



**DESIGN AND IMPLEMENTATION OF A PCB FOR A VERTICAL FARM
IRRIGATION SYSTEM**

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BENIN CITY,

EDO STATE.

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**A PROJECT SUBMITTED TO THE DEPARTMENT OF COMPUTER
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**IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD
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COMPUTER ENGINEERING**

DECEMBER,2025.

CERTIFICATION

I hereby certify that this project **DESIGN AND IMPLEMENTATION OF A PCB FOR A VERTICAL FARM IRRIGATION SYSTEM** for the award of B.Eng. was conducted and duly presented by Ayara Elijah Omeza (ENG2009615) of the department of Computer Engineering, Faculty of Engineering, University of Benin, Benin City.

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Date

DEDICATION

I am dedicating this project to the Almighty God, whose grace, wisdom, and strength have been infinite and helped me in my course of study. He has always been my anchor, inspiration, and propelling force during the times of difficulty and victory. This work is also dedicated to my beloved parents, my siblings, and all my family members; to my uncles, aunts, and everyone who has contributed to my life in one way or another. Your unwavering love, support, and encouragement have been the foundation of my success. Your sacrifices and firm faith in me have always given me more strength to aim at excellence. This project is a witness to your patience, leadership, and never-ending trust in me, for which I owe you a great deal of unremitting gratitude.

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Thank you all.

ABSTRACT

This project aims to design and execute a Printed Circuit Board (PCB) of a Vertical Farm Irrigation System that will utilize Internet of Things (IoT) and Controlled Environment Agriculture (CEA) to bring greater automation, water control, and overall crop yield. The project aims at optimization of irrigation in vertical farming, by offering a convenient, compact, and durable PCB-based solution that can monitor and manage the soil moisture, temperature, and humidity in real-time. It solves the problems of traditional manual irrigation techniques such as inefficiency by incorporating sensor feedback with microcontroller decision-making to guarantee accuracy in water dispersion and energy conservation in a regulated agricultural setting.

The Methodology involved the design, development and the implementation of a two-layer PCB was done with the KiCad Electronic Design Automation (EDA) software. The system architecture is a platform that combines sensing, processing, actuation, interface, and power management into a single platform. It has notable features such as the ESP32 microcontroller as the means of data processing and control, a capacitive soil moisture sensor, a DHT11 temperature and humidity sensor, a PIR motion sensor, a SIM800L GSM to monitor remotely and also connect to the internet, and a 16x2 LCD to display data locally. The buck converter LM2596 makes sure of power supply and a 12V relay powers the pump to allow automated irrigation. The whole circuit was modelled, experimented and developed on a custom PCB to guarantee signal quality, power saving and environmental sustainability.

The results demonstrated that the system was able to automate irrigation in one of the small-scale vertical farm prototypes and ensure the optimal soil moisture and environmental conditions with minimal human interventions. The experimental findings indicated proper sensor measurements, pump activation, and stability of operation in different environmental conditions. PCB-based design was found to be small, dependable and economical and greatly minimized wastages of water and manpower. This project illustrates how PCB-based IoT systems can be used to develop smart and sustainable agriculture to offer a scalable and cost-effective precision irrigation system in developing countries such as Nigeria.

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LIST OF ACRONYMS

AC - Alternating Current

ADC - Analog-to-Digital Converter (or Analog-to-Digital Conversion)

AI - Artificial Intelligence

CEA - Controlled Environment Agriculture

DC - Direct Current

DRC - Design Rule Check

EDA - Electronic Design Automation

EMI - Electromagnetic Interference

ERC - Electrical Rules Check

GPIO - General-Purpose Input/output

GPRS - General Packet Radio Service

GSM - Global System for Mobile Communications

HASL - Hot Air Solder Levelling

I2C - Inter-Integrated Circuit

IC - Integrated Circuit

IDE - Integrated Development Environment

IoT - Internet of Things

IPM - Integrated Pest Management

LCD - Liquid Crystal Display

LED - Light Emitting Diode

LoRa - Long Range

NPK - Nitrogen, Phosphorus, and Potassium

PCB - Printed Circuit Board

PIR - Passive Infrared

PWM - Pulse-Width Modulation

RF - Radio Frequency

RH - Relative Humidity

RX - Receive

SCL - Serial Clock Line

SDA - Serial Data Line

SMS - Short Message Service

SPDT - Single Pole Double Throw

SPI - Serial Peripheral Interface

THT - Through-Hole Technology

TX - Transmit

UART - Universal Asynchronous Receiver-Transmitter

USB - Universal Serial Bus

VIN - Voltage In

Wi-Fi - Wireless Fidelity

CHAPTER ONE

(INTRODUCTION)

1.1 BACKGROUND OF STUDY

The art and science of cultivating plants and other crops as well as rearing animals for food, other human needs, or financial benefit can be referred to as "agriculture" in reference to crop and livestock farming. Since farming is the only source of food, which continues to be our only source of energy and vitality as humans, the agricultural business is a crucial and critical sector of global economies (Emmanuel et al., 2018). Agriculture has been the backbone of a lot of economies in a lot of developing countries by contributing to the security of food and also in terms of security of jobs. Vertical Farming as a whole has emerged as a sustainable solution to food production in urban areas, offering a way to grow crops in vertically stacked layers with controlled environmental conditions. This method reduces land usage and enhances crop yield by maximizing space (Kalantari et al., 2017). There are many challenges are faced in the world of traditional farming where farmers experience scarcity of land, also the change of climates and also in the aspect of resources such as scarcity of water whereby causing deficiency in the aspect of farmers not getting adequate resources necessary for the production of crops. Traditional farming requires manual control which means it requires the manual watering the plants and this is a serious problem because farmers tends to waste water and also utilises a lot of energy from the farmer actively coming to check on the conditions of the farm.

The introduction of vertical farming is an innovative agricultural approach that involves growing crops in vertically stacked layers to ensure that space is utilized, also reduces the water usage of the farmer. One of the critical components of vertical farming is the irrigation system, which ensures that the crops receive the adequate amount of water that is supplied to the farm and which must be efficient and responsive to real-time crops needs. The vertical farming system is developed in a way that the approach emphasizes the creation of temperature and soil moisture sensors that may be positioned in strategic fields to monitor the two variables that crops are most sensitive to: soil moisture and temperature. Based on the current temperature and moisture levels, the sensing system's

feedback control mechanism and centralized control unit manage the water flow into the field in real time (Kar et al., 2020).

1.2 PROBLEM STATEMENT

The high cost of implementation is one of the biggest challenges and is a serious impediment to the smallholder farmers of developing nations. Smart irrigation systems are necessary to be developed so as to make them affordable to encourage their use in large numbers. This difficulty may be the key towards a more sustainable future of agriculture (Akhtar et al., 2024).

Precision and dependability of sensors applied to smart irrigation systems can become a major issue. Good data is necessary in the management of irrigation. The solution to this problem is to utilize high-quality and advanced sensors that have high performance (Akhtar et al., 2024).

Lack of technical knowledge and low awareness of the farmers is another major problem. In most of the developing countries, smart irrigation technologies are not common knowledge. Consequently, it is important to educate the farmers on the benefits of such systems, as well as train them on how to effectively use them as a way of achieving successful integration and adoption.

Precision agriculture coupled with vertical farming is a solution to these issues. In Nigeria, however, such innovative methods of farming are not known and not implemented in practice (Kalantari et al., 2017).

1.3 AIMS AND OBJECTIVES

The aim of this project is to design and implement a PCB for a vertical farm irrigation system utilising the use of Internet of things (IOT) and also technologies and also Controlled Environment Agriculture (CEA) to enhance the precision and accuracy of the whole system to enhance the use of resources, the productivity and also the enhance food security. To achieve this aim, the following objectives will be achieved:

1. To study, identify and select the key components required to carry out the irrigation system of a vertical farm
2. To design the schematics and circuit diagram for the automated irrigation system
3. To design the printed circuit board for the vertical farm that integrates sensors, microcontroller and pump control using a design software.
4. To Implement and integrate the printed circuit board in the vertical farming system by automating the irrigation process based on soil moisture and other sensors
5. To test and evaluate the performance of the system in a controlled environment
6. To design and develop a water proof and dust resistant protective case for the circuit system.

1.4 SCOPE OF STUDY

This study centres on the design and implementation of a printed circuit board (PCB) to automate the irrigation system of a vertical farming setup, employing principles of precision agriculture and also the technologies. The work will be carried out with the use of an adequate Electronic Design Automation (EDA) software to achieve an effective and efficient board that will house all the required components.

The proposed system will incorporate essential hardware components including an ESP32 microcontroller, soil moisture sensors, DHT11 sensors (for monitoring temperature and humidity), a water pump, relay modules, Analog to Digital Converter (ADC), Sim Module, PIR motion sensor and a 16x2 LCD display. A custom PCB will be developed to effectively integrate and manage these components, providing a compact and dependable platform for automated irrigation.

The project scope covers circuit design, simulation, PCB fabrication, and the development of an embedded control algorithm that automates irrigation based on real-time sensor inputs by enhancing water-use efficiency, minimize manual intervention, and improve crop growth conditions within a controlled vertical farming environment.

1.5 RELEVANCE OF STUDY

This design and implementation of a printed circuit board (PCB) in vertical farm irrigation systems is highly applicable in the development of modern agriculture, sustainable development, and technological advancements especially in the emerging economies like Benin or in Nigeria at large.

First of all, it addresses the key inefficiencies in current vertical farming solutions, especially the absence of smart, automated irrigation management. The use of traditional irrigation methods in most urban and peri-urban areas usually results in inefficient water consumption, energy, and unreliable crop yields. The project will provide a small, intelligent device (PCB) to manage water specifically, combining sensors, ESP32 microcontroller, and adaptive control algorithms to control the use of resources efficiently and reduce labour and operational expenses.

This research corresponds to the international trends in developing agriculture and technologies. With the increasing challenges of climate change, and the diminishing of farmland as a result of urbanization, vertical farming with the assistance of automation proves to be a potential solution. This paper shows how embedded systems and IoT-based PCB solutions can be used to deliver data-informed, climate-resistant and environmentally-friendly irrigation supporting climate-resilient and circular farming concepts.

This study is particularly relevant to the agricultural environment in Africa, where low-cost solutions should be scaled urgently. This applicability of the current research fills that gap by creating an open-source, modular and affordable PCB-based irrigation system that has brought smart farming more within the reach of local farmers and rural cooperatives. In most cases, most vertical farms system is built for prototyping that's why most of them consists of a Vero board but this project is focused on building a Printed Circuit Board (PCB) that can be more durable than the traditional systems. Altogether, the presented research can be regarded as a significant bridge between engineering innovation and agricultural progress with the emphasis on the revolutionary role of embedded systems and automation in the future of farming.

CHAPTER TWO

(LITERATURE REVIEW)

2.1 INTRODUCTION TO VERTICAL FARMING

This section provides the overview on vertical farming.

2.1.1 DEFINITION OF VERTICAL FARMING

Vertical farming is a production method that involves growing crops in regulated indoor environments where parameters such as light, nutrient levels, and temperatures are strictly controlled. Vertical farming involves a plant that is cultivated in a stacked layer that may be raised vertically to several stories, vertically stacked layers or other vertical inclined surfaces. This innovative approach ensures the maximum growth of crops and the use of resources by implementing innovative approaches such as hydroponics, aeroponics, and lighting. Hydroponics is a process of cultivating crops in water with or without physical support by an inert substance such as sand or gravel whereas Aeroponics is the cultivation of crops in air/ mist conditions with no soil and minimal water (Al-Kodmany, 2018). Vertical farm agriculture is a very promising alternative to the traditional farming system especially in urban areas where land is scarce, whereby the high level of technology and automation is integrated.

2.1.2 IMPORTANCE OF VERTICAL FARMING

Vertical farming has a lot of significance in the modern-day agriculture. Vertical farming is under many challenges, and many have been solved due to innovations in the contemporary agriculture. The dramatic decrease in water consumption and other systems also reduces the water wastage by 80 percent which is one of the important solutions. Vertical farms may consume as much as 90 percent less water than the conventional farming practices (Despommier, 2009). The other significant benefit is the space efficiency. Vertical farming enables farmers to make the most of the limited urban space by piling layers of crops upwards, thus becoming a sustainable farming method in over-crowded locations (Banerjee & Adenaeuer, 2014). Vertical farming also dispenses with

the needs of massive land by meaning that you do not need a large size of land to begin growing crops. Crops are then attached to trays and then are piled up in a layer.

2.1.3 CHALLENGES OF VERTICAL FARMING IN NIGERIA

Although vertical farming is rapidly gaining acceptance in various parts of the world as a disruptive innovation in the agricultural industry, the adoption of vertical farming in Nigeria is fraught with many challenges that prevent large-scale adoption and scaling. Such challenges are associated with the infrastructural weaknesses of the country, economic constraints, gap in technology, and lack of policy. These barriers are critical towards the consideration of the viability of vertical farming systems integration in the agricultural environment of Nigeria.

Unstable and expensive power supply is one of the greatest problems of vertical farming in Nigeria. Vertical farming systems are very intensive in artificial lighting, environmental control units, sensors, and automation systems to control the parameters of growth of plants in terms of light intensity, temperature, humidity and nutrient values. The systems need a constant source of power to operate effectively. Nigeria has however, unpredictable power supply, and the expensive nature of other sources of energy, like diesel generators or solar power, makes running the business quite expensive. This complicates the process of vertical farms having stability in production and making profits (Kaiser et al., 2024).

The other obstacle of vertical farming in Nigeria is the economic viability. It has a huge financial investment in infrastructure, technology, and maintenance to establish a vertical farm. Recent technologies like hydroponics, aeroponics, and aquaponics rely on advanced technology to circulate water, feed nutrients, provide artificial light, and regulation. These technologies are either imported or very expensive to be manufactured locally such that most farmers in Nigeria cannot afford the initial cost of set up. Also, recurrent expenses of conducting business especially electricity use, replacing parts of the machine and the technical maintenance add to the financial strain. Consequently, vertical farming remains largely inaccessible to the small and medium-scale enterprises that constitute the foundation of Nigeria's agricultural sector. (Al-Kodmany, 2018).

2.2 CONTROLLED ENVIRONMENT AGRICULTURE (CEA)

Controlled Environment Agriculture (CEA) is a high-tech form of agricultural production where the environmental conditions (temperature, humidity, light level, carbon dioxide level, water, nutrients) are strictly controlled and regulated in order to maximize the growth of the plants (Vatistas et al., 2022).

2.2.1 DEFINITION OF CONTROLLED ENVIRONMENT AGRICULTURE

Controlled Environment Agriculture (CEA) is a new and high-tech approach to crop production where the plants are cultivated in a fully controlled indoor setting or an outdoor setting where all the parameters concerning the farm are monitored and controlled. As opposed to the conventional open-field agriculture where farmers rely on the natural weather and soil environment, CEA allows farmers to control all the important environmental factors including temperature, humidity, light intensity, carbon dioxide concentration and nutrient supply to provide the best growth conditions. The crops are normally grown in vertically stacked hydroponic beds with artificial light of LED and under such systems, it is possible to make optimal use of space and resources (Dsouza et al., 2023).

In contrast to the traditional open-field agriculture, when farmers rely on the natural weather conditions and soil fertility to produce crops, CEA gives farmers a chance to produce and provide the optimal growing conditions throughout the year. This will ensure that there are constant yields and quality produces despite external environmental changes. CEA systems are generally developed in enclosed or semi-enclosed areas like in a greenhouse and vertical farms. Controlled environment agriculture is associated with one of its characteristics: the application of soilless agricultural methods, such as hydroponics, aeroponics, and aquaponics. Such approaches substitute soil with nutrient-dense water solutions, which allow nutrients to penetrate plants more effectively without consuming much water and fertilizers (Vatistas et al., 2022).

2.2.2 BENEFITS AND ROLE OF CEA IN VERTICAL FARMING

The basic technology which renders the system viable and efficient is Controlled Environment Agriculture (CEA). It offers strictly regulated environments, including

temperature, humidity, light and nutrient content, which enable crops to be cultivated both in stacked layers as well as entirely without having to be subjected to external weather or seasonal variations. Under such control, the plants enjoy best conditions of growth all year round, which means steady and predictable harvests.

CEA also encourages more economical production of food by curbing conventional constraints of land, water and soils. Vertical farms require significantly less water in comparison to traditional farming because soilless aims of farming methods such as hydroponics and aeroponics do not use a large amount of water and require no arable land. This efficiency has seen it possible to create highly productive farms in the urban areas whereby land is scarce and very costly.

By making food production more local to people, CEA will enable vertical farms to be found in or near cities, which will decrease the environmental footprint of long-distance transport and will bring fresh products closer to consumers. This does not only contribute to the preservation of nutritional value of food but also reduces the greenhouse gas emission during storage and distribution. CEA also guarantees steady production of high quality that is capable of satisfying the increasing demand of food in the towns. In addition to increased efficiency, it helps in the development of sustainable food systems as it promotes economic development, environmental protection and social welfare. Essentially, CEA is the force behind vertical farming that allows cities to grow food on a local scale, in a sustainable and efficient manner (Cowan et al., 2022).

2.3 IRRIGATION SYSTEMS IN SMART AGRICULTURE

These irrigation system technologies can be referred to as smart irrigation systems which are modern technology intensive practices of irrigation systems that apply sensors, wireless networks, and automated control systems as efficient means of controlling the use of water in agriculture.

2.3.1 OVERVIEW OF IRRIGATION TECHNIQUES

These methods belong to a greater initiative to make water management sustainable, particularly in those areas where there are water scarcity and effects of climate change. In the conventional irrigation systems, water may be applied in equal amounts over the

fields without regard to actual soil or weather conditions, and thus become overused and wasted. Conversely, smart irrigation technologies are associated with sensors and Internet of Things (IoT) technology that monitors the important environmental and soil parameters. Such parameters are usually the soil moisture content, temperature, humidity, weather, the water quality and in some cases to detect motion around the farm. The information gathered using these sensors is processed by the control systems or cloud-based systems to identify the exact volume of water required by each crop (García et al., 2020a).

2.3.2 AUTOMATION IN IRRIGATION SYSTEM IN VERTICAL FARMING

In vertical farm irrigation system, automation means the use of sophisticated sensor technologies, data and feedback collection, and monitors using the sensors, which make it possible to control the water and nutrient flow to crop products with high precision and monitor self-regulation in most cases using a relay that triggers the pump off and on based on the moisture of the soil. These systems are designed to be very controlled in the sense that there is a proper balance of various parameters like light, temperature, humidity, carbon dioxide and water thus ensuring optimum growth of plants. Real-time data on crop and environmental data are collected and analysed through the application of both mobile and stationary sensors. Crop growth models then process this information to automatically decide the best irrigation setpoints and nutrient levels to give to the plants (Kaiser et al., 2024).

With vertical farming systems, these systems employs the hydroponics, aeroponics and aquaponics that allows effective delivery of nutrients and space management of the plants under the controlled environments causing the process to become automated (Barbosa et al., 2015). There are many technologies that are used, this system uses advanced technologies to optimize and monitor the plant growth in the controlled environments thus making the entire process automated. This automation involves data monitoring, environmental control and irrigation control. Consequently, the system does not need a lot of human control to function and reduces the necessity of manual observation of plants and reduces the rate of human intervention (Beacham et al., 2019).

2.3.3 IOT-BASED IRRIGATION SYSTEMS IN VERTICAL FARMING

In the development of modern irrigation systems, based on the IoT, smart sensors are used, connected to the Internet, allowing to automatize and optimize the irrigation process to achieve enhanced crop productivity. These systems gather dynamic information on the soil moisture, temperatures, humidity and nutrient content by way of dispersed sensors. It transmits the data wirelessly into a central control unit, or a cloud platform that processes it to define the optimal time and quantity of water required. This is then followed by automated pumps and valves that are efficient in water consumption and delivery of resources to plants. (Rajak et al., 2023).

The automation of a vertical farm system involves sensors to a great extent. These sensors record the essential environmental readings like temperature, carbon dioxide concentration and humidity. The automation system works with the collected data and is able to adjust irrigation, climate control, and even lighting systems (Banerjee & Adenaauer, 2014).

Such automation highly decreases the amount of human involvement, decreases labour expenses, and increases the efficiency of the operations. The system is more scalable as it goes on. More so, incorporating additional sensors into the monitoring system significantly enhances the quality and accuracy of gathered information as well as resources and crop yield (Liu et al., 2020).

2.4 PCB DESIGN AND IMPLEMENTATION IN AGRICULTURAL SYSTEMS

This part gives the summary on PCB design and application of PCB in Agricultural systems.

2.4.1 INTRODUCTION TO PRINTED CIRCUIT BOARD

Printed circuits boards (PCBs) are the staple of the contemporary electronic systems; they provide a stable and organized platform on which several components can be incorporated into one, unified unit. The PCBs are essential in agricultural technology development as they enable efficient intelligent systems that are used to enable automation and real-time

monitoring. PCBs provide stable power allocation, flawless information transfer and improved stability due to their ability to link sensors, processors and communication modules in a small footprint. This degree of integration makes circuit design simpler and allows to produce strong and versatile devices that can be successfully used in a variety of environmental conditions, and PCBs are unavoidable in the development of smart and precision farming technologies (Botero-Valencia et al., 2022).

2.4.2 TYPES OF PCBs AND THEIR APPLICATION

There are a number of types of Printed Circuit Boards (PCBs) that are aimed at a particular performance requirements and environmental conditions. The type of PCB used in agricultural and industrial systems is determined by the power demand, complexity of the circuits, exposure to the environment and compact or flexible enclosures (T M et al., 2025a).

- i. Single-sided PCB:** This PCB is of single conductive copper layer and the components are put on the one side and the circuitry is etched on the other. Low-budget agricultural uses like soil moisture sensors, temperature sensors, and simple irrigation controls such as relays and pump are the best-suited application of these boards since it is cheap and simple to manufacture low-cost boards. Single-sided PCBs are simple enough, in spite of their lack of functionality, to be used in simple systems that do not need complex circuitry.
- ii. Double-sided PCB:** This PCB is one with copper boards on both sides of the board. All of these layers are linked with vias, small holes that can conduct signals between sides thus permitting more developed routing of circuits and a unification of components. PCBs with two sides are typically used in relative complex agricultural systems such motor drivers, automated irrigation drivers, and wireless communication. They are highly favoured because of their moderate cost and performance in the usage of IoT-based agricultural appliances in need of various sensor platforms and the ability to transmit data.
- iii. Multilayer PCB:** This PCB is the most superior type that has three or more conductive layers with insulating materials in between. This design enables high-

density circuit designs, increased signal integrity and minimized electromagnetic interference. Multilayer PCBs are common in advanced agricultural systems including self-driven weather stations, automated irrigation systems, and environmental monitoring equipment that uses internet of things. Its large data processing capacity and effective communication would mean that it is suitable to be used within smart farming applications that require real-time control, automation, and scalability.

2.4.3 ROLE OF PCB IN SMART FARMING AND IOT DEVICES

The design and application of Printed Circuit Boards (PCBs) in the agricultural systems today are crucial in coming up with efficient, compact, and intelligent technologies that will establish the future of agriculture. PCBs allow combining various types of sensors (temperature, humidity, atmosphere pressure, rainfall, wind speed, light intensity, etc.) into one properly organized board (T M et al., 2025b). Such structured design allows maintaining steady power flow and consistency of communication among all electronic parts, which contributes to the increased functionality, effectiveness, and accuracy of agricultural equipment. The ability to promote autonomous and sustainable mode of operation is one of the major benefits of PCB-based agricultural systems. PCB enables uninterrupted environmental check and data gathering without necessarily having external sources of power. It also facilitates wireless communication by using technology like the Wi-Fi or 3G where real-time transmission of data is made to the cloud-based systems. This interconnectedness enables farmers and other professionals in the field of agriculture to have a remote view of what is going on in the field, manage resources effectively, and make timely and data-driven decisions (Botero-Valencia et al., 2022).

2.5 PCB DESIGN CONSIDERATIONS IN VERTICAL FARMING

When creating a Printed Circuit Board (PCB) to be used in vertical agriculture, there are some important considerations that shall be made to achieve efficiency, reliability, and flexibility to the agricultural conditions. The PCB is the basis of the integration of sensors, microcontrollers, and actuators, which integrate to automate the irrigation process, and

hence is of paramount importance to the functioning of the design. The location of components, power, signal integrity, environmental protection (humidity and corrosion resistance), and maintenance simplicity, are of importance. An effectively designed PCB system not only boosts performance of the system, but also provides durability and scalability to the real-life vertical farming applications.

2.5.1 INTRODUCTION OF PCB IN AGRICULTURAL SYSTEMS

The electronic systems in smart agriculture today have a basic component of a Printed Circuit Board (PCB). It serves as a physical platform that connects vital elements of microcontrollers, sensors, relays, communication modules, and power circuits. With an automated irrigation system, the PCB simplifies the exchange of data among sensors like the soil moisture sensor, humidity sensor and temperature sensor and actuators like the pumps and solenoid valve among others and the control logic which dictates when and how irrigation is to be conducted.

2.5.2 ENVIRONMENTAL AND OPERATIONAL CHALLENGES

The environmental and operational challenges encountered in the design of Printed Circuit Boards (PCBs) in vertical farming systems challenge the overall reliability and performance of the system. The designs will be done in a manner that the boards must be not susceptible to varying levels of moisture, humidity, and temperatures. It should also be energy efficient in order to facilitate a continuous real time data collection and to save on energy. Stability of the circuit and correct calibration is necessary to minimize the interference of signals in order to maintain accuracy of sensor readings. Cost-effectiveness and the potential of the local manufacture of PCBs also play a fundamental role since they render smart farming technologies affordable to small and medium-sized farmers. Collectively, these features indicate the most significant points of developing powerful, effective, and sustainable PCB-based solutions to the modern agro-systems (agricultural systems).

2.5.3 COMPONENT PLACEMENT AND ROUTING

The layout of heat-generating and non-heat-generating parts may significantly improve thermal performance and electrical efficiency. The design also enhances efficient heat dissipation by placing high-power components strategically and also ensuring that electrical paths are kept to a minimum to reduce signal loss and resistance. Isolating the high-current or heat-generating parts of the system and keeping signal parts separate helps in enhancing system stability and reliability. Simulation-based tools could also be used to predict and deal with thermal hotspots in the design process. In the designing and installation of a PCB in a vertical farm irrigation system, the control circuitry is typically operated in a tight, damp environment, where poor heat removal can lead to component overheating or reliability failure but by observing the placement rules can allow the designers and the design to successfully locate the key components to minimize thermal accumulation such as relay, voltage regulators and sensors. However, the trace lengths between the microcontroller and sensors such as the DHT11 or soil moisture modules should be kept short to ensure signal integrity and to reduce electrical noise (Satomi et al., 2020).

2.6 ENVIRONMENTAL CONTROL SYSTEMS IN VERTICAL FARMING

Vertical farming environmental control systems are critical towards ensuring that the growth of plants is maximized and sustainability is achieved. They control temperature, humidity, nutrient availability, and control of pests and disease through high-tech solutions.

2.6.1 TEMPERATURE AND HUMIDITY CONTROL

Vertical farming systems are reported to be founded on controlled systems in order to maintain optimum temperature and humidity. These both are critical to the health and good growth of plants. In this regard, the advanced technology such as sensors and online systems are integrated to monitor and control in real time environmental parameters (Ahamed et al., 2023).

2.6.2 PEST AND DISEASE MANAGEMENT

Some of the techniques applied in vertical farming include integrated pest management (IPM), biological, and environmental modification in pest and disease control. The modern vertical farm systems have motion sensors to detect the presence of insects, pests and human beings in the farm. The controlled environment has its weaknesses and strengths, it may restrict the penetration of the pests but it may also cause the rapid spread in the system. This intensive supervision and proper control are, in turn, necessary and yet, as it makes use of these motion sensors, it reduces the speed of manual inspection, however, it warns or notifies in case a motion is detected only (Roberts et al., 2020).

2.7 META-ANALYSIS TABLE

Title	Author	Background	Objective	Methodology	Result	Research gap
Microcontroller-based Vertical Farming Automation System	Shomefun T. E, et al	There was need for sustainable solution that allows food crops to be cultivated efficiently within urban areas using minimal land, energy, and water resources.	To minimize power and water consumption involved in the cultivation of plants using a microcontroller-based vertical farming automation system.	Arduino Uno microcontroller was used to control the water irrigation using moisture sensors to monitor soil levels, Solenoid valves that can be activated by the microcontroller when moisture which trigger actions such as irrigation.	Food crops can now be cultivated easily in urban areas by planting in vertically stacked layers in order to save space and use minimal energy and water for irrigation.	There was limited monitoring of important parameters such as humidity, temperature, for environmental monitoring. Focused only on light control and moisture.
Design and implementation of the microcon	Tzu-ching chia et al.	Vertical gardens require efficient resource monitoring.	The aim of the work was to implement an automatic	Using the microcontroller, Analog-to-Digital Conversion (ADC), Low-	A cost-effective and energy-efficient control system for	The data gotten from the sensors were not integrated or stored in

troller control system for a vertical garden application		Low-cost and low-power control systems are essential for optimizing their performance in constrained environments.	irrigation and artificial sunlight control system using the PIC18F 4520 microcontroller for the control of soil moisture and sunlight illumination .	Power Precision Timer, Sleep Mode was utilized and the receiver circuit was designed with low input resistance to reduce noise and interference	soil moisture and sunlight was implemented successfully	a cloud for future references or for data analysis.
Design and Implementation of an Arduino Uno-Based Plant Soil Moisture and pH Sensing Monitoring System	Megh Sahasrabudhe et al	The manual monitoring of soil moisture and pH is tedious and time consuming so the consistent monitoring is essential for plant growth, especially in agriculture.	To develop an Arduino Uno-based system for automatic monitoring of soil moisture and pH levels to maintain optimal conditions for plant health.	An Arduino Uno microcontroller for control and processing while using soil moisture and pH sensors to acquire data and the data is visualised on an LCD and Serial Monitor for real-time parameters.	An Effective real-time monitoring system was developed and reduced need for manual intervention .	There was no automated form of irrigation/smart irrigation and therefore there is a high rate that water is wasted.
Automatic plant monitoring and control system	Harsh Malde et al	Technological advancements have allowed room for automation to ease this	To design and implement a smart plant monitoring and control	An Arduino Uno microcontroller with a GSM module is used and used to get	A real-time monitoring and automated soil moisture	There was no mention that the data was stored in the cloud

		burden of manually monitoring the growth of plant and the health of this plant which can be difficult and time consuming.	system using Arduino Uno, that utilizes GSM-based communication for remote updates and also monitoring.	data from the sensors HL-69 (soil moisture), DHT-11 (temperature and humidity) displays it on a 16x2 LCD display and using actuators automatically control the irrigation system and also control the moisture of the soil based on the range.	control system was achieved whereby the user receives updates via GSM.	for further analysis. This data are sent as text message
IoT-Based Framework for Smart Agriculture	Jian Yang et al	A framework for agricultural field monitoring and irrigation control is proposed using the concept of IoT. Internet of Things provides an efficient solution for smart agriculture and proves its importance for helping farmers by increasing the overall productivity.	To Develop a smart agriculture framework using sensor networks and IoT for enhanced data collection, monitoring, and precision control in farming practices.	Arduino Uno microcontroller connected to the internet with the use of a GSM module was used with smart sensors to monitor soil moisture, temperature, and humidity and the data gotten are been stored and analysed using Thing Speak cloud.	Environmental and soil parameters data were collected successful and stored in cloud and this real – time data were used for data analysis and to enable smart irrigation system	There is no mention of sensor that is used to detect if there is appearance of pests and also the data of soil nutrients in the soil was gathered for further analysis
Design, Constr	Muhammad E. H.		To design and build an	Used an Arduino Uno	A hydroponics	Water consumption

ction and Testing of IoT Based Automated Indoor Vertical Hydroponics Farming Test-Bed in Qatar.	Chowdhury et al		indoor automatic vertical hydroponic system suitable for growing common crops in harsh Gulf region climates, using IoT for monitoring and microcontroller-based automation.	mega as the main microcontroller to interact with sensors to get data based on different parameters and the control system parameters and also power consumption data was also collected as well as an IoT platform was integrated for monitoring and remote access.	automated based system that deals with real-time data and remote monitoring was developed and the system maintained healthy plant growth conditions with minimal human intervention	n is high which leads to wastage as well, high consumption of nutrients, there is a lot of power consumption and also the system is not yet tested for diverse crops or extreme outdoor environment
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2.8 RELATED WORKS

This work focuses on irrigation systems based on the IoT, with the accentuation on the incorporation of sensors, automation methods, and wireless communication tools. It shows how through these systems real-time monitoring of soil moisture, temperature and environmental conditions can be done to achieve water efficiency and increase crop productivity (García et al., 2020b).

This study introduces a microcontroller-based vertical farming system of urban farming. It uses drip irrigation on a soil-moisture reading that is automated to save water, energy and provide the optimum growing condition with a vertical configuration. The system has shown to be effective in terms of its efficient utilization of resources in high-density farming (Emmanuel et al., 2018).

The current research project creates an inexpensive IoT based irrigation system that will incorporate several sensors and will enable automated water flow. It prioritizes low cost, simplicity, and simple integration with existing systems, which makes smart irrigation possible in the case of small-scale and educational farm systems (Puig et al., 2022).

This paper presents a microcontroller-based control system that can be used in vertical gardens. It focuses on automating environmental management activities including irrigation and monitoring of conditions to facilitate healthy growth of the plants and efficient use of resources (Chia & Lu, 2011).

In this paper, a monitoring system is designed using Arduino Uno to monitor the soil moisture and pH levels in plants. The system can irrigate automatically using real-time sensor data, improving the utilization of water and promoting the healthy growth of plants (Sahasrabudhe et al., 2023).

CHAPTER THREE

(METHODOLOGY)

3.1 SYSTEM OVERVIEW

The Vertical Farm Irrigation System is an automated microcontroller-based solution designed to optimize water delivery and environmental monitoring in vertical farming. Its main goal is to ensure healthy plant growth by maintaining optimal soil moisture, temperature, and humidity levels, thereby preventing over- or under-watering while conserving water resources. Unlike traditional systems that rely on manual surveillance and watering, this system enables efficient, consistent, and controlled irrigation with minimal human intervention.

The system integrates key components such as the ESP32 microcontroller, soil moisture sensor, DHT11 temperature and humidity sensor, and a relay-controlled water pump. The sensors continuously collect environmental data, which the ESP32 processes to decide when irrigation is needed. The DHT11 monitors environmental temperature and humidity, while the motion sensor provides security and detects pest activity while the relay module automatically activates the water pump when soil moisture levels are low. Additionally, an I2C LCD display provides real-time feedback to the farmer, showing sensor readings and system status locally.

All components are mounted on a custom-designed PCB, which enhances the system's durability, compactness, and ease of maintenance. The PCB-based design ensures signal stability and energy efficiency while providing a scalable platform suitable for small to medium-scale vertical farms. Overall, the system promotes automation, reduces water and labour costs, and supports precision agriculture through real-time monitoring and intelligent control.

3.2 SYSTEM ARCHITECTURE

The vertical farm irrigation system is constructed as a unified, mechanized site to effectively control water supply as well as to observe environmental factors in a vertical farm. Its architecture integrates sensing, processing, actuation, interface, communication and power management into an integrated system. The Vertical Farm Irrigation System

architecture is designed into several functional layers which interact and coordinate to monitor and regulate the farm environment. This starts with the sensing layer which gathers real-time data about the environment. This is then succeeded by the control and actuation layers which handle the processing of data and carrying out irrigation actions. Lastly, the interface and communication layer control the display of data and remote monitoring. A combination of these layers provides efficient data gathering, decision-making, and the running of the system.

The sensing layer consists of the temperature and humidity sensor, which monitors the environmental conditions to ensure optimal growth of the plant; the soil moisture sensor, which analyses the content of water in the soil to determine the irrigation requirements; the motion sensor (PIR), which check the environmental activity or to provide security and the battery monitor to monitor the power supply so that the device can operate continuously. The control and actuation layer include ESP32 microcontroller which utilizes sensor data to perform irrigation logic, and the firmware logic which includes decision-making algorithms and communication protocols. It also consists of the relay module, which is a component that is safe and can interface the microcontroller with DC water pump and the DC water pump, which can be used to deliver water to the plants when the sensor readings allow.

The interface and communication interface use a 16x2 LCD display with real-time display of sensor values, battery status and system notices and a Wi-Fi/GSM module to allow monitoring of the system remotely, log data and send alerts. Lastly, the power layer has a regulated power supply unit that gives constant voltage on all the components of the system leading to sound operation of the entire system. Its architecture is focused on modularity and the layer-based design, with each layer processing certain functionalities without interfering with others. This design can guarantee reliability, scaling, and energy efficiency, which are essential in the current vertical farming systems.

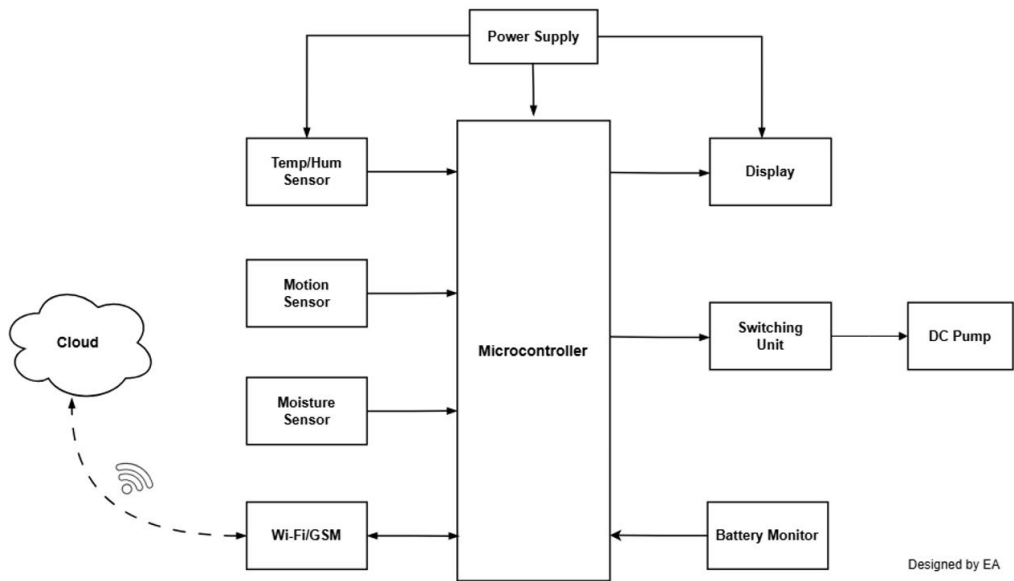


Fig 3.1: Simple Block diagram of system architecture

Figure 3.1 represents the block diagram of the proposed Vertical Farm Irrigation System. It shows how the different functional parts that constitute the system interact. The system will watch environmental conditions including the soil moisture, temperature and humidity and automatically apply irrigation by using a microcontroller-based platform.

3.3 SYSTEM OPERATION PRINCIPLE

The working principle of the Vertical Farm Irrigation System is a matter of automatic identification of environment conditions and smart control of the irrigation with the help of microcontroller-based mechanism. The system is a combination of sensors and actuators in a printed circuit board to enable fine monitoring and control of water flow in a vertical farming system.

On powering up the system, the microcontroller (ESP32) bootstraps all the modules that have been connected on it such as the sensors, the relay, and the communication interfaces. The water content of the soil is constantly measured by the soil moisture sensor and the ambient temperature and humidity are monitored by the DHT11 sensor. The motion sensor (PIR) will detect motion in the farm area which can be utilized in either

activating the system or the conservation of energy like dimming displays when there is no motion.

The microcontroller sends message or signals to the ADC (Analog-to-Digital Converter) which processes the analog signal of the soil moisture sensor and converts it into a digital signal. This value is compared by the microcontroller to a preset value which is the optimum soil moisture value. In case, if the measured value is lower than the threshold, which means that the soil is dry, the microcontroller switches to the relay driver circuit and energizes the DC water pump to irrigate the soil. The microcontroller stops the pump when the desired level of soil moisture is achieved to avoid cases of overwatering.

During this process, the display unit indicates real time sensor values and the battery monitor ensures that the system is not being overpowered. The ESP32 also handles data communication with the cloud via Wi-Fi or GSM connection allowing users to monitor the performance and conditions of the environment of the system remotely with the help of an IoT interface. This system is self-directed, external to the environment by detecting environmental parameters, undertaking logical decisions according to set programmed thresholds and carrying out control actions. This closed-circuit functioning can guarantee effective water management, constant environmental conditions and a better sustainability in the vertical farming applications.

3.4 HARDWARE DESIGN AND COMPONENTS

The Vertical farm Irrigation System hardware design is a combination of various electronic parts which together perform sensing, control, and actuation functions. A printed circuit board (PCB) is used to implement the entire circuit, thus making it more compact, more reliable and easier to maintain. The microcontroller, sensor modules, relay and pump control unit, and the power supply section are the primary hardware components.

3.4.1 MICROCONTROLLER (ESP-32 DEVKIT-V1)

The ESP-32 DEVKIT-V1 is a microcontroller and this microcontroller is the central processing unit that is in charge of all the sensing, processing, and control activities in the system. The ESP-32 coordinates the sensors, relays, and other modules involved in the connection so that the automation of the irrigation processes is highly effective.

It is a 5V microcontroller that is built in with Wi-Fi and Bluetooth, which enables smooth wireless operation and remote monitoring. Making it very applicable in the real-time data acquisition and control fields, it has a dual core processor and several GPIO pins. The ESP-32 is connected to the peripheral devices by the common protocols like I2C, SPI, and UART, which increases its adaptability and versatility in the design of the embedded systems.

Key Specifications:

- i. **Operating Voltage:** 5V
- ii. **Logic Voltage:** 3.3V
- iii. **Flash Memory:** 4 MB
- iv. **SRAM:** 520 KB
- v. **Input Voltage:** 7–12V (via VIN or USB)
- vi. **Digital I/O Pins:** 30 (with multiple PWM outputs)
- vii. **Analog Input Pins:** 12-bit ADC
- viii. **Communication Protocols:** I2C, SPI, UART, Wi-Fi, Bluetooth

The ESP-32 DEVKIT- V1 collects data on the related sensors which include soil moisture, temperature, and humidity sensors. It processes the data to calculate the need of irrigation, activates the relay to turn on the pump, and sends real-time data to the monitoring interface to be displayed. It is fitted in a printed circuit board (PCB) making it compact, efficient and reliability in the system is enhanced.

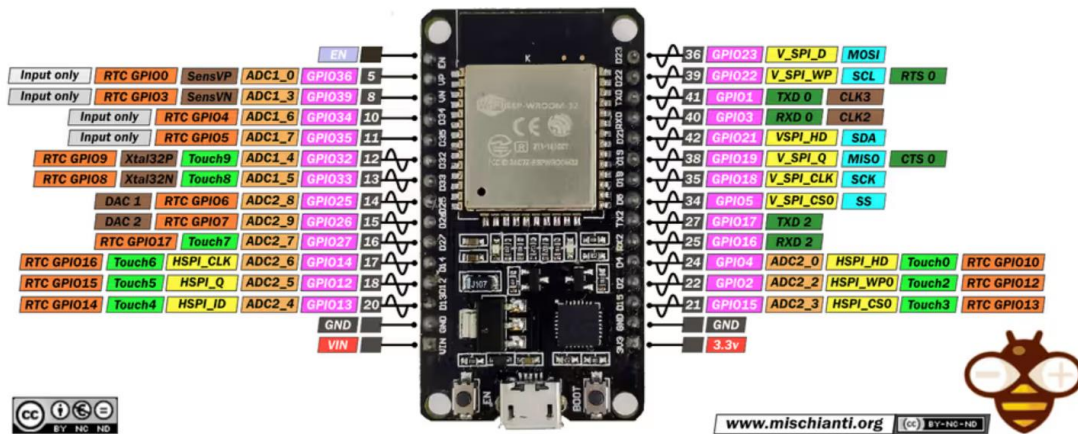


Fig 3.2: Microcontroller (ESP32-Devkit-V1)

This ESP-32 DEVKIT- V1 is reliable because of its flexibility and ability to consume very little power and incorporation of various functionalities into an already compact system. It has a fast processing speed and wireless communication capabilities which avoids the implementation of external network modules reducing the cost and circuit complexity. Moreover, it has a broad community base, convenient to program due to the Arduino IDE, and can work with many sensors, and is, therefore, very appropriate when it comes to research and prototyping in embedded and IoT-based agricultural systems.

3.4.2 GSM MODULE (SIM800L)

The GSM module as applied to the Vertical Farm Irrigation System is the SIM800L which is a small high-cost effective GSM/GPRS module that facilitates wireless communication between the microcontroller and external communication devices or cloud platforms. It enables the system to receive and send data through SMS or internet thus offering a remote access and control of the irrigation operations.

SIM800L uses quad-band frequencies (850/900/1800/1900 MHz) and thus has a strong network connectivity in most locations. It has a serial communication (UART), so can be connected with ESP32 microcontroller and has features SMS messaging, voice call and GPRS data transfer.

Key Specifications:

- i. Operating Voltage: 3.4 – 4.4 V DC
- ii. Communication Interface: UART (AT commands)
- iii. Quad-band GSM/GPRS network coverage
- iv. GPRS multi-slot class 12 communications
- v. Compact design for easy PCB integration

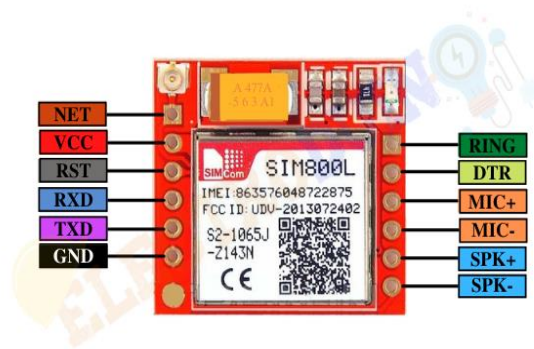


Fig 3.3: SIM800L

The SIM800L module will be preferred since it will be an easy and convenient way of remote communication and the irrigation system can communicate sensor data or notifications to users through SMS or the internet. Its small size, low power consumption and compatibility with ESP32 makes it a perfect solution to embedded IoT integration projects such as vertical farm irrigation where real-time monitoring and control is necessary even when in locations lacking Wi-Fi.

3.4.3 CAPACITIVE SOIL MOISTURE SENSOR

The Capacitive soil moisture sensor measures the water content of soil and the sensing element is not in direct physical contact with the soil. It also records the moisture content which is detected as changes in capacitance unlike resistive sensors which give less accurate yet durable measurements. The result is an analog voltage, which changes with soil moisture level, that will be inputted into the ESP32 to be processed and another decision made regarding irrigation.

Key Specifications:

- i. Operating Voltage: 3.3V – 5V
- ii. Output Type: Analog
- iii. Sensing Principle: Capacitance change
- iv. Corrosion-resistant design

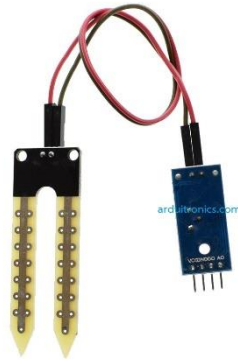


Fig 3.4: Capacitive Soil Moisture Sensor

The capacitive soil moisture sensor has been favoured by its high durability, non-corrosion ability and ability to measure the soil moisture at different conditions. The use of its analog output makes it readily compatible with ESP32 microcontroller, which will provide a reliable means to detect soil dryness and control the irrigation pump behaviour, thus making maximum use of water resources.

3.4.4 DHT11 (TEMPERATURE AND HUMIDITY SENSOR)

DHT11 sensor is used to measure temperature and relative humidity which are vital measurements that can be used to sustain the best conditions under which plants grow. It has a thermistor, which measures temperature and a capacitive humidity sensor, which measures the price of moisture in surrounding air. The sensor sends digital information to the ESP32 in order to monitor the environment in real-time.

Key Specifications:

- i. Temperature Range: 0°C to 50°C ($\pm 2^\circ\text{C}$ accuracy)
- ii. Humidity Range: 20% – 90% RH ($\pm 5\%$ accuracy)

- iii. Operating Voltage: 3V – 5V
- iv. Single-wire communication digital output

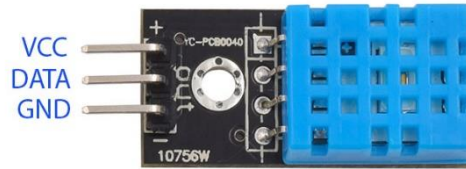


Fig 3.5: DHT11 Sensor

The reason why DHT11 is chosen is that it is easy, cost-effective, and consumes less power to check the temperature and humidity. Its ability to be compatible with ESP32 and stable digital output allows it to be used in the maintenance of the required microclimate to allow crop growth in a vertical farming setup.

3.4.5 PIR MOTION SENSOR

Passive Infrared (PIR) motion sensor is a sensor that determines the movement of a human being or an animal within its line of view based on the changes in the infrared radiation. It improves the system with an added security feature that identifies intruders or movement in the farm premises so as to protect the system.

Key Specifications:

- i. Operating Voltage: 4.5V – 20V
- ii. Detection Range: Up to 7 meters
- iii. Output Type: Digital (HIGH/LOW signal)
- iv. Variable delay and sensitivity



Fig 3.6: PIR Motion Sensor

The PIR motion sensor is selected because it offers a relatively cheap and low-powered method of motion detection. Its extensive detection and simple integration with the ESP32, allow useful tracking of human or animal movement as this provides an enhanced security to the vertical farm installation.

3.4.6 LCD DISPLAY MODULE (16x2)

The Liquid Crystal Display (LCD) is a 16x2 graphic display that is used as the visual interface of the Vertical Farm Irrigation System. It shows real-time parameters of the system which include soil moisture level, temperature, humidity, pump status and network connection status. This enables one to track environmental conditions, as well as the working state of the system without involving any third-party equipment and software.

LCD works based on the principle of liquid crystals in which the alphanumeric characters are formed out of the liquid crystals by arranging them to block or unblock light exposure to electric fields. It is connected to the ESP32 microcontroller via an I2C module and allows connection pins to be shortened to 4 instead of 16, allowing it to be wired and PCB-designed more easily.

Key Specifications:

- i. Display Format: 16 characters 2 lines
- ii. Operating Voltage: 5V DC
- iii. Serial communication interface: I2C
- iv. Character Type: Alphanumeric (5x8 pixel matrix each character)
- v. Backlight: LED (brightness can be changed)

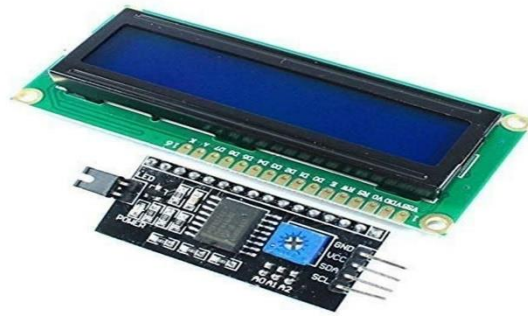


Fig 3.7: 16x2 LCD Display Module

The 16x2 LCD is the choice due to the fact that it offers an easy, low-cost, and low-power means of information representation of the key system. Its I2C compatibility allows it to easily be combined with the ESP32 and use other GPIO pins elsewhere. It is also provided with the ability to see, stay and also provide a real-time feedback that is necessary to monitor the field area in a vertical farm environment.

3.4.7 LM2596 BULK CONVERTER

The integrated circuit here is in the power supply unit which provides the required and constant voltage that is needed to run all the parts of the Vertical Farm Irrigation System. The system takes 12V DC as an input, which is reduced to 5V DC by an LM2596 buck converter IC. This controlled 5V supply drives the ESP32Microcontroller, sensors, and other low voltage peripherals in the circuit.

LM2596 is a step-down (buck) voltage regulator with high efficiency that has the ability to supply up to 3A of continuous load current with high line and load regulation. It instead of the linear regulation utilizes a switching method which lowers the amount of heat generated thereby guaranteeing greater power efficiency which is paramount in the constant operation of a programmed irrigation setup.

Key Specifications:

- i. Input Voltage: 4V – 40V DC
- ii. Output Voltage: Adjustable (1.23V – 37V DC)
- iii. Output Current: Up to 3A

- iv. Conversion Efficiency: Up to 92%
- v. Switching Frequency: 150 kHz



Fig 3.8: LM2596 IC

The LM2596 is suggested as it is known to offer a stable power supply, as well as make the power supply to the whole system efficient and reliable and allow only minimal power loss. Its capability to reduce its input voltage from 12V to 5V when needed can be considered ideal to power ESP32 and sensors without raising operational temperatures. Also, it is small, cheap, and simple to fit on the PCB, and thus is suitable in embedded systems, such as this Vertical Farm Irrigation System, where long term stability and power efficiency are very important.

3.4.8 RELAY AND PUMP

The main purpose of the relay is to regulate the work of the water pump according to control signals of the ESP32 microcontroller. On sensing dryness or if it is below the threshold value, the soil moisture sensor will trigger the ESP32 to provide a signal to the relay module to activate the water pump. When the soil has attained the required moisture content or it is above the defined threshold value, then the relay switches off the pump, thereby saving water and therefore achieving effective irrigation. In this unit, a single-channel 12V relay module is used, and it is the product that offers the connection between the ESP32 control circuit and the high-power water pump. The 12V supply drives the relay coil and the control pin of this relay is connected to the ESP32 in a transistor driver circuit to amplify the signal and provide electrical isolation.

Key Specifications:

- i. Relay Type: Electromechanical single channel relay
- ii. Operating Voltage: 12V DC
- iii. Switching Capacity: 10A 250V AC / 10A 30V DC
- iv. Input Control: ESP32 Logic signal (through transistor driver)
- v. Isolation: Relay Module, optocoupler protection (on certain relay modules)



Fig 3.9: 12V Pump and 12V SPDT Relay

The 12 V relay is used as it can provide a stronger coil actuation and superior electrical isolation over the 5 V relays and thus it is more dependable to control inductive loads such as water pumps. It is capable of operating with increased current and voltage with high safety, which guarantees high durability and constant switching behaviour. The fact that it is compatible with the 12V power supply line within the system also makes it easy to wire and it minimizes losses in converting voltages. It is therefore the best fit in this automated irrigation system where reliability and safety are of paramount importance in order to ensure that the system operates continuously.

3.4.9 ANALOG TO DIGITAL CONVERTER (ADS1115 IC)

ADS1115 will be a high-precision 16-bit analog-to-digital converter (ADC) in the Vertical Farm Irrigation System to enhance the precision of the analog sensor readings, and in specific cases, the capacitive soil moisture sensor. Because the number of analog-to-digital conversion channels available internally on the ESP32 may be slightly

nonlinear and noisy in its higher resolutions, the ADS1115 may be used to offer a more solid and accurate conversion of analogue signals into digital values to enhance system decision-making. The ADS1115 is a device that interacts with the ESP32 microcontroller through the I2C (Inter-Integrated Circuit) protocol and communication via two data lines only (SDA and SCL). This lowers the wiring complexity and also ensures stability in the transmission of data. The module has four single ended or two differentials inputs enabling several analog sensors to be connected at the same time.

Key Specifications:

- i. Resolution: 16-bit
- ii. Interface: I2C (capable of supporting 860 samples/second)
- iii. Input Channels: 4 single-ended / 2 differentials
- iv. Operating Voltage: 2.0V – 5.5V
- v. Input Type: Analog (voltage-based sensors)
- vi. Pin Count: 10 pins

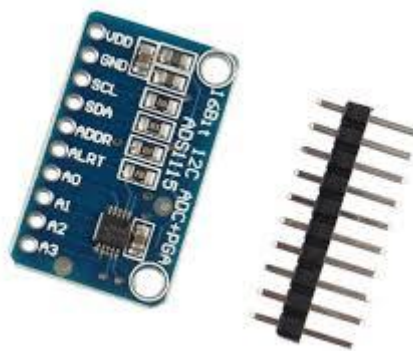


Fig 3.10: ADS1115 ADC

ADS1115 is the Analog to Digital Converter that provides high-resolution and noise-free analog numbers, which is extremely significant in the correct soil moisture and environmental measurement. It also has an I2C interface, thus can be used with the ESP32 without consuming too many of the GPIO pins. It also has a small format size, consumes less power and can accommodate many input channels hence a good component in embedded systems like in this Vertical Farm Irrigation System where the accuracy and efficiency are important factors in enabling automation.

3.5 PCB DESIGN AND LAYOUT

This section provides an explanation of how the designed, simulated, and created printed circuit board (PCB) of your vertical farm irrigation system was created. It is aimed to demonstrate how all the parts (ESP32, sensors, relay, power converter, etc.) were laid out and connected on a small, robust and practical board.

3.5.1 SCHEMATIC DESIGN USING KICAD

The Vertical Farm Irrigation System schematic design was created with the help of the KiCad (version 9.0.2) a free and open-source EDA software, and it is used to automate electronic design. The schematic is the graphic depiction of the rational relationships among all the circuit components and the starting point of PCB layout generation. It is subdivided into a number of functional sections as shown below.

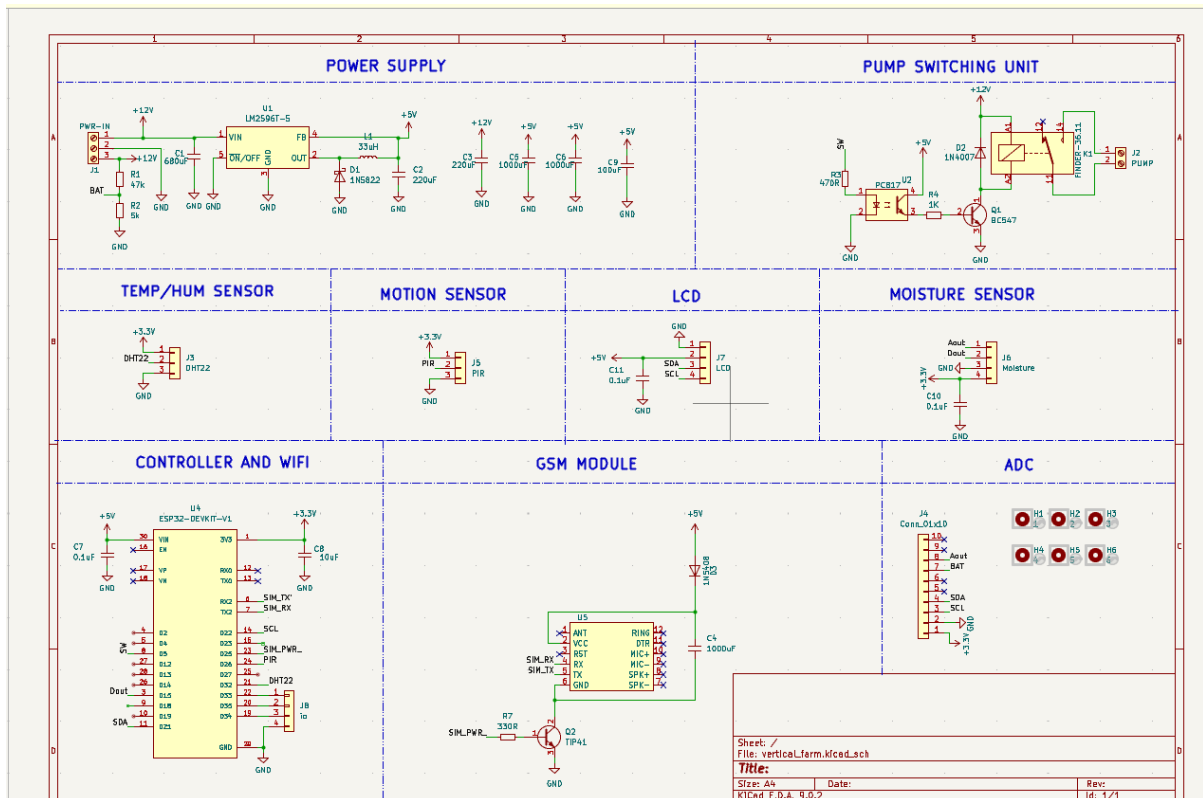


Fig 3.11: Schematic Diagram of the Vertical Farm

3.5.1.1 POWER SUPPLY SECTION

The power supply part uses LM2596 buck converter to reduce the 12 V DC input voltage into a regulated 5 V output.

The ESP32 microcontroller, sensors, GSM, and ADC and display unit are powered by this 5V rail. This part includes the capacitors of the values 100uF, 200uF, and 1000uF to filter noise and stabilize voltage.

The LM2596 was used in this project because it has a good efficiency of up to 92 percent, compact and can operate on higher input voltages with minimal heat dissipation thus make it suitable in low power agricultural automation systems.

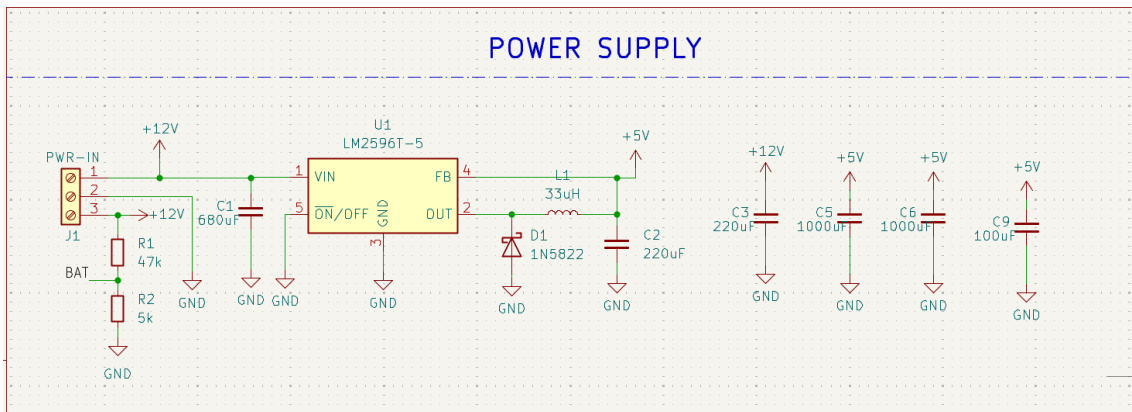


Fig 3.12: Schematic Diagram of the Power Supply

3.5.1.2 MICROCONTROLLER AND WIFI SECTION

The ESP32 DEVKIT-V1 microcontroller is also at the centre of the schematic which handles and does all the data processing, control, and communications.

It takes inputs in the form of sensors, control algorithms, ADC and manages the output devices. The ESP32 has a 3.3V logic operation with built in Wi-Fi and Bluetooth making it wireless and allowing it to be used in the transfer and monitoring of data.

The ESP32 was selected due to the fact that it has a dual-core processor, internal wireless features, low power usage, and several GPIO pins that it has, which makes it capable of being used in a smart irrigation system that is based on the IoT.

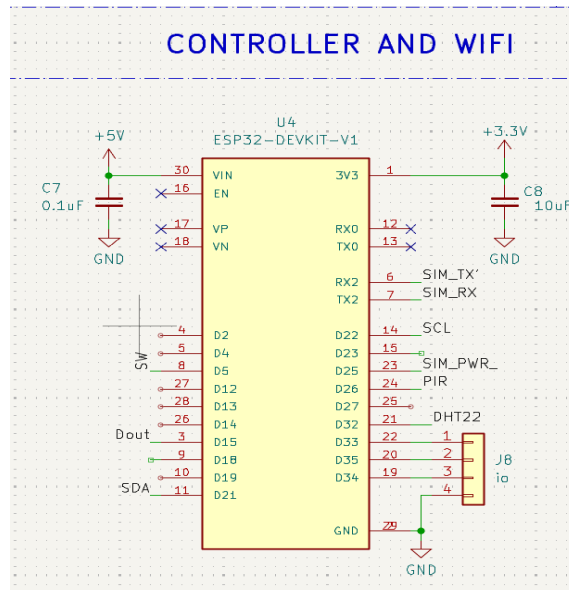


Fig 3.13: Schematic diagram of the ESP-32 Microcontroller

3.5.1.3 SENSOR SECTION

In this section, there are three major sensors that are used in monitoring the environment. Capacitive Soil Moisture Sensor monitors the level of soil moisture based on the variation of capacitance. It gives an analog signal and it is converted to digital form with the help of the ADS1115 ADC. The capacitive type was chosen because it had good durability and resistance to corrosion over resistive sensors.

The DHT11 Temperature and Humidity Sensor is a single-wire digital sensor that supplies the ESP32 with the temperature and relative humidity. This was selected as it is cheap, user-friendly and applicable in low-precision agricultural sensors.

The PIR Motion Sensor will be able to identify movement in the farm vicinity or environment and this may mean that there are people or pests around and detected. PIR sensor has been chosen due to the low consumption of power and the ability to detect.

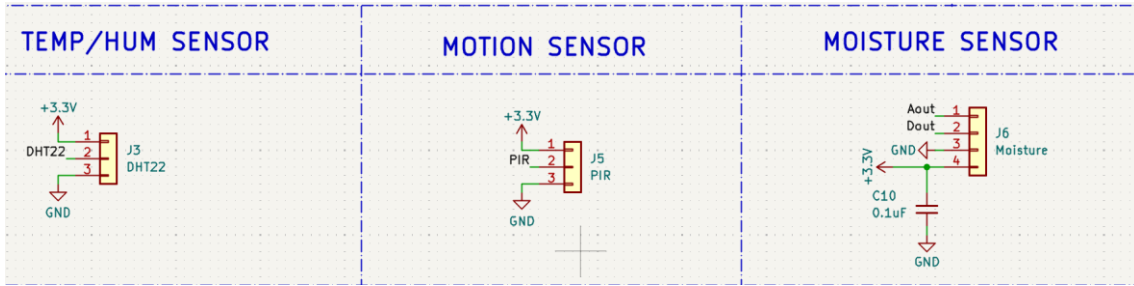


Fig 3.14: Schematic diagram of the various sensors

3.5.1.4 GSM COMMUNICATION MODULE SECTION

The SIM800L GSM module has SMS remote communications through status alert and notification. It is fed by a transistor driver (TIP41) and has filtering capacitors to even out the voltage fluctuations. The SIM800L was also chosen because it is small, consumes low power, and can be easily integrated with the ESP32 to have the system be able to work even in places where there is no Wi-Fi signal. It communicates with the ESP32 using the RX and TX pins by sending and receiving signals or information.

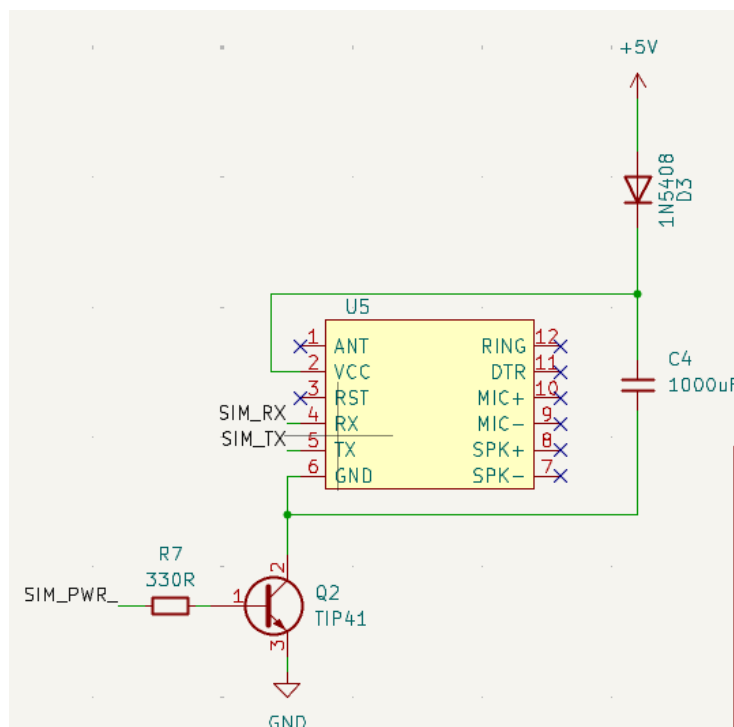


Fig 3.15: Schematic diagram of the SIM800L module

3.5.1.5 ADC INTERFACE SECTION

This ADS1115 10-pin ADC module is used to enhance and improve the accuracy of the analog signal gotten from the ESP32 or sensors. It can convert analog sensor data (particularly the soil moisture sensor) to 16-bit digital data with accuracy using the I2C protocol.

ADS1115 was chosen due to its high resolution, four channels input, and compatibility with ESP32, which provides a system with better sensor measurements and stability.

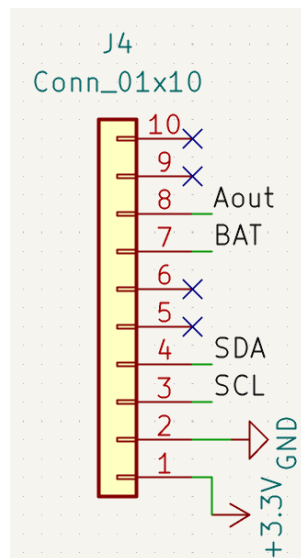


Fig 3.16: Schematic diagram of the ADC interface

3.5.1.6 DISPLAY SECTION

The ESP32 is connected to a 16x2 LCD display where the readings of the system such as temperature, humidity, soil moisture, and pump status will be displayed via an I2C interface. It has been selected as it is cheap, requires less power, and enables easy real time visualization of environmental data.

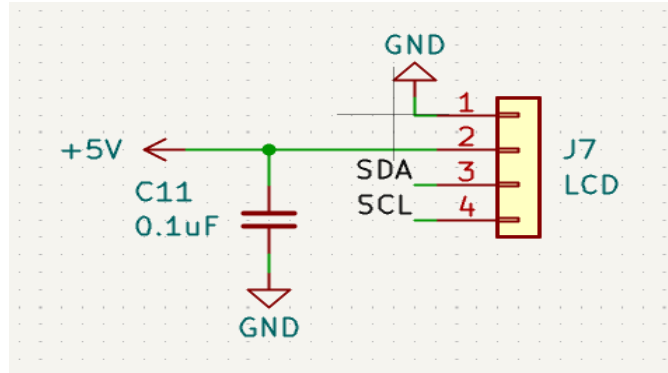


Fig 3.17: Schematic diagram of the LCD/ display

3.5.1.7 RELAY AND PUMP CONTROL SECTION

In this part, a 12V relay is mounted to switch on the operation of the water pump. A transistor (BC547) is used to drive the relay coil and an optocoupler (PC817) is used to isolate the two. The transistor is safeguarded by a flyback diode (1N4007), against reverse current during switching a relay. This arrangement provides a safe and secure system to switch between the low voltage control circuit and the high current pump.

The 12V relay was chosen because of its capability to serve a moderate load, availability and suitability to the power design of the system.

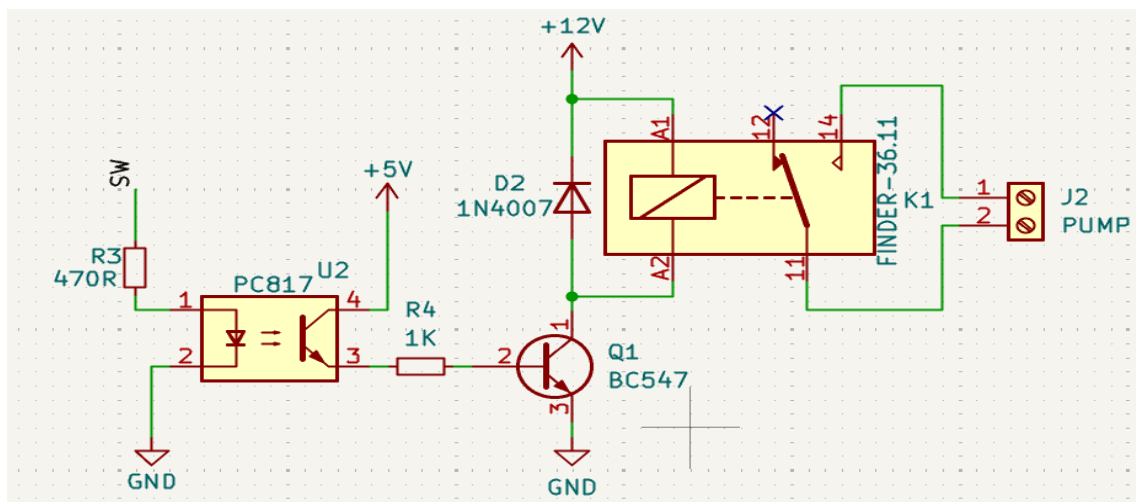


Fig 3.18: Schematic diagram of the relay and pump

3.5.1.8 CIRCUIT VERIFICATION

The schematic was checked through the Electrical Rules Check (ERC) of KiCad to verify the designers of the schematic like open nodes, short circuit, or unintentional nets before being transferred to PCB layout.

The verification was successful, and all pieces were properly interconnected, which guaranteed the reliability and functionality of the PCB design and fabrication phase.

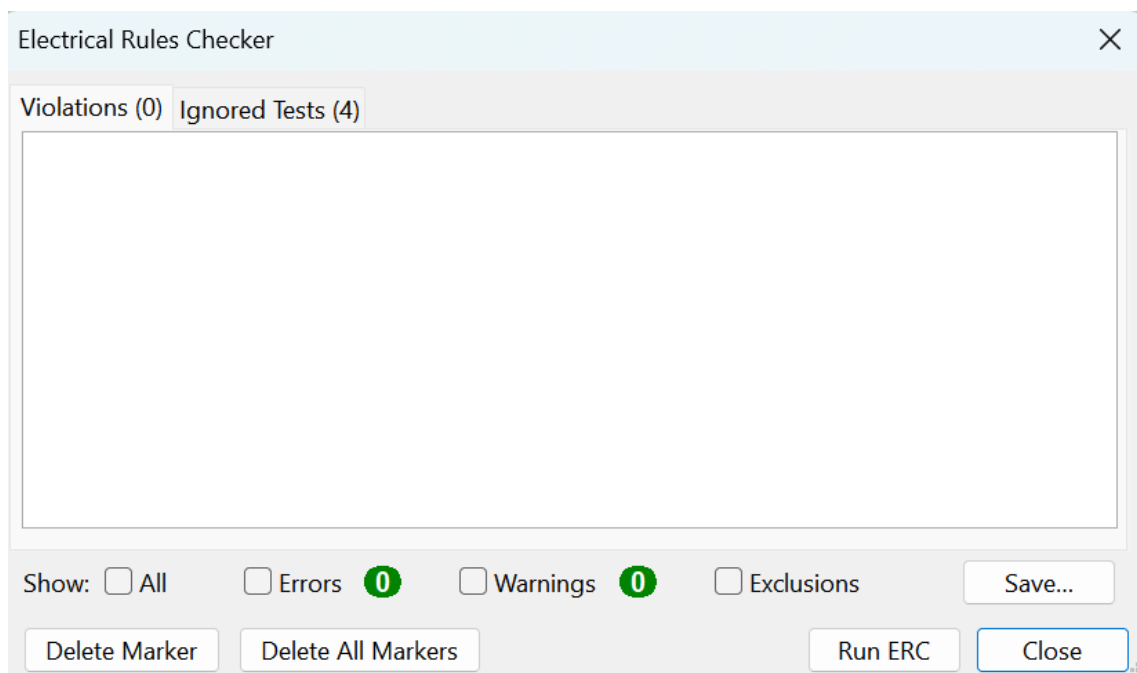


Fig 3.19: The Electrical rule check (ERC) with no errors detected.

3.5.2 PCB LAYOUT DESIGN AND ROUTING

The Printed Circuit Board (PCB) layout is the physical representation (implementation) of the circuit developed in the schematic. It gives the electrical interconnectivity between the elements in a small board and makes it efficient, signal integrity, and noise minimizing. KiCad was used to design and routed the PCB, with best practices of mixed-signal embedded systems.

The design was divided into functional blocks in order to make routing easier, minimize signal interference and enhance maintainability. The printed circuit board (PCB) was laid

This uppermost layer (red) carries the majority of the traces of power and signals, particularly those of the ESP32, GSM module, and sensors. The lowermost layer (blue) is utilized as the ground plane most of the time, and it offers a low-impedance return path to signals and minimizes electromagnetic interference (EMI). The separation provides cleaner signals and better system wide performance.

3.5.2.2 COMPONENT PLACEMENT

The location of the component was strategically positioned in such a way that there is efficient flow of the signal and less interference. The LM2596T-5 regulator, diodes, inductors, and capacitors are concentrated in the upper-left corner to concentrate the heat and ensure short thick power traces. The SIM800L GSM module is placed on the upper-right hand corner and does not have any connections to the high-speed digital signals, to create the minimum noise and achieve high stability of the network. The ESP32-DEVKIT-V1 is placed in the middle of the board, and it is the basal of control hubs with few traces towards the peripherals. The pump and relay control circuitry is located at the bottom-right corner in order to isolate high current switching with sensitive analog and communication areas. Finally, the sensor connectors such as the moisture sensor, temperature/humidity sensor, and motion sensor connector are on the left side of the board to be accessed easily as well as the organization of the wiring in the board.

3.5.2.3 POWER AND GROUND ROUTING

Power and ground routing was done to maintain the voltage stability and flow of current in the most efficient manner across the board. The 12V power input is fed into a screw terminal connector at the top-left and directly filtered, and then converted to 5V using the LM2596T-5 module. Power lines (12V and 5V) are done in wide copper traces to minimize voltage drops and also bigger current loads, particularly towards the relay and GSM module. The ground plane is continuous and diffused over the bottom layer to reduce the number of ground loops and voltage drop-offs. Ground vias are deliberately positioned close to the high current parts such as the relay coil and voltage regulator to enhance current flow as well as heat dissipation.

3.5.2.4 SIGNAL ROUTING AND TRACE OPTIMIZATION

Signal routing was done to optimally guarantee performance and reduction of interference. All high-frequency or analog signals were taken in short and direct traces to minimize the loss of voltage and noise. TX and RX signal pairs between the ESP32 and SIM800L were brought to the same line to minimize signal loss and noise pickup. The I2C lines of the temperature and humidity sensor were laid with almost the same length to ensure the appropriate timing and synchronization. The trace between the moisture sensor and the ESP32 ADC pin was shorted and kept isolated of high-current lines because this trace was part of the analog signal and noise was not to be coupled with the analog signal and give incorrect results.

3.5.2.5 THERMAL AND NOISE CONSIDERATIONS

The design considerations in this PCB were thermal management and noise suppression. LM2596T-5 voltage regulator and diodes have been placed and spaced with enough copper to facilitate the heat dissipation. Decoupling capacitors got as near to the power pins of integrated circuits as possible to filter transient noise. The GSM module includes a massive ground pour under the GSM to stabilize voltage and enhance grounding of RF. The isolation of relay switching traces around sensitive analog signal regions was also done to ensure that electromagnetic interference (EMI) did not cause sensor readings and microcontroller performance.

3.5.2.6 VIA USAGE AND LAYER INTERCONNECTION

The top and bottom layers were connected by means of vias so that the electrical performance should remain stable. Power vias were increased in size to support increased currents and also to offer a solid interlayer interconnection. Signal vias were reduced to a minimum and reserved to places of need to prevent the creation of resistance and inductors at fast signal paths. The positioning of the vias was optimally done to allow efficient routing as well as preserve the integrity of the power and ground connections.

3.5.2.7 CONNECTOR ORIENTATION AND ACCESSIBILITY

The connector orientation was made to be user friendly and easy to assemble. Each sensor

connector is located at the board edges as this enables simple connecting and disconnection in testing or in the field. The power and output points are well labelled to avoid errors in wiring to ensure reliability in connection. The ESP32 header and GSM module pins have also been situated in accessible positions and this enables the convenient programming, debugging or replacement of these components when the need arises.

To enable communication, power delivery and integration of external sensors, the PCB contains a few connectors as well as interface points. 12 V DC is supplied to the power input connector at the top-left corner and filtered and regulated to 5 V. The ESP32 header on the middle gives one access to GPIOs, ADCs, UART, lines to control sensors, the GSM module, and relay lines. The top-right connector is the SIM800L which also manages GSM communication by means of TX and RX lines and has a large capacitor of 1000uF which helps stabilize the current. The sensor connector pads, which are soil moisture, temperature/humidity, and motion sensor, are easily externally connected off of the left side, and the relay and pump output terminal on the bottom-right, supply external loads.

Connectors, relays and other mechanical stressed or high- current components were selectively done in the Through-Hole Technology (THT). This option will provide increased solder joint strength, mechanical stability and easy manual soldering in prototyping or repair. The THT parts are especially applicable in the power and relay parts where the current capacity and reliability are important.

3.5.2.8 DESIGN RULE CONSIDERATIONS

The whole PCB layout in Kicad passed the Design Rule Check (DRC) and has the right amount of clearance, trace width and pad spacing. Power traces (especially 12V and 5V) were made wider (about 50 mils) to allow greater current carrying capacity, and the normal signal lines are 10- to 15-mil wide. The board has holes to fit the board to the role of mechanical stability and to fit in an enclosure. Black silkscreen labels are organized properly and the font is clear so that it is easy to identify the components and fix them during the assembly.

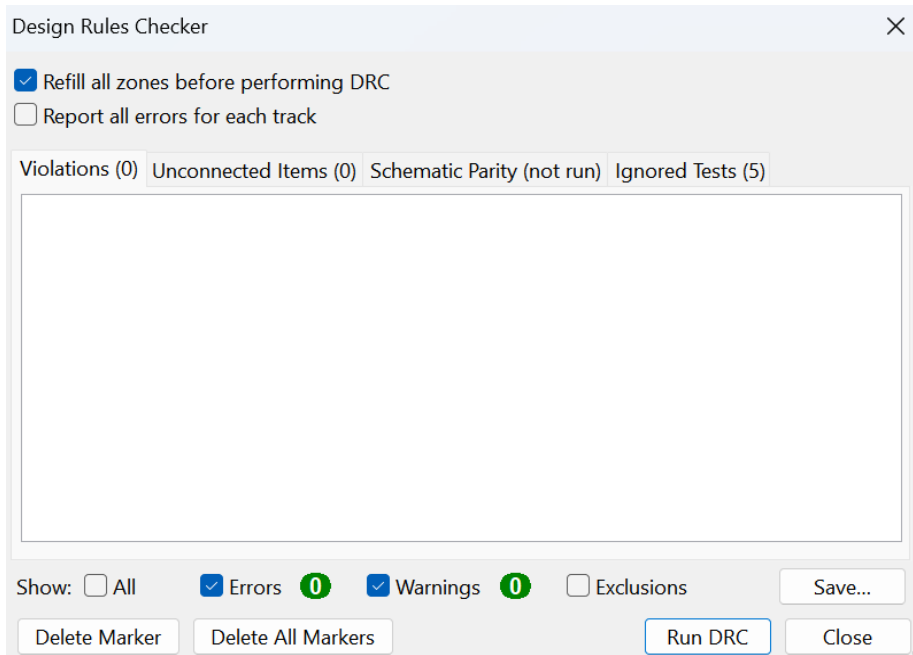
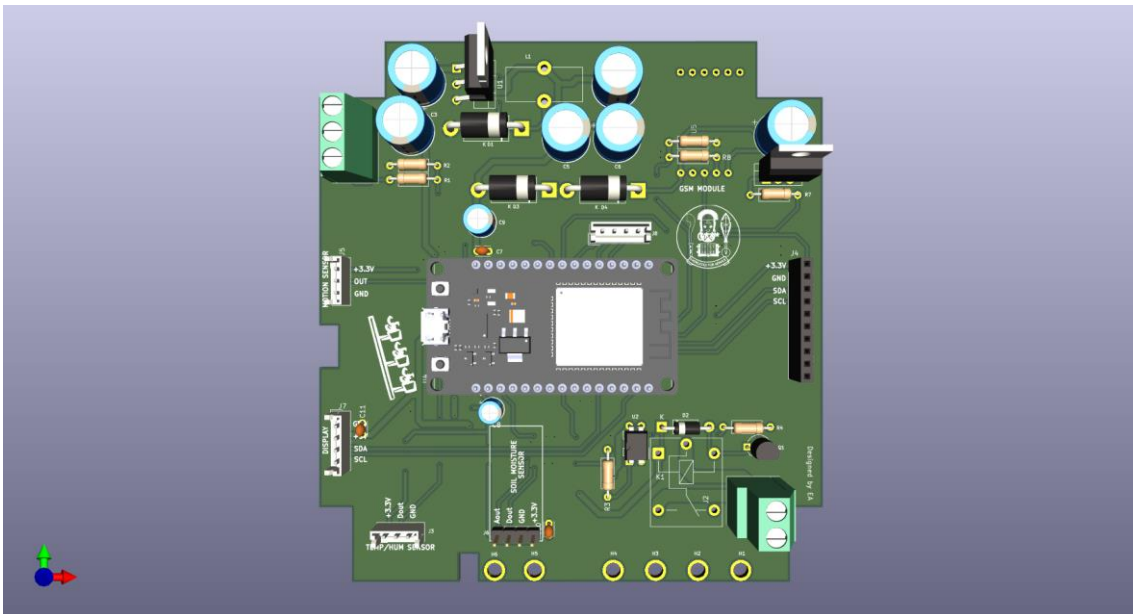


Fig 3.21: Design rule check (DRC) showing no errors detected.

3.5.2.9 3D PCB VISUALISATION



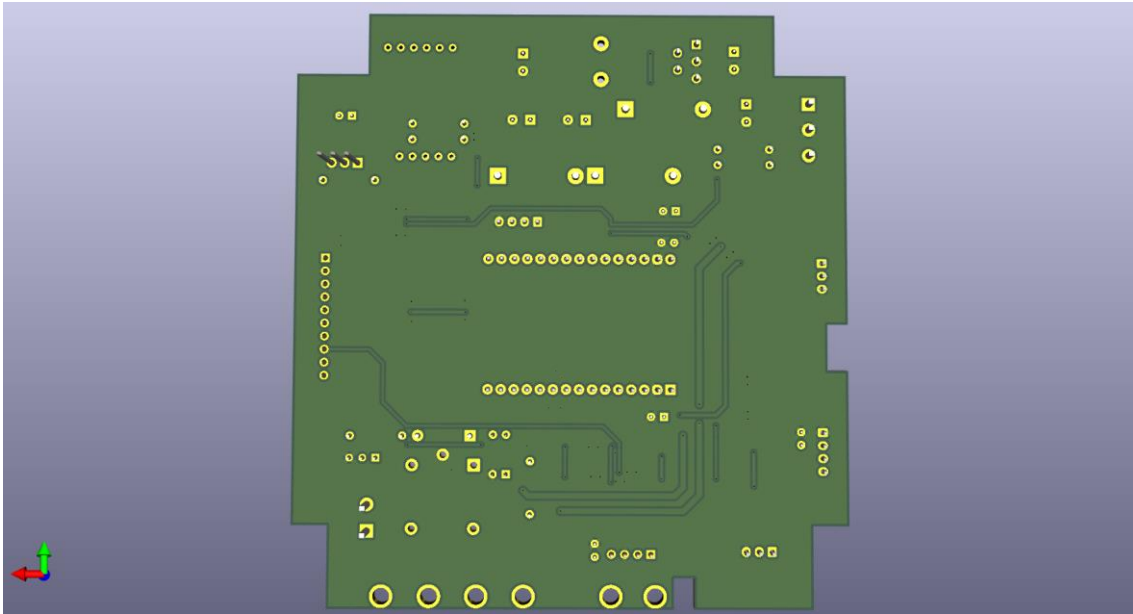


Fig 3.22: Diagram depicting visualisation of the PCB using the KiCAD Software.

The 3D PCB view is used to visualize the complete board in place displaying the layout of all the components, connectors and mechanical aspects. It is used in checking physical fit and clearance of components as well as overall aesthetics prior to fabrication. The connection of the ESP32, GSM module, relay, and sensor connectors can be checked using the 3D model to prevent the part of the components that are touching.

The visualization is also helpful to detect the clarity of the silkscreen, the locations of the mounting holes, and the accessibility of the connector which is very important when designing and planning assembly of the enclosure. It bridges the gap between electronic and mechanical design, so that the product in the end is not only functionally efficient, but also has a professional look. The 3D model is used to ensure that the components are placed in the most efficient way to be cooled, wired easily and installed safely as a mechanical component. It also enables early identification of any possible conflict that would arise like overlapping parts or connectors that would hinder wiring of pumps, valves, or sensors.

3.5.3 CREATION OF THE PCB AND SOLDERING

The design PCB was fabricated by JLCPCB, which is an online professional PCB manufacturing company. The finished schematic and PCB layout was initially exported

as Gerber, the Gerber format contains all the required design layers in the format of the top and bottom copper layers, solder mask, silkscreen, and drill files.

The design was checked with the help of KiCad, 3D viewer, and Design Rule Check (DRC) software to determine that all the electrical connections, hole sizes, and clearances were the required specifications and uploaded Gerber files to the JLCPCB site.

The board was made based on the following parameters:

- i. Board dimensions: 93 mm × 116 mm
- ii. Number of layers: 2 (double-sided PCB)
- iii. Material: FR-4 (Glass Epoxy)
- iv. Board thickness: 1.6 mm
- v. Copper thickness: 1 oz (35 μm)
- vi. Solder mask color: Green
- vii. Silkscreen color: White
- viii. Surface finish: HASL (Hot Air Solder Leveling)

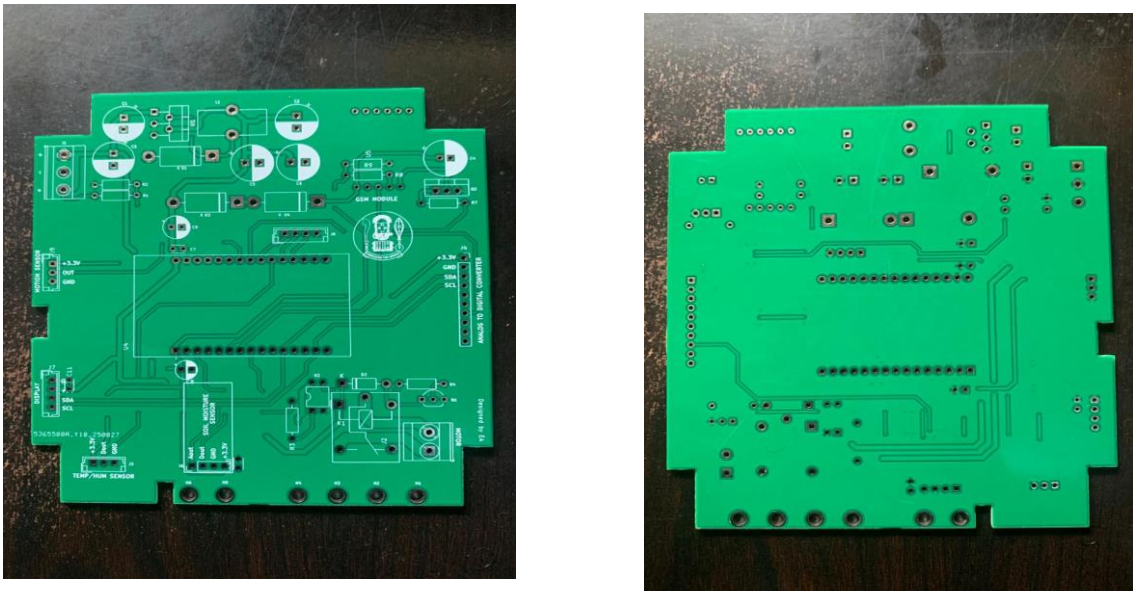


Fig 3.23: Diagram showing the fabricated PCB from the design.

Fabrication phase was completed and the PCB manufactured returned with correctly drilled holes, labelled well and smooth solder pads that can be used to finish component mounting.

The PCB Software used was Through-Hole Technology (THT), which was used to assemble the components onto the PCB. Electronic parts in this approach had leads of wire which were pushed into pre-drilled holes on the board and soldered to pads on the other side. This was selected due to mechanical strength, ease of manual soldering and applicability in prototyping and testing during small scale production.

Manual soldering was performed using a lead-free soldering iron and temperature-controlled soldering iron and lead-free solder. The assembly was done in a sequence, and a few passive components (resistors, diodes and capacitors) were assembled first, then connectors, relay modules, and then the ESP32 header pins. Precaution was observed to achieve the right orientations of polarized parts and the solder joints.

CHAPTER FOUR

(RESULTS AND DISCUSSION)

4.1 PCB DESIGN OUTPUT (SCHEMATIC AND LAYOUT VIEW)

KiCAD software was used to create the schematic and PCB layout to allow all the components of the Vertical Farm Irrigation System to be placed on one board. The schematic represented linkages between ESP32 microcontroller, soil moisture sensor, DHT11 sensor, PIR motion sensor, GSM module, relay circuit and power supply unit. The design had been well organized to reduce signal interference, effective current flow and clear routing of both analog and digital components.

The layout view focused on the layout positioning of the components, whereby the ESP32 module was laid in the middle of the layout to have easy access and routing balance. To eliminate the electromagnetic interference, the GSM module and relay circuit were installed on different sides, and capacitors and resistors were located close to their components to minimize noise. The last PCB was produced and soldered, resulting in a small and dependable board, which is capable of being deployed to automated irrigation.

4.2 SYSTEM ASSEMBLY AND IMPLEMENTATION

Then, components were soldered and placed on the PCB after fabrication. The ESP32 acted as a central processing unit and processed the input variations on the soil moisture sensor and the DHT11 sensor, and also manipulated the relay linked between the water pump and the sensors. The GSM module was also linked to allow remote communication in the future. The sensors were connected via clearly labelled headers making them simple to set up and maintain.

The modular layout also allowed easy troubleshooting during assembly and avoided wiring congestion, as was the case with Veroboard implementations. The small size also increased the physical strength of the system and its electrical performance. When the system was powered on, it started correctly and the sensors and modules were responding as expected demonstrating that everything was assembled and functioning properly.

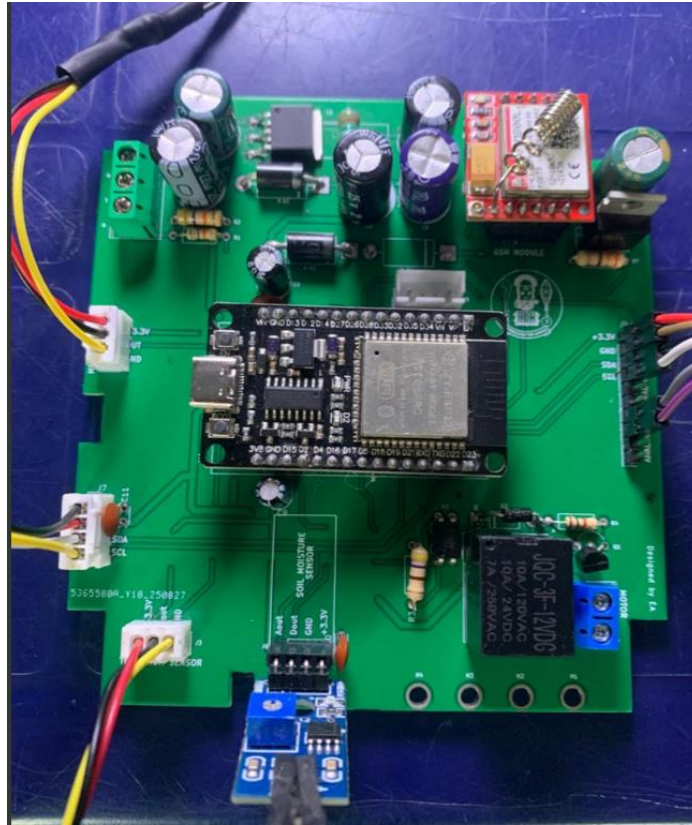


Fig 4.1: Diagram showing the assembling of the components on the board

4.3 EXPERIMENTAL/HARDWARE SETUP

In order to assess performance of the system, the circuit was fed by a regulated 12V DC supply which was stepped down to 5V by the bulk converter. To measure the real time moisture level, the soil moisture sensor was inserted in a soil sample. The DHT11 sensor was placed to monitor temperature and humidity of the air in the surrounding. The sensor readings were processed using the ESP32 microcontroller, which then showed the sensor on the LCD module attached.

Irrigation threshold levels were pre-programmed so that if the soil moisture is below 30% so that once the moisture content of the soil dropped below this point, the ESP32 used to turn on the relay controlling the water pump. The relay automatically switched off after the moisture exceed 70%. This has been repeated in order to guarantee system reliability and accuracy of response.

4.4 PERFORMANCE EVALUATION

The Vertical Farm Irrigation System was tested to determine its performance in terms of functionality, efficiency, and responsiveness of the PCB board developed. The testing was based on the precision of the sensor measurements, the response time and consistency of automatic switching to the pump and integration of the sensing, control and actuation functions. The operational stability of the system, the accuracy of automation and the energy efficiency were studied through systematic testing of the system under different soil moisture conditions and temperature conditions. The subsections below provide the results and observations of the performance tests.

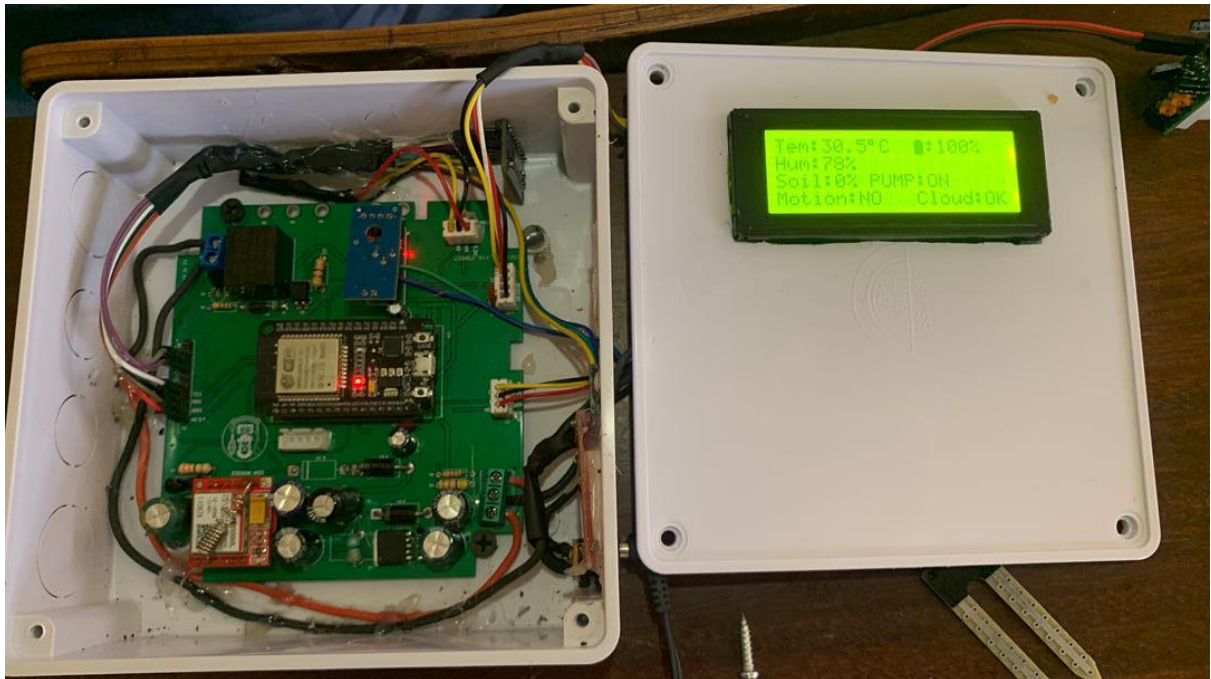


Figure 4.2: Overview of the integrated system during testing.

4.4.1 SOIL MOISTURE AND TEMPERATURE RESPONSE

The soil moisture sensor was found to be accurate and tested constantly under various soil conditions during testing. Once the soil was dry, the sensor output was below 30% and this triggered an instant controller response. With the process of irrigation, the sensor recognized the increasing moisture content and sent the information to the ESP32, which halted the pump on reaching the required threshold.

The DHT11 sensor was also able to provide both the ambient temperature and humidity

simultaneously and consequently display the readings on the LCD. The expected environmental conditions were in line with the readings and this proved accurate calibration and sensor accuracy. This feedback mechanism was reliable and demonstrated that the system was capable of delivering real-time environmental monitoring that could be used in vertical farming. 4.4.2 automatic pump activation results.

4.4.2 AUTOMATIC PUMP ACTIVATION RESULTS

The relay module worked effectively to switch on a water pump with variations of moisture. Switching of the pump ON to OFF was gradual and took a few seconds of the threshold passing. The automatic pumping system saved time since it did not require manual changing, and also minimized the amount of water wasted. The tests carried out during several cycles ensured that the circuit did not change and the relay switched steadily and did not switch falsely, which proved the correctness of the control circuitry.



Figure 4.3: LCD showing the Pump off and on based on the threshold values

4.4.3 LCD INTERFACE RESULTS

The LCD interface gave real time feedback of the soil moisture, temperature, and humidity content of the soil as well as displaying if motion was detected or not and also showing if the system is connected to the cloud platform, which made it simple to interpret the environmental conditions. The interface was simple and needed minimum

training to the user. The device was user-friendly with easy adjustment of threshold values and response of the system on testing. This underpins its implementation in rural and urban farming settings, as well as by individuals with low technical background.



Fig 4.4: Environmental Results showing on the LCD Display

4.5 DISCUSSION OF RESULTS

The designed Vertical Farm Irrigation System managed to prove that the automated irrigation process requires minimum human interference. The PCB design enhanced compactness, reliability of the system and stability of the signals. The soil moisture sensor and DHT11 sensor were useful to provide real-time information about the environment, and the ESP32 was useful in processing the inputs and operating the relay and the pumping unit. The findings revealed rapid response time, low power use as well as correct sensing in different test conditions. There were various issues that were experienced during design and testing.

These were the space limitations in PCB layout, voltage variation when the pump current was large, and problems in calibration of sensor because of environmental changes. Also, there was an initial electromagnetic interference on the sensor readings by the pump which was reduced by adding decoupling capacitors and flyback diodes. Nevertheless, optimization made the PCB Irrigation system effective despite the challenges.

The scalability of the system was also provided. The design of its PCB is modular and thus accommodates easily other sensors like a pH sensor, water level sensor, or a light sensor.

The Wi-Fi features of the ESP32 open up IoT opportunities of monitoring and controlling vertically with the cloud, thus the system can be scaled to large or commercial-scale vertical farms. An expansion of the power system can also be introduced to facilitate the functioning of solar, which contributes to enhancing sustainability and allows it to be used in isolated regions.

4.6 COMPARISON WITH EXISTING SYSTEMS

The automated PCB-based system is precise, consistent, and saves a lot of water as compared to traditional or conventional irrigation systems since manual watering is always done at the behest or judgement of the human being. In traditional practices, excesses and deficits of irrigation are common resulting in the wastage of resources and low crop production. The automated system provides ideal soil moisture by use of sensor-based feedback and closed-loop control.

The PCB system is more durable, stable, and maintainable when compared to prototypes based on veroboard. Veroboard systems are generally plagued with loose connections, complicated wiring and little scalability. On the contrary, PCB-based design is well-organized, with good solder joints and compact design, which minimizes noise interference and maintenance costs. In spite of the fact that the cost of fabrication at first is somewhat more, the PCB system is cheaper in the long run owing to its reliability and low maintenance requirements.

In general, the PCB-based Vertical Farm Irrigation System has shown a great enhancement in terms of automation, precision, and sustainability. It combines the old and the new approaches to irrigation and provides a powerful, efficient and scalable solution to precision agriculture and smart vertical farming.

Table 4.1: Comparison between existing systems

PARAMETER	TRADITIONAL FARMING	VEROBOARD-BASED SYSTEM	PCB-BASED SYSTEM
Automation	Manual Watering	Partially automated	Fully automated
Water Consumption	High and inconsistent	Moderate	Controlled and efficient
Reliability	User dependent	Wiring problems	Highly stable and compact
Scalability	Hard to scale	Limited	Modular and Scalable
Power Consumption	Variable	Moderate	Optimised with DC regulation
Cost Efficiency	Low (labour intensive)	Medium	High (low maintenance)

CHAPTER FIVE

(CONCLUSION AND RECOMMENDATIONS)

5.1 SUMMARY OF FINDINGS

The PCB-based Vertical Farm Irrigation System developed was effective to automatize the procedure of soil moisture sensor and irrigation control. The incorporation of sensors, ESP32 microcontroller, and actuation parts on a two-layer PCB enhanced the functioning of the system as it simplified the wiring and increased the signal stability. The soil moisture sensor was effective in sensing dry soil conditions and switching on the pump that was controlled by the relay, whereas the DHT11 sensor was effective in measurements of temperature and humidity. The PIR motion sensor was another intelligence added to human activity detection.

The PCB layout allowed to ensure effective communication between all modules and the reduction of interference to the minimum so that the design turned out to be compact, reliable, and energy-saving. The experiment proved that the system was independent of human control with the limited use of human resources, which was associated with the fast response time and the power stability. The PCB system was found to be more precise, scalable and long lasting compared to the traditional and veroboard based irrigation systems, which confirmed its appropriateness to the current vertical farming setup.

The ESP32 microcontroller was used as the main control unit with sensor data being correctly processed and leading the relay module to operate the water pump according to the soil moisture level. DHT11 and soil moisture sensors were used to measure the environmental parameters which included soil moisture, temperature and humidity and this was effectively monitored by the system. Inclusion of PCB design ensured reduced size, high connection reliability and reduced errors arising due to loose connection of wires in breadboard implementations. The system was efficient in that it retained the optimum soil moisture to support the growth of the plants as well as minimizing human intervention and hence the design objectives were achieved.

5.2 LIMITATIONS OF THE PROJECT

As much as the Vertical Farm Irrigation System PCB was implemented as a two-layer design with great success, there were some limitations realized in the course of development. The component density around ESP32, GSM module, and relay section was very high giving rise to narrow trace spacing along with numerous vias making signal interference more likely. The GSM and power regulation circuits generated electromagnetic noise that sometimes interfered with sensor readings, showing that grounding and EMI isolation had to be improved.

The temporary current demands during the transmission of GSM data and switching relay also caused power variation indicating the necessity to have even thicker power traces or a better power-plane architecture. They also found that in extended operation thermal build up occurred around the LM2596 regulator and relay components because the copper area could not dissipate heat and the absence of thermal vias.

The small size of the layout led to assembly problems including solder bridging and aligning problems, whereas the limited antenna placement minimally affected GSM signal strength. In spite of these limitations, the PCB was still efficient, and showed capabilities to functionally integrate sensing, control, and actuation units, and has potential to better power distribution, EMI handling, and thermal design in the next generation version.

5.3 FUTURE WORK RECOMMENDATIONS

The further development of the Vertical Farm Irrigation System can be aimed at the improvement of the PCB design and the functionality of the system. Replacing a two-layer with a four-layer PCB would enhance the organization, the signal integrity, and the power distribution of all the circuits and reduce interference to a minimal level. Adding sophisticated protection devices like voltage regulators, reverse polarity devices, and current-limiting fuses would be a way of increasing durability and reliability particularly in adverse conditions.

Other sensors, such as the pH and light intensity, NPK sensors and CO₂ detectors would have the potential of enhancing the accuracy of environmental monitoring, as well as the

nutrients in the soil to increase crop yield. Integrating AI with a camera can also provide farmers with visual feedback in real time by monitoring crop development, pest infestation, and the onset of plant stress or disease, and so on.

Wi-Fi, GSM or LoRa wireless communication technologies would be able to provide remote monitoring and control through IoT dashboards. Renewable energy sources such as solar panels and battery systems have the potential to render the set up more sustainable and energy efficient. Lastly, the system would be more self-sufficient and responsive to various farming conditions and the different types of crops to implement AI that predicts the crop yield given the type of crop under cultivation, and the nutrients in the soil would be more effective.

5.4 FINAL CONCLUSION

The project successfully met its main objective which was to design and implement a dependable and reliable two-layer PCB to automate the irrigation system of vertical farms. A closed loop process of irrigation was demonstrated with the implementation of sensing, processing and actuation units, which could perform without human interference. Its small size and modular architecture enable the expansion and use of the system in the field of IoT.

Generally, the PCB-based was superior to conventional irrigation systems with regard to precision, efficiency, and sustainability. It offers a platform to expand the creation of smarter farming systems, which will enhance the development of the modern smart agricultural technology.

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