification. ResNet also uses the idea of residual connections, which can be used to address the vanishing gradient problem and enable training of extremely deep networks. ResNet is highly accurate and is also efficient in training due to the stacking of residual blocks. It is pre-trained on massive datasets such as ImageNet, and it makes use of transfer learning to alter it to classify the leaves of lettuce. The model provides the probabilities of the different classes of leaves and it is possible to determine the healthy and diseased leaves correctly, thus allowing the identification of diseases early and improved control of crops.

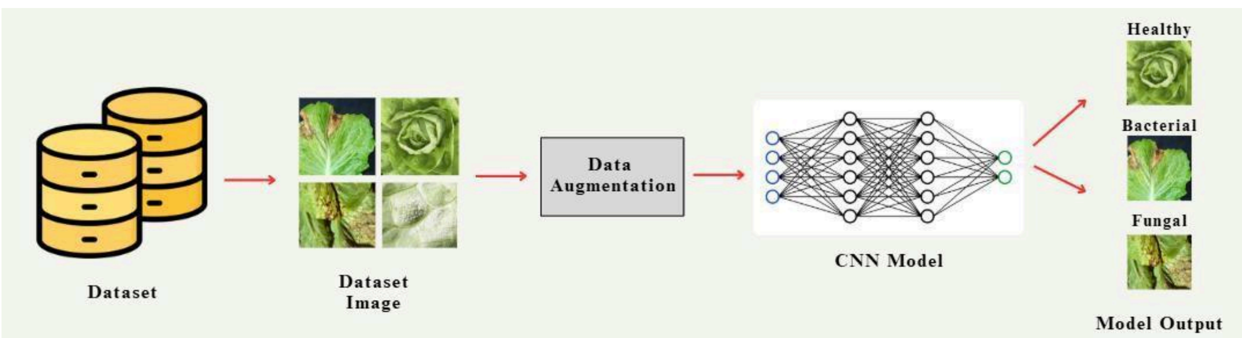


Fig.23: The proposed methodology's overall architecture

Data Description:

The data of this study is openly accessible on Kaggle and consists of 2813 images of lettuce leaves, which are categorized into three groups, namely: Healthy, Fungal, and Bacterial. To achieve successful training and evaluation, the data is divided into 80 percent training, 10 percent validation, and 10 percent testing so that the model can be trained to learn patterns of the training data, and the model can be evaluated on unseen validation and testing data.

Model Output:

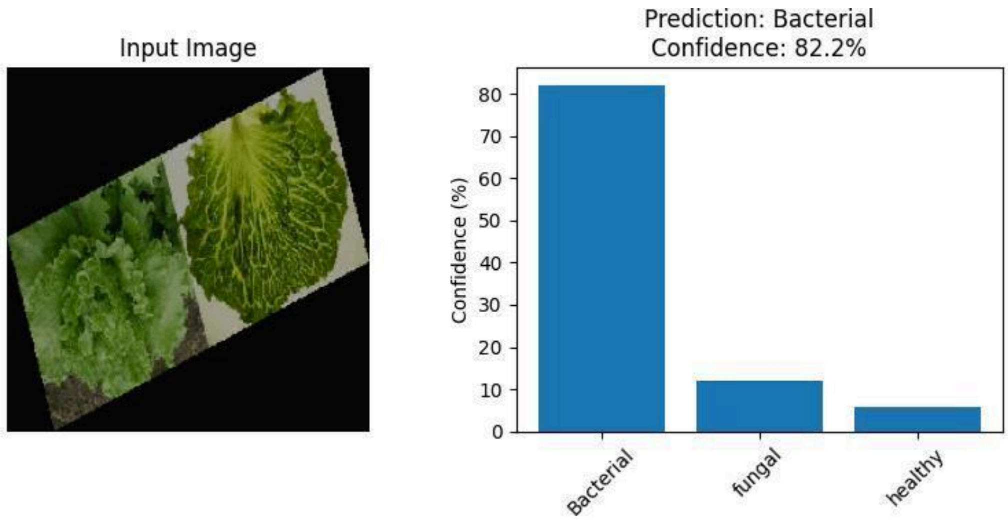


Fig.24: Output of the Model Prediction of Bacterial Leaf

The model is accurate in the identification of bacterial infection in the leaf with a confidence of 82.2 and the appearances are typical of yellowing and spots. The confidence chart shows one of the indications that the system is able to differentiate between the symptoms of bacteria and other diseases with fungal and healthy categories having significantly lower confidence scores.

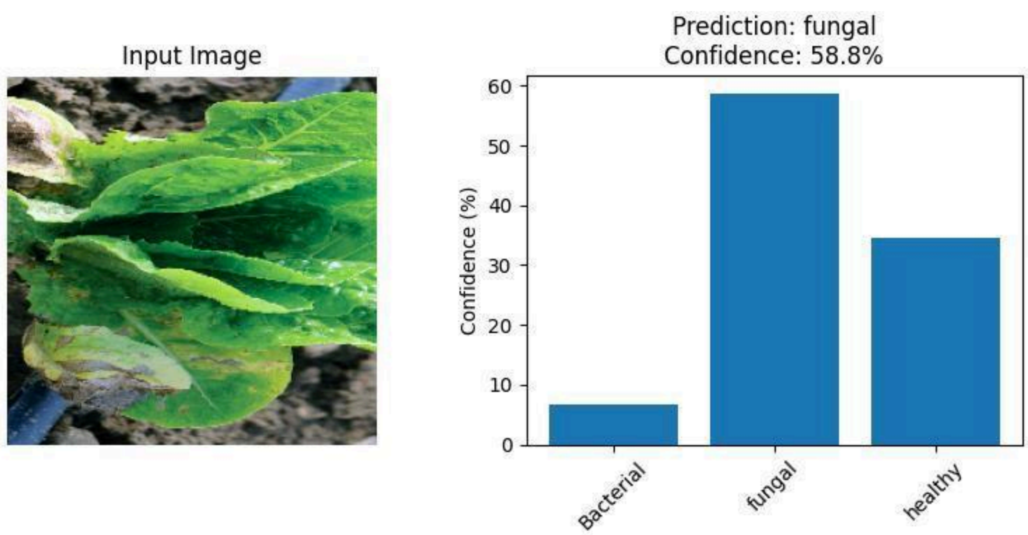


Fig.25: Output of the Model Prediction of Fungal Leaf

In this picture, the fungal infection has been on the leaf and identified with a confidence of 58.8, which is characterized by mottled and discolored look typical of fungi diseases. Although the confidence is not as high as the bacteria detection, the system still manages to identify the fungus characteristic of the disease in comparison to poor bacterial or healthy categories.

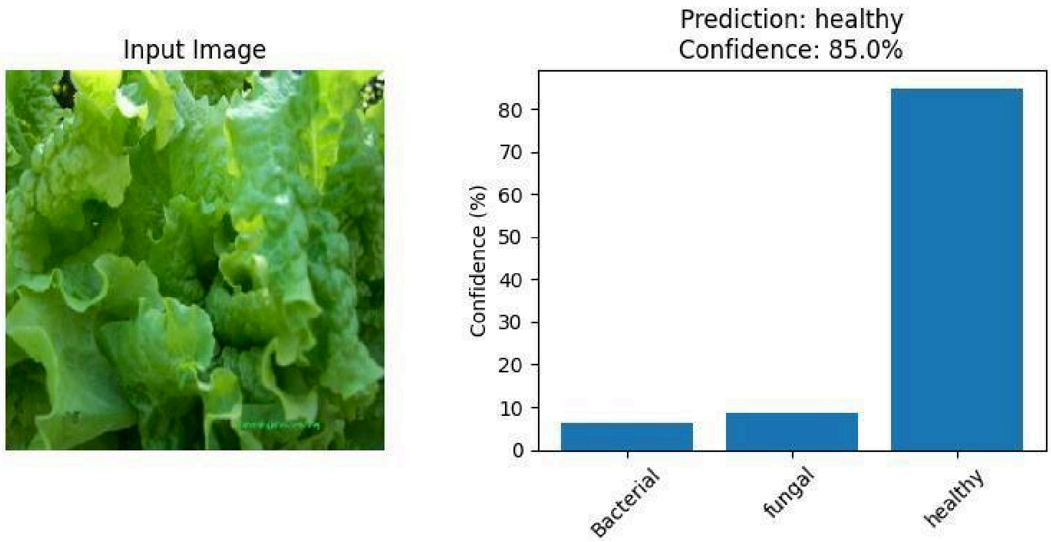


Fig.26: Output of the Model Prediction Healthy Leaf

The highest percentage of confidence of the model is at 85.0 percent when recognizing the healthy lettuce leaves that are vibrant green with no disease manifestations. The reason is that the structure of the clean, uniform leaves enables the model to determine with certainty that the plants were healthy and those with bacterial or fungal infections. Validation accuracy and training:

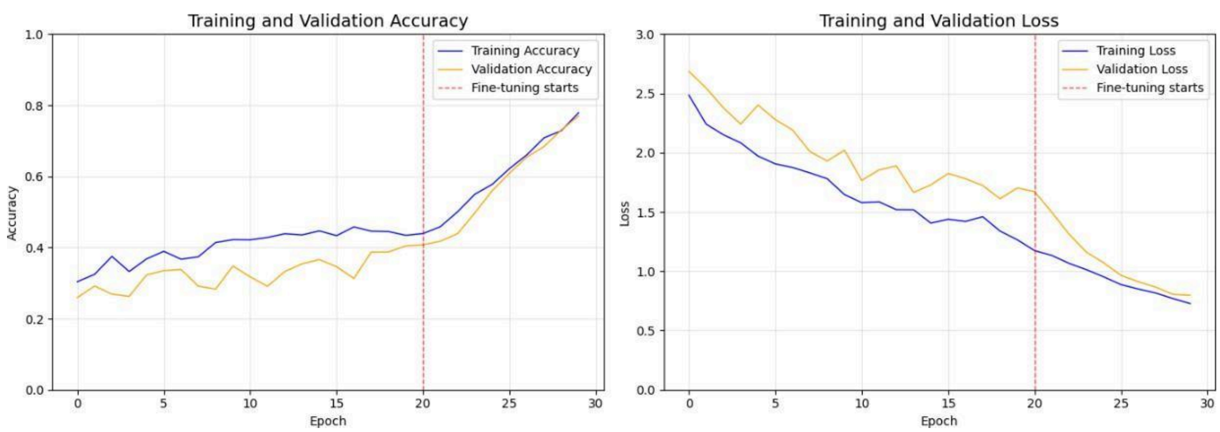


Fig.27: Training and Validation Accuracy and Loss of the Model.

This accuracy curve shows the learning of the model in 30 training epochs. The model initiates with an accuracy of about 20-40, which represents its initial parameter prior to acquiring meaningful trends due to the data. The model is more precise with each first 20 epochs as the model acquires the underlying features and overall trends of the data. An immense enhancement is made after epoch 20, which is the fine-tuning stage (marked by the red dashed line). At this stage, the accuracy of the training will shoot up showing that the model is effectively adjusting to the data and learning more elaborate characteristics. The accuracy of the validation also follows the same pattern, yet at a lower rate, indicating that the model is extrapolating well to unobserved data.

The loss graph, however, is interesting in terms of the pattern. The trend of both training and validation loss in the first 20 epochs is more or less constant, indicating that the model is not overfitting but is learning. As soon as the fine-tuning starts, the training loss decreases to nearly zero, meaning that the model is fitting the training data very well. Meanwhile, the validation loss also reduces but can have some spikes that indicate slight variations in performance on the validation set. This trend is indicative that fine-tuning contributes significantly to the reduction of training error of a model with a usual good generalization. Nonetheless, the extremely steep loss decrease between training and validation would be a sign of possible overfitting.The increase in the validation accuracy with the reduction in the validation loss are indicative that the model is not overfitting badly, but it is worth closely observed to ensure that there is uniform generalization in this instance.

Confusion Matrix Analysis:

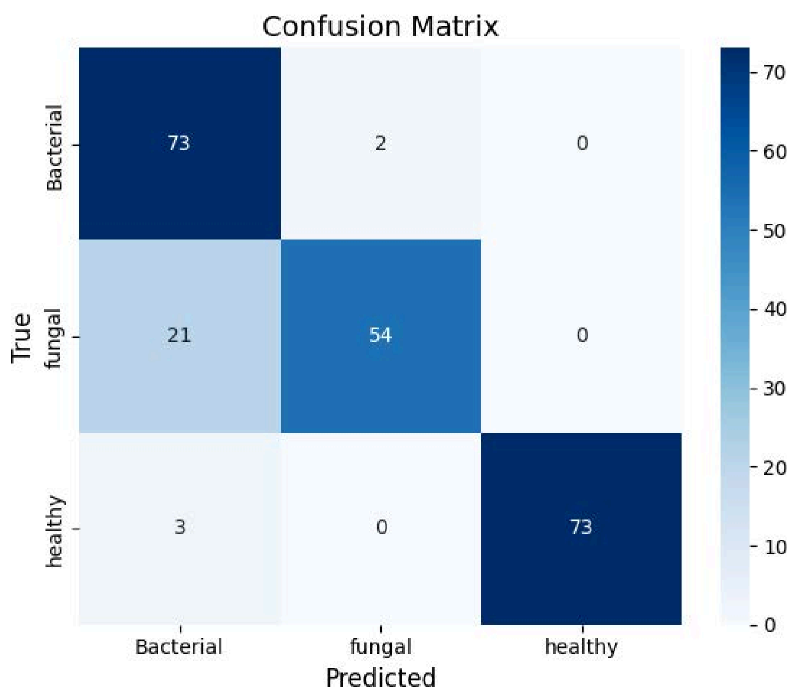


Fig. 28: Confusion Matrix Analysis for Model

The confusion matrix is used to compare the model of lettuce disease detection in three classes namely Bacterial, Fungal and Healthy. As it can be seen in the matrix, our model is very good in general with especially good results on the Bacterial and Healthy leaves. In the Bacterial diseases, the model was in the correct classification of 73 of 75 disease cases and only 2 cases were misclassified to Fungal. The class Healthy is displayed as perfectly precise with 73 correct hits and few mistakes (3 cases are wrongly displayed as Bacterial). Nevertheless, the class Fungal is the most difficult in classifying it, having 54 out of 75 total cases correct and 21 misclassified cases as Bacterial. This implies that the model occasionally fails to draw the line between Bacterial and Fungal infections which is clinically explainable because the two types of diseases may have similar visual similarity on the leaves of lettuce. The dark blue diagonal shape reflects greater values (correct predictions), whereas the light blue off diagonal shapes represent misclassifications. Generally, this matrix shows that there is good Model performance with room of improvement, in particular differentiating between Bacterial and Fungal diseases.

Classification Report:

Classification Report:

	precision	recall	f1-score	support
Bacterial	0.75	0.97	0.85	75
fungal	0.96	0.72	0.82	75
healthy	1.00	0.96	0.98	76
accuracy			0.88	226
macro avg	0.91	0.88	0.88	226
weighted avg	0.91	0.88	0.88	226

Fig. 29: Classification Report of our Model from Colab.

In this classification report, we are providing a comprehensive performance report of your lettuce disease detection model in the three disease categories. The model has a high level of performance as it has a total accuracy rating of 88 percent in the 226 test samples. The Healthy class performs exceptionally with a perfect precision (1.00) i.e. when the model is predicting a leaf to be healthy, it is correct 100 per cent of the times with high recall (0.96) and best F1-score (0.98). Fungal class is very precise (0.96) and less accurate (0.72) in terms of recall, which means that whereas the model is highly correct when it forecasts fungal disease, it will fail to detect approximately 28% of real cases of fungi. However, the Bacterial class exhibits the contrary with a lesser precision (0.75) but a very high recall (0.97) indicating that the model can correctly detect 97% of the bacterial infections, but has a higher number of false positives, which false alarms in other diseases as bacterial. This is in line with the results of the confusion matrix in which bacterial and fungal diseases were frequently confused. Both macro and weighted averages depict consistent performance indicators (0.91 precision, 0.88 recall, 0.88 F1-score), which means that balance performance is achieved across classes when taking the class distribution into account. The strength of this model is the fact that it can detect healthy leaves right and pick the majority of bacterial infections, although the detection of fungal illness could be improved to minimize false negative.

Design Approach 02 (MobileNet)

Machine Learning Model: Here we use the MobileNet, which is a simplified Convolutional Neural Network (CNN) designed to be used in mobile and embedded vision applications. Together these screens show how this application can convert the environmental data into manageable controls and combine sensor networks, real time analytics and user friendly interfaces to establish a complete hydroponic ecosystem. Such precision makes it possible to conduct indoor farming throughout the year, which ensures the resources are optimized, and it also makes smart farming sustainable. This type of architectural innovation is of much significance as it greatly lowers the number of parameters and the complexity of computation (latency) without affecting the performance. With the support of the large data sets such as ImageNet, the model is fine tuned to identify the condition of lettuce leaf effectively. Such light design will allow real time, on device inference in real time through the mobile interface meaning that healthy and diseased leaves can be detected in real time to make immediate agricultural decisions.

Model Output:

Fig. 30: MobileNet Model Output for Bacterial Detection.

The figure reflects the performance of the MobileNet model in the classification of health of plant leaves. It shows real-time inference, in that the model processes a live camera stream to give an output with a predicted class and a confidence score 94.1% and 86.1% of both image detection of bacteria. Generally, the results support the high accuracy and applicability of the model to low-latency, on- device disease detection.

Training and validation accuracy:

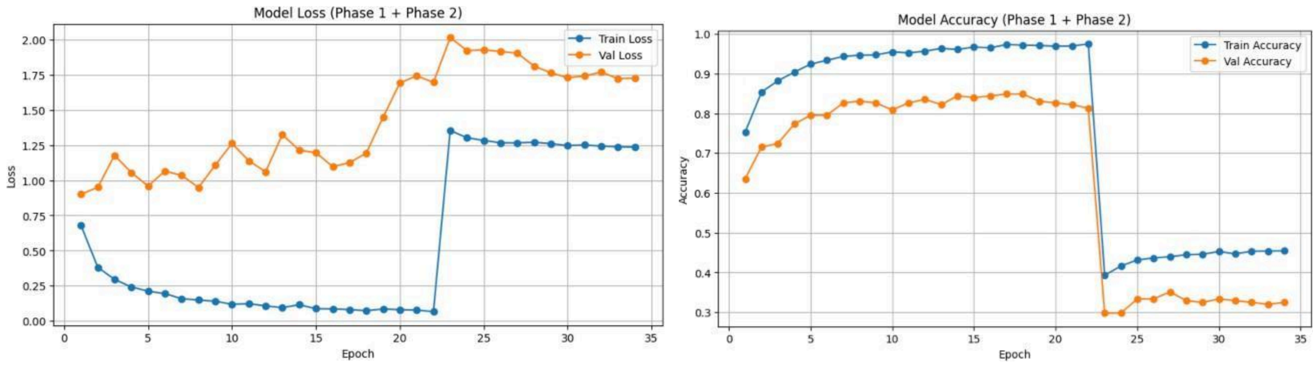


Fig.31: Training and Validation Accuracy and Loss of the Model.

The accuracy and loss curves depict unstable training process that is split into two periods. During the initial stage, MobileNet model shows good learning power, where training and validation accuracy rapidly ascended to almost 98 and 85 percent respectively. Nevertheless, the loss curve of this time shows the initial signs of overfitting when the validation loss starts to separate and increase even when the training loss drops. The epoch 23 critical point is a critical point and is probably the beginning of a fine-tuning phase. At this particular stage, the model is prone to catastrophic forgetting with the accuracy of the training and validation going down to around 40 percent and the loss skyrocketing drastically. This means that the parameters of the second phase were too aggressive and therefore the model lost the feature patterns it had successfully learned during the first phase and could not recover later in the other epochs.

Confusion Matrix:

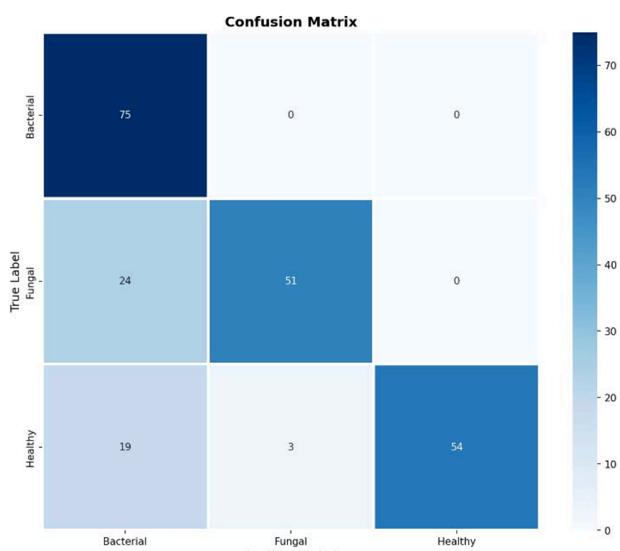


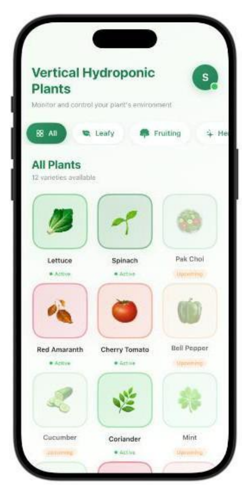
Fig.32: Confusion Matrix Analysis for Model

The confusion matrix demonstrates the precise effects of the performance problems of the model, showing that there is a serious bias to the Bacterial class. The model was perfectly sensitive to Bacterial diseases and made it right on every 75 samples, with no wrongful identifications. This was however at the expense of accuracy where this model virtually over-predicted this category. Mighty many samples of other categories were misidentified as Bacterial: namely, 24 Fungal and 19 Healthy wrongly identified samples. As a result, the Fungal and Healthy classes were negatively affected and had only 51 and 54 correct predictions, respectively. This trend implies that although the model can identify the Bacterial features, it cannot differentiate them with other leaf conditions and breaks down its decision-making frontier, which makes the model collapse to the Bacterial class in case of uncertainty.

2.4.6 Mobile Application

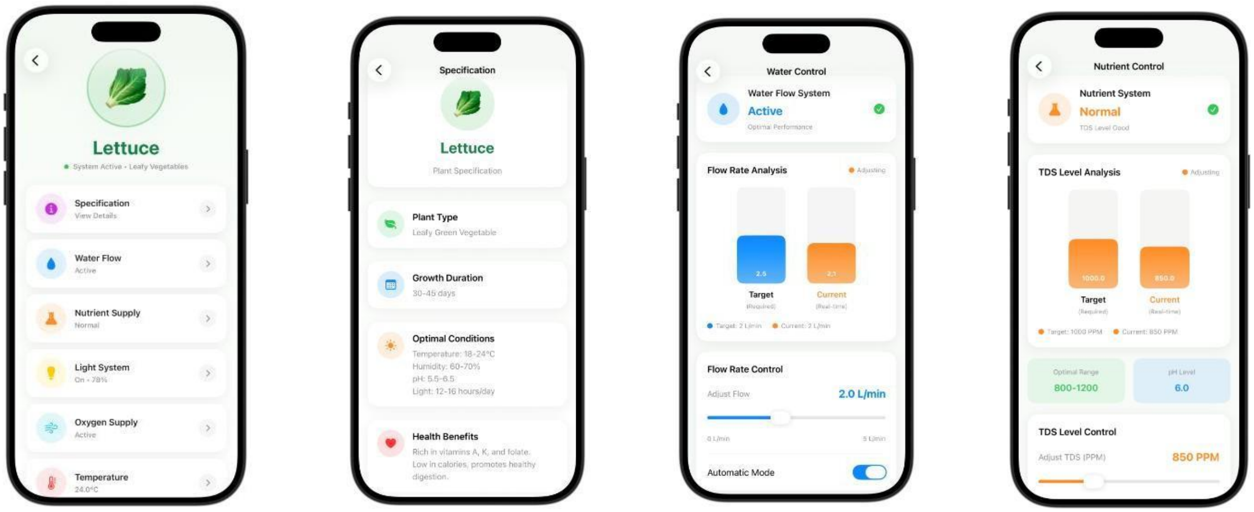
Swift programming language on Xcode was utilized to create a vertical hydroponic system so that the overall system can be controlled and monitored in a continuous manner. Using the application, it is possible to monitor the most important environmental parameters in real-time, including temperature, humidity, water level, the content of the nutrients, and the pH value. The user interface is well-designed and allows the user to access sensor data and get alerts when the conditions go out of the desirable range, and to change system settings manually or automatically. The system is expected to enhance the efficiency of the growth of plants by ensuring that the best growing conditions are maintained with the least amount of water and nutrient wastage. The sensors gather the data that is processed and delivered in the mobile application allowing the user to make informed decisions without necessarily having to monitor the devices physically all the time. The system also facilitates distance usage where farmers or users can monitor and operate the hydroponic system anywhere. The following is the UI of the mobile application:

Login interface:



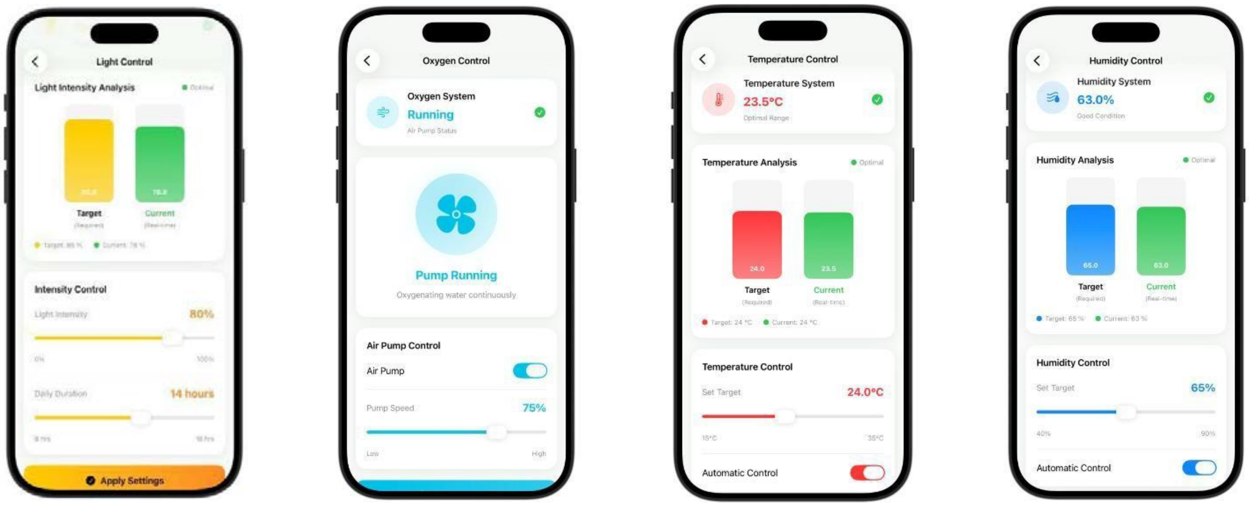
Having a modern and clean green-themed interface, users are able to create an account rapidly by providing minimum information about themselves including name, email, and password. When logged in, users will be able to control the growth of plants, manage crops, and read real-time data on vertical farming in a user-friendly dashboard.

Plant Control interface:



Such interfaces show the nature of the control and monitoring of plant in the Indoor Vertical Hydroponic System application that is plant-specific. After selecting a plant species, the system will provide a detailed description of biological properties, the lifecycle of the species, its best environmental factors, and nutritional value. The information will assist users in making sound judgments when it comes to crop control and harvesting time. Besides informational parameters, the interface also has real-time status reporting of hydroponic growth factors which include water flow, the nutrient delivery (TDS), oxygen supply, temperature, humidity and light exposure. All parameters will be dynamically updated using sensor feedback on sensors that are incorporated into the hydroponic construction.

The system allows interactive control functions where the user can control the rates of water flowing as well as the concentrations of nutrients used in the system using the intuitively designed sliders and toggles. The manual and automatic modes contribute to flexibility that gives the user the option to fine-tune the variables to experimental cultivation or give the automated optimization algorithm the mandate to achieve efficiency and consistency in the production. Live graphs are used to compare the target and current values and thus leads to accurate decision-making and performance assessment. The deviations and system responses can be visualized thus giving the user an insight on the behavior of the plant, the resources used and the stability of the environment.



These interfaces represent the environmental control module of the Indoor Vertical Hydroponic System application. Through this module, users can monitor, regulate, and optimize essential environmental parameters that directly influence plant growth and productivity.

The **Light Control** interface allows users to configure light intensity and photoperiod duration according to plant requirements. Target vs. current light levels are visualized using color-coded graphs, enabling precise comparison and quick assessment. Adjustable sliders give users control over both brightness and daily exposure duration, supporting species-specific growth strategies and maximizing photosynthesis efficiency.

The **Oxygen Control** screen manages dissolved oxygen levels in the hydroponic solution through an air pump system. It displays system status, pump activity, and real-time oxygenation performance. Users can toggle between manual and automated oxygen delivery modes while adjusting pump speed for enhanced aeration, root health, and nutrient uptake.

The **Temperature Control** interface monitors and regulates temperature within the hydroponic environment. Real-time sensor feedback compares current temperature to the optimal plant-specific target, helping maintain thermal stability essential for metabolic processes and growth rate regulation. A dedicated slider enables fine-tuning of temperature values, while automatic mode ensures consistent climate control without user intervention.

The **Humidity Control** screen operates in a similar feedback-based manner, tracking moisture levels in the air and comparing actual readings to ideal thresholds. Users can adjust humidity targets to accommodate specific plant needs, promoting healthy transpiration and preventing environmental stress. Automatic control options further enhance convenience and system efficiency.

Collectively, these screens illustrate how the application transforms environmental data into actionable controls, integrating sensor networks, real-time analytics, and user-friendly interfaces to create a fully managed hydroponic ecosystem. This level of precision supports year-round indoor cultivation, improves resource optimization, and contributes to sustainable smart farming practices.

Summary:

Table 08: Overall Summary for Design Approach-01 & 02

Parameter	**Design Approach - 01**	**Design Approach - 02**
Nutrient Delivery	Peristaltic Pumps (4x)	Solenoid Valves (4x)
Lighting Control	Basic LED Controller	PWM + Light Sensor Control
Water Flow Control	Submersible Pump + TDS/pH	Same configuration
Oxygen Regulation	Dissolved Oxygen Sensor and Oxygenator	Current Controller + Electrolysis Cell
Nutrient Precision	Continuous flow control	On/Off digital control
Plant Monitoring	Camera + Image Processing (MobileNet)	Camera + Image Processing (ResNet)

2.5 Conclusion

Taking everything into consideration, Design Approach 01 can be viewed as the most effective solution due to its high accuracy of nutrients and effective calculations. It uses peristaltic pumps to allow continuous flow regulation which gives it the ability to precisely deliver nutrients, where Design Approach 02 cannot with its rigid on/off digital control. Although Design Approach 02 also uses more cumbersome technologies such as ResNet and electrolysis, they only increase the complexity of the system but do not always bring a better practical outcome. The combination of the lightweight MobileNet architecture and the trustworthy oxygenation techniques that Design 01 offers, makes it the most balanced and efficient alternative of high-precision monitoring of plants.

Chapter 3: Use of Modern Engineering and IT Tools. (CO9)

3.1 Introduction

Modern engineering and information technology (IT) tools were highly relied upon in the design and implementation of the indoor hydroponic system to promote crop production. These tools were critical at every stage of the project such as the system design, modeling, simulation, monitoring, control and evaluation of performance. The process of development was more efficient, accurate, and scalable with taking the software of the hardware design, sensor technologies, microcontroller platform, and data analysis tools. In this chapter, there is an emphasis on the choice and successful use of modern engineering and IT tools and how the application of such tools contributed to value addition through enhanced reliability of the system, automation, and the general efficiency of crop production.

3.2 Select appropriate engineering and IT tools

Proteus: Proteus is an electronic design automation (EDA) package that is popular in the design and simulation of analog and digital electronic circuits. Proteus was also used in this project in the design of individual and global subsystems, which made it possible to conduct detailed circuit simulation and realize the various operating states of the circuit. The software was able to provide a smooth simulation of the work of Arduino with different sensors and actuators, as well as implementation and testing Arduino control code. Besides, Proteus was also used to support subsystem verification and scenario based testing, and it was useful in the validation of system behavior and to optimize control logic.

EasyEDA: asyEDA is a computer-aided design automation software platform, which is built upon schematic design and printed circuit board (PCB) layout. The PCB of the control system was optimized to have the smallest number of electrical connections and minimized unnecessary wires in this project using EasyEDA. The software facilitated correct placement of components and routing that enhanced signal integrity and eliminated the possibility of loose connections and wiring errors. Using the EasyEDA to transform the simulated circuits into a small PCB board design facilitated the increase of system reliability, ease of assembly, and overall hardware efficiency of the fully controlled indoor hydroponic system in order to increase crop production.

Matlab: MATLAB was used as an effective analysis and simulation tool to determine the systematic assessment and optimisation of key design parameters of the indoor hydroponic system. It was employed to come up with mathematical models and come up with a simulation graph on how to determine nutrient dosing to facilitate a proper study of nutrient concentration requirements under various operating conditions. To calculate the rate of water flow and set the right pump rating to maintain efficient circulation of nutrient solution and equal distribution throughout the hydroponic facility, MATLAB was also used. Moreover, the required light energy analysis was done to establish the best lighting requirements to promote plant growth, and oxygen requirement analysis was done to ensure that there were the appropriate levels of dissolved oxygen in the root zone. The applicability of MATLAB made it easier to model accurately, and the behaviour of the system could easily be visualized as well as the design assumptions could be proven, which helped to enhance the performance of the system, its reliability, and help in making informed decisions in engineering.

Arduino IDE: The Arduino Integrated Development Environment (IDE) was applied to program and control Arduino Uno R3 microcontroller. It made communication and processing of messages between the Arduino and other sensor modules connected with the interior hydroponic system easy. Pump control algorithms were also developed and implemented using the Arduino IDE and allowed using the automatic operation of the pump dependant upon sensor input and established control conditions. This platform provided an effective code development, testing, and manipulation, which guaranteed a stable real-time management and coordination of the system components.

Google Colab: Google Colab was used as an online development and executable environment of Python-written machine learning code applied in this project. The platform also gave access to high-performance GPU facilities thus greatly lowering the time of model training and allowed to effectively process large image sets. Data preprocessing, augmentation, model training and validation were done on Google Colab. In this work, deep learning models that were built on EfficientNetB4 and ResNet were trained with two different methodological approaches, so that they could be compared in terms of performance. Standard performance measures (accuracy, precision, recall, and loss curves) were used to model evaluate the employed performance measures. The application of Google Colab allowed quick experimentation of machine learning models, reproducibility and effective evaluation besides requiring specific local computation facilities.

SketchUp: The structural design of the vertical indoor hydroponic system used SketchUp as a modeling and visualization tool of the architectural design in 3D. It was employed to create in-depth three dimensional models of the entire system layout, consisting of grow channels, nutrient reservoirs, lighting patterns and service frame structures. Through the software, it was possible to assess spatial needs, the ergonomic accessibility and the efficient positioning of components in a inside space. Also, SketchUp was helpful to make some initial estimation of the materials as well as visualization of the structure that helped to confirm the design prior to final design. This strategy minimized construction mistakes, enhanced layout optimization and provided a viable and scalable system design.

Xcode: Xcode was the integrated development environment that was applied in designing and developing the iOS-based application interface of the overall control system. The application interface was created using Swift programming language to allow the user to interact with the indoor hydroponic system and track the control of the system. The application contributed to the centralization of controlling and monitoring of the system parameters and the effective control of the system processes with the help of the convenient user interface. The apple Xcode and Swift were used to provide compatibility with the platform, responsiveness and dependable performance towards the iOS based system control.

Thonny: Thonny was an integrated development environment built on Python on the Raspberry Pi platform to control real-time systems and data acquisition and intelligent analysis. It was employed to drive servo motors to the exact location of the camera, and therefore, systematic images of plants of dissimilar stages of growth were taken. The Thonny was used to interface the Raspberry Pi camera module and obtain real-time images in order to continuously monitor the growth of plants. These images were then fed into the trained machine learning model to do real-time prediction of the health of the plants. Thonny allowed controlling the hardware, getting images, and inferring machine learning, thus making it easy to operate the system and monitor the plants, identify when they were stressed, and make decisions based on the data in the indoor hydroponic system.

3.2 Conclusion

Modern engineering and information technology tools were chosen well and utilized effectively in the development of the indoor hydroponic system, which was a successful one. Proteus, EasyEDA, MATLAB and Sketch up simulation and design tools were used to guarantee proper modeling of the system, optimization of hardware, structural validation and real time control and automation was made possible by the Arduino IDE that facilitated the smooth integration of sensors and actuators. More intelligent data processing and machine-learning-based plant health prediction, including Google Colab and Thonny, were supported, which increases the intelligence and responsiveness of the system. Additionally, centralization and monitoring system through an easy to use iOS application was developed with the help of Xcode. All these tools together resulted in efficiency in designing, minimized errors in development, and maximized the reliability of the system, as well as the scalability of the solution, which was technology based to achieve better production of indoor crops.

Chapter 4: Optimal Solution and Implementation [CO7]

4.1 Introduction

In this part, we compare the two different design strategies to define the best solution and the implementation process. It is important to recognize that one and the same problem can also have several possible solutions, and therefore, this chapter is devoted to the description of our very methodology and explanation of why we chose it.

4.2 Identify optimal design approach

Table 09: Evaluation of Design Approaches and Final Selection

Parameter	Design Approach - 01	Design Approach - 02	Winner	Justification
Nutrient Delivery	Peristaltic Pumps (4x)	Solenoid Valves (4x)	A1	Better flow control
Lighting Control	Basic LED Controller	PWM + Light Sensor Control	A2	Advanced automation
Water Flow Control	Submersible Pump + TDS, pH	Same configuration	Both	Identical systems
Oxygen Regulation	Dissolved Oxygen Sensor and Oxygenator	Current Controller + Electrolysis Cell	A1	Active oxygen control
System Complexity	Moderate	High	A1	Easier maintenance
Automation Level	Advance	Advanced	Both	Better precision
Nutrient Precision	Continuous flow control	On/Off digital control	A1	Variable flow rates
Plant Monitoring	Camera + Image Processing (MibleNet)	Camera + Image Processing (ResNet)	Both	Identical systems
Scalability	Better	Limited	A1	The LED controller allows expansion
Maintenance	Lower	Higher	A1	Fewer complex components

The two designing methods were contrasted in terms of costs, complexity, automation and functionality. The peristaltic pumps applied in Approach 01 guarantee a smoother and more accurate delivery of nutrients as opposed to on/off solenoid valves used in Approach 02. It is also less complex and needs less maintenance to manage and more dependable to be used in the long run. Approach 02, on the other hand, offered an advanced automation with PWM lighting control and an electrolysis cell to control the oxygen level with this approach, allowing it little scalability and active control of environmental factors. This is however at the expense of increased expense, complexity, and maintenance requirements. The two methods are the same in terms of water management and monitoring of plants since both have a similar pump-sensor installed and image processing system. As such, **Approach 01** was selected to be the final design since it is a balance between performance, cost-efficiency, and ease of use, whereas Approach 02 has greater automation but less scalability.

4.3 System Implementation Details

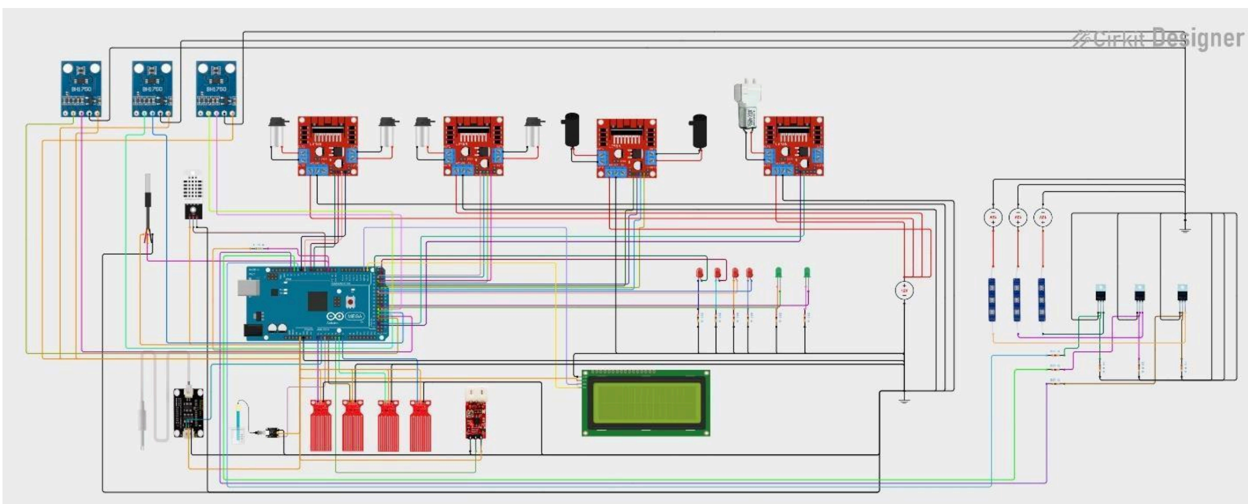


Fig.33: Circuit Diagram of the Selected Approach

In this hydroponic control circuit, the Arduino Mega functions as the central microcontroller, operating sensors and driver circuits. An LED strip acts as the photosynthetic light source, with MOSFET-based switching and PWM control for adjustable intensity and programmed light cycles. A light sensor provides real-time feedback for optimal illumination.

Nutrient delivery is handled by a peristaltic pump driven through a motor driver for accurate dosing, while two submersible pumps manage water circulation and automatic refilling. An oxygen pump supplies dissolved oxygen to support root respiration. Water-quality sensors (TDS, turbidity, temperature, and pH) continuously monitor nutrient solution conditions, and a water-level sensor triggers automatic replenishment when levels drop. Ambient temperature and humidity sensors track the surrounding environment to maintain suitable indoor growth conditions.

LED System

Fig.34: LED Setup (Hardware Connection)

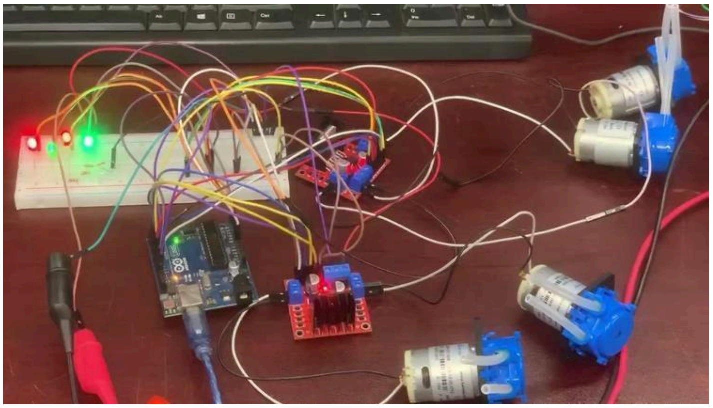
This figure shows the LED hardware of the indoor vertical hydroponic system. Three LED red, blue and white strips were also included in the system to facilitate photosynthetic growth with three independent control systems in form of separate MOSFET driver circuits. The design allows tuning of the light spectrum to set it according to the needs of the plants in terms of category and growth stage.

A 12-16 hours per day light cycle which is programmable was introduced to imitate natural day light exposure. The LED subsystem begins and ends automatically after a dark phase (8 hours) on its own after the active photoperiod, which maintains the correct circadian rhythm, and allows plants to grow in a healthy way.

In order to get the light spectrum regulation in real time, a light intensity sensor was used to measure the illuminated output at the moment. The intensity of LEDs and spectral balance is modulated by a sensor-driven PWM controller according to the needs of a specific plant. This is an adaptive control mechanism that enables targeted spectral control of various crops, increases chlorophyll absorption, and energy efficiency and improves overall growth capacity.

All in all, the LED hardware setup facilitates computerized, spectrum adaptable and energy efficient lighting that can be continuous in indoor cultivation, and provides optimum conditions of growth throughout the plant cycles.

Nutrient Delivery System



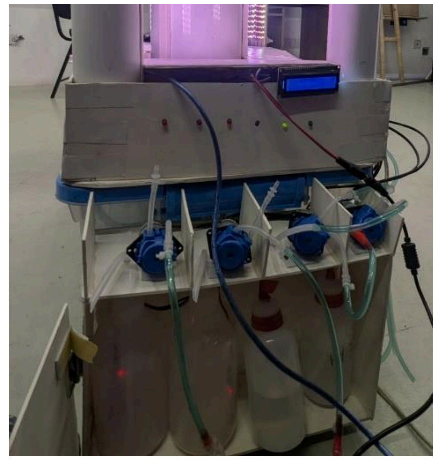


Fig.35: Peristaltic Pump Integration to Supply Nutrient

The figure shows the automatized nutrient delivery subsystem of the hydroponic system. Four pumps are used, four, with Pump-1 and Pump-2 dispensing the two different nutrient solutions (Solution-A and Solution-B), and Pump - 03 and Pump - 04 as pH regulation pumps with pH Buffer Up (pH-7) and pH Buffer Down (pH-4), respectively. The pumps are each operated separately through motor driver circuitry and using pre-set dosing programs to get the correct preparation of nutrients.

Several water-quality meters such as a TDS meter, pH meter, turbidity sensor and a water temperature sensor are used to constantly measure real time parameters of the solution to ensure that the nutrient solution is maintained within the correct chemical composition. Pump-1 operates about 3 minutes then Pump-2 runs after a 5-minute interval, based on the feedback, which ensures maximum nutrient mixing and solubility.

To maintain the pH levels, Pump - 03 is stimulated as soon as the level of pH becomes lower than 5.5, adding pH gradually until it returns to the normal range of 5.5-6.5. On the other hand, Pump - 04 will provide acidic buffer to reduce the pH to the targeted level when the pH is above 6.5. This is a closed-loop feedback mechanism, which allows nutrient stabilization automatically and minimizes human interactions.

The system has real time display in the local control unit as well as remote monitoring using the application interface such that the user can monitor, tune and override nutrient dosing and pH adjustments when necessary. This type of automated dosing and control system would deliver nutrients in a consistent way, better management of solutions, and better health of plants during the hydroponic system.

Water Quality Sensor Setup

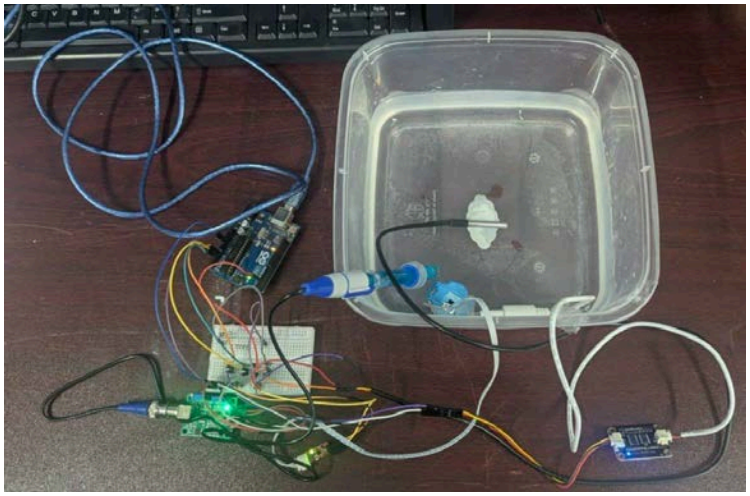


Fig.36: Sensor Calibration to Monitor Water Quality (Hardware Connection)

The configuration shows water quality monitoring in terms of TDS, pH, turbidity and temperature. The individual sensors were all calibrated with a controlled water sample to make sure that the nutrient concentration and acidity are properly measured. There were also temperature changes that were seen to influence ionic mobility and the measurement of TDS and pH, which implies that temperature compensation is necessary in hydroponic monitoring. This calibration verifies that the sensors operate in a stable manner to analyze the water-quality in real time in the system.

Water Flow Control

Fig.37: Water Flow Control Setup (Hardware Connection)

Oxygen Supply

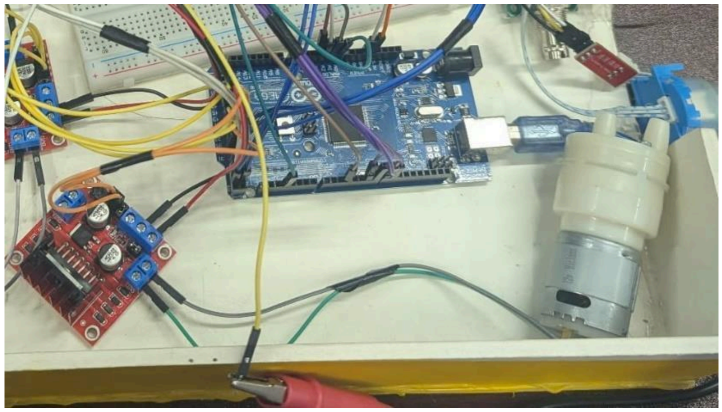


Fig.38: Hardware Connection for Oxygen Supply

In hydroponics, oxygenation is very important as it enables the root to respire and increase uptake of nutrients. An oxygen pump is also incorporated in this system to flow dissolved oxygen continuously into the nutrient reservoir. The local display interface and the mobile application provide the user with the ability to control the pump and monitor the status of its work in real-time, which allows maintaining the uniform delivery of oxygen and identify any failures in the aeration process.

Plant Monitoring System

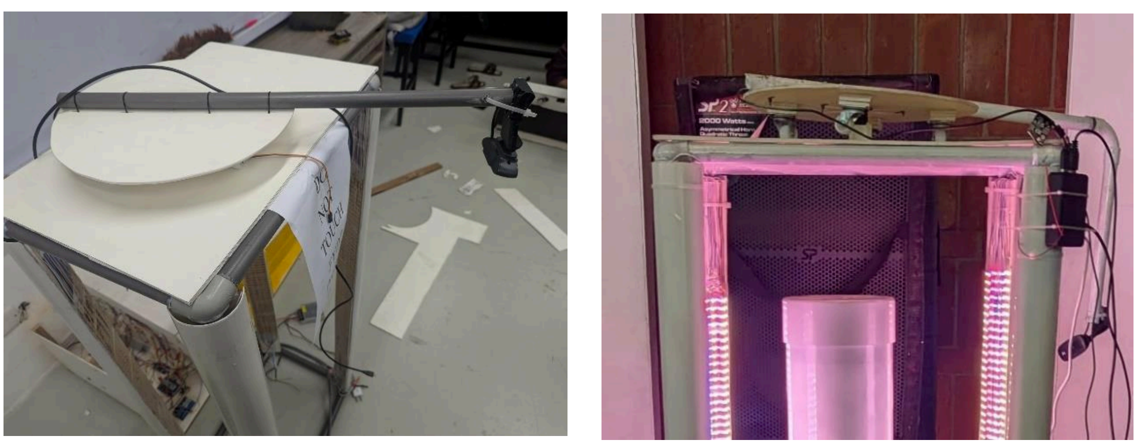


Fig.39: Camera Setup for Plant Monitoring

A camera module will be installed on the robot alongside a servo motor to scan in 360 degrees by moving clockwise and anticlockwise. The sequence of events is as follows: the servo turns 120 degrees, waits about 15 seconds and takes a photo and transmits it to the mobile application through Raspberry Pi. This is repeated two times to give a complete cycle of observation of 360 degrees. Once the clockwise cycle is finished, the servo does the same process in the anticlockwise direction.

Monitoring cycle is a cycle that is carried out after every two hours, through which periodic inspection of the plant conditions can be made in terms of images. The pictures taken could assist in the early identification of the health problems of the plants which could be diagnosed as a bacterial or fungal infection and also in the confirmation of whether the plants are growing normally. This computerized monitoring system, which is vision based, improves real-time monitoring and minimizes the amount of manual inspection.

System Integration and Final Assembly (Prototype): (CO8)

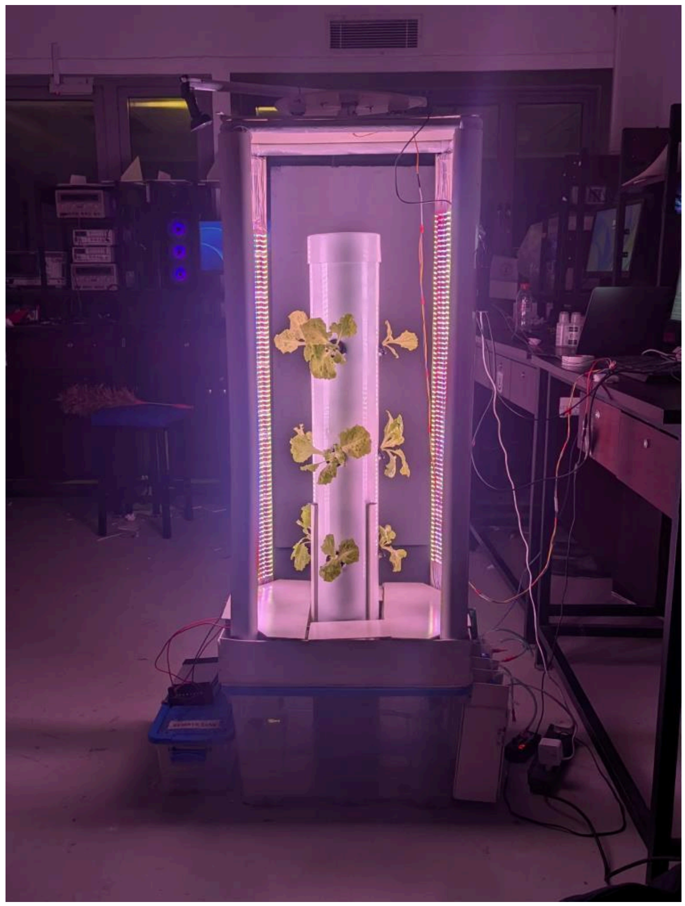


Fig.40: Overall System Prototype.

4.4 Budget of our Prototype

The overall cost of hydroponic system amounts to Tk 29,580 with the biggest share going to microcontroller, sensors and automation parts (Tk 20,860), which point to the investment in smart technology. Other expenses are the PVC structure (Tk 1,800), lighting system (Tk 2,112) and camera/other accessories (Tk 4,808). Although automation initially costs a lot, the system shows financial sustainability due to the positive ROI associated with the prototype sales and crop production and thus it can be applied in urban farming.

Table 10: Budget Analysis

Product name	Quantity	Total price
L298N motor driver	4	500
Water Pump pipe	6ft	180
Net Pot	9	120
Electric pipe	30ft	260
PVC Pipe_6 inches	5ft	350
UPC Cap	1	140
UPC Pipe_3 inches	10ft	550
50L Cargoo	1	950
Arduino Mega 2560 R3	1	1400
Arduino Uno R3	1	480
Raspberry Pi5 8GB and Charger	1	10000
PH Sensor	1	1800
TDS Sensor	1	1100
DHT-22 Temperature Humidity Sensor	1	180
DS18B20 Water Temperature Sensor	1	100
Water Flow Sensor	1	260
Turbidity Sensor	1	650
Water Pump	2	340
Air Pump	1	400
BH 1750 Light intensity Sensor	3	510
Water Level Sensor	4	200
Peristaltic Pump	4	3370
Nutrient A and B	1	600
Mosfet	3	300
SMPS 12V_33A	1	750
Ph-Up and Ph-Down Buffer	1	300
3/20 wire	60ft	850
Web Camera	1	550
Servo 180	1	410
led light	60p	1980
Total		**29580**

4.5 Conclusion

Finally, Design Approach 01 is the best alternative in the situation of indoor vertical hydroponics where accuracy of nutrients, scalability, and efficiency of operation are significant determinants. Although Design Approach 02 has more sophisticated features with ResNet and electrolysis, it is less compatible with sustainable and automated configuration due to the complex nature of the system and strict on/off control functions. The continuous flow model of delivering nutrients, lightweight MobileNet processing, and decreased maintenance needs of Design Approach 01 makes it a reliable and cost-effective solution to accurate real-time crop management.

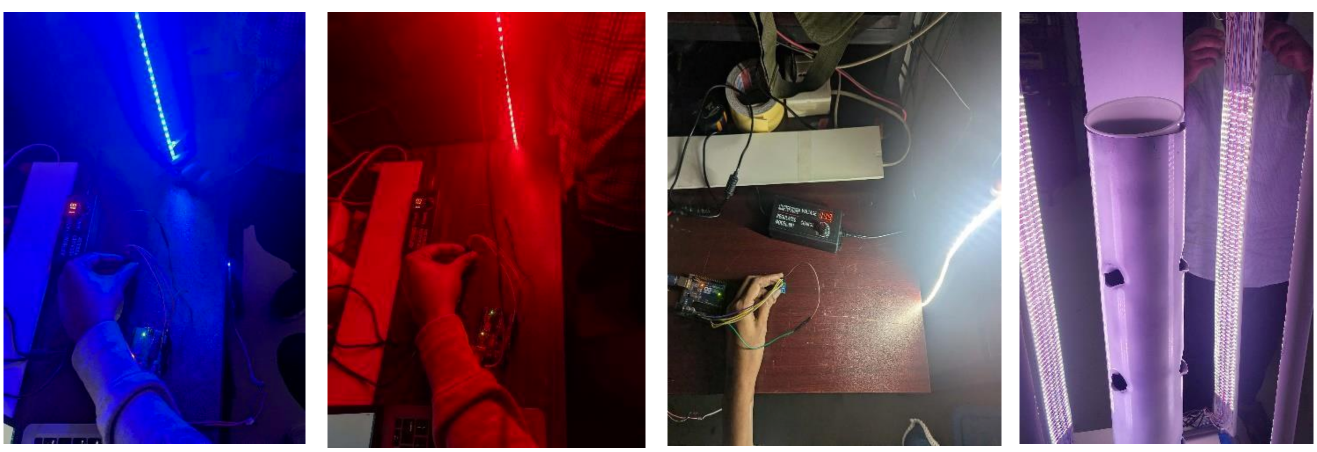
Chapter 5: Data Set

5.1 Introduction

A contemporary way of cultivating plants that do not use soil is hydroponic farming, in which nutrients are added to the water. The method is gaining popularity due to the reduced water usage, faster growth of the plants and the ability to better control the growing environment as opposed with the old-fashioned soil-grown farming. An automated indoor hydroponic system was designed and experimented on in this project to grow lettuce with the use of coco peat (nutritious water) as the growing medium.

The primary aim of this experiment was to monitor the behavior of lettuce plants in the environment of an automated hydroponic system, beginning the process with the germination of seeds up to the early growth of the plants. First, the hydroponic system was used to directly germinate seeds. Nevertheless, the plants grown on the seed medium died early because of the sensitivity of the seed and nutrient shock. Therefore, seedlings that were grown in soil were later transplanted into the hydroponic system. The key parameters, including pH, TDS, water temperature, lighting, and plant health were measured on a daily basis during the course of the experiment in order to determine how the plants behaved and the system remained stable over a 14-day span.

5.2 LED Intensity



(i) (ii) (iii) (iv)

Fig.41: (i) Measuring Blue LED Intensity and Providing 160-180 lumens/m² per strip. **(ii)** Measuring RED LED Intensity and Providing 360-880 lumens/m² per strip. **(iii)** Measuring White LED Intensity and Providing 50-60 lumens/m² per strip. **(iv)** Measuring Total LED Intensity and Providing 6500-7500 lumens/m² per column

5.3 Tap Water Quality

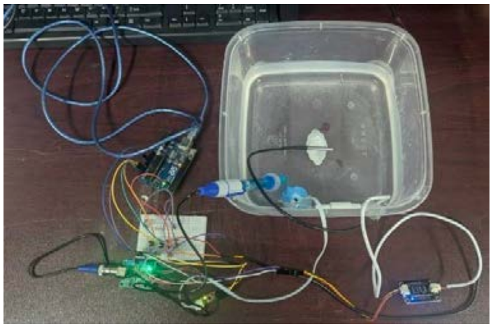


Fig. 42: Tap Water Quality Test

Parameter	Session - 01 (High Temp)	Session-02 (Low Temp)	Status
Temperature (°C)	33 - 36.25 Avg: 34.92	26.06 - 26.75 Avg: 26.31	Variable
pH Level	7.19 - 7.51. Avg:7.35	8.09 - 8.46 Avg: 8.30	Alkaline
TDS (ppm)	188 - 197 Avg: 92	194 - 200 Avg: 197	Low
Turbidity (NTU)	0	0	Clear Water

Table 11: Tap Water Quality Test Result

Under two temperature conditions, TDS, pH, temperature, and turbidity sensor tested the quality of tap water. It was revealed that there were temperature differences between 26 and 36 o C and this confirmed that the temperature of tap water varies with environment. The alkalinity of the pH was maintained in both sessions and rose with decreased temperatures. The values of TDS were low (188-200 ppm) and it this means that the nutrient supplementation is necessary in the hydroponic systems. Turbidity was 0 NTU with clear water with no turbidities. Altogether, tap water is transparent and can be used as a foundation in hydroponics, however, it requires pH regulation and the addition of nutrients.

5.4 Nutrient Delivery

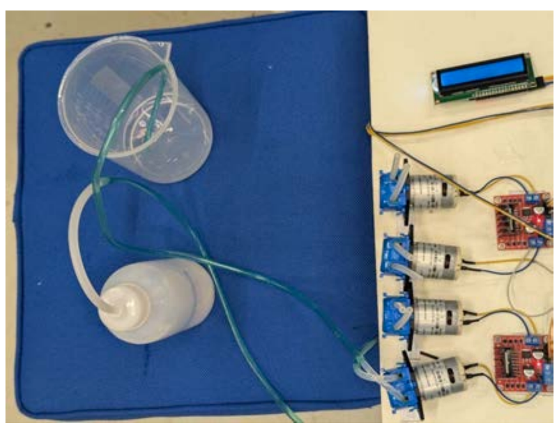


Fig. 43: Nutrient Delivery (Time Observation: 100mL/3min)

The figure demonstrates the time-based nutrient delivery test performed using the peristaltic pump subsystem. During the experiment, a calibrated container was used to measure the volume of nutrient solution dispensed over a fixed time interval. The pump delivered approximately **100 mL of solution within 3 minutes**, indicating a stable and consistent flow rate suitable for hydroponic nutrient dosing.

5.5 Plant Growth Monitoring

Seed Germination and Selection Table:

Table 12: Seed Germination Data and Analysis

Day	Condition Applied	Stage	Number of Seeds	Remark
1	Plain water and Indirect sunlight	Seeds sown	35	Seeds placed in a Hydroponic medium (Coco peat)
3	Plain water and Indirect sunlight	Seeds Germinated	18	Partial germination observed
11	Plain water and 1 hour of direct Sunlight	Healthy plant with 2 small leafs	12	Uniform growth Selected
12	Plain water and 1 hour of direct morning sunlight	2 plants become weak and other plants are healthy	10 (healthy) + 2 (unhealthy)	Early Stage Sensitivity
13	Added 4 drops of nutrient with water and 1.5 hours of direct morning sunlight	Gradual plant weakness	12 plants are weakly alive	Early-stage nutritious water shock
14	Stopped adding nutrients and direct sunlight	The plants wilted completely	0	No survival observed

Following the failure of the seed-grown seedlings, 18 soil-grown plants were selectively taken and transplanted into the hydroponic system in coco peat and a nutrient solution. The plants were able to adapt to the new growing condition and live. However, black or dark spots were observed on some leaves. These symptoms are likely due to transplant shock and adjustment in nutrient uptake as the plants transitioned from a soil-based environment to a water or nutrient-based environment. Such leaf discoloration is common when root systems experience changes in nutrient availability and growing conditions. To mitigate the appearance of black spots on leaves, we applied neem oil to affected leaves, and the black spots are gradually disappearing.

Plant observation over 14 days:

Table 13: Plant Observation Data

Day	Plant observation	Leaf Symptoms	Treatment Applied	Remark
1	Transplant a soil-grown plant into a water-based system	None	None	Plants introduced to the hydroponic setup
2	Roots are adjusting to excessively wet coco peat	None	None	Leaves appear healthy; no symptoms detected.
3	The plants seem healthy	None	None	No symptoms detected.
4	Leaves slightly wilting	Some leaf spots are starting	None	Early Transplant Stress
5	Leaves slightly wilting	Leaf spots are present	None	Stress symptoms observed
6	Wilting was no longer observed	Spots become more visible	None	Stress symptoms present
7	Plant stable	Symptoms spreading leaf-to-leaf	None	Stress symptoms present
8	Some leaves darkening	Black spots noticeable	Infected leaves removed; neem oil applied	Stress continues
9	The plants show improved health	Black spots are less visible	Neem oil applied	Recovery observed
10	The plants show improved health	No new spots	None	Recovery observed
11	Growth normal	No new spots, New leaf growth observed	None	Recovery observed, no dark spots on new leaves
12	Normal growth	Almost no spots	Reduced unhealthy leaves, applied neem oil	Improvement maintained
13	Normal growth	Almost no spots, New leaf growth observed	None	Improvement maintained
14	Normal growth	Almost no spots	None	Healthy plants

Lettuce Plant data while adjusting for Hydroponic:

Table 14: Sensor and Nutrients Data of Pre-Adjustment Phase

Nutrient AandB (mL)	Water (L)	pH	TDS	Water Temp.
5 mL + 5 mL	1 L	5.7-6.15	782	24
		5.9-6.55	635	23
		6-7.01	585	20
		6.01-7.35	420	20

Lighting Data: Morning Time

Table 15: Light Supply Data of Pre-Adjustment Phase

Time	Light Intensity (lumens)
7:00 – 8:00 AM	5,000 – 10,000 lux
8:00 – 9:00 AM	10,000 – 20,000 lux
9:00 – 11:00 AM	20,000 – 30,000 lux

Observation: Plants Affected by Bacterial Disease and Showing Stress Symptoms

- pH value increases because water temperature decreases.
- TDS value also decreased.
- The plants were placed under high-intensity sunlight after 11:00 AM

Fig. 44: Stressed and Infected Plant Leaf.

Plant Growth Data in a Hydroponic System:

Table 16: Data of Post Plantation Phase in System

Day	Plant Height (cm)	Number of Leaves	Leaf Length (cm)	Root Health	Remark
1	8-8.5	3-5	2.5 - 8	Healthy	Healthy
2	8 - 9	4 - 6	3 - 10	Healthy and Growing	Healthy
3	8.5-9	4-7 (1 new leaf)	4-10	Healthy	New leaf emerged
4	8.5-9	5-7	4-10.5	Healthy	Stable Growth
7	9 - 9.2	5 - 7	5 - 11	Slightly stressed and Growing	Stressed and slower growth
8	9 - 9.5	5 - 8 (1 new leaf)	5 - 11.2	Slightly stressed but Healthy and Growing	Growing
9	9 - 10	5- 10 (1-2 new leaf)	0.5-12	Slightly stressed but Healthy and Growing	Growing

Controlled Parameter (Daily):

Table 17: Dataset of Controlled Parameter of System

Day	Avg Water Temp (C)	Avg Humidity (%)	Lighting Hours	Water pH	Avg TDS	Avg Turbidity	Remark
1	23.1	67	2	6.3	589	481	Turbidity is high because of Aan airbubble and Coco Peat (it's harmless)
2	22.25	64.15	3	6.1	577	476	Turbidity is high because of an air bubble and Coco Peat (it's harmless)
3	20	63	3	5.75	560.5	335	Turbidity condition same, pH (maybe because of aeration) and TDS are slightly low, but no need to add nutrients now, oxygenator needs to be adjusted
4	21.2	62	3	5.8	551	336	Turbidity condition same, pH slightly rises as TDS decreases
7	22	65	3	6	584	50	After cleaning the water tank turbidity is within a safe range, and the system is stable
8	21.4	65.3	3	5.71	571.5	43	The system is stabilizing, and the plants are taking nutrients

LED Intensity (%) vs. Lumens:

Table 18: Light Intensity Data

LED Intensity	Lumens
100%	9200 - 12,100
75%	6700 - 8800
50%	4500 - 5900
25%	2400 - 3200

Peak Lumens of individual LEDs:

Table 19: Individual Light Intensity Data

Red	2200 - 2700 lumens (100%)
Blue	870 - 1250 (100%)
White	6700 - 8800 (100%)

System Operating Power Data:

Table 20: System Operating Power Data Measurement on Various Condition

Parameter	Measurement	Condition
SMPS Output Voltage	11.11 V DC	Full Load Condition
LED Input Voltage	236.4 V AC	Mains Input
LED System Consumption	12 V, 17 A	Full Load
Other Subsystem Consumption	12 V, 0.66 A (≈ 8 W)	Microcontroller + Sensors

Performance Evaluation of Indoor Hydroponic System (Lettuce Cultivation):

Table 21: Performance Data and Evaluation

Performance Domain	Parameter	Observed Value	Unit	Evaluation
Plant Growth	Leaf Growth	50-60% Faster	-	Faster
	Root	Healthy	-	Healthy
	Plant Health	Slightly stressed	-	Slightly stressed but healthy
	The total plant survives	12 plants out of 15 plants	-	23% higher survival than soil-based.
Cultivation Time	Germination Period	3	Days	Faster
Resource Efficiency	Total Nutritious Water consumption	0.5 - 0.7	L	High water efficiency
	Water use efficiency	500 - 600	g/L	Efficient
	Electrical energy consumption	2.65 kWh/day	kWh/day	Moderate
System Stability	pH fluctuation	5.6 - 6.2	-	low
	Average nutrient pH	5.9	-	Within an acceptable range
	TDS range	500 - 800	-	Optimal
Crop Health	Survival rate	23	%	Good

Germination of Seeds (Failed):

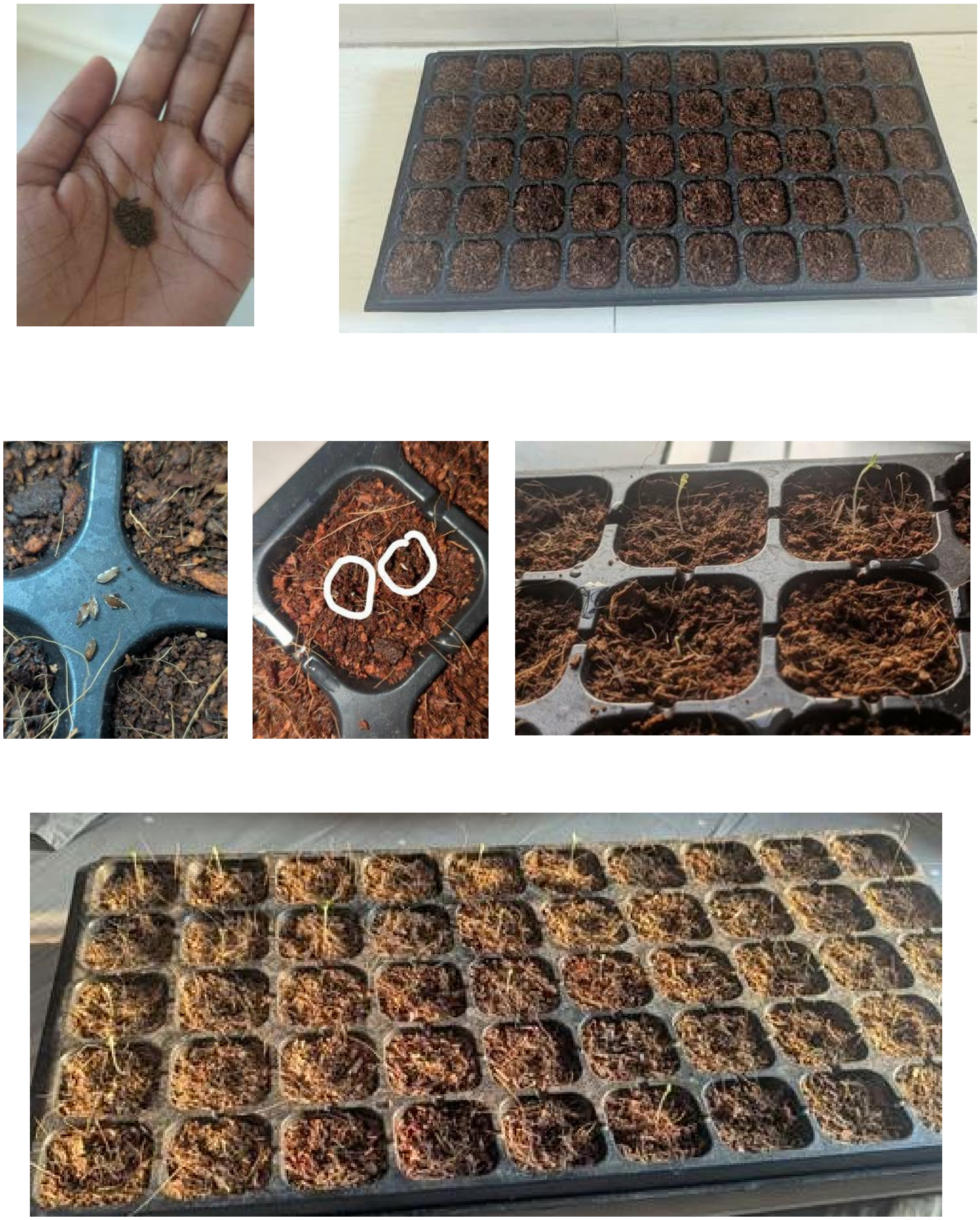


Fig. 45: Seeds Germination Stages

Plant Transplant Process:



(i) (ii) (iii)

(iv)

(v)

Fig. 46: Plant Transplant Processes (Soil to Hydroponic System)

Growing Stages:

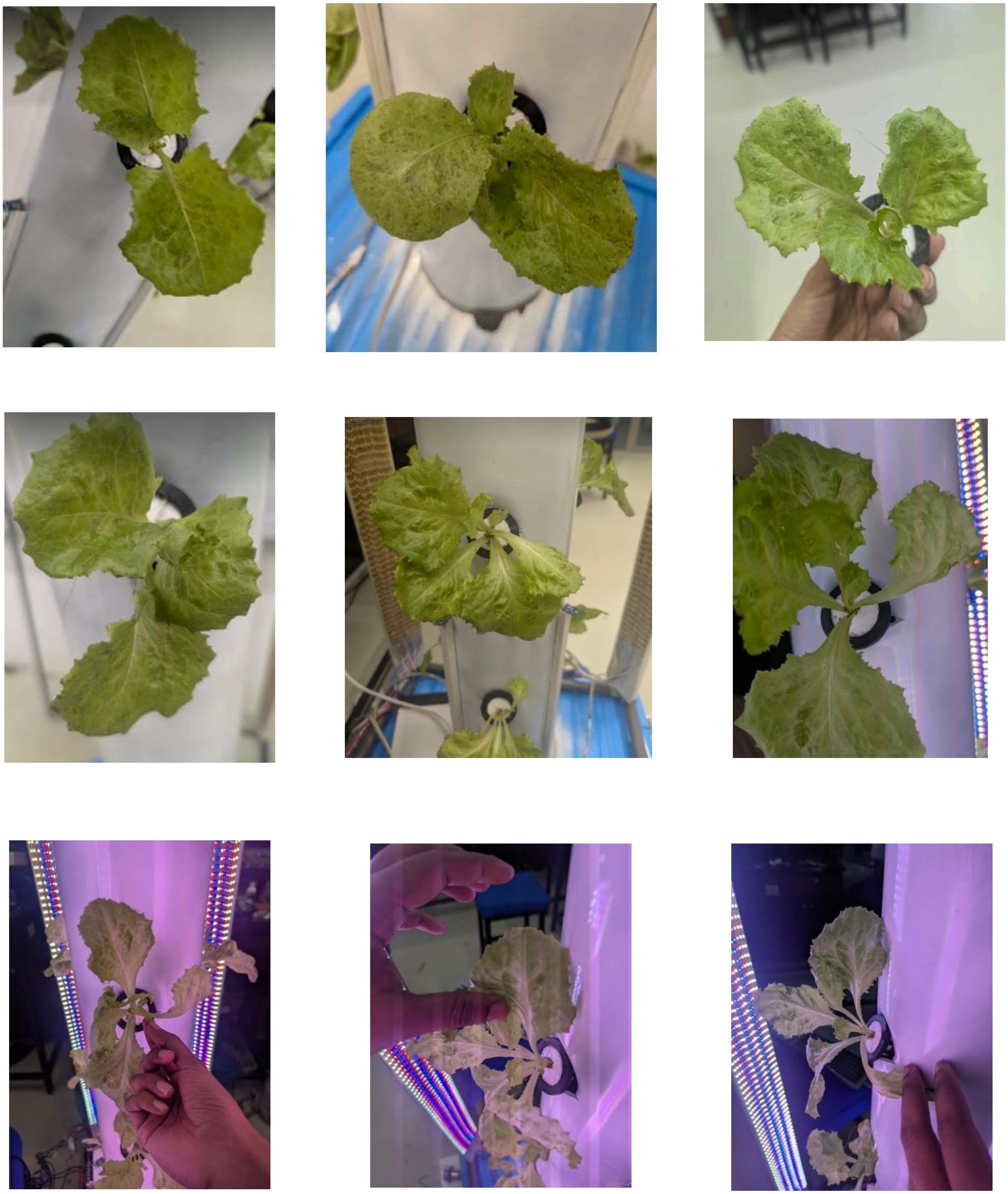


Fig. 47: Plants' Growth Observation

Plant Growth Measurement:

New Leaf Observation

Leaf Quantity Observation

Plant Health Observation

Larger Leaf Length

Smallest Leaf Length

Plant Height

Fig. 48: Plant Growth Measurement of Hydroponic System

5.6 Data Analysis

Seed Germination and Early Failure: 35 lettuce seeds got soaked in plain water at the onset of this experiment and planted under indirect sunlight using coco peat. Success was partially achieved by the third day since only 18 seeds germinated. Despite the healthy look of the seedlings at the start of its growth, the seedlings were very sensitive at the initial growth stage. The plants became weak and they were wilted to death gradually when nutrients and more sunlight were introduced. It means that young seedlings could not withstand sudden access to nutrients and direct sun rays, and they encountered the problem of nutrient shock and dehydration stress. The fact that direct germination of seeds in a hydroponic system can only be controlled with extreme care at the initial stage of growth is illuminated by this stage of the experiment.

Transplantation and Plant Adaptation: Plants growing on soil were transplanted to the hydroponic system after fail in seed-grown plants. The depression symptomatic to the plants during the initial days was mild as leaves were slightly wilted and some leaves had black or dark spots. These symptoms must have been due to transplant shock as the roots were adapting to a water based nutrient system rather than soil based environment. In order to curb the problem, infected leaves were pulled off and neem oil rubbed. Slowly the plants started to recuperate. At Day 9, the dark spots began to fade away, and no additional symptoms began. Since Day 11, the growth of new leaf was observed and by Day 14 the plants came back to normal and healthy growth. This indicates that lettuce plants are able to adjust to hydroponic systems after a period of adjustment.

Water Quality, Nutrients, and System Stability: Water quality was monitored within the course of the experiment. The pH was largely acceptable because it was mostly between the recommended pH of 5.6 to 6.2 that is favorable in the growth of lettuce. Minor changes in pH were noted upon a decrease in the temperature of the water, which proved the dependence between temperature and the pH levels. The values of TDS dropped slowly due to the nutrient uptake by the plants which is a normal indication of a healthy nutrient uptake. The air bubbles and coco peat particles led to high turbidity in the first days, which did not have any adverse impact on the health of plants. The turbidity levels were reduced greatly after cleaning the water tank, and the system became more stable.

Lighting and Environmental Conditions: The plants were subjected to natural morning lighting and LED lighting. The intensity of the light rose slowly in the early morning, and then it became high after 11:00 AM. It was found that plants subjected to high levels of direct sunlight had stress symptoms implying that lettuce plants do not enjoy bright sunlight but moderate light. The lighting system installed was LED giving a balanced mix of red, blue, and white light to allow healthy growth of the leaves without having to consume too much energy.

Plant Growth and Performance: he data of plant growth indicated that the plant height, number of leaves, and length of leaves increased steadily. Following the regular appearance of new leaves meant that photosynthesis and uptake of nutrients were healthy. Despite some days of stress, which were observed to be minor, the plants grew. The survival rate of the plants planted using soil was lower than that planted using transplantation and 12 of 15 plants were found to survive. The controlled nutrient delivery has been shown to be effective through the faster growth of leaves in the hydroponic system of 50-60%.

Energy and Resource Efficiency: The hydroponic system used a fairly minimal quantity of water which was approximately 0.5-0.7 liters and therefore very efficient in terms of water conservation. The daily usage of energy was recorded at 2.65 kWh, which is average in the case of an indoor system. In general, the system exhibited a positive equilibrium of growth performance and resource consumption of plants.

5.7 System Verification & Result (CO8)

Table 22: Project Verification

Specification	Proposed	Achieved
PVC Structure & Plant Spacing	2.5-6 ft PVC, 3-25 cm in spacing	4 ft PVC, 16 cm horizontally & 25 cm vertically
Light energy plants need	6,000 to 43,200 lumens	6000 to 10,000 Lumens using PWM controller
Water Flow & TDS	Lettuce 2-3 L for 16 plants per day; TDS 500-2000 mg/L	Maintained via nutrient solution system (TDS - Avg 590 to 560 for Growing stage lettuce, Consume 700ml per day 9 plants
Nutrition & pH	1.3-5.2 ml/L(growth stage), pH 5.5-6.5	5ml Solution A + 5 ml of solution B per Litter, pH average 5.75 - 6.3
Oxygen Concentration	5-8 mg/L	Partially maintained
Temperature & Humidity	22–26°C (day), 18–22°C (night); 50-70% humidity	Couldn’t control, Partially maintained
Total Energy Consumption	Average 0.6 kWh/day (4-6 ft setup) without grow light	0.192 kWh/day(4 ft setup) without grow light, with LED it’s 2.65 kWh/day

5.8 Conclusion

This initiative shows that indoor hydroponic agricultural system can become an effective and green way to grow lettuce provided that the environmental regulation is ensured. Direct seed germination in the hydroponic system did not work, but transplanting seedlings grown on soil was a successful practice. The plants were able to adapt after passing through the first transplant stress, and displayed healthy growth. The findings affirm that hydroponic systems could attain growth rate, water efficiency, and survival rates that were superior as compared to the traditional farming systems which were based on soil. Special attention should be paid to the control of the nutrients, the quality of lighting and water, and all that during the early days of plant growth. In general, the designed hydroponic system was stable, efficient and appropriate to grow lettuce indoors, which indicates its possibility to be used in small-scale sustainable agriculture.

Chapter 6: Impact Analysis and Project Sustainability

6.1 Introduction

The proposed hydroponic system is designed to create positive impacts across environmental, economic, societal, health, cultural, legal, and safety dimensions. By integrating sensors, automated nutrient and water delivery, and energy-efficient technologies, the system enhances resource efficiency, ensures food safety, and promotes sustainable urban agriculture. Its adoption can improve crop yield, reduce environmental footprint, and support community engagement in modern, technology-driven farming practices.

6.2 Impact (CO3)

***Environmental Impact*:** The environmental benefits of hydroponic farming are significant. Since soil is not used in these systems, there's no worry about soil degradation or erosion, which are common problems in traditional agriculture. Hydroponics reduces water usage by up to 90% compared to conventional farming. This is crucial, especially in areas where water is scarce or where agriculture consumes a lot of water. Additionally, because the system is designed to be energy-efficient and resource-efficient, it requires fewer inputs like water and nutrients, leading to less waste and a smaller environmental footprint. The integration of smart farming technologies, such as sensors and automated systems, ensures that every aspect of the growing process, from light to water and nutrient levels, is constantly optimized. This makes the entire farming process more sustainable and helps reduce the overall impact of farming on the environment [11].

Economic Impact: Hydroponic farming can have positive economic effects by making farming more efficient and profitable. With the help of smart technologies, crops are grown faster and more accurately. This leads to higher yields in a shorter amount of time and with lower resource usage. Hydroponics also offers year-round production, which means farmers don't have to rely on the seasons-they can grow crops no matter what the weather is like. This reduces crop failure risks caused by weather conditions like droughts or floods. The ability to grow food locally in urban areas also lowers transportation costs, making food more affordable [12]. Furthermore, because less manual labor is needed, the farming process becomes more cost-effective. The smart monitoring systems reduce the need for human intervention and optimize growing conditions, making farming less labor-intensive and more automated. This can create new jobs in technology, engineering, and urban farming sectors, supporting the growth of the local economy [13].

Societal Impact: Hydroponics could play a major role in improving food security in cities. By bringing farming to urban areas, it becomes possible to grow fresh produce right where people live. This is particularly important for cities that have limited access to arable land and rely heavily on imported food. As urban populations continue to grow, the demand for locally grown food will rise. Hydroponic farming helps meet this demand by making it possible to grow healthy food in places that were previously unsuitable for traditional farming. This could reduce dependence on external food sources, ensuring that cities have a reliable food supply [11]. It also fosters a sense of community engagement. People may become more involved in growing their food, and this could lead to greater awareness about the benefits of sustainable farming practices. Additionally, the technology involved in hydroponic farming can create new jobs in the areas of tech-driven agriculture, thus opening up opportunities for people to work in emerging industries related to smart farming.

Health Impact: One of the biggest benefits of hydroponic farming is that it allows for the production of healthier food. Since hydroponic systems don't require pesticides or herbicides, the crops grown are free from the chemicals often used in traditional farming. This makes hydroponically-grown food safer and healthier to consume. Additionally, because the environment is carefully controlled using smart technologies, crops are less likely to contract diseases that might otherwise require the use of chemicals or antibiotics to manage. By producing food in this way, we can reduce exposure to harmful substances that are often present in traditional, chemically-treated crops [12]. The ability to control growing conditions such as light, temperature, and nutrients ensures that the crops are healthier and more nutritious. Not only does this improve food quality, but it also directly contributes to the health and wellness of consumers by ensuring they have access to fresh, high-quality produce without harmful additives.

***Cultural Impact*:** Hydroponic farming could create a cultural shift in how we perceive food production. In many cities, farming is associated with rural areas, but with hydroponics, it is possible to grow food right in the heart of cities. This may lead to a change in how people think about agriculture, especially in urban settings. Urban farming could be seen not only as a viable option but also as a sustainable and smart solution to food security and urban planning [13]. The more we see hydroponic farms in urban environments, the more they could influence people's understanding of food sustainability. Hydroponic systems also have the potential to change how we view the environment - people could start to realize that sustainable practices like growing food with fewer resources can lead to a healthier world. The integration of smart technology into the farming process might inspire future generations to adopt greener and more innovative ways of growing food. Additionally, seeing this in action could reduce cultural barriers related to traditional farming methods, helping communities embrace eco-friendly farming practices in urban environments.

Legal Impact: The legal side of hydroponic farming is important because it has to follow rules that keep our food safe and protect the environment. One of the big advantages of hydroponics is that it doesn't need harmful chemicals like pesticides, which means the crops are healthier and meet food safety standards [13]. Hydroponics also helps save resources like water and land, which is good for the environment. Because of these benefits, governments might create new policies or incentives to encourage people and businesses to adopt sustainable farming practices. For example, they might offer tax breaks or funding for urban farmers who use smart farming technologies. Also, as the systems become more common, hydroponic farms must follow rules related to labor rights and waste disposal, ensuring that the process remains safe and legally compliant [12].

Safety Impact: When it comes to safety, there are a few things to consider, especially when we're using automated technologies and advanced systems that involve robotic arms and sensors. Since these systems might be used in public spaces, like parks or urban rooftops, it's important to make sure they're safe for people around them. This includes using speed controls and collision avoidance features so the system doesn't accidentally run into people or pets [12]. Since hydroponic systems also rely on electricity to run lights, pumps, and sensors, they need to be designed with waterproof and well-insulated electrical parts to avoid risks like electric shocks.

Mechanical safety is also a big deal, especially with things like robotic arms or conveyor belts that move the plants around. These systems need safety barriers and emergency stop buttons to prevent any injuries. Lastly, the food produced in these systems needs to be clean and safe. That means following hygiene standards to ensure no bacteria or harmful substances end up in the food we eat [13].

6.3 Sustainability (CO4)

The sustainability of a project involves considering various environmental, social, and economic aspects to evaluate how well the project can meet the current needs of stakeholders while ensuring that future generations are not compromised. A key method to assess sustainability is conducting a SWOT analysis, which evaluates the Strengths, Weaknesses, Opportunities, and Threats of the project. The SWOT analysis for this project is below:

The project had to be evaluated to determine if it aligned with any Sustainable Development Goals (SDGs). This project aligns with several Sustainable Development Goals (SDGs).

SDG 3 - Good Health and Well-being: This system improves health by providing fresh, pesticide-free food grown indoors. It promotes eating healthy fruits and vegetables, which helps people stay healthy and avoid diseases like obesity and heart problems. The project encourages a healthier lifestyle by making clean food more available.

SDG 6 - Clean Water and Sanitation: In this system, water is recycled and reused, meaning that instead of using large amounts of water for irrigation, only a small amount is needed. This closed-loop system helps conserve water, making it ideal for regions where water is scarce. For instance, an indoor farm using hydroponics could grow large amounts of food using 90% less water than traditional farming methods. This responsible water use helps ensure that clean water is available for other essential needs in communities, like drinking and sanitation.

SDG 12 - Responsible Consumption and Production: Using fewer resources like water, energy, and space makes food production more efficient and less wasteful. Additionally, by growing food indoors, the project reduces the need for land clearing and environmental destruction that can occur with traditional farming. As a result, food is produced in a way that minimizes environmental harm, encourages responsible consumption, and reduces the overall carbon footprint of agriculture. This method of growing food helps shift society toward more eco-friendly agricultural practices, reducing waste and supporting sustainability.

6.4 Conclusion:

Overall, the optimal hydroponic design offers a comprehensive solution that balances productivity, sustainability, and safety. It minimizes resource waste, ensures nutritious and chemical-free produce, and fosters social and cultural acceptance of urban agriculture. Compliance with relevant IEEE standards further guarantees reliable operation, making the system a safe, efficient, and scalable approach to addressing food security and sustainable farming challenges in urban environments.

Chapter 7: Engineering Project Management. [CO11, CO14]

7.1 Introduction

Project management is the discipline of applying the right expertise to keep a project on track, ensuring it is delivered on time and within budget. The initial phase involves setting clear goals and defining strict timelines. This framework helps in mapping out the project's objectives, procedures, and deliverables. Crucially, management is not just about supervision; it also facilitates regular information exchange between participants and stakeholders. Additionally, preparing contingency plans for unforeseen issues is vital. The true value of project management is demonstrated when the final solution is delivered successfully within the deadline.

7.2 Define Plan and Engineering Project

Table 23: Timeline for FYDP-P

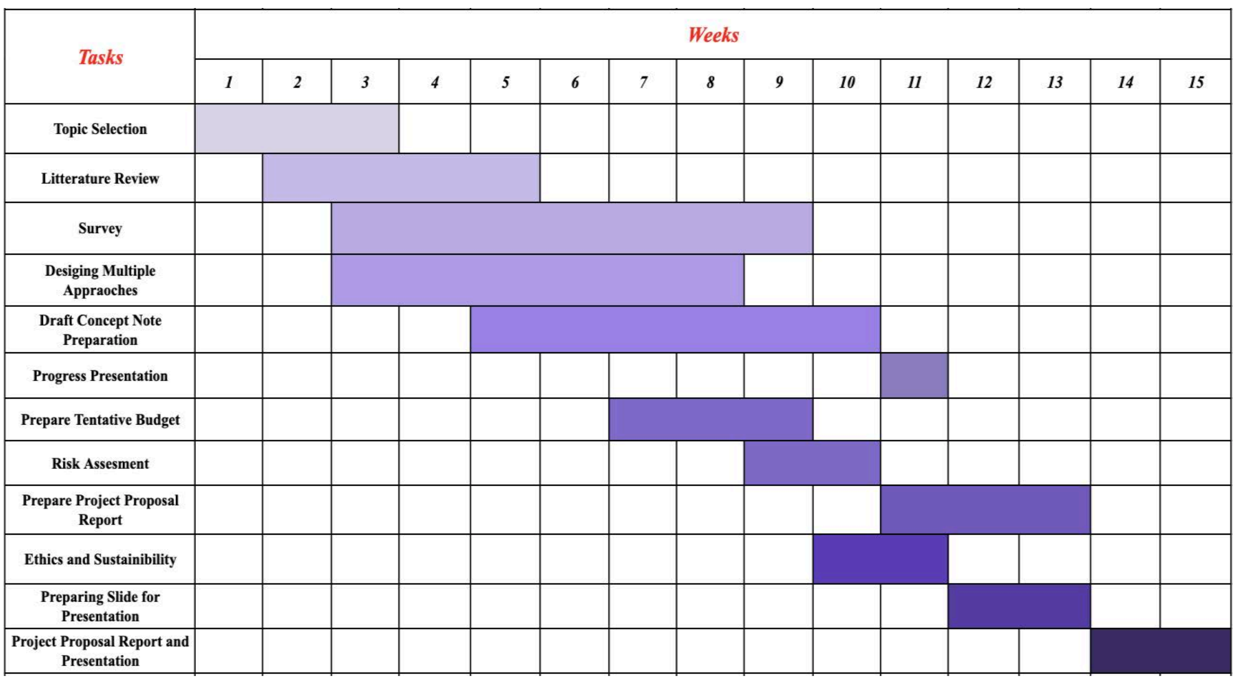


Table 24: Timeline for FYDP-D

Tasks	Weeks													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Finalize Design														
Design-01 Simulation														
Design-02 Simulation														
Analysis and Comparison														
Selecting the Best Approach														
Final Presentation														
Final Report Submission														

Table 25: Timeline for FYDP-C

Tasks	Weeks													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Resource Sourcing														
Construction of Subsystem														
Testing and Debugging														
Subsystem Integration														
Testing and Refining														
Project Validation														
Final Project Demonstration														

7.3 Evaluate project progress

Since the beginning of our project idea, we knew that there were major activities to be performed according to the timeline of our project as laid out by the FYDP committee to be sure that the targets of every project stage were met. Meeting with ATC panel every week was essential in building some systematic structure in the sense that, assignments were given depending on the discussion and feedbacks made by the panel members. Our main objective upon completion of the FYDP-P phase was to be able to develop a complete project proposal which explained the problem statement, initial budget, design strategies and expected project impact clearly.

Though the timeline proposed was observed to a large scale, some of the critical activities were unable to be completed on schedule and were displayed in the next phase. Besides, the original design strategies were not fully applicable to the project requirements, which were subject to improvement during the FYDP-D phase. The changes in politics also influenced the progress made during this stage, causing delays in the activities and the necessity to adjust the entire schedule that is determined as in the new numbers.

The last stage of the project was especially difficult, especially when integrating the sensors and gathering data. The sensor node breakdowns slowed down the process of collecting data and the replacement of parts damaged also consumed more time because most of the parts were to be bought online and there was a delay in delivery. These difficulties notwithstanding, all the project milestones were met, and the fully deployed prototype was available in time until the final presentation. On the whole, the project schedule played a crucial role in ensuring that the team members remained focused even though they had different schedules and other outside commitments. The allocation of tasks during the project did not only make the project progress consistently but also helped us grow professionally and personally by helping us develop a sense of teamwork and responsibility.

7.4 Conclusion

Finally, we were able to overcome a series of technical and logistical challenges based on well-developed project management principles. We were not always able to meet all the deadlines in the initial schedule but the strategic blueprint was an invaluable resource, it kept the team down to earth. This field of study allowed us to cope with the challenges and manage to present all the desired project outcomes.

Chapter 8: Economic Analysis. [CO12]

8.1 Introduction

Economic analysis is necessary to analyze the practicality and viability of any engineering system in terms of financial feasibility. In the case of indoor hydroponic farming, it is essential to know the initial cost of the investment and the returns that could be expected particularly in terms of scalability, commercialization and consumer adoption. The analysis is aimed at finding out the key cost elements that are used in the development of the proposed hydroponic farming prototype and determining its economic feasibility in terms of Return on Investment (ROI). The cost of the entire system would entail costs of structural materials, automation and control components, lighting systems and monitoring accessories. Even though smart technologies have the effect of raising the initial investment, they are efficient in improving the efficiency of the system, minimizing resources wastage, and enhancing crop productivity. Consequently, this cost benefit analysis does not only show the cost allocation, but also determine the profitability of the system both in the perspective of prototype selling and in the perspective of annual crop production. The findings will give a clue to whether the suggested system is both financially viable and can be implemented in real-life.

8.2 Economical Analysis

The economical analysis evaluates the total cost required to develop the hydroponic farming prototype and estimates its potential return on investment (ROI). The cost breakdown is summarized based on the major components used in the system.

Cost Breakdown of the System

Table 26: Cost Breakdown

Equipment	Price(TK)
PVC Structure	1800
Microcontroller, Sensors, etc.	20860
Lighting System	2112
Camera and Other Accessories	4808
Total	29580

Table 27: Return of Investment(ROI) Analysis

Consumer Perspective	**ROI (%)**
Selling Prototype	35.19%
Crop Production (Annual)	31.03%

The total system cost consists of four main components:

PVC Structure (Tk 1800): This includes pipes and fittings used to build the hydroponic frame and plant support system.
Microcontroller, Sensors, etc. (Tk 20,860): This is the highest cost component and includes the microcontroller unit, environmental sensors (temperature, humidity, water level, pH), control circuitry, and wiring. These components enable automation and smart monitoring.
Lighting System (Tk 2,112): Artificial grow lights are used to ensure proper photosynthesis, especially in indoor environments where natural sunlight is limited.
Camera and Other Accessories (Tk 4,808): This includes a camera module for monitoring plant growth and other accessories such as power supplies, connectors, and mounting materials.

Total Cost Calculation

The total cost of the system is calculated as:
Total Cost = PVC Structure + Microcontroller and sensors + Lighting System + Camera and Accessories

Total Cost = 1800 + 20860 + 2112 + 4808 = Tk 29,580

Return on Investment (ROI) Analysis

ROI is used to measure the financial benefit of the system compared to its initial cost. Two perspectives are considered: selling the prototype and annual crop production.
ROI Formula
The general formula for ROI is:
ROI (%) = (Net profit / Total Investment) × 100%
Where,
Net Profit = Total Revenue − Total Cost

Consumer Perspective

SellingPrototype: If the prototype is sold after development, an ROI of **35.19%** indicates that the selling price generates a profit of 35.19% over the initial investment.
Crop Production (Annual): For annual crop production, the system achieves an ROI of **31.03%**, showing that revenue generated from selling crops over one year can recover a significant portion of the investment while still producing profit.

8.3 Cost-Benefit Analysis

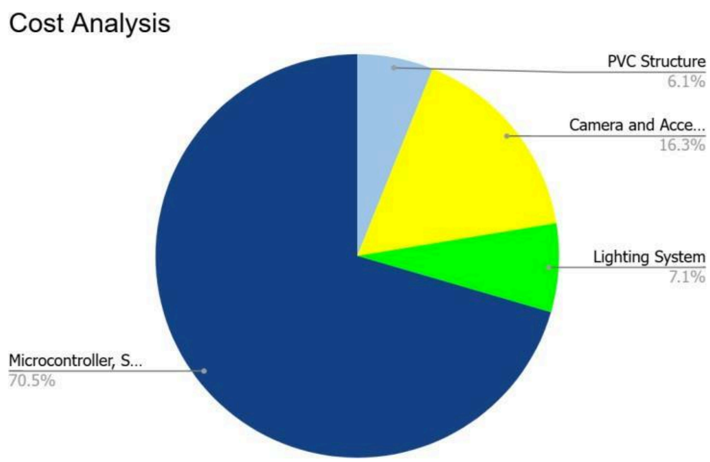


Fig. 49: Pie Chart for Cost Analysis

Figure 11 gives a pie chart of the cost of the components of the system. As indicated in the chart, the largest percentage of the total cost is attributed to the microcontroller and the sensors indicating the significance of smart automation in the system. There are other elements like lighting, structure and accessories that play smaller roles but essential roles within the entire budget.

8.4 Conclusion

As seen in the economic analysis, the system is economically viable despite the high startup costs of automating the system because of the automation elements. The positive ROI figures in the prototype selling view and the crop production view demonstrates that the hydroponic system shows a great opportunity in commercial and small scale urban farming.

Chapter 9: Ethics and Safety. [CO13, CO2]

9.1 Introduction

Ethical and safety considerations play a crucial role in the design and implementation of modern engineering systems, particularly those deployed in public and environmentally sensitive spaces. In the context of smart hydroponic farming, it is essential to ensure that the system operates responsibly, safely, and sustainably while minimizing risks to people, the environment, and resources. This section addresses the ethical responsibilities associated with environmental sustainability, public interaction, data transparency, and social inclusivity, as well as the safety measures required to protect users, operators, and surrounding communities.

The proposed system integrates automation, IoT, and machine learning technologies, which introduce additional ethical and safety challenges related to data integrity, system reliability, and human interaction. Therefore, the system is designed in alignment with relevant IEEE standards to ensure compliance with international best practices. By incorporating ethical design principles and comprehensive safety mechanisms, the project aims to deliver a secure, trustworthy, and socially responsible solution for indoor and urban hydroponic farming.

9.2 Ethical Consideration (CO13)

This project is designed with several critical ethical considerations that ensure it is both socially responsible and environmentally beneficial. One of the primary concerns is its environmental impact. Given the critical issues of resource scarcity and climate change, the project focuses on using water-efficient and energy-efficient systems, significantly reducing water usage compared to traditional farming methods. This approach supports sustainable farming practices and aligns with global eco-friendly standards, such as **IEEE 1680-2009**, which sets the guidelines for the environmental performance of electronic products, ensuring the system uses energy-efficient materials like ABS for its components. By reducing water consumption, the system offers a sustainable alternative to conventional agriculture, contributing to long-term environmental goals. Public interaction with the system is another critical ethical consideration. As the system operates in shared urban spaces like community gardens or rooftops, it mustn't cause harm or inconvenience to the public. To ensure the safety of people and animals, the system will incorporate clear visual and auditory signals to communicate its actions. These measures promote transparency, fostering public trust and ensuring the system integrates smoothly into everyday life. This is in line with **IEEE 1471**, which emphasizes safety standards for systems operating in public spaces and ensuring reliable and predictable behavior.

Furthermore, the system employs machine learning models to optimize plant growth, and these models must be trained on diverse and representative datasets. If the data models are biased or unrepresentative, they could result in misclassification or inefficient use of resources, which could lead to public distrust and reduced system effectiveness. Ensuring fairness and transparency in the system's machine learning algorithms is not only vital for accuracy but also for building trust with users. This approach aligns with **IEEE 1888**, which supports effective sensor network communication, ensuring the integrity and transparency of the data collection process.

Finally, accessibility and inclusivity are central to the project's ethical framework. The system must be affordable and deployable in resource-constrained settings, ensuring that it benefits not only urban areas but also rural communities facing challenges related to traditional farming. This approach contributes to global sustainability and aligns with broader social equity goals, promoting the widespread adoption of efficient farming technologies. The inclusivity of the project is further supported by **IEEE 11073-20601**, which ensures the accessibility and security of IoT systems that are deployed in various contexts, benefiting all communities.

9.3 Safety Consideration (CO2)

The system is designed with various safety measures to protect users, operators, and the environment. These measures also follow important standards like **IEEE 802.15.4-2020** for ensuring wireless communication remains safe and reliable, and **IEEE 1680.2-2024** for energy efficiency.

Mechanical Safety: The system has moving parts like pumps, motors, and conveyors that could potentially cause accidents. To prevent this, all moving parts are enclosed in protective barriers to keep people safe. Additionally, there are emergency stop buttons built into the system so that if something goes wrong, the operators can stop it immediately. This ensures that, even if there's a malfunction, the system won't cause harm to anyone around it. These safety features follow the guidelines from **IEEE 1680.2-2024**, ensuring that all components are energy-efficient and operate safely.

Electrical Safety: Because the system relies on electrical components, it's crucial to make sure they are safe, especially since the system will work in environments where it could be exposed to moisture or water. All electrical parts are insulated and waterproofed to prevent short circuits or electric shocks. This is important to protect both the operators and anyone near the system. By adhering to **IEEE 802.15.4-2020**, the system ensures that any wireless communication used, such as notifications or control signals, will not interfere with safe system operation.

Public Interaction: The system is designed to be used in public spaces like community gardens or urban rooftops, so it mustn't harm or interfere with people or animals. To keep everything safe, the system will include clear alerts, such as flashing lights or sound signals, to notify people when it's in motion or operating. This ensures that everyone is aware of the system's actions and can avoid accidents. The use of clear communication follows **IEEE 1471**, which sets safety standards for systems working in public spaces to ensure they behave predictably and safely.

Material Durability: The system will be exposed to a range of environmental conditions, such as humidity, temperature changes, and possibly contact with water and nutrients. Therefore, the materials used in the system are selected for their durability and resistance to wear and corrosion. This ensures that the system remains safe and functional over time, even in tough conditions.

Environmental Adaptability: The system is built to function smoothly in a variety of indoor environments, where conditions like humidity or temperature may fluctuate. The system will remain stable and efficient, regardless of these changes. This adaptability is crucial to ensure the system continues to work safely and effectively, whether it's in a very humid area or a drier one. Additionally, the system complies with **IEEE 1888**, ensuring that data collected from sensors in varying environmental conditions is communicated effectively, without impacting system performance.

Safe Handling of Materials: Since the system handles water, nutrients, and waste, it's essential to make sure these materials are managed safely to avoid health risks. The system is designed to reduce direct human contact with these materials by using automated processes. This not only helps in keeping things hygienic but also ensures that the waste is properly handled, preventing contamination. The system's handling methods align with **IEEE 11073-10472-2023**, which focuses on remote monitoring and ensuring the safe operation of systems involving material handling.

Fail-Safe Mechanisms: In case something goes wrong, the system includes fail-safe mechanisms that allow operators to immediately stop the system. This is critical to ensure that, if a malfunction occurs, it doesn't lead to unsafe conditions. These fail-safes are an important part of the system's design, ensuring that it remains reliable and safe even when unexpected issues arise. The fail-safe approach follows **IEEE 11073-20601**, ensuring that all IoT devices in the system are secure, and any malfunction can be quickly identified and handled safely.
By including these safety features and following international safety standards, the system is designed to be reliable and safe for use in a variety of environments. These measures ensure the system can operate securely, providing a safe and efficient solution for urban agriculture.

9.4 Conclusion

In conclusion, this hydroponic farming system is designed to be ethically responsible and safe. Ethically, it promotes environmental sustainability, transparency in data use, and accessibility for diverse communities, aligning with global sustainability goals. From a safety perspective, protective enclosures, waterproof components, fail-safes, and compliance with IEEE standards minimize risks for users and the environment. Together, these measures ensure a reliable, sustainable, and efficient solution for modern urban agriculture.

Chapter 10: Conclusion and Future Work

10.1 Project Conclusion

The suggested hydroponic system provides an efficient, safe and sustainable solution to modern urban agriculture. The system has the potential to optimally utilize water and resources, which may include automated nutrient delivery, sensor technology, and energy-saving technologies to generate high-quality pesticide-free foods and eliminate the need to rely on the traditional soil-based farm. Its modular character, safety and the possibility of future upgrades through provision of automatic pest controllers and decision support systems and water recycling make it flexible to both small scale and large scale applications. In general, the system does not only deal with food security and environmental issues.

10.2 Future Work

Automatic Pesticide Spraying Pest Control: Despite the present system being focused on pest-free cultivation, the introduction of an automatic (pesticide spraying) system can be viewed as a compromise to cases where the crops are at risk due to the presence of a pest outbreak. This aspect would be based on sensors or the use of images to monitor pests at a very early stage and apply specific doses of bio-pesticide or organic treatment where the plant requires it, and reducing the level of chemicals in the environment. Pest control is efficient, safe and environmentally friendly due to automation that guarantees timely intervention, labor reduction and avoidance of over-application.

Compact Product Design to get ready to market: Once the system is improved to a compact modular design it will be in a better position to be commercially produced and adopted by consumers. The smaller footprint and ergonomic design and the unifying of parts (pumps, sensors, lights, and control units) would allow the product to be installed easily in residential buildings, schools or urban farms. The readiness of the design to the market also enhances the portability, lowers the cost of materials, and promotes a wide adoption, which places the system as an affordable urban agriculture solution.

Decision Support System (DSS): Adding a decision support system (DSS) to the system will enable the system to monitor the major parameters like pH, total dissolved solids (TDS), temperature, and pest activity on the fly. The DSS is capable of notifying or presenting visual dashboards to the operators in case abnormal conditions are identified so that the operators can take corrective measures. Predictive technology improves crop control, minimizes the threat of nutrient deficiencies or pest infestations and guarantees increased yields and makes the system more user-friendly and proactive.

Connection to a Mobile or Web Application: The connection with our developed application of hydroponic system would enable the users to remotely monitor and operate the system. Nutrient flow, lighting, water circulation or the activation of pest control mechanisms could be controlled by users through smartphones or computers. Live data visualization and control contribute to convenience, accessibility of system administration to non-technical users, and scalability in terms of use in urban or community farms.

Recycling Water to Use in Large Scale Agriculture: Water in large scale or commercial hydroponics: In large scale or commercial setups it is important to implement a water recycling process in order to achieve maximum sustainability. The system can be used to filter, sterilize, and reuse nutrient-rich water, which will cut down on the amount of water used and reduce waste. Effective management of water does not only reduce the costs incurred in the operation, but also promotes the sustainability of the environment in areas experiencing water shortage, and also ensuring the availability of nutrients to support the growth of healthy crops.

Chapter 11: Identification of Complex Engineering Problems and Activities

11.1 Identify the Attribute of A Complex Engineering Problem (EP)

	Attributes	**Put a tick (√) as appropriate**
P1	Depth of knowledge required	√
P2	Range of conflicting requirements	√
P3	Depth of analysis required	√
P4	Familiarity of Issues	√
P5	Extent of applicable codes	
P6	Extent of stakeholder involvement and needs	√
P7	Interdependence	√

P1 - Depth of Knowledge Required

Indoor vertical hydroponic systems require a deep insight into a wide range of engineering and scientific fields, including electrical and electronic engineering, control systems, fluid mechanics, the Internet of Things, data analytics, and plant physiology. Light design, nutrient injections, water supply, oxygenation, and environmental management cannot be fulfilled with the primitive knowledge of engineering. In this connection, the project meets the necessary demand of high technical and theoretical profundity.

P2 - Range of Conflicting Requirements

The system should also be able to fulfill high crop productivity and at the same time reduce the water use, energy consumption and operational expenses. At the same time, it should maintain the health of plants, system stability and ease of use. These demands are antagonistic in nature because increasing the amount of light or water to boost growth will in proportion increase the amount of energy and resources spent. These contradictions are mitigated by the project through the implementation of sensor-based control, as well as optimisation-oriented design.

P3 - Depth of Analysis Required

The project has integrated careful analysis of engineering, including the calculation of the sizing of hydraulic pumps, energy, and efficiency of LED sources, modeling of the flow of nutrients, and the application of MATLAB to evaluate the performance of the project. The simulation of the proteus was used to test the electronic and control subsystems and this showed that the design is not baseless but based on quantitative analysis as opposed to experimentation.

P4 - Familiarity of Issues

This project includes non-routine engineering tasks introduced by indoor hydroponic installations like nutrient imbalance, oxygen deprivation at root areas, light attenuation across the distance and rigorous regulation of the environment inside the confined areas. The problems do not just solve the standard electrical or mechanical engineering problems, but rather are multidisciplinary problems which require multidisciplinary problem-solving, making the project inherently complex.

P6 - Extent of Stakeholder Involvement and Needs

The system will benefit a group of stakeholders, such as urban farmers, consumers, sustainability authorities, and researchers. It touches upon water conservation, energy efficiency, operational ease, and food safety issues. The variety of needs of these groups creates the necessity of sensible judgment in engineering and systematic trade-offs analysis.

P7 - Interdependence

There is high interdependence between all subsystems (lighting, nutrient delivery, water circulation, oxygen, temperature, humidity, and control software). Any changes in any parameter will always be transferred to other parameters and this requires combined monitoring and control. This interconnection is very strong and supports the complexity of the engineering challenge.

11.2 Attributes of Complex Engineering Activities

	Attributes	Put a tick (√) as appropriate
A1	Range of resources	√
A2	Level of interaction	√
A3	Innovation	
A4	Consequences for society and the environment	√
A5	Familiarity	√

A1- Range of Resources

The project utilizes a vast range of materials; they include sensors, microcontrollers, pumps, LEDs, nutrient solutions, mechanical frames, and software, including MATLAB and Proteus. These various parts make the engineering exercise quite complicated to manage and integrate.

A2 - Level of Interaction

Sensors and actuators help to create continuous communication between the environment and the unit. The controller processes the environmental data and then actively controls lighting, pumping and dispensation of nutrients in a real-time manner. This high level of interaction between hardware, software and biological processes justifies the inherent complexity of the activity.

A4 - Consequences for Society and the Environment

The system positively impacts sustainable agriculture by limiting the use of water, cutting down on the land requirement, and allowing food to be produced all-year round. It also promotes food security and environmental stewardship especially in urban environments, which gives the project a significant socio-environmental value.

A5 - Familiarity

The idea and realization of an automated, IoT-experienced vertical hydroponic system forms an outstanding engineering venture. It requires trial, maximizing the performance of the system, and integrating the disciplines, which makes it a non-standard and complex engineering activity.

Code (Final Design) :

System Code:

```
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <OneWire.h>
#include <DallasTemperature.h>
#include <DHT.h>

const int PIN_NUTRIENT_A = 6;
const int PIN_NUTRIENT_B = 8;
const int PIN_PH_BASE    = 24;
const int PIN_PH_ACID    = 26;
const int PIN_CIRC_PUMP  = 28;
const int PIN_REFILL     = 30;
const int PIN_OXYGEN     = 50;

const int PIN_SENSE_SOL_A  = A0;
const int PIN_SENSE_SOL_B  = A3;
const int PIN_SENSE_MAIN   = A6;
const int PIN_SENSE_RES    = A7;

const int PIN_PH_PROBE     = A2;
const int PIN_TDS_PROBE    = A1;
const int PIN_TURB_PROBE   = A5;
const int PIN_TEMP_WATER   = 2;
const int PIN_DHT_AIR      = 3;
const float PH_LOW_LIMIT   = 5.8;
const float PH_HIGH_LIMIT  = 6.2;
const int   LEVEL_THRESHOLD = 250;
const unsigned long DOSING_INTERVAL = 30000;

LiquidCrystal_I2C lcd(0x27, 20, 4);
OneWire oneWire(PIN_TEMP_WATER);
```

```
DallasTemperature waterTempSens(&oneWire);
DHT dht(PIN_DHT_AIR, DHT22);

struct {
 float ph, wTemp, aTemp, hum;
 int tds, turb;
 bool solA_Ok, solB_Ok, mainLow, resOk;
 bool pNutrient, pBase, pAcid, pRefill;
} sys;

unsigned long lastSenseUpdate  = 0;
unsigned long lastDisplayUpdate = 0;
unsigned long doseTimer        = 0;

void setup() {
 Serial.begin(9600);
 int outputs[] = {6,8,24,26,28,30,50};
 for(int p : outputs) {
   pinMode(p, OUTPUT);
   digitalWrite(p, LOW);
 }

 pinMode(PIN_SENSE_MAIN, INPUT_PULLUP);

 lcd.init();
 lcd.backlight();
 waterTempSens.begin();
 dht.begin();

 digitalWrite(PIN_OXYGEN, HIGH);
 digitalWrite(PIN_CIRC_PUMP, HIGH);

 lcd.setCursor(0,0); lcd.print("HYDROPONICS PRO V7");
 lcd.setCursor(0,1); lcd.print("SYSTEM STARTING...");
 delay(2000);
```

```
 lcd.clear();
}

void loop() {
 unsigned long now = millis();

 if (now - lastSenseUpdate >= 1000) {
   updateSensors();
   runSafetyLogic(now);
   lastSenseUpdate = now;
 }

 if (now - lastDisplayUpdate >= 2000) {
   updateLCD();
   updateSerial();
   lastDisplayUpdate = now;
 }
}



void updateSensors() {
  sys.solA_Ok = (analogRead(PIN_SENSE_SOL_A) > LEVEL_THRESHOLD);
 sys.solB_Ok = (analogRead(PIN_SENSE_SOL_B) > LEVEL_THRESHOLD);
 sys.mainLow = (digitalRead(PIN_SENSE_MAIN) == LOW);
 sys.resOk   = (analogRead(PIN_SENSE_RES) > LEVEL_THRESHOLD);

 float voltage = analogRead(PIN_PH_PROBE) * (5.0 / 1023.0);
 sys.ph = 3.5 * voltage;

 waterTempSens.requestTemperatures();
 sys.wTemp = waterTempSens.getTempCByIndex(0);
 sys.aTemp = dht.readTemperature();
 sys.hum   = dht.readHumidity();
 sys.tds = map(analogRead(PIN_TDS_PROBE), 0, 1023, 0, 1500);
```

```
 sys.turb = map(analogRead(PIN_TURB_PROBE), 0, 1023, 100, 0);
}

void runSafetyLogic(unsigned long now) {

 if (now - doseTimer >= DOSING_INTERVAL) doseTimer = now;
 if (now - doseTimer < 5000) {
   sys.pNutrient = true;
   digitalWrite(PIN_NUTRIENT_A, HIGH);
   digitalWrite(PIN_NUTRIENT_B, HIGH);
 } else {
   sys.pNutrient = false;
   digitalWrite(PIN_NUTRIENT_A, LOW);
   digitalWrite(PIN_NUTRIENT_B, LOW);
 }

 sys.pBase = (sys.ph < PH_LOW_LIMIT && sys.solA_Ok);
 sys.pAcid = (sys.ph > PH_HIGH_LIMIT && sys.solB_Ok);
 digitalWrite(PIN_PH_BASE, sys.pBase);
 digitalWrite(PIN_PH_ACID, sys.pAcid);

 sys.pRefill = (sys.mainLow && sys.resOk);
 digitalWrite(PIN_REFILL, sys.pRefill);
}

void updateLCD() {
 lcd.setCursor(0,0);
 lcd.print("pH:"); lcd.print(sys.ph, 1);
 lcd.print(" TDS:"); lcd.print(sys.tds);
 lcd.print("   ");
 lcd.setCursor(0,1);
 lcd.print("W:"); lcd.print(sys.wTemp, 1);
 lcd.print("C A:"); lcd.print(sys.aTemp, 1);
 lcd.print("C  ");
 lcd.setCursor(0,2);
```

```
 lcd.print("Main:"); lcd.print(sys.mainLow ? "LOW " : "OK  ");
 lcd.print("Res:"); lcd.print(sys.resOk ? "OK" : "LO");
 lcd.setCursor(0,3);
 lcd.print("PUMP:");
 lcd.print(sys.pNutrient ? "N" : "-");
 lcd.print(sys.pBase ? "B" : "-");
 lcd.print(sys.pAcid ? "A" : "-");
 lcd.print(sys.pRefill ? "R" : "-");
 lcd.print(" Hum:"); lcd.print((int)sys.hum); lcd.print("%");
}

void updateSerial() {
 Serial.print(F("PH: ")); Serial.print(sys.ph);
 Serial.print(F("| TDS: ")); Serial.print(sys.tds);
Serial.print(F("| TANK: ")); Serial.println(sys.mainLow ? "REFILL" : "OK");
}
```

LED Control:

```
#include <SoftwareWire.h>
const int RED_PWM_PERCENT   = 100;
const int BLUE_PWM_PERCENT  = 50;
const int WHITE_PWM_PERCENT = 25;
const float AREA = 2.5;

const int redPin   = 10;
const int bluePin  = 11;
const int whitePin = 9;

SoftwareWire redWire(A4, A5);
SoftwareWire blueWire(2, 3);
SoftwareWire whiteWire(4, 5);

void setup() {
 Serial.begin(9600);
 pinMode(redPin, OUTPUT);
 pinMode(bluePin, OUTPUT);
 pinMode(whitePin, OUTPUT);

 redWire.begin();
 blueWire.begin();
 whiteWire.begin();

 initSensor(redWire);
 initSensor(blueWire);
 initSensor(whiteWire);

 Serial.println("Column-01  | Column-02  | Column-3");
 Serial.println(" LUMENS    | LUMENS     |  LUMENS");
}
```

```
void loop() {
 int pwmRed   = map(RED_PWM_PERCENT, 0, 100, 0, 255);
 int pwmBlue  = map(BLUE_PWM_PERCENT, 0, 100, 0, 255);
 int pwmWhite = map(WHITE_PWM_PERCENT, 0, 100, 0, 255);

 analogWrite(redPin, pwmRed);
 analogWrite(bluePin, pwmBlue);
 analogWrite(whitePin, pwmWhite);

 float lumRed   = readLux(redWire) * AREA;
 float lumBlue  = readLux(blueWire) * AREA;
 float lumWhite = readLux(whiteWire) * AREA;

 printStats(RED_PWM_PERCENT, lumRed);
 Serial.print("| ");
 printStats(BLUE_PWM_PERCENT, lumBlue);
 Serial.print("| ");
 printStats(WHITE_PWM_PERCENT, lumWhite);
 Serial.println(); // New line

 delay(1000); // Refresh every second
}

void initSensor(SoftwareWire &sw) {
 sw.beginTransmission(0x23);
 sw.write(0x10);
 sw.endTransmission();
}

float readLux(SoftwareWire &sw) {
 sw.requestFrom(0x23, 2);
 if (sw.available() == 2) {
   uint16_t raw = (sw.read() << 8) | sw.read();
   return (float)raw / 1.2;
 }
```

```
 sw.requestFrom(0x5C, 2);
 if (sw.available() == 2) {
   uint16_t raw = (sw.read() << 8) | sw.read();
   return (float)raw / 1.2;
 }
 return 0.0;
}
void printStats(int percent, float lum) {
 Serial.print(percent); Serial.print("%");
 if(percent < 100) Serial.print(" ");
 if(percent < 10)  Serial.print(" ");
  Serial.print("   ");
 if(lum < 1000) Serial.print(" ");
 if(lum < 100)  Serial.print(" ");
 if(lum < 10)   Serial.print(" ");
  Serial.print(lum, 1);
 Serial.print(" lm    ");
}
```

Code (Camera Monitoring):

```
import cv2
import time
import numpy as np
from gpiozero import AngularServo
from gpiozero.pins.lgpio import LGPIOFactory
factory = LGPIOFactory()
SERVO_PIN = 18
servo = AngularServo(SERVO_PIN, min_angle=0, max_angle=360,
                    min_pulse_width=0.0005, max_pulse_width=0.0025,
                    pin_factory=factory)

cap = cv2.VideoCapture(0)
print("Loading model... Please wait.")
print("Model loaded successfully!")

def preprocess_image(frame):
   img_rgb = cv2.cvtColor(frame, cv2.COLOR_BGR2RGB)
   img_resized = cv2.resize(img_rgb, (224, 224))
   img_normalized = img_resized / 255.0
   img_batch = np.expand_dims(img_normalized, axis=0)
   return img_batch

def detect_disease(original_image):
   print("  > Processing image...")
   processed_image = preprocess_image(original_image)
   result_label = "Simulated Result: Healthy"
   timestamp = time.strftime("%Y%m%d-%H%M%S")
   filename = f"plant_{result_label}_{timestamp}.jpg"
   cv2.imwrite(filename, original_image)
   print(f"  > Detected: {result_label}")
   return result_label

def main():
```

```
    try:
        print("Plant Monitoring System Started")
        target_angles = [0, 120, 240]

        while True:
            print("\nStarting rotation cycle...")

            for angle in target_angles:
                print(f"[Motor] Rotating to {angle}°")
                servo.angle = angle

                print("[System] Waiting 15s...")
                time.sleep(15)

                ret, frame = cap.read()
                if ret:
                    detect_disease(frame)
                else:
                    print("[Error] Camera failed.")
                time.sleep(1)

            print("Cycle complete. Returning to start...")
            servo.angle = 0
            time.sleep(5)

    except KeyboardInterrupt:
        print("\nStopped by user.")
        cap.release()
        cv2.destroyAllWindows()
if __name__ == "__main__":
    main()
```

Code (Image Processing-MobileNet):

```
import tensorflow as tf

print("="*80)
print("PLANT DISEASE DETECTION - SYSTEM CHECK")
print("="*80)
print("\nTensorFlow Version:", tf.__version__)

gpus = tf.config.list_physical_devices('GPU')
if len(gpus) > 0:
    print("GPU Available:", gpus[0].name)
    print("Training will be fast (30-60 minutes)")
else:
    print("WARNING: GPU NOT DETECTED")
    print("Go to: Runtime > Change runtime type > GPU > Save")

print("\nModel: MobileNetV2 (Transfer Learning)")
print("="*80)

import sys
print("Installing required packages...")

!{sys.executable} -m pip install -q opencv-python-headless
!{sys.executable} -m pip install -q scikit-learn
!{sys.executable} -m pip install -q matplotlib
!{sys.executable} -m pip install -q seaborn
!{sys.executable} -m pip install -q gdown

print("All packages installed successfully")

import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns
import cv2
import os
import json
import zipfile
import warnings
import re
from datetime import datetime

from sklearn.metrics import classification_report, confusion_matrix
```

```
from tensorflow import keras
from tensorflow.keras import layers
from tensorflow.keras.applications import MobileNetV2
from tensorflow.keras.preprocessing.image import ImageDataGenerator
from tensorflow.keras.callbacks import ModelCheckpoint, EarlyStopping, ReduceLROnPlateau

from google.colab import files
import gdown

warnings.filterwarnings('ignore')
plt.style.use('default')

print("All libraries imported successfully")
print("\nKey Libraries:")
print("  TensorFlow:", tf.__version__)
print("  NumPy:", np.__version__)
print("  OpenCV:", cv2.__version__)

IMAGE_SIZE = (224, 224)
BATCH_SIZE = 32
EPOCHS_PHASE1 = 50
EPOCHS_PHASE2 = 30
LEARNING_RATE_PHASE1 = 0.001
LEARNING_RATE_PHASE2 = 0.0001

CATEGORIES = [
    'Bacterial',
    'Fungal',
    'Healthy'
]

NUM_CLASSES = len(CATEGORIES)

print("="*80)
print("CONFIGURATION")
print("="*80)
print("\nImage Size:", IMAGE_SIZE)
print("Batch Size:", BATCH_SIZE)
print("Phase 1 Epochs:", EPOCHS_PHASE1)
print("Phase 2 Epochs:", EPOCHS_PHASE2)
print("\nNumber of Classes:", NUM_CLASSES)
print("\nDisease Classes:")
for i, cat in enumerate(CATEGORIES, 1):
    print(f"  {i}. {cat}")
print("="*80)
```

```
print("="*80)
print("ACCESSING DATASET FROM GOOGLE DRIVE")
print("="*80)

from google.colab import drive

print("\nMounting Google Drive...")
drive.mount('/content/drive')
print(" Drive mounted!")

DRIVE_FILE_PATH = "/content/drive/MyDrive/FYDP_Image Processing/lettuce"

if os.path.exists(DRIVE_FILE_PATH):
    print(f"\n Found dataset folder: {DRIVE_FILE_PATH}")
    dataset_base = DRIVE_FILE_PATH
    print(" Using dataset directly from Drive")
else:
    print(f"\n ✗  Dataset folder not found at: {DRIVE_FILE_PATH}")


import shutil

print("\n" + "="*80)
print("FIXING FOLDER NAMES")
print("="*80)

for split in ['train', 'test', 'valid']:
    split_path = os.path.join(dataset_base, split)

    if os.path.exists(split_path):
        print(f"\n{split}/:")

        old = os.path.join(split_path, 'fungal')
        new = os.path.join(split_path, 'Fungal')
        if os.path.exists(old) and not os.path.exists(new):
            shutil.move(old, new)
            print(f"   Renamed fungal → Fungal")

        old = os.path.join(split_path, 'healthy')
        new = os.path.join(split_path, 'Healthy')
        if os.path.exists(old) and not os.path.exists(new):
            shutil.move(old, new)
            print(f"   Renamed healthy → Healthy")
```

```
        for cat in CATEGORIES:
            cat_path = os.path.join(split_path, cat)
            if os.path.exists(cat_path):
                count = len([f for f in os.listdir(cat_path) if f.endswith(('.jpg','.png','.jpeg'))])
                print(f"  {cat}: {count} images")

print("\n Folder names corrected!")

print("="*80)
print("LOADING DATA")
print("="*80)

def load_images_from_folder(base_path, split_name):
    images = []
    labels = []

    split_path = os.path.join(base_path, split_name)

    print(f"\nLoading {split_name.upper()} set...")
    print("-" * 60)

    for idx, category in enumerate(CATEGORIES):
        cat_path = os.path.join(split_path, category)

        if not os.path.exists(cat_path):
            print(f"  {category:12s}: Folder not found")
            continue

        image_files = [f for f in os.listdir(cat_path)
                      if f.lower().endswith(('.jpg', '.jpeg', '.png'))]

        print(f"  Loading {category:12s}: ", end='', flush=True)

        loaded_count = 0
        for img_name in image_files:
            img_path = os.path.join(cat_path, img_name)

            img = cv2.imread(img_path)
            if img is None:
                continue

            img = cv2.cvtColor(img, cv2.COLOR_BGR2RGB)
            img = cv2.resize(img, IMAGE_SIZE)
```

```
            images.append(img)
            labels.append(idx)
            loaded_count += 1

        print(f"{loaded_count} images")

    if len(images) > 0:
        images = np.array(images, dtype='float32') / 255.0
        labels = np.array(labels, dtype='int32')
        print(f"  Total: {len(images)} images")
    else:
        images = np.array([])
        labels = np.array([])

    return images, labels

X_train, y_train = load_images_from_folder(dataset_base, 'train')
X_val, y_val = load_images_from_folder(dataset_base, 'valid')
X_test, y_test = load_images_from_folder(dataset_base, 'test')

print("\n" + "="*80)
print("DATA LOADING SUMMARY")
print("="*80)
print(f"\nTraining set:   {len(X_train)} images")
print(f"Validation set: {len(X_val)} images")
print(f"Test set:       {len(X_test)} images")

print("\nClass Distribution:")
for idx, category in enumerate(CATEGORIES):
    train_count = np.sum(y_train == idx)
    val_count = np.sum(y_val == idx)
    test_count = np.sum(y_test == idx)
    print(f"  {category:12s}: Train={train_count:4d}, Val={val_count:4d}, Test={test_count:4d}")

print("\n Data loading complete!")

print("="*80)
print("DATASET VISUALIZATION")
print("="*80)

fig, axes = plt.subplots(3, 5, figsize=(15, 9))
fig.suptitle('Sample Images from Training Set', fontsize=16, fontweight='bold')

for i, category in enumerate(CATEGORIES):
    category_indices = np.where(y_train == i)[0]
```

```
    print(f"{category}: {len(category_indices)} images")

    for j in range(5):
        if j < len(category_indices):
            idx = category_indices[j]
            img = X_train[idx]
            axes[i, j].imshow(img)
            axes[i, j].set_title(category, fontsize=10, fontweight='bold')
            axes[i, j].axis('off')
        else:
            axes[i, j].axis('off')

plt.tight_layout()
plt.show()

print("\n Visualization complete!")

category_mapping = {str(idx): name for idx, name in enumerate(CATEGORIES)}
with open('disease_category_mapping.json', 'w') as f:
    json.dump(category_mapping, f, indent=2)

print(" Category mapping saved: disease_category_mapping.json")

print("="*80)
print("DATA AUGMENTATION")
print("="*80)

datagen = ImageDataGenerator(
    rotation_range=20,
    width_shift_range=0.2,
    height_shift_range=0.2,
    shear_range=0.2,
    zoom_range=0.2,
    horizontal_flip=True,
    brightness_range=[0.8, 1.2],
    fill_mode='nearest'
)

sample = X_train[0:1]
print(f"Sample image range: [{sample.min():.3f}, {sample.max():.3f}]")

fig, axes = plt.subplots(2, 5, figsize=(15, 6))
fig.suptitle('Data Augmentation Examples', fontsize=16, fontweight='bold')

axes[0, 0].imshow(sample[0])
```

```
axes[0, 0].set_title('Original', fontsize=10, fontweight='bold')
axes[0, 0].axis('off')

sample_aug = (sample * 255).astype(np.uint8)

i = 1
for batch in datagen.flow(sample_aug, batch_size=1):
    row, col = divmod(i, 5)
    augmented_img = batch[0].astype(np.float32) / 255.0
    axes[row, col].imshow(augmented_img)
    axes[row, col].set_title(f'Augmented {i}', fontsize=10)
    axes[row, col].axis('off')
    i += 1
    if i >= 10:
        break

plt.tight_layout()
plt.show()

print("\n Data augmentation configured")

print("="*80)
print("BUILDING MODEL")
print("="*80)

base_model = MobileNetV2(
    input_shape=(*IMAGE_SIZE, 3),
    include_top=False,
    weights='imagenet'
)

base_model.trainable = False

inputs = keras.Input(shape=(*IMAGE_SIZE, 3))
x = layers.RandomFlip("horizontal")(inputs)
x = layers.RandomRotation(0.1)(x)
x = layers.RandomZoom(0.1)(x)
x = base_model(x, training=False)
x = layers.GlobalAveragePooling2D()(x)
x = layers.BatchNormalization()(x)
x = layers.Dense(256, activation='relu')(x)
x = layers.Dropout(0.5)(x)
x = layers.Dense(128, activation='relu')(x)
x = layers.Dropout(0.3)(x)
outputs = layers.Dense(NUM_CLASSES, activation='softmax')(x)
```

```
model = keras.Model(inputs, outputs)

model.compile(
    optimizer=keras.optimizers.Adam(learning_rate=LEARNING_RATE_PHASE1),
    loss='sparse_categorical_crossentropy',
    metrics=['accuracy']
)

print(f"\n Model built - {model.count_params():,} parameters")

checkpoint = ModelCheckpoint(
    'best_disease_model.keras',
    monitor='val_accuracy',
    save_best_only=True,
    mode='max',
    verbose=1
)

early_stop = EarlyStopping(
    monitor='val_loss',
    patience=10,
    restore_best_weights=True,
    verbose=1
)

reduce_lr = ReduceLROnPlateau(
    monitor='val_loss',
    factor=0.5,
    patience=5,
    min_lr=1e-7,
    verbose=1
)

callbacks = [checkpoint, early_stop, reduce_lr]
print(" Callbacks configured")


print("="*80)
print("TRAINING PHASE 1: FROZEN BASE MODEL")
print("="*80)

start_time = datetime.now()

history1 = model.fit(
```

```
    X_train, y_train,
    validation_data=(X_val, y_val),
    epochs=EPOCHS_PHASE1,
    batch_size=BATCH_SIZE,
    callbacks=callbacks,
    verbose=1
)

phase1_time = (datetime.now() - start_time).total_seconds() / 60

print(f"\n Phase 1 Complete - {phase1_time:.1f} minutes")


print("="*80)
print("TRAINING PHASE 2: FINE-TUNING")
print("="*80)

base_model.trainable = True
for layer in base_model.layers[:-30]:
    layer.trainable = False

model.compile(
    optimizer=keras.optimizers.Adam(learning_rate=LEARNING_RATE_PHASE2),
    loss='sparse_categorical_crossentropy',
    metrics=['accuracy']
)

start_time = datetime.now()

history2 = model.fit(
    X_train, y_train,
    validation_data=(X_val, y_val),
    epochs=EPOCHS_PHASE2,
    batch_size=BATCH_SIZE,
    callbacks=callbacks,
    verbose=1
)

phase2_time = (datetime.now() - start_time).total_seconds() / 60

print(f"\n Phase 2 Complete - {phase2_time:.1f} minutes")
print(f" Total training time: {phase1_time + phase2_time:.1f} minutes")


history = {
```

```
    'accuracy': history1.history['accuracy'] + history2.history['accuracy'],
    'val_accuracy': history1.history['val_accuracy'] + history2.history['val_accuracy'],
    'loss': history1.history['loss'] + history2.history['loss'],
    'val_loss': history1.history['val_loss'] + history2.history['val_loss']
}

fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(16, 6))

ax1.plot(history['accuracy'], label='Training')
ax1.plot(history['val_accuracy'], label='Validation')
ax1.axvline(x=EPOCHS_PHASE1, color='gray', linestyle='--')
ax1.set_title('Model Accuracy')
ax1.set_xlabel('Epoch')
ax1.set_ylabel('Accuracy')
ax1.legend()
ax1.grid(True)

ax2.plot(history['loss'], label='Training')
ax2.plot(history['val_loss'], label='Validation')
ax2.axvline(x=EPOCHS_PHASE1, color='gray', linestyle='--')
ax2.set_title('Model Loss')
ax2.set_xlabel('Epoch')
ax2.set_ylabel('Loss')
ax2.legend()
ax2.grid(True)

plt.tight_layout()
plt.savefig('training_history.png', dpi=150)
plt.show()

print("="*80)
print("MODEL EVALUATION")
print("="*80)

best_model = keras.models.load_model('best_disease_model.keras')

test_loss, test_accuracy = best_model.evaluate(X_test, y_test, verbose=0)

print(f"\nTest Accuracy: {test_accuracy*100:.2f}%")
print(f"Test Loss:     {test_loss:.4f}")

y_pred = best_model.predict(X_test, verbose=0)
y_pred_classes = np.argmax(y_pred, axis=1)

report = classification_report(y_test, y_pred_classes, target_names=CATEGORIES, digits=4)
```

```
print("\n" + report)

with open('classification_report.txt', 'w') as f:
    f.write(report)

cm = confusion_matrix(y_test, y_pred_classes)

plt.figure(figsize=(10, 8))
sns.heatmap(cm, annot=True, fmt='d', cmap='Blues',
            xticklabels=CATEGORIES, yticklabels=CATEGORIES,
            square=True, linewidths=2)
plt.title('Confusion Matrix', fontsize=16, fontweight='bold')
plt.ylabel('True Label')
plt.xlabel('Predicted Label')
plt.tight_layout()
plt.savefig('confusion_matrix.png', dpi=150)
plt.show()

num_samples = 12
indices = np.random.choice(len(X_test), num_samples, replace=False)

fig, axes = plt.subplots(3, 4, figsize=(16, 12))
axes = axes.flatten()

for idx, sample_idx in enumerate(indices):
    img = X_test[sample_idx]
    true = CATEGORIES[y_test[sample_idx]]
    pred = CATEGORIES[y_pred_classes[sample_idx]]
    conf = y_pred[sample_idx][y_pred_classes[sample_idx]] * 100

    axes[idx].imshow(img)
    axes[idx].axis('off')

    color = 'green' if true == pred else 'red'
    title = f"True: {true}\nPred: {pred}\n{conf:.1f}%"
    axes[idx].set_title(title, fontsize=9, color=color, fontweight='bold')

plt.tight_layout()
plt.savefig('sample_predictions.png', dpi=150)
plt.show()

model.save('plant_disease_model_final.keras')
print(" Final model saved: plant_disease_model_final.keras")

print("="*80)
```

```
print("DOWNLOADING FILES")
print("="*80)

files_to_download = [
    'best_disease_model.keras',
    'plant_disease_model_final.keras',
    'disease_category_mapping.json',
    'training_history.png',
    'confusion_matrix.png',
    'sample_predictions.png',
    'classification_report.txt'
]

for filename in files_to_download:
    if os.path.exists(filename):
        files.download(filename)
        print(f"  Downloaded: {filename}")

print("="*80)
print("TRAINING SUMMARY")
print("="*80)
print(f"\nTotal Training Time: {phase1_time + phase2_time:.1f} minutes")
print(f"Final Test Accuracy: {test_accuracy*100:.2f}%")
print(f"\nFiles Created:")
print("  • best_disease_model.keras")
print("  • plant_disease_model_final.keras")
print("  • disease_category_mapping.json")
print("  • training_history.png")
print("  • confusion_matrix.png")
print("  • sample_predictions.png")
print("  • classification_report.txt")
print("="*80)


print("="*80)
print("TEST WITH YOUR OWN IMAGES")
print("="*80)

test_model = keras.models.load_model('best_disease_model.keras')

print("\nUpload test images:")
uploaded = files.upload()

if len(uploaded) > 0:
    for filename in uploaded.keys():
```

```
        img_array = np.frombuffer(uploaded[filename], dtype=np.uint8)
        img = cv2.imdecode(img_array, cv2.IMREAD_COLOR)
        img_rgb = cv2.cvtColor(img, cv2.COLOR_BGR2RGB)

        img_resized = cv2.resize(img_rgb, IMAGE_SIZE)
        img_normalized = img_resized / 255.0
        img_input = np.expand_dims(img_normalized, axis=0)

        prediction = test_model.predict(img_input, verbose=0)
        class_idx = np.argmax(prediction[0])
        confidence = prediction[0][class_idx] * 100
        disease = CATEGORIES[class_idx]

        plt.figure(figsize=(6, 6))
        plt.imshow(img_rgb)
        plt.title(f"{disease}\nConfidence: {confidence:.2f}%", fontsize=14, fontweight='bold')
        plt.axis('off')
        plt.show()

        print(f"\n{filename}:")
        print(f"  Disease: {disease}")
        print(f"  Confidence: {confidence:.2f}%")
        print(f"  Probabilities:")
        for i, cat in enumerate(CATEGORIES):
            print(f"    {cat}: {prediction[0][i]*100:.2f}%")

print("\n Testing complete!")
```

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LogBook of FYDP-P

Date/Time	Attendee	Summary of Meeting Minutes	Responsible	Comment by ATC
17/02/2025 (Monday)	1. Tuli 2. Samir 3. Sadman 4. Sazzadul	1. Need to narrow down the scope for the proposed and shortlist 2 ideas. 2. Need to finalize the problem statement. 3. Prepare a draft proposal note for both ideas before meeting the chair	Task 1: All Task 2: Sadman, Samir, Tuli	Task 1: Done
20/02/2025 (Thursday)	1. Tuli 2. Samir 3. Sadman	1. Shortlisted 1 problem 2. Needs more literature	Task 3: All Task 2: All	Shortlisted 2 ideas from 3 and will try to do the tasks before meeting the chair officially (20.02.2025)
	4. Sazzadul	review 3. Identifying the functional and non-functional requirements	Task 3: All	Task 2: Done Task 3: Partially done
23/02/2025 (Sunday)	1. Tuli 2. Samir 3. Sadman 4. Sazzadul	1. Based on the feedback, the functional and non-functional requirements should be corrected according to the user's needs. 2. Start working on the Specifications	Task 1: All Task 2: All	Task 1: Partially done Task 2: Partially done
27/03/2025 (Thursday)	1. Sadman 2. Sazzadul	1. Need to correct the requirements and specifications	Task 1: All	Task 1: Partially done

02/03/2025 (Sunday)	1. Tuli 2. Samir	1. Requirements and specifications are almost correct. Need some modification. 2. Prepare two different design approaches and block diagrams.	Task 1: All Task 2: Samir, Sadman, Tuli	Task 1: Done (After suggestions, changes were made for the concept note) Task 2: Need Modification.
09/03/2025 (Sunday)	1. Tuli 2. Samir 3. Sadman 4. Sazzadul	1. Specifications and non-functional requirements are alright. 2. Identifying accurate functional requirements. 3. Modification of the block diagram.	Task 2: All Task 3: Tuli, Samir, Sazzadul	
16/03/2025 (Sunday)	1. Tuli 2. Samir 3. Sazzadul	1. Along with adjusting the requirements, add more details to the specification. 2. Block diagram correction	Task 1: Samir, Sazzadul, Tuli Task 2: Sadman, Samir	Task 1: Done Task 2: Done
06/04/2025 (Sunday)	1. Tuli 2. Samir 3. Sazzadul	1. Work on the designs. 2. Add Constraints 3. Prepare for the progress presentation	Task 1: Tuli, Samir Task 2: Sazzadul, Tuli	Task 1: Partially Done Task 2: Partially Done. Need to add more constraints.
13/04/2025 (Sunday)	1. Tuli 2. Samir 3. Sadman 4. Sazzadul	1. Checked the Final concept note and made some corrections 2. Suggestions about the slide for the progress presentation.	Task 1: All Task 2: All	Task 1: Done Task 2: Done

17/04/2025 (Thursday)	1. Tuli 2. Samir 3. Sazzadul 4. Sadman	1. Attended the progress presentation.	Task 1: All	Task 1: Feedback on presentation
26/04/2025 (Sunday)	1. Tuli 2. Samir	Suggestions to complete the report for the project proposal	Task: All	Task: Feedback on the report
3/05/25 (Sunday)	1. Tuli 2. Samir 3. Sazzadul	Suggestions to complete the slide for the Final presentation	Task: All	Task: Done
5/05/25 (Monday)	1. Tuli 2. Samir 3. Sazzadul 4. Sadman	Mock presentations were given, and suggestions were given for some slide modifications.	Task: All	Task Done
7/05/25 (Wednesday)	1. Tuli 2. Samir 3. Sazzadul 4. Sadman	The day before the final presentation, Mock presentation 2 was given, and feedback from ATC was taken accordingly	N/A	Task: All done

LogBook of FYDP-D

Date/Time	Attended	Summary of Meeting	Responsible	Comment by ATC
22/06/2025 (Sunday)	Tuli Samir	1. Selecting some plants and their nutrient requirements 2. Learning the importance of rate calculation for the design part.	Task 1: All Task 2: Samir, Tuli	Do a literature review and incorporate the rating calculation.
29/06/2025 (Sunday)	Tuli Samir	1. Air flow and Oxygen flow rating calculation 2. 3D modelling of hydroponic tower	Task 1: Tuli, Samir Task 2: Samir, Sazzadul	Done Need more research, and 3D modeling is partially done
13/07/2025 (Sunday)	Tuli Samir	1. Along with the 3D modelling , Plant-wise grow LED rating calculation	Task 1: Samir, Sazaadul. Task 2: Tuli, Samir	Task 1: Partially done Task 2: done
17/07/2025 (Thursday)	Tuli Samir	Two or More solution block diagram for every sub - control system	Task : Tuli, Samir	Task : Done
20/07/2025 (Sunday)	Tuli Samir	Nothing much to specify only the feedback on block diagram	Task : Samir, Tuli	Task : Partially Done
Mid-Week	-	-	-	-
06/08/2025 (Wednesday)	Tuli Samir	Need to correct the sub - control system block diagrams	Task : Samir, Tuli	Task: Done.
10/08/2025 (Sunday)	Tuli Samir Sadman Sazzadul	Starting the Proteus Simulation of sub-control systems and Prepare for the progress presentation.	Task 1: Samir, Sadman Task 2: All	Task 1: Done Task 2: Done

12/08/2025 (Tuesday)	Tuli Samir	Work on the design's Overall block diagram for two solution	Task: Tuli, Samir	Task : Done
14/08/2025 (Thursday)	Tuli Samir Sadman Sazzadul	1. Attended the progress presentation	Task : All	Task : Feedback on presentation
19/08/2025 (Tuesday)	Tuli Samir	1. Working for proteus simulation. Suggested to complete the simulation for two design approaches' solution 2. Advised to work on Image processing	Task 1 : Sadman Task 2: Samir	Task 1: Partially done Task 2: Done
24/08/2025 (Sunday)	Tuli Samir Sadman Sazzadul	Advised to presenting the rating changes through MATLAB plots	Task: Samir, Tuli	Task: Done
25/08/25 (Monday)	Tuli Samir	Suggestions on graphs	Task: Samir, Tuli	Task: Done
26/08/25 (Tuesday)	Tuli Samir	Feedback on Final presentation slides (Calculation Part)	Task: Samir, Tuli	Task Done
27/08/25 (Wednesday)	Tuli Samir	Day before Final Presentation, feedback on presentation slides	Task All	Task: All done

LoogBook of FYDP-C

Date/Time	Attended	Summary of Meeting	Responsible	Comment by ATC
12/10/2025 (Sunday)	Samir Sadman Sazzadul	1. Component purchasing 2. Sensor calibration	Task 1: Samir, Sazzadul Task 2: All	Task 1: Done Task 2: Partially done.
19/10/2025 (Sunday)	Tuli Samir Sadman Sazzadul	1. Along with the sensor calibration , Structural frame build-up	Task: All	Done
26/10/2025 (Sunday)	Tuli Samir Sadman Sazzadul	1. App integration 2. Sub system hardware set up.	Task 1: Samir. Task 2: All	Task 1: Partially done Task 2: Partially done
6/11/2025 (Thursday)	Samir Sadman Sazzadul	Working on sub system build up and App integration parallely	Task 1: All Task 2: Samir	Suggestions for app improvements.
17/11/2025 (Monday)	Tuli Samir Sadman Sazzadul	4 sub system build ups were done , working on integrating the sub-systems together. Suggested to working on plants	Task : All	N/A
24/11/2025 (Monday)	Tuli Samir Sadman Sazzadul	Task : Alongside sub-system hardware assembly, plants were selected and seeds sown for the project prototype. Task : Work on PCB design	Task 1: All Task 2: Tuli Task 3: Sadman	N/A

09/12/2025 (Wednesday)	Tuli Samir	Task1 : All sub system implementation in the structure. Task 2: Seeds germination failed. So, suggested to Transfer the soil-germinated plant to the hydroponic setup and observed its survival	Task 1: All Task 2: Tuli	Task 1: Partially Done Task 2: Done
11/12/2025 (Thursday)	Tuli Samir Sadman Sazzadul	Suggested to collect the Data of every steps	Task: All	Task: Done
14/12/2025 (Sunday)	Tuli Samir Sadman Sazzadul	Progress presentation	Task: All	Task: Feedback on presentation
21/12/2025 (Wednesday)	Tuli Samir Sadman Sazzadul	Working on veroboard circuit soldering	Task : Sazzadul, Samir	N/A
25/12/2025 (Sunday)	Tuli Samir Sadman Sazzadul	Feedback on system	N/A	N/A
28/12/2025 (wednesday)	Tuli Samir Sadman Sazzadul	Advised on system Data	Task: All	Task: Done
04/ 01/ 26 (Sunday)	Tuli Samir Sadman Sazzadul	Feedback on Poster	Task: All	Task Done
05/01/26 (Monday)	Tuli Samir Sadman Sazzadul	Final Poster Presentation and showcase	Task All	Task: All done