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IoT based Customizable Vertical Farming Solution for Palestinian Plants

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2022-2023

ACKNOWLEDGEMENTS

In the name of “Allah”, the most beneficent and merciful who gives us strength, knowledge and helped us to get through this project.

We would like to express our sincere gratitude to several individuals and organizations for supporting us throughout our Graduation project. First, we wish to express our sincere gratitude to our supervisors, Dr. Eng. Sami Salamin and Dr. Eng. Mousa Farajallah, for their enthusiasm, patience, insightful comments, helpful information, practical advice and unceasing ideas that have helped us tremendously at all times in our research and writing of this document. Their immense knowledge, profound experience and professional expertise have enabled us to complete this document successfully. Without their support and guidance, this project would not have been possible. We could not have imagined having better supervisors in our study.

We would like to take this opportunity to acknowledge and thank our families and friends for their support and encouragement throughout this journey. Their love and guidance have been a constant source of motivation and strength, and we are truly grateful to have them in our lives. Without their unwavering support, we would not have been able to accomplish all that we have. We are deeply grateful to each and every one of them, and we will always be thankful for the role they have played in our lives. Thank you, from the bottom of our hearts.

Abstract

Water and land are both considered limited resources. A new farming technique was introduced to solve this issue which is Vertical Farming. This technique is one of the best solutions because it improves global food security and addresses environmental degradation issues. Moreover, no harvest would be harmed by a severe weather event, and it can quickly minimize the cooling and heating of water by indoor temperature.

Manual controlling and monitoring processes in this technique are complicated, and the labor cost is expensive. This project aims to save users efforts by affording practical controlling and monitoring tools and reduce the cost by providing users with a customizable module for different vertical farm usages and scales. Also, it reduces and nearly eliminates manual labor works by affording an IoT based monitoring and controlling Vertical Hydroponic Farm with a database that will contain all needed information for the controlling process. Finally, the system offers the users real-time monitoring of the system's main parameters and the ability to control the system remotely via the web page. Moreover, the system provides information about plants which could be used by plant researchers to understand how different parameters affect plant growth. The system is easy to use that makes normal people who don't have agriculture knowledge able to use the system for offering house needs of different kinds of plants.

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Introduction

Overview

This chapter contain seven sections, the first section is about the motivations and importance of our project. It explains the reasons that make us believe in this project. The second section will be about the problem statement which describes the problem that we aim to solve. The third section will provide a short description of our project. The fourth section contains the objectives of our project. The fifth section represents the system requirement. The sixth section will provide the system limitations. The seventh section represents the project schedule.

1.1. Project motivation and importance

Due to rising population and peak country development, alternative options for feeding the masses while minimizing land use are being sought. Water and land are both considered finite resources. As a result, farmland must be reduced in order to provide more land for housing and building. On the other hand, Farmland is essential for producing oxygen and sustaining food supplements all over the world. Vertical farming is one of the most recent technologies introduced in the agricultural field to address the issue of land use [1].

Vertical farming is one of the best alternatives. It has the potential to improve global food security while also addressing environmental degradation issues. No harvest would be harmed by a severe weather event. It can easily minimize cooling and heating water by indoor temperature. It contributes to poverty reduction, food safety, and human well-being. Vertical gardening's effectiveness is determined by food demand and supply, urban population and density, technological advancement, water and energy supply, and weather conditions [2].

1.2. Problem Statement

Vertical farming is one of the best solutions for decreasing farming spaces problem. However, it's hard for farmers to monitor and control vertical farms manually, also vertical farms need continuous monitoring for system main parameters by an expert, which increases the cost for them also increases failure percentage, which doesn't encourage farmers to purchase it.

Project main objective is to design an IoT based vertical farm that can be monitored and controlled easily by farmers, the proposed solution will decrease cost as it has a programmed system that stores the suitable conditions for each plant, the system will be controlled depending on it automatically. Also it enables the users to easily control and monitor system parameters via web application so it will be easy for researchers and farmers to use. Moreover, study different conditions effects on specific crops.

1.3. Short Description of our project

The project's aim is to design a dedicated, customizable, expandable and smart vertical farm module. Such a module uses state-of-the-art technologies to control and monitor a set of parameters which is (pH, TDS, Humidity, temperature, water temperature and light) which is essential for plant growing and quality based on well-examined and defined conditions using the IOT platform.

The system will be implemented using a number of sensors and pumps that are interfaced to a microcontroller, the sensor will measure the pH, TDS and water temperature for the nutrient solution in the nutrient solution tank and the humidity, temperature and light for the plant. The sensor will collect data and send it to a microcontroller, the microcontroller will send the data to a gateway using MQTT. There is optimal data for each plant in the database. The user can choose a crop to plant, this data will be installed on the gateway, then the gateway will make the correct decision based on optimal data. The system stores the collected data in the database and represent it in a web application.

1.4. Project Objectives

The main objectives of this system are:

- Designing and implementing vertical farming modules that can be easily used and monitored by the end-user.

- Creating a database of Palestinian plants that our module uses to monitor and adapt control for each plant offering the optimal growing conditions.

- Our system will provide various configurable options to meet users' needs and demands, e.g., different product quality and tastes.

- Providing cloud computing, by offering the end-user the ability to online monitor and control the module conditions easily and effectively.

1.5. System requirements

The system requirements can be summarized as:

1.5.1. Functional requirements

- The system should be able to collect data such as pH, TDS, Humidity, temperature, water temperature and light.
- The user can choose the mode of the system to be automated mode or user mode.
- Allow user monitor system parameters such as pH, TDS, Humidity, temperature, water temperature and light via webpage.
- Automatically control system parameters according to predefined thresholds.
- The user can control the system via webpage.

1.5.2. Non-Functional requirements

- Accuracy: Ensuring that the system has high accuracy in detecting and modifying readings.
- Usability: The extent of using the system and the application should be easy and understandable for users, depending on the components of the system and the technologies used in it.
- Scalability: The ability of the system to deal with the increasing number of vertical farming units without reducing the overall quality of the service provided to any vertical farm unit.
- Maintainability: All components are easily serviceable and replaceable.
- Reliability: The system is intended function to do all it's under stated conditions without failure for a given period of time.

1.6. System limitation

System limitation may be having influence on the system performance, or can affect the system implementation, we explained some of limitation that we faced throughout system implementation:

1. The cost limitation may have the biggest impact on the project implementation.
2. Electrical usage in the system, it may be related to the cost limitation, also it depends on the system design manner.
3. Type and amount of organisms(plants) used in the system, because this will have an impact on implementation of the system.
4. Availability of some important sensors used in the system in the markets, and ability to purchase these sensors because of the very high cost of some sensors.
5. Ability to find the suitable alternative components and solutions for the system when not available.
6. Permanent need for the internet.

1.7. Project Schedule

Table 1 Project Schedule

Task	Duration(weeks)												
	Second Semester							First Semester					
Planning													
Project requirement													
Analyzing and design													
Project development													
Project test and maintenance													

1.8. Report Outline

The rest of the report is organized as follows: Chapter 2 presents a theoretical background of the project. Chapter 3 introduces the system design. Chapter 4 presents the implementation, testing, the result and discussion. The conclusion is presented in chapter 5.

Theoretical Background

Overview

This chapter will describe the theoretical background and the literature review of the project, and also presents a list of hardware components which will be used in system design and implementation.

2.1. Vertical farming

2.1.1. Definition of vertical farming

Vertical farming is one of the newest concepts in urban farming, gaining increased popularity worldwide due to the increasing population, accompanied by substantial growth in food demand. In addition, farming spaces are decreasing as long as the city's areas are expanding and shared resources become a problem [3]. In brief, vertical farming refers to the production of plants on vertically inclined surfaces stacked in multiple layers rather than farming on one level. Using vertical farming, you are able to produce food without human intervention, as it can be done in a controlled indoor environment [4].

2.1.2 Applied systems for vertical farming:

Vertical farming uses the three most widely applied systems, which are vertical home farms, in-store vertical farms and indoor vertical farms, all of which can be used to grow crops. Firstly, vertical home farms are smaller units for household consumption that can be controlled. Following that, there are the in-store vertical farms, which are found in grocery stores and allow customers to both inspect and purchase directly in the store. The indoor vertical farms are larger farms the consumer usually does not have access to, while consumer interaction is only available when they are met with the packaged product [4].

All types of crops could theoretically grow inside vertical farming. However, there is a limited number of cultivated cultivars that are most suitable for indoor, mainly crops that are small in height, planted in height densities and have a small growth cycle [4].

2.1.3. Agriculture techniques of vertical farming

In VF, there are mainly two different agriculture techniques that are commonly used: hydroponics and aeroponics, which utilize nutrient-rich water instead of soil for plant nourishment. Thus, VF does not require fertile land in order to be effective, while it uses less water and occupies less space compared to the conventional agricultural systems. Furthermore, VF is able to provide all-year-round production, independent of external weather conditions, since the entire process is in a closed loop with complete environmental control [4].

Hydroponics is an approach to developing vegetation barring soil. Instead of having their roots supported and nourished by soil, the plant is often irrigated and supported with the aid of an inert developing medium like coco pan and is fed through nutrient-rich water that is indispensable to maintain plant growth. Hydroponic structures use 60–70% much less water than regular conventional agriculture [5]. In this method, the plant roots are immersed in the mixture of essential nutrients of the plant instead of the soil, in which case the nutrients have to be mixed in the right proportions.

Hydroponic have become so popular today since they enjoy certain benefits over traditional methods of farming. According to experience, plants that have grown with the help of hydroponics proved to grow faster. They get ripe in a shorter time and yield ten times more crops than soil-based cultivation. Moreover, they contain more nutrients than crops produced in soil [6].

Aeroponics is a method of growing plants without soil. Instead, roots are suspended in the air and irrigated with a nutrient-dense mist. This differs from hydroponic systems where plant roots are regularly submerged in a nutrient-rich solution. In aeroponics, the roots have greater access to oxygen, which results in healthier plant rootstock and significantly faster crop growth rates and increased yield [7].

Plants sustain themselves by a process called photosynthesis. Plants absorb sunlight through chlorophyll (a green pigment in their leaves). The light's energy allows them to split water molecules they have absorbed through their roots. The hydrogen molecules combine with carbon dioxide to produce carbohydrates; which plants use to nourish themselves. Oxygen is then released into the atmosphere, which plays an important role in maintaining the habitability of our planet. Plants do not require soil to photosynthesize. They need the soil to supply them with water and nutrients. Nutrients can be dissolved in water and applied directly in the root zone of plants through flooding, misting, or immersion. Hydroponic innovations have shown to be more efficient and versatile than traditional irrigation in terms of direct exposure to nutrient-filled water [8].

2.1.4 IoT Impact on Vertical Farming

IoT is a system where some devices can be connected through the Internet without human assistance and make decisions by analyzing the necessary data through intercommunication. The Internet of things facilitates several advantages in our daily lives which makes our activities easier. Firstly, increase the efficient resource utilization as well as monitor resources [9]. Secondly, as the devices of IoT interact and communicate with each other and do a lot of tasks for us, then they minimize the human effort, then it saves time [10]. Finally, IoT allows users to access real-time information about their devices from any part of the world [11]. By implementing IoT, many activities can be done in VF without human intervention, from monitoring and analyzing data using IoT to setting the right time to plant crop seedlings, determine soil moisture, provide irrigation, determine the right amount of nutrients, apply fertilizers, and harvest crops [12]. Also, it will allow for efficient crop growth and it can determine the right growing conditions for crops smartly, it would serve as a fully automated, scalable, sustainable farming system that can be easily maintained [12].

2.2. Literature Review

Hydroponic farming is not a new farming technique at all, and a lot of pervious projects tried to use IoT and Automatic control to reduce costs and to improve productivity as Idees and Arab. (2022) [13] implemented a Smart Aquaponics Monitoring System using IoT, the system contains 3 main parts hydroponic farm, fish tank and biofilter, the water full of nutrient is taken from fish tank to biofilter to convert into suitable form to use in hydroponic part, they use to monitor main parameter in biofilter tank such as pH, temperature, total dissolved solid, humidity and water level using blynk IoT platform with mobile app. However, the implemented system lacks a major parameter monitoring which is EC, EC is the measurement of nutrient in solution, moreover the system is controlled manually and they use leaf color as indicator of nutrient lack in the solution, so they use to manually add nutrients into. Chowdary et al (2020) [14] implemented an IoT based Automatic Indoor hydroponic vertical farm. They use to monitor nutrient solution pH, electrical conductivity and temperature, also system water flow, water level, humidity, temperature and electrical consumption for each component using Thingspeak IoT platform with web page and mobile app. Moreover, they use to control water level, nutrient and pH level in nutrient solution automatically depending on sensors measurement and pre-defined thresholds must be installed for each different crop, the system has been tested with different crops. However, system controlling processes can't be done remotely using IoT apps. Ruscio et al. (2019) [15] Implemented a low-cost raspberry-pi based hydroponic vertical farm monitoring system with camera to capture pictures and sensors to collect data about the system main parameter pH, EC …etc. The data collected is monitored by sending it into remote database (SQL) this database will be central access point so the user can access data with webpage that will display the data for user anytime and anywhere using any web browser, the data displayed will be last hour sensor read for each parameter and it can be updated to the current read if wanted, the pictures captured is saved in local database and monitored by user to know plant status. However, the system is controlled manually neither automatically nor using the IoT platform. Perwiratama et al. (2019) [16] proposed a smart hydroponic farm with IoT-based climate and nutrient manipulation system, it composed of sensors that collect data about water level, water flow, humidity, pH, nutrient level and light. The microcontroller sends collected data to main computer which is responsible of taking decision about controlling those parameters by stop or adding nutrient, open roof if more light is needed, add water if the level is below defined threshold, increase pH or decrease it and control humidity depending on pre-defined threshold and proposed algorithm to control the system into optimal environment. However, end users can't monitor those parameters remotely also they can’t control with IoT apps. (2018) [17] Implement a system that monitoring the Health status of the plants using a Computerized system, the system consists of two part, the first one which depend on camera that take image then the computer process it and classified the diseases into one of three mildew type also give an approximate proportion of the type of disease. The second one examine the humidity and temperature for the crop environment. However, they don’t monitor any another parameters and don’t control any of them and don’t use the IOT platform. (2019) [18] Implemented a robot, which is capable of planting seeds and automating irrigation. The system work in two stages, the first stage will plant the seeds in specific locations using an air pump. The second stage the soil moisture sensor will read the humidity of soil, then decide when watering is needed and the specific amount of water required for each plant, using the water pump to water the plants. They only monitor and control the humidity but they don’t do that for the other parameters and they don’t use IOT platform.

The aim in our project is to design a vertical farming system based on the IoT concept. that can monitor and control system parameters automatically. Our system will monitor pH, nutrient level, water level, water temperature, humidity, light intensity, and temperature. We will make a database for Palestinian plants that we will depend on it for controlling our system. All previous projects have focused on goals but none of them achieve full IoT based hydroponic system that covers our proposed goals, and none of them attempt to reduce the electrical cost of the system by implemented solar panel system, there is no such project in Palestine that does monitor and control system parameter using IoT, moreover none of the project made database to use it in controlling operation.

2.3. Project requirements and components

This section describes the main hardware and software components that are required for our system. In addition, we add a brief justification for certain choices.

2.3.1. Hardware Requirements

In this section, the hardware components that will be used in our project are shown.

2.3.1.1 Microcontroller

In our system we propose using the IoT platform to monitor hydroponic nutrient solution parameters such as pH level and Electrical Conductivity, so we need a controller that has a Wi-Fi connection feature. We aim to maintain 6 sensors so we need a number of pins to cover system needs. Also, we need to store information about optimal parameters that will be compared with the current sensor read, so we need SRAM suitable for this amount of information. We need a flash memory with size to store control and monitor programs that will run on the microcontroller and we want to purchase a cost-effective microcontroller so the whole product(module) won't be so expensive to buy.

In Table 2 we mention some of the microcontrollers available in the Palestinian market and we make a comparison between them to choose the best choice for our project [19].

Table 2 comparison between microcontrollers

	ESP32 DIV	Arduino Mega 2560	Arduino Uno R3	Arduino MKR
Price point	$10.99	$38.93	$19.99-$23.00	$24.24 - $71.00
Microcontroller	Tensilica Xtensa LX6	ATMEGA2 560	ATmega328P	SAMD21 Cortex-M0+
Clock speed	Up to 240 MHz	16 MHz	16 MHz	32.769KHz (RTC); 48MHz
Flash memory	4 MB	256 KB	32 KB	256 KB

EEPROM	4 KB	4 KB	1 KB	None
SRAM	320 KB	8 KB	2 KB	32 KB
Digital I/O pins	39	54	14	22
PWM Digital I/O pins	16	12	6	12
Analog I/O pins	17	16	6	8
Shield compatibility	No	Yes	Yes	Specialty shields or use MKR2UNO Board
Wireless connectivity	Wi-Fi, Bluetooth	No (can added by using shields)	No (can added by using shields)	Wi-Fi, GSM, Lo-Ra, Sigfox

We used ESP32 because it contains a self-contained Wi-Fi connection module. Having an ESP32 with its built-in module is better on the economic scale than an Arduino with a Wi-Fi module add-on. At the processing scale, the 160 or 240 MHz is an advantage over the 16 MHz provided by the Arduino and this processing power is sufficient for our work [20].

2.3.1.2 Vertical farming structure and Essential Components

Various vertical hydroponic systems such as A-frame, Zig-zag, vertical hydroponic tower, Zip Grow tower and vertical Nutrient Film Technique (NFT) system were available. Amongst the various vertical hydroponic systems available, the concept and design of the vertical NFT system will be used in this project. It is due to the simplicity in the design, ease in its assembly, easy configurability of the LED, high productivity of plants within a small place, and the strong supporting system that holds the structure [21].

In this project, we made a vertical NFT system, which consists of two shelves. Each shelf is holding two polyvinyl chloride (PVC) pipes, and each pipe consists of four planting holes. The dimensions of the vertical NFT hydroponic systems are 92 cm (L) × 84 cm (W) × 92 cm (H) as shown in Figure 1:

Figure 1 Plants frame

2.3.1.2.1. Sensors

The sensors proposed in the module have been selected according following criteria:

- Being real time sensors by having a small response time, so they reflect changes in module parameters without big delay, it’s important in module monitoring and controlling.
- Giving right and precise reading for module parameters by having small error rates.
- Covering the ranges of reading that may appear in the system.

- Being compatible with the chosen microcontroller.
- Being compatible with both indoor and outdoor environments without having any difference in reading.
- Being compatible with all temperature and pH ranges that may appear in the system.
- having acceptable cost to promote end users purchase our system.

1- Humidity sensor and Air temperature sensor

Imbalanced level of humidity will produce an ill and low-quality crop, also a lower crop yields, each plant species has a different humidity level that it grows in. Moreover, we must maintain the temperature of the air in order to maintain the growth of the plants because the temperature has a direct effect on it.

DHT11 sensor was used to measures both humidity and air temperature for our proposed module, it’s a real time sensor with 0.5Hz sampling rate it can measure all possible humidity and temperature level that may appear in the system 0-100% humidity readings with 2-5% accuracy and -40 to 80°C temperature readings ±0.5°C accuracy, it’s a low-cost sensor and has a low power consumption 3-5V power and I/O, with a small size, which is good for IoT application [22].

The connection of DHT11 with ESP32 is shown in Figure 2:

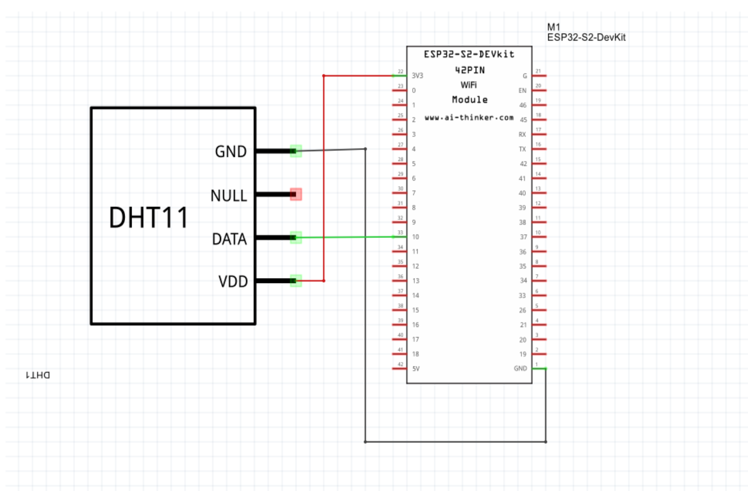


Figure 2 The connection of DHT22 with ESP32

2- *Light sensor*

We need sensor to measure the light intensity of the system, Table 3 shows the different options of the light sensor.

Table 3 LDR sensor versus BH1750

Sensor	Specifications
LDR	1. Cheaper 2.Less precision
BH1750	1.Expensive 2.High precision

The light-dependent resistor was used in our project that has a high sensitivity (due to the large area it can cover), easy employment, low cost, high light-dark resistance ratio, and the BH1750 not available in the market [23].

The LDR sensor is very responsive to light. When the light is stronger, then the resistance is lower which means, when the light intensity increases then the value of resistance for the LDR will be decreased drastically to below 1K. Connection of LDR with ESP32 is shown in Figure 3:

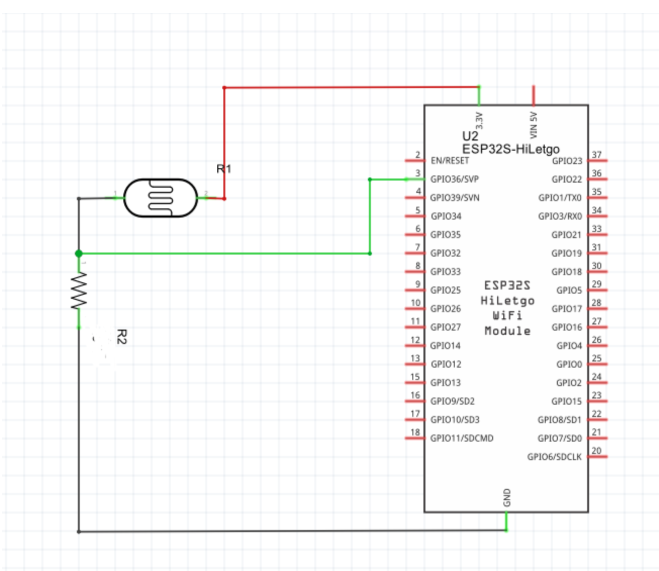


Figure 3 The connection of LDR with ESP32

2.3.1.2.2. Artificial light

Using artificial light in growing crops is a revolutionary scientific farm practice. At the beginning, vertical farms used fluorescent lights to support the crop growth. However, with the development of LED light technology, fluorescent lights are slowly being replaced by the new, energy-efficient bulbs. The best practice is to use the purple lights, i.e., the combination of red and blue LED lights [24].

Purple LEDs are more effective than any other artificial light source used in vertical farming. It provides the plants with wavelengths needed for photosynthesis, growth, and flower formation. For growing flowering plants, we need a high intensity of red and blue lights, while non-flowering plants need a high intensity of red light only [25].

2.3.1.3. Nutrients solution control components

2.3.1.3.1. Nutrients container

A nutrient container is used to reserve the nutrient solution that would be supplied to the vertical NFT system. Since it is a closed system, all the excess solution would return to it. The ideal container should be made from plastic material, using metal containers is prohibited as they are reactive materials. Moreover, it should block the light to pass through it to prevent the formation of algae [21]. The size of the container should be big enough to hold the right amount of the solution, and this amount is decided according to the number of plants in the system. Number of plants between 40–50 should use a minimum of 5 gallons (18.9271 L), by adding another 20–25 plants, the amount would be increased by 1 gallon (3.78541 L) [21]. The vertical NFT system has two pipes distributed on three shelves and each pipe has nine holes to grow the plants, and the number of plants in the system can be calculated:

$$number\ of\ plants = number\ of\ pipes \times number\ of\ shelves \times number\ of\ holes \quad (1)$$

So, the number of plants that can be grown in this system is 2 × 2 × 4 = 16. 16 plants would use 1.6 gallons of water (six L), The amount of nutrient solution needed to be inside the container was almost equal to six L. However, since the NFT system would have 30% losses of water due to the consumption of plants and water evaporation from heat, 30% of six L is equal to two L, for that an extra L was added to compensate for any water losses, which gave in total eight L inside the container. For this design, the container size was equal to 18 L in order to leave some space on the top of the container for the exposure to air. So, we should choose a container that has a capacity of 18 L.

2.3.1.3.2. Nutrient solution tank sensors

1- pH sensor

This sensor is used to measure pH in water as different level of pH in water will affect plant ability to absorb needed nutrient from nutrient solution, it's crucial in hydroponic system to control pH level, pH is the scale of acidity or alkalinity in solution, it indicates hydrogen ions in the solution, when this ion percentage increases the solution become more acidic, and when it decreases the solution will become a basic(alkaline) solution, this scale for pH is between (1-14), the need for adjusting pH to the optimal range in the solution is enabling plants to absorb the needed nutrients from solution[21], as there is a relationship between plants nutrient absorbing from solution and pH level, the following table indicates optimal pH level for different crops:

Table 4 pH level for different plants

Plant	Needed pH level
Parsley	5.5-7.0
Strawberry	4.0-6.0
Pea	6.0-7.0
Zucchini	6.0

When the PH level is greater than the appropriate range we need to:

- Increase the amount of nutrients added to the solution taking into account appropriate nutrient range for each crop.
- Use phosphoric acid or nitric acid with small concentrations to modify acidic level.

When the PH level is smaller than the appropriate range we need to:

- Increase water level.
- Decrease solution temperature to the optimal level (20-25)℃.
- Use calcium carbonate or potassium carbonate with small concentrations to modify acidic level.

Atlas Scientific pH Kit 0-14 pH sensor was used as it is a real time sensor which is an advantage for our IoT monitoring, it has a small response time 95% in 1s, it has a very small error rate as the accuracy is +/– 0.002 and the resolution is +/- 0.001 it measures all possible different value for pH as its measuring range is 0− 14, it has a wide temperature range to work in which is -5− 99 °C, it could be put to measure solution pH in Solution Tanks till 70m depth, it has a good life as its Life expectancy is about ~2.5 Years +. Finally, good to know that one of the proposed and tested applications for this sensor is Hydroponic farming [26].

The connection of pH with ESP32 is shown in Figure 4.

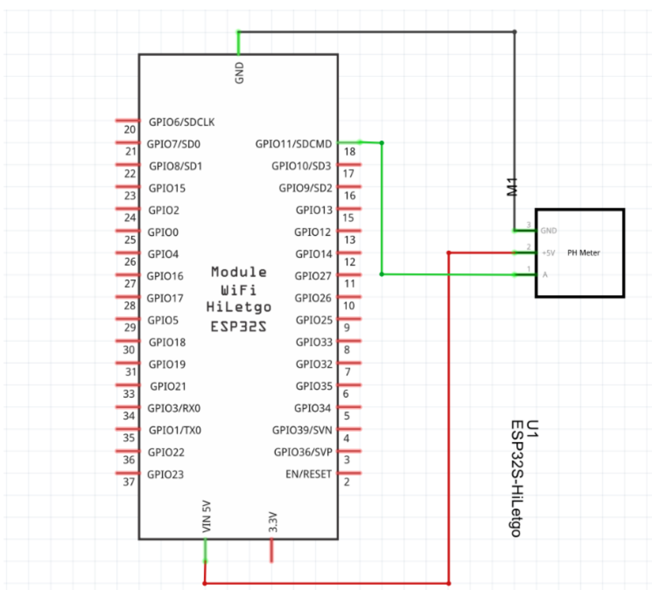


Figure 4 The connection of pH with ESP32

2-Total Dissolved Solids sensor

TDS indicates the percentage of salts dissolved in the hydroponic solution, the higher of observed TDS value indicates high percentage of dissolved salts in solution and vice versa.

TDS value in hydroponic solution must be adjusted to the optimal value for the plant, so that plant could absorb salts and nutrients from the solution with appropriate amounts needed by this plant taking into account that each plant has a different optimal TDS value [21].

To adapt TDS value in solution.

First If the observed value is lower than the optimal value, we should:

- Increase the quantity of nutrients and fertilizers.
- Monitor the pH value of the solution (as the salt dissolved in the water rises the pH level rises).

If the observed value **exceeds** the optimal value, we should:

- Stop any addition of nutrients and fertilizers.
- Add water to the solution till allowed level.
- Monitor the pH value of the solution.

TDS Meter Probe Water Quality Monitoring V1 from amazon was purchased for project, the sensor has Input Voltage: DC 3.3 ~ 5.5V, Output Voltage: 0 ~ 2.3V, TDS Measurement Range: 0 ~ 1000 ppm and TDS Measurement Accuracy: ± 10% F.S. (25 ℃) its suitable for measurement range we need also have error range acceptable to system requirement [27].

We can use EC sensor from Atlas instead of TDS which do the same work but it gives more precise readings, it has smaller error rates but it has the problem of staying long time in water as letting it in water more than ten minutes will cause a problem to the sensor readings later and it will be damaged [28].

The connection of TDS with ESP32 is shown in Figure 5.

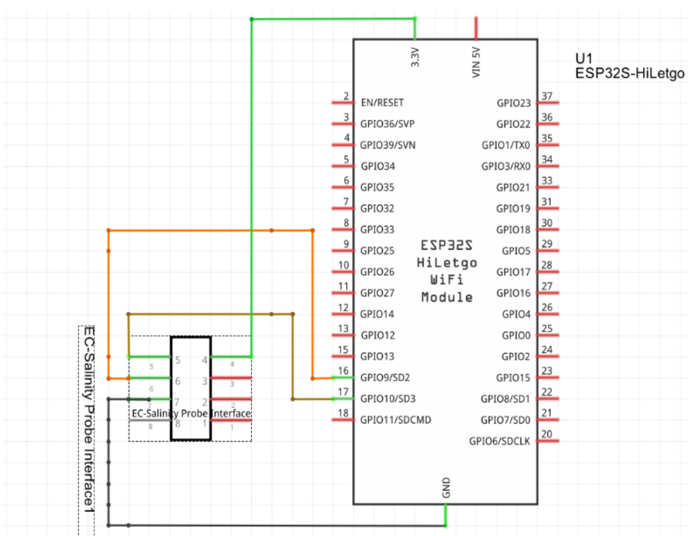


Figure 5 The connection of TDS with ESP32

3- Water temperature sensor

The temperature of the nutrient solution influences the absorption of water and nutrients in plants, since the root has a direct link to the solution. In addition, the temperature of the solution significantly affects the properties and behavior of the solution as:

- Raising the temperature reduces the amount of dissolved oxygen in the solution.
- Increasing temperature will limit calcium uptake in plants.
- More stable and appropriate weather will improve crop productivity.

Atlas Gravity™ Analog Temperature Kit was used as it is a real time sensor measure the temperature of nutrition solution in the nutrient container which is an advantage for our IoT monitoring, it has a small response 90% in 8s, it has a small error rate as the accuracy is +/- (0.3 + (0.005*t)), it measures all possible different value for temperature may occur and rise in our module as its measuring range is 5 − 200,000 µS/cm, it has a wide temperature range to work in which is -50˚C to 200˚C, it has a good life as its Life expectancy is about 15 years. Finally, good to know that one of the proposed and tested applications for this sensor is Hydroponic farming [29].

The connection of the water temperature sensor with ESP32 is shown in Figure 6.

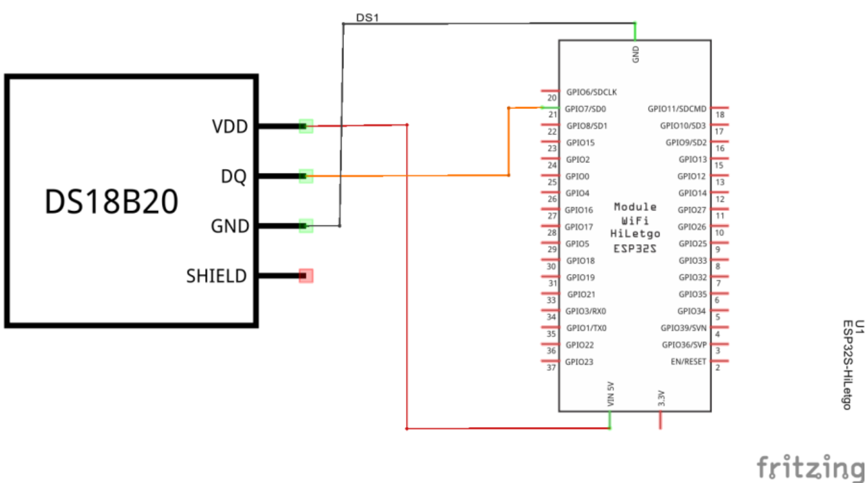


Figure 6 water temperature sensor connected to ESP32

2.3.1.3.3. Relay

Relays are used where it is necessary to control a circuit by an independent low-power signal, or where several circuits must be controlled by one signal. The main advantage of relay with auto coupler is the high electrical isolation between input and output terminals that allow relatively small digital signals to control relatively large AC voltage, power and current. And there is LED for indication for the power and output status [30].

2.3.1.3.4. Dosing pump

Whenever the amount of nutrients in nutrient solution decreases, fertilizer full of nutrients must be added, the quantity to be added is a small quantity, so the required pump should meet this requirement, the same apply for pH up and pH down so three pumps from amazon were chosen. They can pump 4.8 Liter Per Hour. One for the nutrients, and the other two pumps for pH Up and down. The dosing pumps were not turned ON initially during system initialization rather when the system was running for a while (after first 30 min), the TDS and pH level were evaluated and based on that 5 mL of nutrient and pH up/down were injected in the system in each injection, however after each injection, the system waited for 10 min before next injection as it takes time to stabilize the TDS and pH of the system. During this period, the dosing pumps were not activated based on the level of TDS and ph.

2.3.1.3.5. Air Pump

As the roots are directly linked to the nutrient solution, it’s very important that this solution provide enough oxygen to those roots, as it’s the only way the root get them for their healthy grow, when the amount of oxygen decreases the growing rate and process will be weaker [31], If oxygen dropped below 3 or 4 mg per L, that will prevent root growth also it will change to the brown color, this will be the first symptom of oxygen lack [31]. HITOP Dual Outlet Aquarium Air Pump Aerator was chosen as an air pump to provide plant roots with required oxygen, it is a super silent aquarium air pump and it has a long service life, also it has a lower failure rate, it can be used for water tanks with a capacity range of 20 to 100 gallon [32].

2.3.1.4. IoT gateway

IoT gateways bridge the gap between field control/sensor nodes and the client cloud, allowing field data to be used for manufacturing process optimization, remote management, and preventative maintenance, IoT gateway can provide additional security for the IoT network and the data it transports, also it only sends the necessary filtered data to the cloud. Raspberry Pi 3 Model B+ was chosen as IoT gateway [33].

2.3.2. Software components

2.3.2.1. Software IDEs

2.3.2.1.1. Arduino IDE

The Arduino Integrated Development Environment - or Arduino Software (IDE) - makes it is easy to write code and upload it to the board. This software can be used with ESP32 boards. IDE Contains a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions, and a series of menus. It connects to the Arduino and Genuine hardware to upload programs and communicate with them.

2.3.2.1.2. VS Code

VS code was used to develop webpage code, VS code is a source-code editor made by Microsoft with the Electron Framework, for Windows, Linux and macOS. Features include support for debugging, syntax highlighting, intelligent code completion, snippets, code refactoring, and embedded Git.

2.3.2.1.2. Python PyCharm

PyCharm was used to develop Raspberry PI code which was used as a gateway, PyCharm is a dedicated Python Integrated Development Environment (IDE) providing a wide range of essential tools for Python developers, tightly integrated to create a convenient environment for productive Python, web, and data science development.

2.3.2.2. Software Languages

2.3.2.2.a Hardware

1. *Python*

   Python used for developing Raspberry PI controller code, Python is an interpreted, object-oriented, high-level programming language with dynamic semantics. Its high-level built in data structures, combined with dynamic typing and dynamic binding, make it very attractive for Rapid Application Development, as well as for use as a scripting or glue language to connect existing components together.

2. *C*

   The C programming language is a procedural and general-purpose language that provides low-level access to system memory. A program written in C must be run through a C compiler to convert it into an executable that a computer can run.

2.3.2.2.b webpage

1. *JavaScript, HTML and CSS*

   HTML, JavaScript and CSS were used to develop webpage, the HTML was used to write webpage structure, CSS was used for styling and JavaScript for functionality of the web page.

2.3.2.3. Cloud services

2.3.2.3.1. HiveMQ broker

HiveMQ is an MQTT broker and a client based messaging platform which uses MQTT protocol for fast, reliable and efficient bi-directional data transfer to and from IoT devices.
It was used to push of data between our microcontrollers themselves and microcontrollers with web application.

2.3.2.3.2. Real time database firebase

A remote database is to be used for storing all needed information about plants and each plant optimal grow environment and parameters such as: pH, TDS, Temperature, Humidity, Light Intensity, when start growing a crop in the module all crop information will be installed on the

MCU to use in automated controlling process, Firestore Google database was chosen, since it is scalable, reliable, available and easy to use database.

2.3.2.4. Type of software application

A web application is developed with the aim of allowing users to monitor and control hardware part of the system, using web application will give the users the ability to monitor and control system more flexibility for both small and large systems, compared to mobile phone applications which makes it limited to monitor and control small systems only.

2.3.2.5 MQTT: The Standard for IoT Messaging

MQTT (MQ Telemetry Transport) is a lightweight, publish-subscribe network protocol that transports messages between devices. The protocol usually runs over TCP/IP, however, any network protocol that provides ordered, lossless, bi-directional connections can support MQTT. It is designed for connections with remote locations where resource constraints exist or the bandwidth is limited [34].

2.4 Summary

The theoretical background concept, literature review, hardware and software component are introduced in this chapter.

Design chapter

3.1. Overview

In this chapter, we will cover the overall design of the system and the integration of its components, showing the block diagram, and schematic diagram, as well as details about the hardware and software components, we will use.

3.2. System Block Diagram

Our proposed IoT based automated vertical hydroponic farm system consists of four parts: vertical farm unit, nutrients solution control, temperature control unit, IoT platform and online database. The overall block diagram is shown in Figure 7. All the sensors connected to the vertical hydroponic system can be monitored from the IoT platform on any smart device. Each part of the block diagram will be discussed in detail in this chapter.

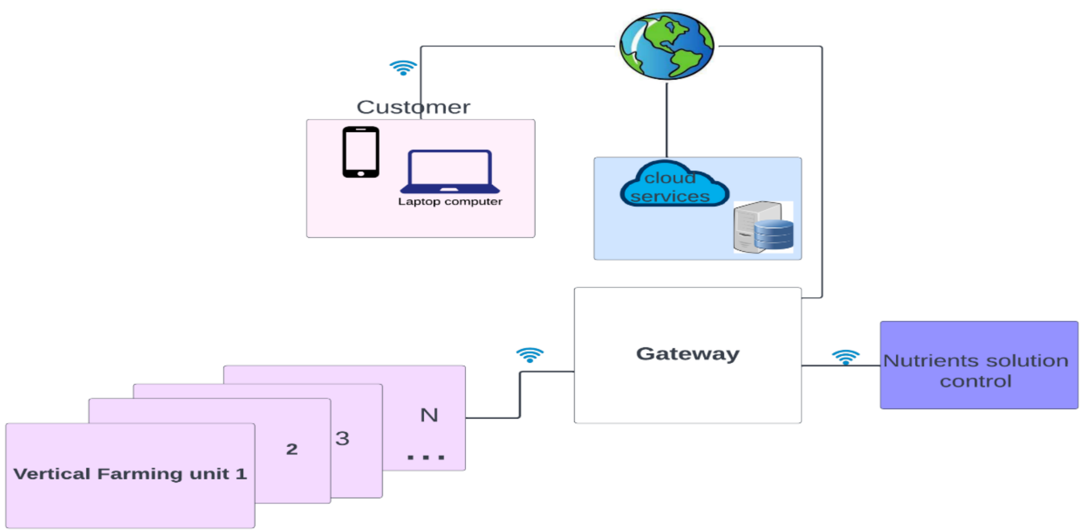


Figure 7 Block diagram of vertical hydroponic system

3.2.1. Vertical farm unit

The vertical farm unit contains mainly: the plant frame, light intensity sensor, artificial light, temperature and humidity sensors as shown in Figure 8, plant frame is the part in which the plant grows. The Light sensor detects the amount of light falling on the plants. If the amount of light is above the required light, the artificial light will be turned off while in case that the amount of light is less than the threshold, the artificial light will be turned on and adapted to the needed amount by the plant. Temperature will be measured by temperature sensor and will be adapted into optimal range with air conditioner. All previously mentioned parameters will be monitored online via mobile application, also they can be controlled remotely by the end-user.

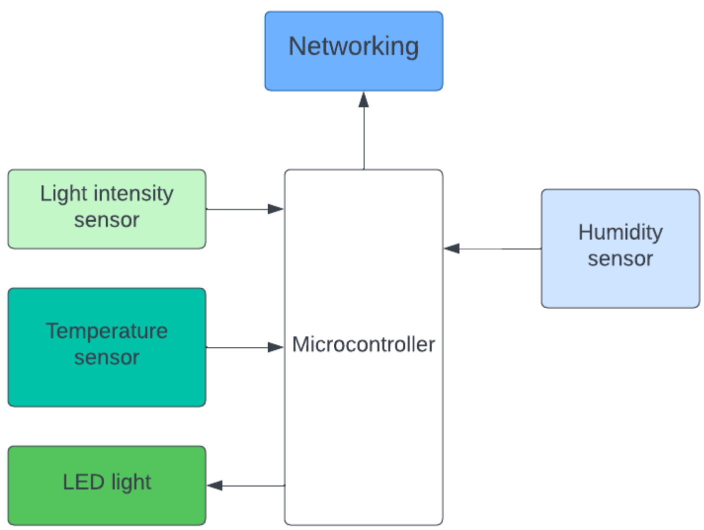


Figure 8 Block Diagram of vertical farming unit

3.2.2. Nutrients solution control Unit

Keeping nutrients level in the optimal range for each plant, obtaining the right pH level to allow plants to absorb the nutrient and controlling water temperature and water level is the main tasks done by the Nutrient solution control unit. The Total Dissolved Solids sensor detects electrical conductivity which represents nutrients level in the solution, if the TDS level decreases the nutrients pump will work to raise it again. If the pH value increases to the optimum range a pH down pump will work, and if it decreases than the optimum level a pH up pump will work to raise the level of pH. If the water level sensor detects a decrease in water level than a specific value, a clean water pump will be turned on.

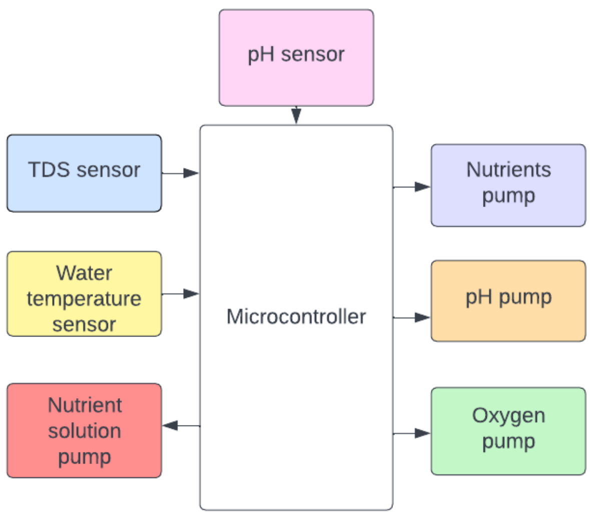


Figure 9 Block diagram of Nutrients solution control unit

3.3. Flow Chart

3.3.1 System flow chart

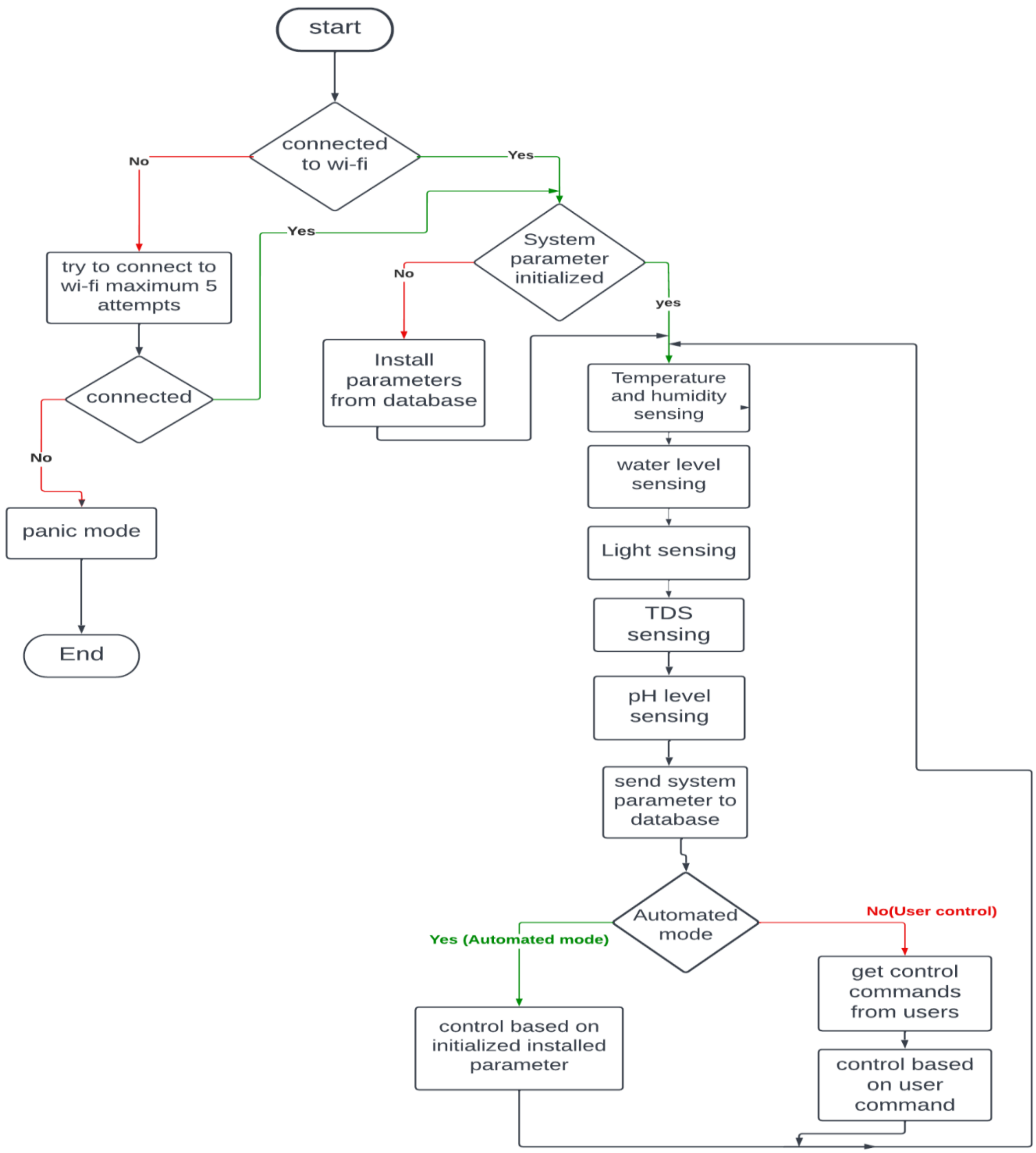


Figure 10 System flow chart

3.3.2 pH level control

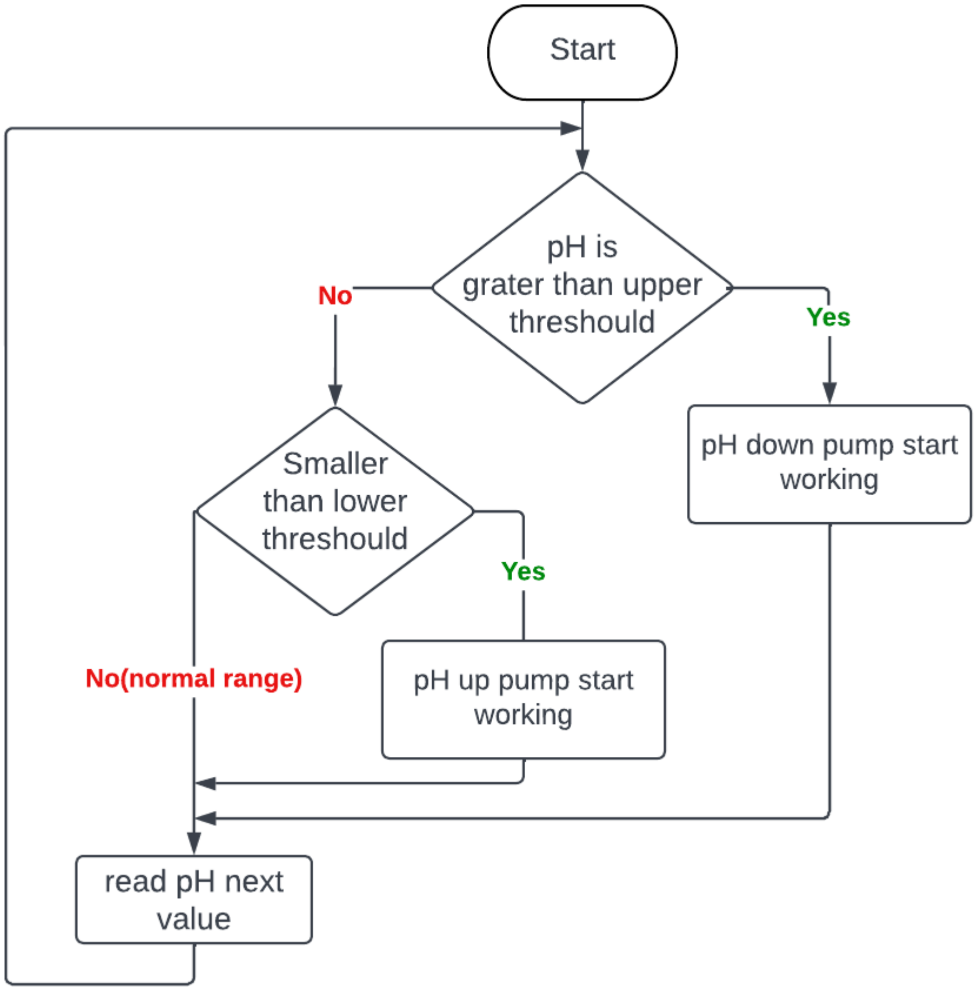


Figure 11 pH sensor control flow chart

3.3.3 TDS control

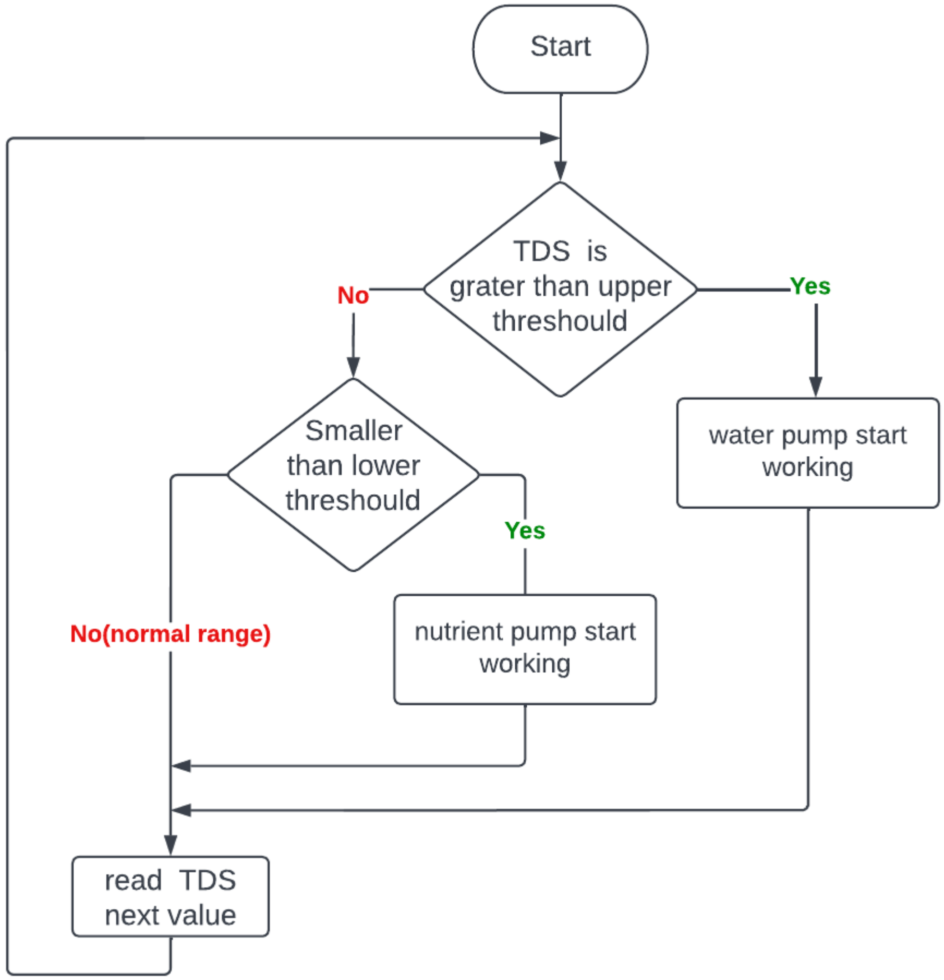


Figure 12 TDS sensor flow chart

3.3.4 Light control

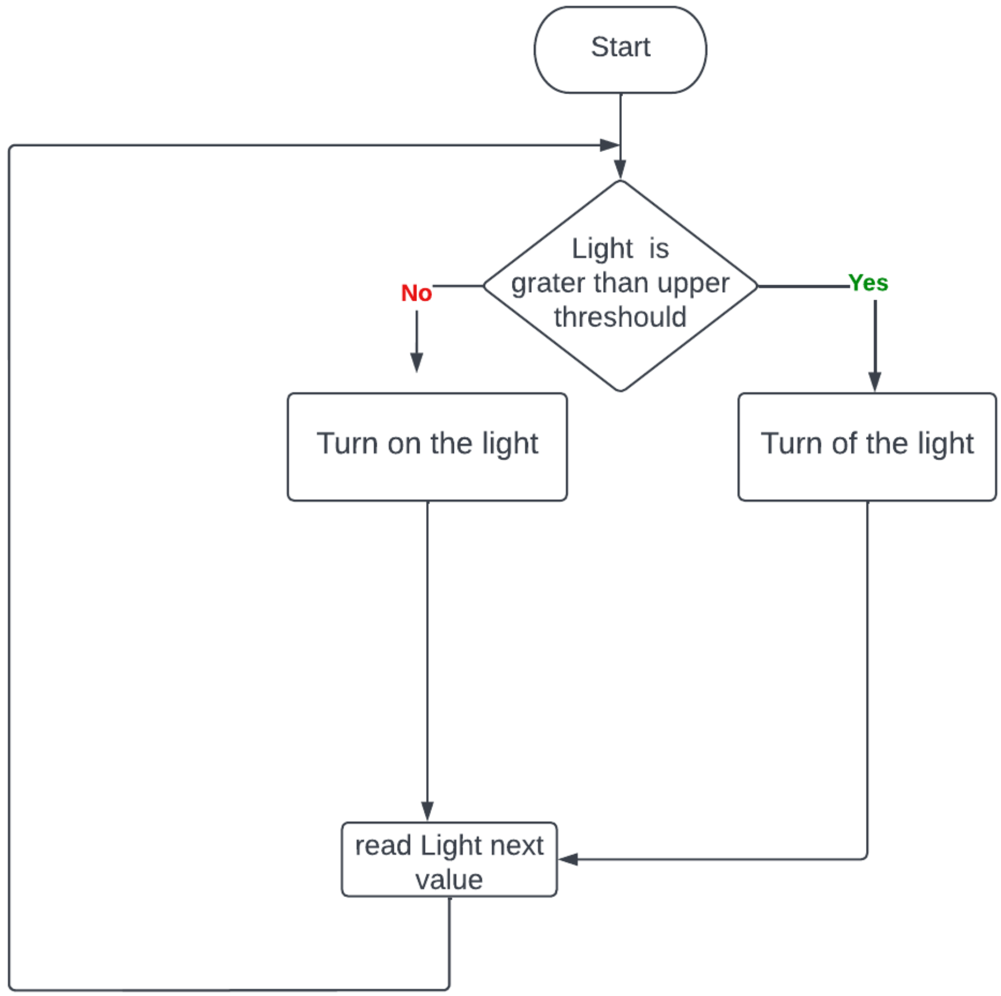


Figure 13 Light control flow chart

3.4 Cost Table

This table contain the cost for each component of the module, the total cost is estimated

Table 5 cost table

Piece	Price($)
Frame with water pump	90
pH sensor	40
EC sensor	70
Water level sensor	4
Water temperature sensor	3
Light sensor	1.5
Three small pumps	3*(10)
Nutrient solution pump	25
Air pump	12
Artificial light	8
Container	5
ESP32	3*(21)
Raspberry pi 3 model B	35
Total cost	344.5$

3.5 Summary

The overall design of the system, the block diagram, and schematic diagram, as well as flow charts are provided in this chapter.

The following chapters will describe the implementation of our system and the evaluation of its effectiveness in comparison with traditional techniques.Therefore, more details regarding the various hardware components of the system and its software will be provided. Furthermore, it describes the module tests of each subsystem and testing of the whole system and the obtained results.

Chapter four

System implementation, testing, results and discussion

4.1 Overview

This chapter introduces a description of the implementation, implementation issues, implementation challenges, validation results and discussion of the results.

4.2 Description of the implementation

4.2.1 Software Implementation tools:

Python code is used to build the algorithm of the system that will be on the gateway so as to perform a control operation and also used to connect with the database. After the code is written, it is installed on the gateway.

C code is just used as a partial interface between humans and the Microcontroller to
instruct the Microcontroller so as to perform a particular operation. After the code is written, it is compiled.

To implement the webpage and its integration with MQTT protocol and firebase, JavaScript, HTML, and CSS were used.

4.2.2 Description of the implementation

1. Was purchased the necessary sensors and pumps for the project, the frame that consists of two shelves was made.
2. We connected all ESP32 with raspberry pi using the internet and then connected the raspberry pi with the database.
3. Each shelf in the frame has its own ESP32 that is connected to a temperature and humidity sensor, light sensor, and artificial light.
4. There is another ESP32 dedicated to the nutrient tank that is connected with a pH sensor, TDS sensor, water temperature sensor, three small pumps (one for nutrients and the others for pH up and down), and a big bump for the nutrient solution.
5. Get data from each sensor and send it to raspberry pi to make the control needed based on the optimal value that was installed in the raspberry pi.
6. The raspberry pi sends data to the database each period of time.
7. When the web application runs, it fetches data from the MQTT broker to display it to the user through several interfaces and fetches data from the database to display a history for the plant.
8. The user can control all the pumps and the artificial light through the web application.
9. This process continues as long as the Internet connection is not lost.

Web Application implementation:

Using the website, the users will be able to view real-time data for several important parameters that are critical for the success of his vertical farm, and control these parameters to optimize the user system's performance.

Our website is implemented using a combination of Java script, HTML, and CSS, as well as several libraries and frameworks including PahoMQ, Chart.js, Bootstrap, Google Fonts and Icons, and Firebase. These tools allow us to create a user-friendly and visually appealing interface that is easy to navigate and use.

On this website, the user will be able to view data for various parameters such as pH, TDS, humidity, temperature, and water temperature in the form of charts and graphs. These charts are created using the Chart.js library, which allows us to easily display and analyze the data in an intuitive way.

In addition to viewing data, the user will also have the ability to control these different parameters using this website. This can be done through the use of various sensors and controls, such as pH pumps, nutrient pumps, light and water pump. The PahoMQ library is used to facilitate communication between these devices and the website, allowing you to remotely control your vertical farm from anywhere with an internet connection.

Overall, this website is an essential tool for anyone looking to monitor and control their indoor vertical farm in real-time, and ensure that their plants are receiving the optimal conditions for growth.

Sign in page:

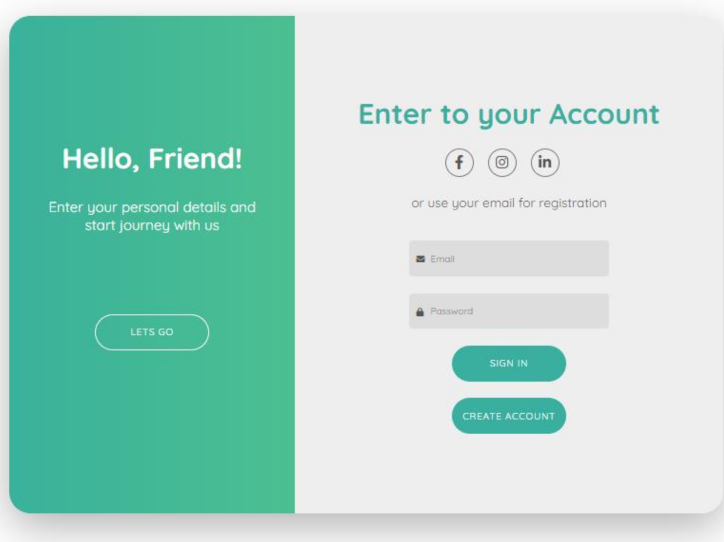


Figure 14 Sign In page

In the sign-in page for our indoor vertical farm system, the user will be able to access all of the features and functionality of our system by entering his login credentials. To sign in, the user can simply enter his username and password in the designated fields, and then click the "Sign In" button. If the user does not have a username and password, he can create an account by clicking the "Create Account" button. This will allow users to access all of the features and functionality of our system, including real-time data monitoring and control of your vertical farm. Once the user is signed in, he will be able to view and manage his vertical farm from anywhere, using any device with an internet connection. Our system is designed to be user-friendly and easy to use, so the user can quickly and easily get the information he needs to keep his vertical farm running smoothly.

Choosing plant page:

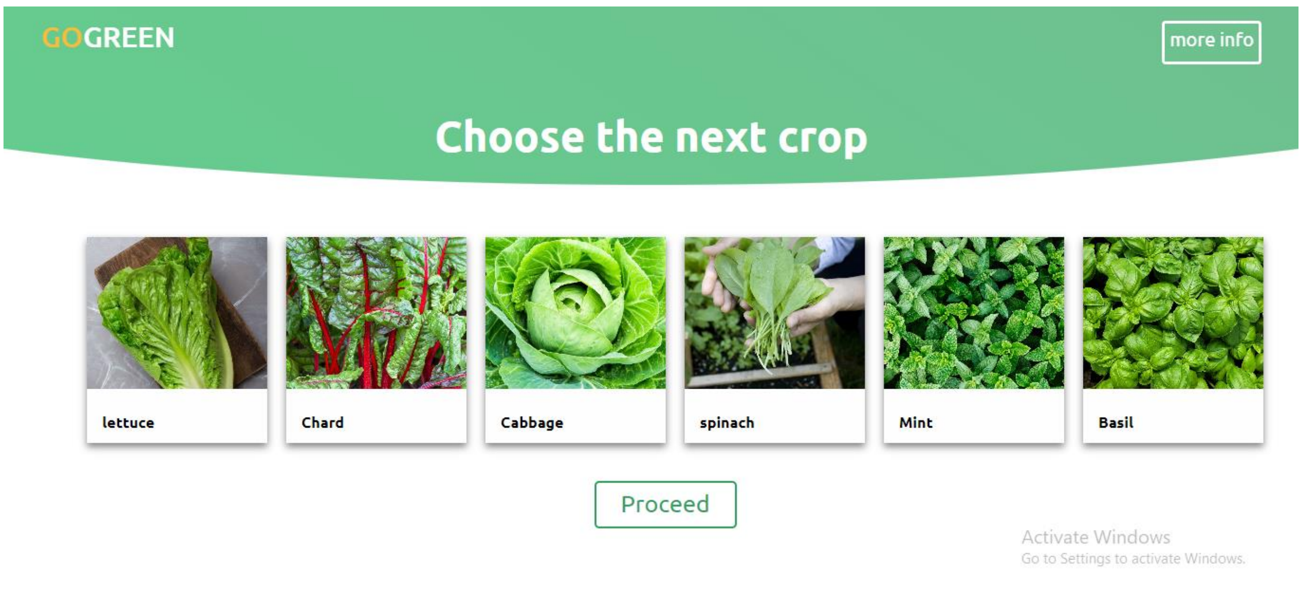
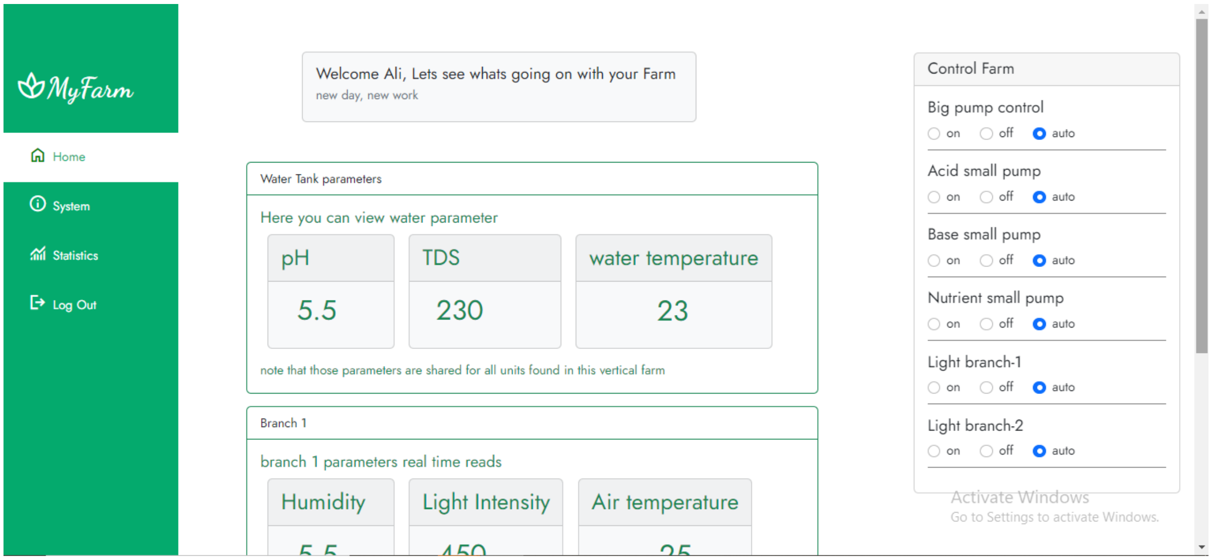


Figure 15 choosing plant page

In our indoor vertical farm plant selection page, the user will be able to choose the plants that he wants to grow in his vertical farm system from a wide variety of options. All of the plant data and information on this page is retrieved from our Firebase database, which is constantly updated with the latest information about our plants.

To choose the plant, the user can simply browse through our selection and click on the plants that he is interested in. He can view detailed information about each plant, including its growth requirements and suitable environmental conditions. This can help users make informed decisions about which plants are the best fit for your indoor vertical farm system.

Monitor and Control Page:



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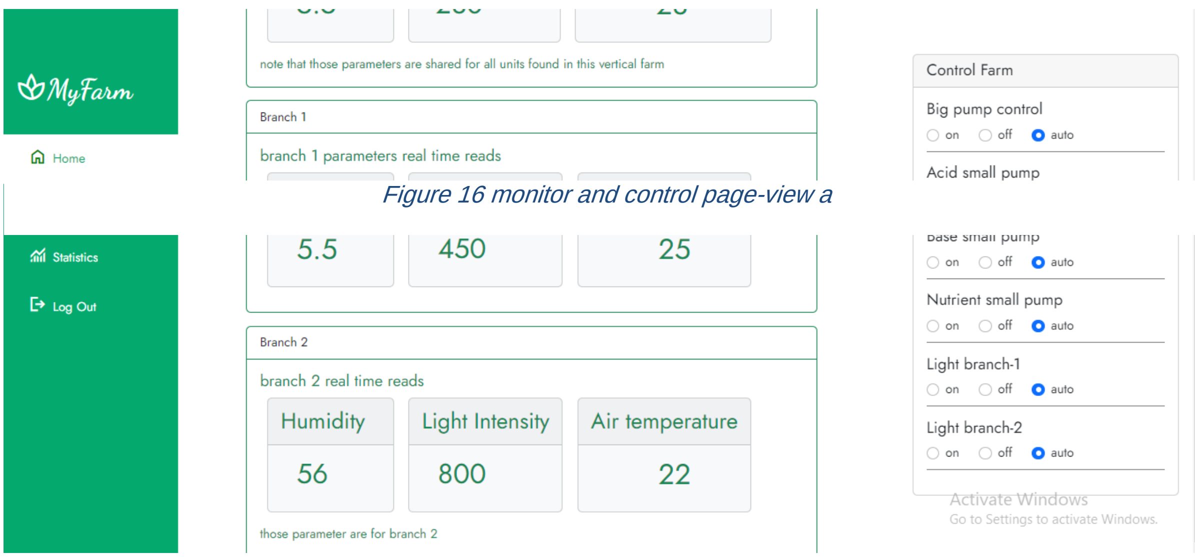

Figure 16 monitor and control page-view a

Figure 17 monitor and control page-view b

vertical farm monitoring and control page, the user will be able to view real-time data for several important parameters that are critical for the success of the user vertical farm. These parameters include: pH, TDS, Humidity, Water temperature. Moreover, on this page, you will have the ability to control these different parameters. This can be done through the use of various sensors and controls, susuch as nutrient pump, acid pump, base pump, and lights. By adjusting these parameters, you can ensure that your vertical farm is operating at optimal conditions for plant growth.

Statistics Page:

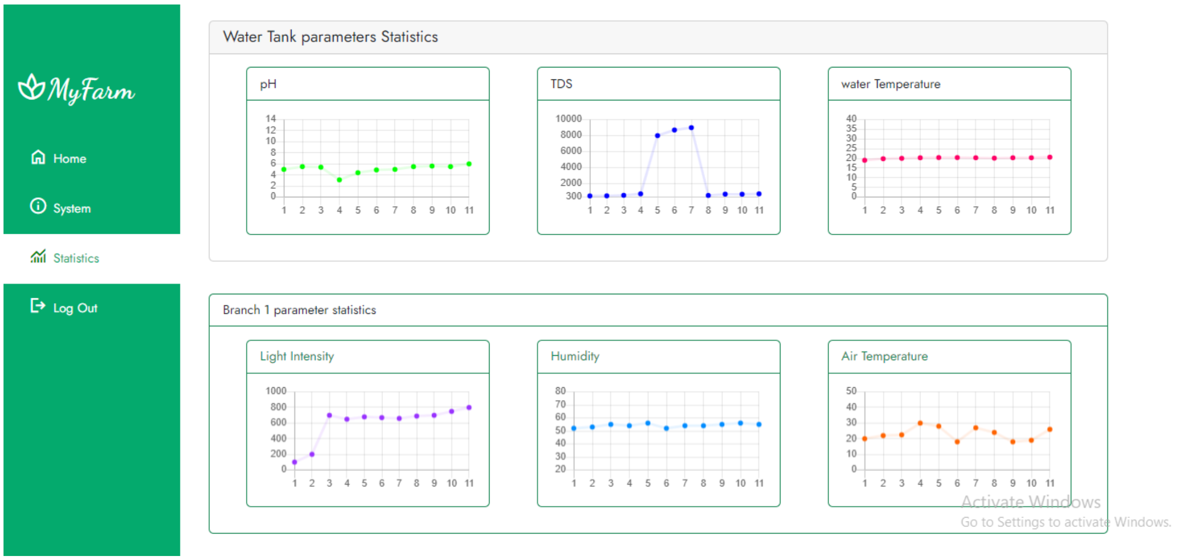

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Figure 18 statistics page

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door vertical farm data visualization page, the user will be able to view real-time data for his vertical farm plants in the form of charts and graphs. This data is retrieved from our Firebase database, which is constantly updated with the latest information from our sensors and monitoring systems. We use the Chart.js library to create these charts and graphs, which allows us to easily display and analyze the data in an intuitive and user-friendly way. The user will be able to view data for various parameters, such as pH, nutrient levels, and environmental conditions, and compare these data points over time to get a better understanding of your vertical farm's performance. This can help you identify trends and patterns in the data, and make informed decisions about how to optimize your vertical farm's operation. So, this page is a useful tool for anyone interested in understanding and improving the performance of their indoor vertical farm.

4.3 Implementation issues

TDS sensor affecting the pH sensor when they are measuring in the same (water)tank. The solution was to connect the two sensors to different power supply by connecting the pH sensor to Vcc and ground and the TDS sensor with two GPIO pins, one is programmed as high(Vcc) and the other as low(ground).

4.4. implementation challenges

One of the major challenges we faced during the project was the availability of certain tools and equipment. Since we were located in Palestine, it was difficult to find some of the specific tools that we needed for the project in local stores. We had to rely on online stores to purchase these tools, which added an additional layer of complexity to the project.
Another challenge was the cost of some of the sensors that we needed to use. These sensors were quite expensive, which put a strain on our budget and required us to carefully consider which sensors were absolutely necessary for the project. Overall, the lack of availability and the high cost of certain tools and equipment were significant challenges that we had to overcome during the project.

4.5 Validation result

4.5.1 Hardware testing

We tested the connection of each NodeMCU ESP32 with the raspberry pi and all NodeMCU ESP32 were tested with all sensors, pumps, and lights.

Figure 19 represents the project we did the tests on.

Figure 19 full system

4.5.2 Software testing

During the software testing process, we conducted various tests to ensure that all of the features of the software were working properly. One of the tests involved connecting to an MQTT broker and fetching data from it. We also tested the sign up and sign in functionality, as well as the ability to connect to firebase and send and receive data from it. Another important test was the ability to display data coming from firebase as a chart, which required the software to be able to process and display the data in a visually appealing way. In addition, we tested the ability to send control orders to the hardware part of the system, which was essential for the proper functioning of the software. Overall, all of these tests were successfully passed, which demonstrated the reliability and robustness of the software. Table 6, Table 7, and Table 8 show some of the tests that we have carried out.

Table 6 Software testing

Case	Expected Output	Obtained Output	Pass/Fail
Connect to the internet	Connect to the internet	Connect to the internet successfully Pass	Pass
Connect to the MQTT	Connect to the MQTT	Connect to the successfully	Pass
Get necessary data from the database	Get data from database	Get data successfully	Pass
Get necessary data from sensors	Get data from all sensors	Get data successfully	Pass
Send data to gateway(Raspberry Pi)	Send data that is read from sensor to the gateway(Raspberry Pi)	Send data successfully	Pass
send data from gateway to database	Send data to database	Send data successfully	Pass

Table 7 Sensors testing

Case	Expected Output	Obtained Output	Pass/Fail
The pH sensor start sensing to measure the acidity or alkalinity of the water	The pH sensing to acidity or alkalinity of the water	The pH sensing successfully	Pass
Open the dosing pump that connected with pH+ solution if pH is less than the threshold	Open the positive pH dosing pump	Open the positive pH dosing pump successfully	Pass
Open the dosing pump that connected with pH- solution if pH is greater than the threshold	Open the negative pH dosing pump	Open the negative pH dosing pump successfully	Pass

The TDS start sensing to indicate the Total Dissolved Solids in a solution	The TDS sensing to indicate the Total Dissolved Solids in a solution	The TDS sensing successfully	Pass
Open the dosing pump that connected with nutrient solution if the TDS is less than the threshold	Open the nutrient dosing pump	Open the nutrient dosing pump successfully	Pass
The LDR sensor start sensing the amount of light	The LDR sensing amount of light	The LDR sensing successfully	Pass
Open artificial light if light is less than the threshold	Open artificial light	Open artificial light successfully	Pass

Web application section:

web application tests:

Table 8 Web page testing cases

Test	Result
User Can Sign up to the system, and sign in with the same account he signed up with also retrieve the data related with the account	pass
Connect to system by connecting to MQTT Broker send and receive data	pass
Display data coming from microcontrollers	pass
Send Control Orders to MQTT broker	pass
Connect to firebase	pass
Display data coming from firebase as a chart	pass
Send data to firebase	pass

4.6 Results and Discussion

From the first stages of the project implementation we were following the purpose objectives of the system. Components have been connected and programmed to achieve the requirements of the system. After that, we turned on the system and chose the plant that was planted by using the webpage. After that, the data for this plant installed from the database to raspberry pi and the system started to work automatically based on the data installed in it. We monitored the parameters via a web page.

The pH of the water tank was not suitable for the plant so the dosing pump (pH-) pumped acid automatically to the water and the nutrients pump pumped nutrients to make TDS in the suitable range. After the nutrient solution got ready we turned on the big pump that pumped the nutrient solution to the frame as a cycle.

We tried to control the dosing pump (pH-) by turning it on via a web page which made the nutrient solution acidic, automatically the dosing pump(pH+) was turned on.

The artificial light turned on because the light in the room was less than the threshold. When we increased the light than the threshold the artificial light turned off. We also tried to turn on the artificial light by using the web page and increased the light intensity for the plant and despite that artificial light was still turned on.

After a period of using the system, we were able to see the history of the system based on the data stored in database.

Website results and Discussion:

Our website that used for vertical farming system controlling and monitoring, was successful in achieving its objectives. The website was designed to allow users to remotely monitor and control their vertical farming systems, and to provide real-time data about the performance of the farm.

The website was tested by the team of the project, as we use the website to monitor and control our vertical farming system. The results of the testing showed that were able to successfully connect to our system, monitor and control it using the website.

The website also provided real-time data about the performance of the farm, including temperature, humidity, and nutrient levels. This data was displayed using chartjs and other visualization tools, which made it easy for users to understand and interpret the data.

Overall, the testing results showed that the website was effective in achieving its objectives. The website's ability to remotely monitor and control vertical farming systems, as well as provide real-time data about the performance of the farm, made it a valuable resource for users of vertical farming systems.

Some potential benefits of the system include:

- Improved efficiency and productivity: By allowing users to remotely monitor and control their farms, the website would enable them to make real-time adjustments to their systems based on the data being collected. This could lead to more efficient use of resources and improved crop yields.
- Increased transparency and accountability: By providing real-time data about the performance of the farm, the website would enable users to track the progress of their crops and identify any issues that may need to be addressed. This could increase accountability and help ensure that the farm is operating at its best.
- Enhanced user experience: The use of chartjs and other visualization tools would make it easy for users to understand and interpret the data being collected, which could improve the overall user experience. Additionally, the ability to remotely monitor and control the farm would make it more convenient for users to manage their systems.

Overall, the integration of MQTT and firebase, as well as the use of chartjs and other visualization tools, would likely make the website a powerful and valuable resource for users of vertical indoor hydroponic farms. It would provide them with the tools and information they need to optimize the performance of their systems and increase efficiency and productivity.

Chapter five

Conclusion and Future work

5.1 Overview

The chapter introduces a summary of the project, the future directions, and future work.

5.2 Conclusion

Our project focused on designing and developing a dedicated, customizable, expandable, and smart vertical farm module. Such a module uses state-of-the-art technologies to control and monitor a set of parameters that is essential for plant growth and quality based on well-examined and defined conditions using the IoT platform. At the end of the project, we were able to monitor the pH, TDS, Humidity, temperature, water temperature, and light and were able to control all pumps and artificial light. Also, the user can see the history of the system on the web page using the values that are stored in the database. Finally, we could design and implement vertical farming modules based on IoT that can be easily used by the end user. Through the course of this project, we were able to successfully design and build a functional prototype of the customizable automatic indoor vertical farming solution. We conducted several trials to test the effectiveness of the system in different use cases, and found that it was able to do its work efficiently. The automation of the system will result in significant cost and resource savings, making it a sustainable and cost-effective solution for producing fresh produce in urban environments.

5.3 Future work

In the future, we look forward to adding important features to the system, the most important can be:

1- Developing a smart algorithm (i.e., machine learning (ML)) to make the system smart for online decisions, and to have the ability to predict and report any problems. Moreover, most of the ML works are located in the cloud to save energy and utilize the computational performance of the hosting server.

2- Developing the system to support renewable energy, i.e., compatible with solar energy, as an alternative or supplement for conventional energy resources, and to enable using the module almost anywhere.

3- Introducing waste treatment capabilities, to keep waste as minimum as possible to keep the system environmentally friendly.

4- Provide plant disease detecting and reporting features using image-based deep learning techniques.

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Appendix A- Schematic diagram

Figure 20 Schematic diagram

Appendix B- comparison between our project and previous related projects

Table 9 comparison between our project and previous related projects

	Smart aquaponics Monitoring System Via IoT techniques	Monitoring the Health status of the plants using a Computerized system	Garden Bot	Our System
Goals	Design an independent real time smart aquaponics monitoring prototype that combines between hydroponics system and aquaculture system using IOT.	Implement a system that monitors the health status of the plants by detect any possible disease that affecting plant leaves.	Implemented a robot, which is capable of planting seeds and automating irrigation.	we could design and implement vertical farming modules based on IoT that can be easily used by the end user with the ability to monitor and control system parameters .
Succeeded in	saving the water consumption and reducing the use of pesticides and fertilizers, which can be considered as a green technology..	Check the environmental conditions surrounding plants, like temperature and humidity, in addition the changes that happened upon the leaves .	save water, reduce the amount of work for people, thus reducing time.	Save time and cost, save the water consumption, reduce the amount of work for People by monitor and control the system parameters.
Design component	Arduino and Raspberry Pi Controllers, pH, Water Temperature, Total Dissolved Solids (TDS), Temperature Sensor	Laptop, camera , Arduino uno microcontroller, Humidity and Temperature sensor, Servo motor	Arduino Mega Microcontroller, stepper motor, ultrasonic sensor.	ESP32 microcontroller, Raspberry Pi Controllers, Humidity and Temperature sensor, Water Temperature, Total Dissolved Solids (TDS), Temperature Sensor, pH sensor Dosing pump, Air pump, artificial light
Full remote control	No	No	No	Yes
View data remotely	Yes	No	No	Yes
Can be used by non-expertise	No	Yes	Yes	Yes

Different from our project	Our system is a hydroponic system that will monitor and control system parameters automatically, while their system is an aquaponics system that monitor the parameter that the plant need but has no control on the system parameter.	Our project will monitor the humidity and temperature that the plant need to grow, while their project check the temperature and humidity, in addition the changes that happened upon the leaves.	Our system will control and monitor the system parameter such as pH, TDS, while this system only monitor and control the soil moisture of the seed.	

Appendix c- ESP32 diagram

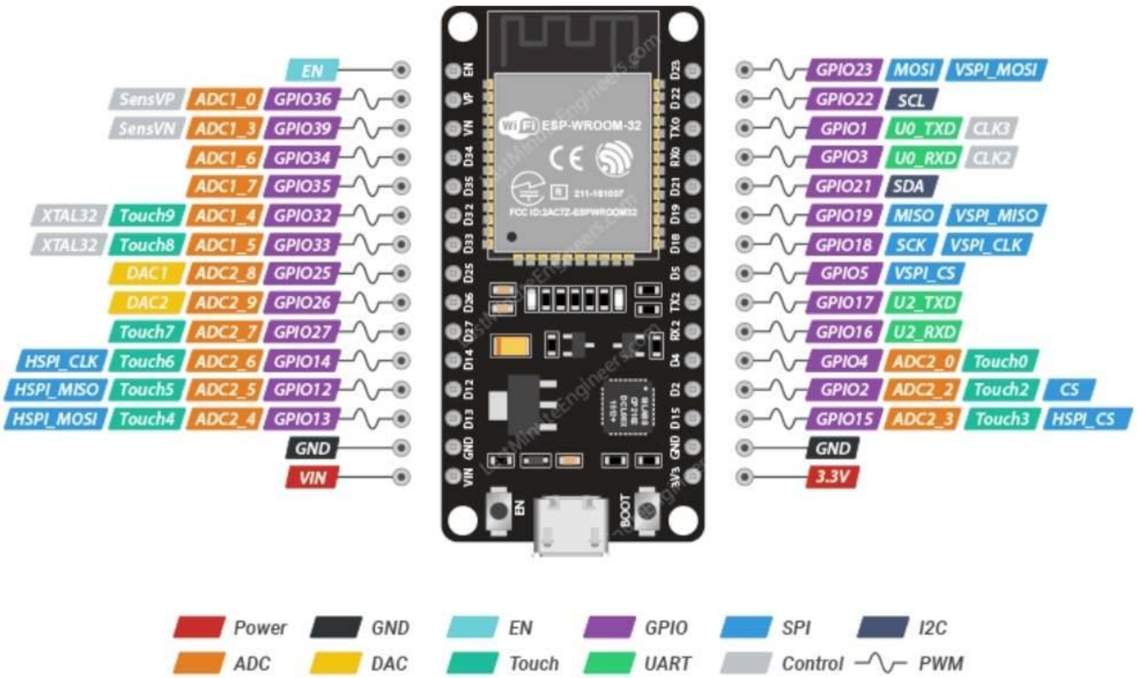

Figure 21 ESP32 diagram