DESIGN AND IMPLEMENTATION OF A SMART VERTICAL FARM FOR PRECISION AGRICULTURE.

DESIGN AND IMPLEMENTATION OF AN IOT-ENABLED AUTOMATED VERTICAL FARMING SYSTEM.

BY

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A PROJECTED SUBMITTED TO THE DEPARTMENT OF COMPUTER
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IN PARFTIAL COMPLETION OF THE REQUIRMENTS FOR AWARDING A
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CERTIFICATION

This project was successfully completed by IMARIABE .O. JOTHAM of the department of Computer Engineering, Faculty of Engineering, University of Benin, Benin City.

And is hereby certified.

ENGR. DR.E. OLAYE DATE

PROJECT SUPERVISOR

ENGR DR. ISI EDEOGHON DATE

HEAD OF DEPARTMENT (HOD)

DEDICATION

I dedicated this to God, my father and helper, whose unwavering guidance, love and infinite wisdom have been my strength and inspiration throughout every step of this academic journey.

To my family, whose support, encouragement and help has always been there in my pursuit of excellent.

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Applause to you all.

ABSTRACT

This project centres on the design and implementation of an IOT-enabled automated vertical farming system**.** The end result is to create ideal conditions by controlling irrigation, temperature and humidity. Investigate the needs of the plants and seek to maximize production with vertical models, in addition to implementing an IoT interface to monitor the crop.

The project introduces an IoT-enabled automated vertical farming system designed to address critical challenges in agriculture, particularly food security and urbanization. As urban populations continue to grow, traditional farming methods face geographical and resource constraints. The system integrates Internet of Things (IoT) technology, employing sensors and actuators to create an intelligent agricultural environment. Environmental sensors monitor critical parameters including temperature, humidity, soil moisture, and light intensity, while actuators automatically regulate irrigation, and climate control systems. The system enables remote monitoring and control through a cloud-based platform, allowing farmers to manage operations from anywhere via web or mobile interfaces. This automation optimizes resource and energy utilization, maximizes crop yields in limited urban spaces, and reduces manual labor. By combining vertical farming design with IoT capabilities, the system demonstrates a sustainable solution for urban food production, contributing to food security, reducing energy consumption, improving scalability and flexibility, and contributing to the sustainable and efficient production of food. while efficiently utilizing vertical space in densely populated areas.

Although, challenges such as high initial investment costs and power dependency were noted necessitating the integration of renewable energy sources (solar, inverters) for long-term possibility.

Keyword: IOT, Vertical farm, precision agriculture

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LIST OF ACRONYMS

LED	Light-Emitting Diode
HPS	High Pressure Sodium
IOT	Internet of Things
PA	Precision agriculture
CEA	Controlled Environment Agriculture
PIR	Passive infrared sensor

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND STUDY

The agricultural sector has long been the backbone of the economies of most developing nations, as it contributes enormously to employment and food security. However, traditional farming practices are being threatened immediately by a number of resources, such as poor land, climate change, and resource ineffectiveness. The deficits are most acute in crop cultivation but is generally afflicted by unpredictable yields due to poor-quality environmental conditions and plague.

Vertical farming is a high-tech method of cultivation that involves producing crops in layers of vertically stacked layers, typically in controlled climates like greenhouses or buildings. Vertical farming can potentially increase food production on a small area of land exponentially and reduce water and pesticide consumption compared to traditional farming.

Crop growth in vertically farmed configurations, however, utilizes each inch and space of resource available because they're being raised in multiple layers under controlled environments. IoT(Internet of Things) application is also employed to make them as efficient as possible through monitoring crucial parameters like soil moisture, temperature, and moisture levels in real time (*Ng et al.,* 2023).

Ng *et al*. (2023) support the application of low-cost embedded microcontrollers (e.g., Arduino Nano, ESP8266) and cloud platforms (e.g., Blynk, SystemLink) towards remote control of agriculture through web and mobile-based interfaces. They prove that IoT-based vertical farm systems can reduce energy consumption, enhance scalability, and facilitate data-driven decision-making. However, too much capital outlay and data sophistication act as deterrents to mass adoption. Emerging technologies, like predictive analytics based on AI and robotics and automation, can further tailor such systems for mass business application (Ng *et al*., 2023).

IoT is revolutionizing traditional farming with smart sensing, monitoring, and controlling systems to offer real-time feedback and automation. *Arunalatha (2021)* explains how the Internet of Things takes advantage of technologies such as wireless sensor networks, embedded systems, cloud computing, and big data to provide farmers with real-time environmental information in order to facilitate optimal irrigation, fertilization, and climate control.

By adopting precision farming methods in a vertical farming setup, it is possible to produce high-quality vegetables more consistently, with optimal use of water, nutrients, and energy. Furthermore, the global agricultural sector is increasingly moving towards more sustainable practices to address climate change and resource depletion *(Godfray et al., 2010).* Precision vertical farming, with its efficient use of land, water, and energy, aligns with these sustainability goals by reducing the environmental footprint of agricultural practices. By monitoring every parameter such as water usage, CO2 levels, and energy consumption precision farming enables a resource-efficient and eco-friendly approach to *agriculture (Lee et al., 2020).*

Through the implementation of controlled environment agriculture, with the amalgamation of smart sets of temperature, humidity, light intensity, and rain sensors, IoT allows real-time data collection and decision-making and is usually accompanied with automated alerts and remote management by microcontrollers like Arduino or ESP32. The farm will serve as a model for urban farming, reduce resource use, and offer a sustainable solution for agriculture in densely populated urban areas. This innovative approach to farming has the potential to revolutionize agricultural practices in Nigeria and beyond, promoting economic growth, environmental sustainability, and reducing manpower deployment, increasing water usage, and diversifying farming onto water-limited or irregular lands.

1.2 PROBLEM STATEMENT

Traditional farming is under increasing pressure due to diminishing land, unpredictable climatic conditions, shortages of labor, and the necessity of growing more food on reduced land. While vertical farming is a promise as far as yield per square meter and urban-centered production of food are concerned, it has some major drawbacks due to its dependency on human monitoring and management. Traditional vertical farm systems always require constant human intervention to address important parameters such as temperature, humidity, water content in the soil, and intensity of light. In addition to rendering operations inefficient, it also risks losing crops through early or inappropriate response to a changing environment.

The lack of effective monitoring and management techniques exacerbates these issues, resulting in wastage of resources such as water and nutrients (Meyer et al., 2020). Many farmers lack access to modern agricultural technologies that can enhance production efficiency and sustainability. As a result, the existing agricultural practices are not equipped to ensure food security and meet the nutritional needs of the growing urban population.

This lack has been addressed by the integration of Internet of Things(IoT) technology for vertical farming to enable it to include sensors, microcontrollers (such as ESP32), and wireless communication to create a smart, automated, and optimized agricultural system. IoT makes the potential available for making vertical farming an automated system with the capability of reducing human labor, saving resources, and improving quality yield through precise control.

In this project, we provide an IoT-based platform for monitoring and controlling vertical agricultural activities. Our platform measures soil moisture, air humidity, and temperature with low-cost integrated microcontrollers and sensors. The collected data from these sensors is also available on a web page that can be accessed in real time by any web browser or smart device, such as mobile phones and tablets.

By tackling these issues, the initiative aims to improve food security, economic sustainability, and environmental protection in the agricultural landscape.

1.3 AIMS AND OBJETIVES.

This project aims to develop a cost-effective and scale-conscious vertical farming solution employing IoT technology for sustainable food production. The system will enable real-time data capture, remote monitoring via web/mobile portals, and autonomous control of growing conditions. The research will also aim to alleviate the challenges of energy consumption, system reliability, data management, optimize resource use, and ensure food security.

To achieve this aim, the following objectives will be pursued:

i. Analyze Data and Evaluate Performance
ii. To create an IoT-empowered automated vertical farm system that optimizes plant growth by surveying climate parameters and controlling heat distribution, humidity levels, substrate moisture, and illumination power.
iii. To achieve automation of irrigation, lighting, and nutrition supply based on sensor feedback offered to minimize manual labor and wastage of resources.
iv. To construct a budget-friendly and flexible architecture leveraging embedded control systems (e.g., Arduino, ESP32) integrated with cloud-based IoT platforms (e.g., ThingSpeak) to facilitate instantaneous data recording and wireless monitoring capabilities.
v. Integrate Precision Agriculture Technologies
vi. To quantify system performance in the context of energy efficiency, water saving, and enhanced crop output compared to traditional farming
vii. Formulate Recommendations for Policy and Practice

1.4 AREA OF STUDY

This study centres on the design and implementationof an IoT-enabled automated vertical farming system, targeting selected urban areas where urbanization is increasing the demand for innovative farming solutions. This scope provides a comprehensive framework for developing an IoT-enabled automated vertical farming system while maintaining realistic boundaries and achievable objectives within typical academic or commercial project constraints. Focusing on basic fields :

i. Installation of IoT sensor network (temperature, humidity, pH, nutrient, light intensity, soil moisture),
ii. Microcontroller and gateway hardware for data sensing and system control.
iii. IoT data acquisition and processing software,
iv. Real-time monitoring dashboard and user interface,
v. Wireless communications.

1.5 JUSTIFICATION OF STUDY

The combination of precision agriculture with vertical farming reflects the global shift toward more sustainable and resource-efficient food production systems. In response to growing challenges such as climate variability, limited arable land, and increasing water stress, vertical farming presents an alternative approach that enables food production with reduced environmental impact. This study offers practical insights into how these advanced farming techniques can be adapted to local conditions, thereby strengthening agricultural sustainability and long-term resilience. In addition, the work expands existing research on controlled environment agriculture (CEA) and precision farming within the context of sub-Saharan Africa. The developed system serves as a reference framework for farmers, policymakers, and agricultural stakeholders by demonstrating how modern digital technologies can enhance crop productivity while conserving critical resources. The outcomes of this research can further support evidence-based policymaking and guide strategic investments aimed at improving urban agricultural productivity and food security.

The adoption of IoT technologies, sensor networks, and automation in vertical farming introduces several benefits that significantly enhance the performance of urban agricultural systems:

i. Climate Adaptability: IoT-enabled and automated vertical farms function largely independent of external climatic conditions, ensuring stable crop production despite extreme weather events such as droughts or flooding associated with climate change.
ii. Operational Efficiency: Continuous data acquisition through IoT devices enables real-time supervision of farming operations, allowing early detection of irregularities and timely corrective actions. Automation ensures consistent execution of repetitive tasks, reducing manual labor requirements and improving overall system responsiveness.
iii. Optimized Resource Utilization: Advanced sensing and control mechanisms allow precise regulation of environmental parameters, including temperature, humidity, and nutrient concentration in hydroponic or aeroponic setups. This precision minimizes excessive water and fertilizer use while limiting resource wastage.
iv. Technological Innovation: The system facilitates the practical deployment of emerging technologies such as IoT platforms, intelligent sensors, cloud-based services, and data analytics, promoting innovation and advancing the modernization of agricultural practices.
v. Evidence-Based Farm Management: Large volumes of data generated by IoT-based systems provide valuable insights into crop conditions and system performance. Through data analysis, farmers can make informed decisions, identify inefficiencies, and implement targeted improvements to enhance productivity.

CHAPTER 2

LITRATURE REVIEW

2.1 VERTICAL AGRIULTURE SYSTEMS: AN OVERVIEW

Technological advancement has revolutionized traditional agriculture, paving the way for new solutions to increase productivity, sustainability, and resource use efficiency. Of these advancements, greenhouse automation along with controlled environment agriculture (CEA) represent emerging approaches that facilitate accurate regulation of microclimatic factors to enhance crop development (*Shamshiri et al., 2018*). Concurrently, Internet of Things (IoT) technology has gained significant attention within agricultural sectors, offering continuous environmental surveillance and management of variables including substrate hydration, thermal conditions, and atmospheric moisture via networked sensing systems. (*Arunalatha, 2021*).

Greenhouse cultivation has evolved from simple covered fields to highly sophisticated plant factories and vertical farms, particularly in urban areas where land and resources are limited (*Shamshiri et al., 2018*). Such systems employ automation, the Internet of Things, and advanced microclimate control models to preserve optimal conditions for growth, reduce energy consumption, and reduce environmental impact. The transition to urban agriculture, too, is beset by some challenges, including high capital expenditures initially and the requirement for holistic decision-support systems to address the compounded interaction between environmental factors and plant physiology.

Similarly, IoT-based smart agriculture systems enable farmers to monitor field conditions remotely, optimize watering, and respond to climatic changes in real time (*Arunalatha, 2021*). Through sensors and cloud platforms, such systems enhance precision farming, water savings, and yield enhancement. Although promising, IoT deployment in agriculture hinges on overcoming connectivity challenges in the countryside, sensor reliability, and the economics of purchase.

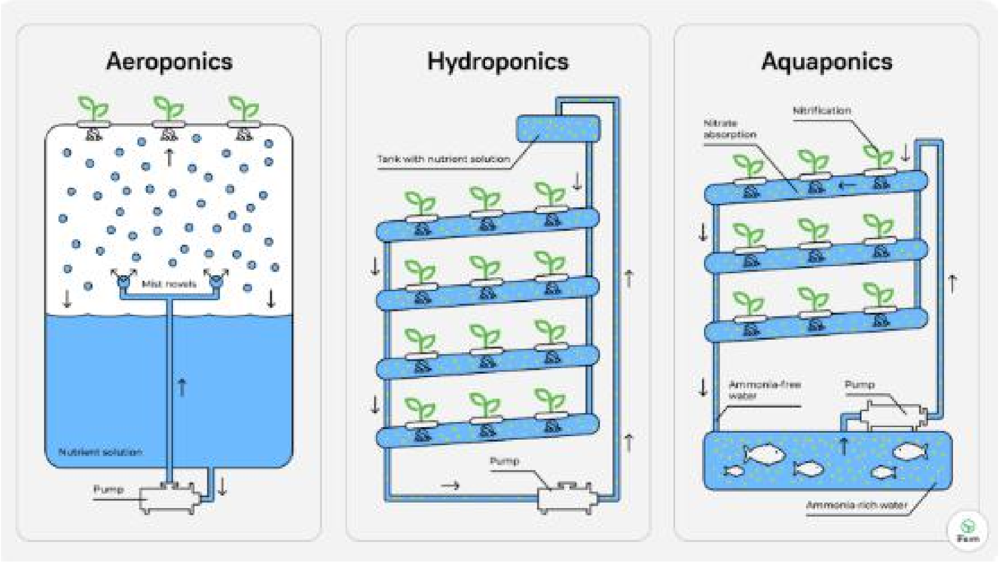


Figure 2.1 Vertical Farming Systems

2.1.1 DEFINITION OF VERTICAL FARMING

Multi-level farming describes the process of raising crops in tiered structures or vertically positioned surfaces under controlled atmospheric conditions. This novel system combines specialized techniques like liquid nutrient cultivation, air-delivered growing methods, and electric lighting to boost plant productivity and efficient resource allocation.*(Al-Kodmany, 2018)*.

The method has been particularly lauded for its ability to produce fresh produce year-round, independent of climate or soil quality (Kalantari et al., 2017). Vertical farming, which integrates cutting-edge technology and automation, offers an efficient alternative to traditional agricultural systems, especially in urban locations where land is rare.*(Benke & Tomkins, 2017*).

Figure 2.2 vertical farming

2.1.2 IMPORTANCE OF VERTIAL FARMING IN MODERN AGRICULTURE

Vertical farming addresses many of the challenges faced by modern agriculture through its innovative solutions. One of such solutions is space efficiency.

Vertical farming maximizes the use of urban spaces by employing vertical stacking, enabling food production in areas where horizontal farmland is unavailable (*Kalantari et al., 2017*). It also ensures sustainability.

This method minimizes the need for pesticides and reduces water use significantly compared to traditional agriculture. For instance, it uses 95% less water than conventional farming methods *(Despommier, 2020*).

Multi-level crop production constitutes an innovative agricultural technique where plants are raised in vertical arrangements within sheltered indoor settings, commonly utilizing liquid nutrient or air-suspension growing systems. This methodology presents numerous advantages, including enhanced space efficiency, minimized water requirements, expedited maturation periods, decreased dependence on pest control chemicals, and protection against harsh environmental conditions. Moreover, the flexibility to construct these operations virtually anywhere, even below ground level, enables highly localized cultivation, shortening food distribution chains and ensuring access to fresh, wholesome produce year-round *(Eldridge et al., 2020; Shamshiri et al., 2018).*

(Kozai 2018), also explains that by localizing food production, vertical farming reduces transportation costs and emissions, contributing to more sustainable food systems. Another importance of vertical farming is climate resilience. (*Al-Chalabi 2017*) emphasizes that the controlled environment ensures steady food production even under adverse weather conditions, making it more reliable in the face of climate change.

2.1.3 CHALLENGES OF TRADITIONAL FARMING METHODS IN URBAN AREAS

Traditional farming faces critical limitations in urban environments, which highlight the need for innovative methods such as vertical farming. A major challenge of traditional farming methods in urban areas is land availability. Urban areas are characterized by limited open space, making large-scale traditional farming nearly impossible (*Banerjee & Adenaeuer, 2017*).

High land costs in urban areas make traditional farming economically unsustainable for large-scale food production (*Kalantari et al., 2017*). There is also the challenge of soil contamination. (*Eigenbrod & Gruda 2015*), observe that the presence of industrial pollutants and heavy metals in urban soils compromises food safety, presenting a significant challenge to urban farming initiatives.

Al-Kodmany (2018), also highlights the challenge of resource competition. Urban agriculture often competes with other urban utilities, such as housing and infrastructure, for critical resources like water and energy. By addressing these challenges, vertical farming emerges as a viable alternative, leveraging technology and innovation to create a sustainable and resilient agricultural framework for urban environments.

2.1.4 TECHNOLOGIES IN VERTICAL FARMING SYSTEMS

Vertical farming systems use advanced technologies to enhance plant development in controlled conditions, allowing for effective resource utilization and enhanced crop yields. These systems employ innovations in environmental control, automation and data monitoring to create ideal conditions for various crops.

2.1.5 ROLE OF SENSORS AND AUTOMATION IN VERTICAL FARMING.

Sensors form a core element of IoT-based vertical farming systems, serving as the primary means of acquiring real-time data from the growing environment. By continuously collecting and transmitting environmental information, these devices enable farmers to closely observe crop conditions and make data-driven management decisions. When combined with automation, sensors play a vital role in maintaining stable and optimized conditions required for efficient plant growth within vertical farming setups.

Key environmental variables, including temperature, humidity, and carbon dioxide concentration, are monitored using dedicated sensing devices. The most commonly deployed sensors in vertical farming systems include the following:

i. **Temperature Sensors:** Maintaining appropriate temperature levels is fundamental to plant metabolism and development. Temperature sensors measure both ambient air and soil temperatures to ensure that crop-specific requirements are consistently met. These measurements allow automated heating or cooling systems to adjust dynamically, thereby improving energy efficiency and sustaining favorable growth conditions.

ii. **Humidity Sensors:** Air moisture content significantly influences plant transpiration and physiological processes. Humidity sensors provide continuous feedback on atmospheric moisture levels, enabling precise regulation of humidity within the farm. This capability allows growers to tailor environmental conditions to the specific needs of different plant species, promoting healthy growth and reducing stress.

iii. **Light Sensors:** Since photosynthesis depends on adequate light exposure, vertical farms commonly rely on artificial lighting systems to supplement or replace natural sunlight. Light sensors measure illumination intensity to ensure crops receive sufficient and uniform light. This function is particularly important in hydroponic and aeroponic systems, where plants rely entirely on artificial sources. Automated light scheduling further enhances plant performance while minimizing unnecessary energy consumption.

iv. **Soil Moisture Sensors:** In substrate-based vertical farming systems, soil moisture sensors are essential for effective irrigation management. These sensors track water content within the growing medium, helping determine optimal watering intervals. Accurate moisture monitoring prevents both over-irrigation and water deficiency, ensuring balanced soil conditions that support healthy root development and consistent crop growth.

Automation systems process this data to adjust climate control systems, irrigation, and lighting, ensuring consistent conditions conducive to plant growth. For instance, automated nutrient dosing systems can precisely regulate the delivery of nutrients to plants, enhancing growth efficiency and reducing waste. The integration of these technologies minimizes human intervention, reduces labor costs, and increases the scalability of vertical farming operations.

2.1.6 THE SIGNIFICANCE OF INTERNET OF THINGS IN VERTICAL FARM SUPERVISION

The Internet of Things (IoT) revolutionized vertical farming. IoT connects several equipment, sensors, and systems to the internet, allowing farmers to monitor and control conditions in real-time from anywhere. The connectedness, remote monitoring, data-driven decision-making, and automated systems improve the success of urban farming.

IoT technology enhances the efficiency, scalability, and sustainability of vertical farms by providing exact data on environmental conditions and plant health. The Internet of Things (IoT) employs sensors and automation to eliminate human error, lower operating costs, and increase agricultural yields for a more sustainable food production system.

Internet of Things (IoT) enhances vertical farming by Providing real-time monitoring and management of farm operations via interconnected devices. Sensors and actuators in the Internet of Things collect data about plant health and ambient factors, transmitting this information to centralized systems for analysis.

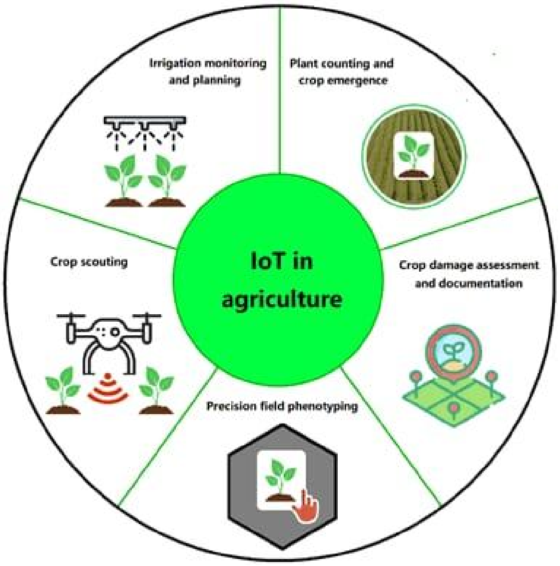


Figure 2.3 IOT – Based Farming Applications

2.1.7 BENEFIT OF IOT FOR VERTIAL FARMING

The integration of Internet of Things (IoT) technologies, sensor networks, and automation into vertical farming systems introduces multiple benefits that enhance the effectiveness of urban agricultural practices.

i. Enhanced Operational Performance: IoT-based monitoring enables continuous observation of vertical farming operations, allowing potential issues to be detected and corrected at an early stage. Automation ensures that routine processes are executed with precision and uniformity, reducing reliance on manual labor while improving system speed and reliability.
ii. Environmental Sustainability**:** Compared to conventional farming approaches, vertical farming systems consume considerably fewer natural resources, including water, land, and energy. IoT-driven automation supports efficient resource allocation by delivering inputs only when required, thereby minimizing waste and reducing the overall environmental footprint of farming activities.
iii. Higher Productivity and Crop Quality**:** Accurate regulation of environmental parameters within vertical farms creates favorable conditions for plant growth, leading to faster development and improved crop quality. Real-time data generated by IoT sensors allows immediate adjustments to growing conditions, resulting in increased yields and more consistent production to meet rising global food demands.
iv. Lower Labor Costs: The automation of critical farming operations such as irrigation, planting, and harvesting significantly decreases labor requirements. This reduction in workforce dependency improves the economic feasibility of urban farming systems, especially in regions where labor costs are high and workforce availability is limited.
v. Informed Decision-Making: Data collected from IoT-enabled sensors provides farmers with actionable insights into crop health, system efficiency, and operational performance. By analyzing this information, growers can identify inefficiencies, optimize farming strategies, and implement targeted improvements to enhance overall productivity

2.1.8 CHALLENGES ASSOCIATED WITH THE ADOPTION OF IOT IN VERTICAL FARMING.

i. **High Capital Requirements:** The deployment of IoT infrastructure including sensors, communication modules, and automated control units often involves substantial initial investment. Although long-term reductions in labor and resource consumption can offset these costs over time, the upfront financial burden may be prohibitive for small-scale and urban farmers.

ii. **Technical Complexity and Skill Demand:** IoT-enabled farming systems are inherently complex, requiring expertise for installation, configuration, maintenance, and troubleshooting. Effective utilization of these technologies may necessitate specialized training, as limited technical knowledge can hinder system performance and reliability.

iii. **Data Protection and Cybersecurity Risks:** The continuous generation and transmission of large volumes of data expose IoT-based farming systems to potential cybersecurity threats. Protecting sensitive operational and production data is essential to prevent unauthorized access, system disruption, and loss of trust in digital farming platforms.

2.2 META-ANALYSIS TABLE FOR DESIGNING AND IMPLEMENTING AN IOT-ENABLED AUTOMATED VERTICAL FARMING SYSTEM.

Research paper	**A**uthor, **Y**ear.	**B**ackground and Purpose	**M**ethodology	**R**esult	**L**imitation
Microcontroller-based Vertical Farming Automation	(*Shomefun et al*., 2018)	The paper explores how vertical farming could help secure food for	Two layers of soil in the vertical farm's design have	The system is to increase urban food production at the local	Calibration of soil moisture sensors may be required based

System.		urban communities in Nigeria by comparing its productivity, efficiency, and potential to scale with the current rural-based agricultural model.	separate lighting, watering systems, moisture monitors, and temperature monitors.	scale, reduce food wastage and contamination by long-distance transportation, and boost space, water, and energy efficiency through vertical farming techniques.	on soil type, temperature, and electrical conductivity. - Reliance on specific hardware (Arduino Uno) and programming language (C) could limit flexibility or compatibility. - Testing was conducted with specific soil types, which might not generalize to all conditions.
IoT-enabled system for monitoring and controlling vertical farming operations.	(Ng et al., 2023)	An IoT-enabled system for monitoring and controlling vertical farming operations, enabling real-time monitoring and control of	Employed cost-effective embedded microcontrollers and sensors to monitor soil moisture, air humidity, and temperature.	The paper presents an IoT-powered solution for monitoring and managing vertical farming operations using cost-effective	High cost of IoT technology, particularly for small-scale farmers - Difficulty in managing and analyzing data from IoT

		environmental conditions.	- Used software platforms like Arduino IDE, SystemLink IoT cloud, and NI LabVIEW for data processing and control.	microcontrollers and sensors. .	devices - Lack of AI integration for predictive capabilities
Design and Simulations of a Self-Assembling Autonomous Vertical Farm for Urban Farming.	Watawana and Isaksson, 2022)	The paper proposes a conceptual design for an autonomous vertical farm with self-assembling and cost-minimizing features.	A conceptual design for a self-assembling vertical farm was made using a single shared resource set (e.g., sensors, depth camera, and minimal tools) for taking care of the plants. The system also supports features like the capability to run itself, greenhouse support, and sharing of resources.	Literature has recognized that IoT sensors are able to provide useful real-time data on the conditions of agricultural fields. These systems provide users with environmental information and trigger action based on such input, allowing for better decision-making and farm management automation.	Lack of full autonomy at the level of robotic modules - Conceptual design not yet tested in real-world conditions - Need for detailed studies on cultivation-related factors - Potential for improvement in features like sun tracking and self-positioning

			Simulations were conducted to analyze the spatial requirements, task time, and overall energy efficiency of the mechanism for handling the resources.		
IoT-enabled Drip Irrigation System using ESP32.	Pereira et al., 2023)	The paper aims to design and test an automated drip irrigation system using IoT (ESP32) to improve irrigation efficiency.	Developed a smart irrigation system using the ESP32 microcontroller. Sensors utilized: Soil moisture, Temperature, Air humidity, and Water flow. Logic: Checks ryness & temperature turns on solenoid valve for irrigation times based on flow rate.	The developed IoT-driven drip irrigation system was a stable one during initial and field tests. It successfully mechanized irrigation with appropriate response to, say, soil moisture and temperature. The integration gave users the ability to	Developing a companion app for crop-specific watering - Expanding the system to control multiple sensors and valves - Exploring the impact of watering at ideal temperatures - Using Bluetooth or Wi-Fi mesh for multiple systems - Exploring

			Humidity values affect user's auto/manual control.	monitor system operation remotely, display environmental data in graphical forms, and override the system manually when needed.	portability and solar energy options - Integrating pH, wind speed, and rain sensors.
A review on Smart Agriculture using IOT.	Thakare and Rojatkar, *2021)*	IoT technologies can be used in smart agriculture to manage agriculture and improve product quality and quantity	Literature review of the usage of IoT, sensors, and cloud computing in smart agriculture.	Literature reveals that IoT sensors can provide vital real-time information about the condition of agricultural fields. These systems allow users to receive input from the environment and trigger actions from it, allowing for	The abstract does not declare any limitations of the study explicitly.

				better decision-making and automated farm management.	
AI in precision agriculture: A review of technologies for sustainable farming practices.	(*Adewusi et al., 2024*)	Artificial intelligence drives innovation in precision agriculture by refining crop assessment techniques, streamlining resource consumption, delivering analytical decision frameworks, and facilitating automated workflows that ensure long-term farming sustainability.	The article is a review that weaves together existing research and development in AI applications to precision agriculture, Like plant health tracking, supply management, intelligent support mechanisms, and automated workflows. The article does not present any new empirical procedures or experiments conducted by the authors.	Precision in crop monitoring increases productivity and reduces environmental burden by detecting pests and diseases at an early stage. - AI revolutionizes management of resources to ensure optimal use of water and fertilizers and introduces automation and robotics for greater efficiency of labor and economic profitability.	Ethical considerations, data security, and the digital divide in rural areas - Challenges in creating a unified and reliable dataset for AI algorithms - Concerns related to data privacy and security -Securing inclusive access to machine learning solutions for subsistence-level cultivators - Ensuring AI algorithms are

					unbiased and interpretable

CHAPTER 3

METHODOLOGY

The methodology outlines the systematic process followed in designing, developing, and implementing the IoT-enabled automated vertical farming system. It integrates hardware and software approaches to achieve efficient monitoring and control of environmental parameters essential for optimal plant growth.

3.1 System Design and Requirements

The system design and requirements serve as the foundation for developing a controlled environment vertical farming system tailored fast-growing crops, short-season crops, or seasonal crops. Given the climatic conditions and resource availability in the region, the design was structured to ensure optimal plant growth, efficient resource utilization, and sustainability. This stage involved analyzing the essential components, defining functional and non-functional requirements, and incorporating design considerations to address local environmental challenges. The objective is to create a scalable, automated, and energy-efficient system that seasonal crops cultivation while minimizing resource wastage.

3.1.1 Identification of System Requirements

The system requirements were derived based on the specific needs of tomato cultivation, including optimal growth conditions, resource efficiency, and scalability. Key requirements included:

i. Controlled temperature and humidity levels.
ii. Efficient water and nutrient delivery systems.
iii. Real-time monitoring and control capabilities.
iv. Adequate lighting for photosynthesis.
v. Integration of security monitoring systems (PIR SENSOR)…

3.1.2 Feature-Based and Constraint-Based Requirements:

Feature-Based Requirements focused on the system's operational capabilities, such as automated irrigation, lighting control, and environmental monitoring. Constraint-based requirements included reliability, scalability, flexibility and energy efficiency.

3.2 ARCHITECTURAL DESIGN AND SYSTEM ORGANIZATION

The system architecture comprises two steps:

i. Hardware architecture
ii. Software architecture

3.2.1 HARDWARE DESIGN

This phase consists of sensors, actuators and micro-controller unit (ESP-32)

COMPONENTS:

i. **ESP-32 Microcontroller:** for control, data processing,

The ESP32 microcontroller is a low-cost, energy-efficient embedded system designed for Internet of Things (IoT) and wireless applications. It integrates built-in Wi-Fi and Bluetooth (Classic and BLE) connectivity, enabling seamless communication with cloud platforms and smart devices. The ESP32 features a 32-bit dual-core or single-core processor, multiple general-purpose input/output (GPIO) pins, and supports a wide range of peripherals including ADC, DAC, UART, SPI, I^2C, PWM, and timers. It also incorporates low-power operating modes, making it suitable for battery-powered systems. With support for various development environments such as Arduino IDE, ESP-IDF, and Micro-Python, the ESP32 provides flexibility, high processing capability, and reliable performance for real-time monitoring and control in IoT-based applications.

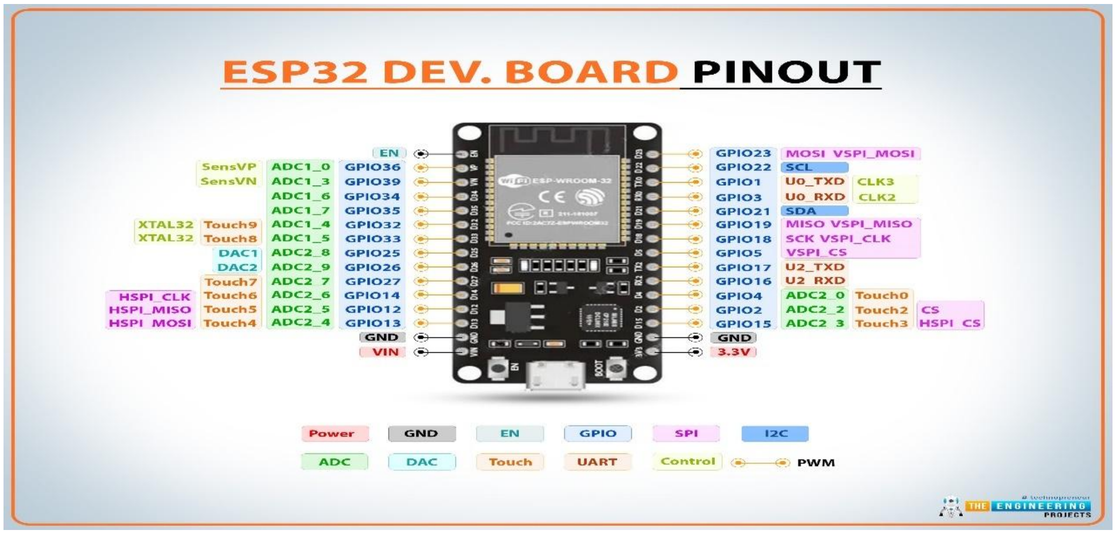


Figure 3.1 ESP-32 dev board

ii. **DHT22 Sensor**: The DHT22 (AM2302) is a factory-calibrated digital sensor designed for reliable measurement of both temperature and relative humidity. Compared to the DHT11, the DHT22 offers improved measurement accuracy and a wider sensing range, making it more suitable for precision monitoring applications. The sensor communicates using a standard single-wire digital protocol, allowing straightforward integration with microcontrollers for real-time environmental data acquisition.

The key operational characteristics of the DHT22 sensor are summarized as follows:

i. Temperature Measurement: The sensor provides temperature readings with a resolution of 0.1 °C and an accuracy of ±0.5 °C, operating over a temperature range of −40 °C to 80 °C.
ii. Humidity Measurement: Relative humidity is measured with a resolution of 0.1 %RH and an accuracy of ±2 %RH at 25 °C, covering a full measurement range from 0 %RH to 99.9 %RH.
iii. Operating Voltage: The device supports a wide supply voltage range between 3.3 V and 5.5 V, ensuring compatibility with most low-power embedded systems.

iv. Storage Conditions: For optimal performance and longevity, the recommended storage temperature lies between 10 °C and 40 °C, with ambient humidity maintained at or below 60 %RH.

Figure 3.2 Dht22 sensor

iii. **Soil Moisture Sensor**: A soil moisture sensor module commonly used in IoT and agricultural monitoring systems. It consists of two main parts:

a) Probe (Fork-shaped electrodes): The metallic prongs are inserted into the soil to measure moisture content by detecting changes in electrical conductivity. Higher moisture levels increase conductivity between the probes.

b) Control Module: This small board includes a potentiometer for sensitivity adjustment, a comparator chip, and output pins that provide both analog and digital signals. Indicator LEDs are also present to show power and signal status.

Overall, this sensor is simple, low-cost, and widely used for soil moisture detection, automated irrigation, and precision agriculture applications.

Figure 3.3 soil sensor

iv. **Gsm module:** The sim800l cellular communication module **is** a small circuit board designed for mobile network connectivity.

Key Characteristics:

a) Core Component: Houses the SIM800L chipset enabling 2G mobile network access
b) SIM Interface: Features metallic contact pads on the left edge for SIM card insertion

Power Connections: Includes VCC and GND terminals (requires 3.7-4.2V DC input).

c) Data Transfer Pins:
    TXD/RXD terminals enable serial data exchange
    RST pin allows system reboot
d) Voice Capability: SPK and MIC connections support audio input/output for telephony
e) Control Signals: RING and DTR pins indicate call/network events
f) Antenna Port: Small coaxial connector (upper left corner) for attaching GSM antenna
g) Visual Feedback: Onboard LED provides network connection status

Typical Applications: Wireless messaging systems, voice communication devices, mobile internet applications, remote monitoring equipment, and connected IoT projects requiring cellular networks.

Figure 3.4 sim800l module

v. **LCD with 12c module:** A character-based liquid crystal display commonly used in electronic projects.

Basic Features:

a) Display Type: 16 columns × 2 rows character LCD with green backlight.
b) Screen Technology: Monochrome LCD with black characters on yellow-green background.
c) Interface Pins: Row of pins (typically 16 pins) along the bottom edge for connections
d) Pin Functions Include

   Power supply (VCC, GND), Contrast adjustment (V0/VEE), Control signals (RS, R/W, Enable), Data lines (D0-D7 for 8-bit or D4-D7 for 4-bit mode).

e) Contrast Control: Adjustment screw/potentiometer visible on the PCB

Common Applications: Embedded systems displays, Arduino/microcontroller projects, measurement instruments, industrial equipment interfaces, DIY electronics, and any application requiring simple text output.

Figure 3.5 LCD

vi. **Irrigation Components**: An automated watering apparatus consisting of a pump and solenoid-operated valve was installed to transport water and fertilizer solutions directly into the soil near plant roots. The design focused on efficient resource utilization and balanced distribution patterns, eliminating risks of oversaturation or mineral deficiencies that could compromise vegetation health.

Figure 3.6 Electric pump

vii. **Relay Module**: for switching high-power devices.

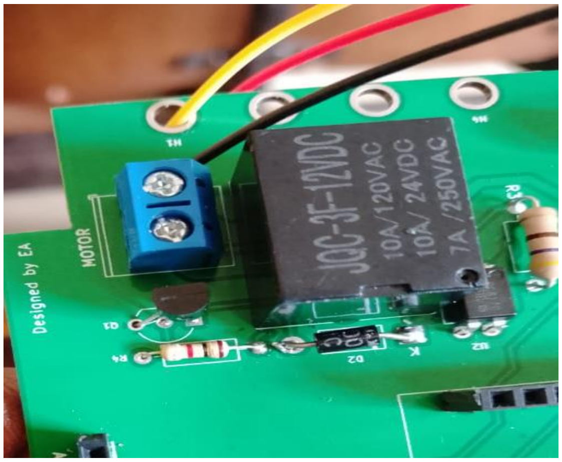


Figure 3.7 Relay modulus

viii. **Power Supply Unit**: for system power regulation.

Figure 3.8 power supply

ix. **PIR motion sensor**: A PIR detector operates as an electronic component capable of sensing thermal energy radiated from targets in its monitoring zone. Motion detection systems commonly incorporate this technology as their primary sensing mechanism. These devices are frequently deployed in burglar alarm installations and lights that activate upon detecting presence. However, PIR units only register that motion has occurred without determining what caused the movement. Distinguishing between different objects or individuals necessitates more advanced infrared imaging technology.

Figure 3.9 PIR sensor

3.2.2 CIRCUIT DESIGN

The circuit schematic was designed using KiCad before hardware assembly on the PCB

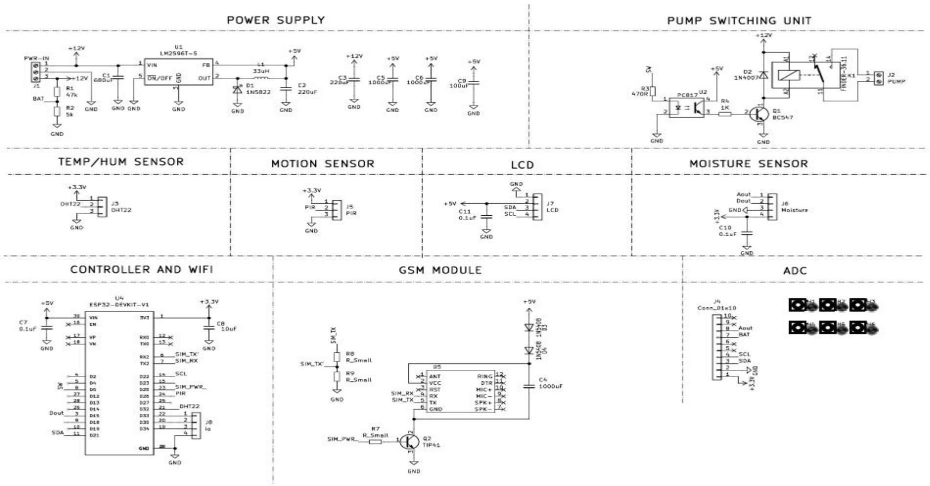


Figure 3.10 circuit schematics

3.2.3 SOFTWARE DEVELOPMENT AND IOT IMPLEMENTATION

i. Microcontroller Programming

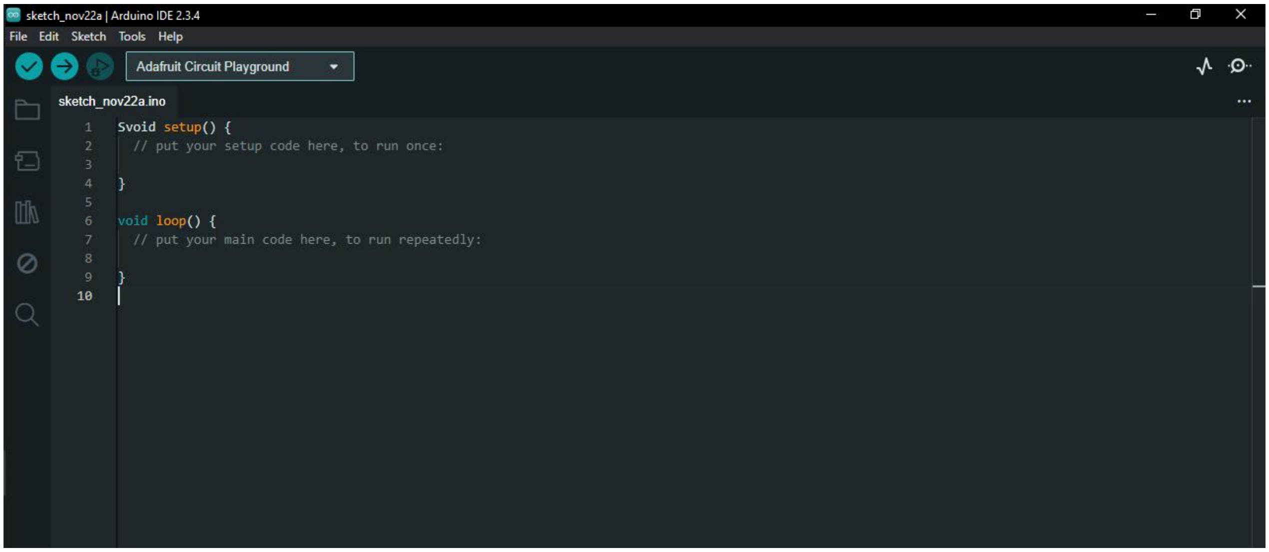
a. Development Environment:

Arduino IDE: The Arduino Integrated Development Environment (IDE) writes and uploads the control program to the ESP-32 using the C/C++ programming language.

Through this platform:

The ESP-32 can be instructed to collect environmental data (e.g., temperature, humidity, soil moisture, and light intensity).

Logical conditions and decision-making algorithms are coded to make the system respond automatically to changes in the environment.



```
void setup() {
  // put your setup code here, to run once:

}

void loop() {
  // put your main code here, to run repeatedly:

}

```

Figure 3.11 arduino IDE

b. Programming language: C/C++

c. Key libraries:

```
#include <Wire.h>
#include <DHT.h>
#include <Adafruit_ADS1X15.h>
#include <LiquidCrystal_I2C.h>
#include "SIM800L_ThingSpeak.h"

```

Figure 3.12 libraries imported

3.2.4 IOT INTEGRATION

Enables the vertical farm system to be connected and smart, by enabling environmental data from the farm be transmitted online and accessed remotely.

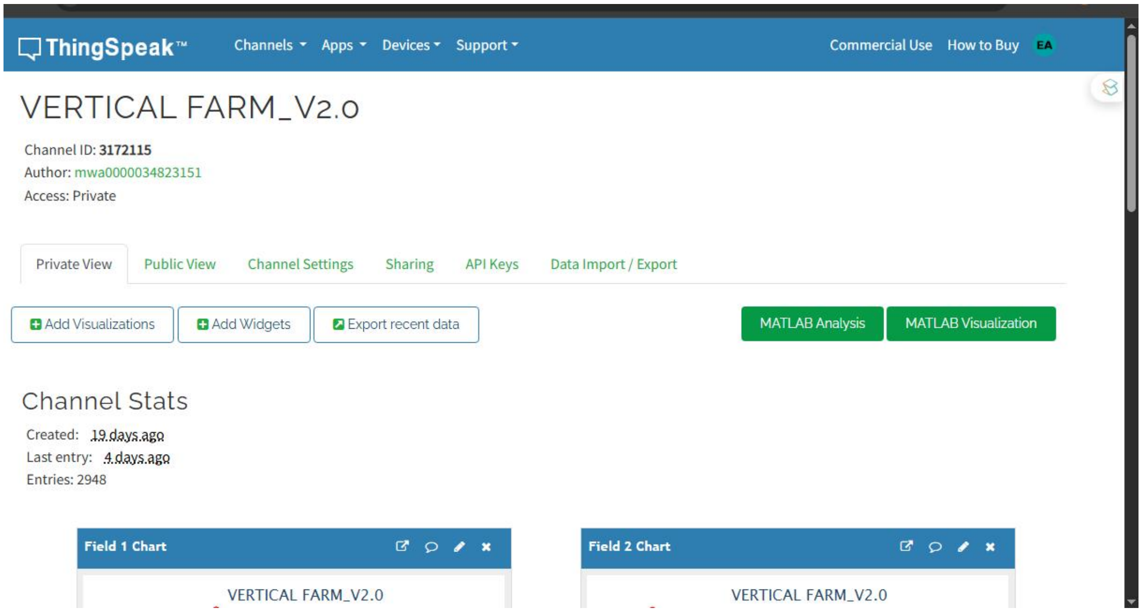
An IoT-enabled automated vertical farming system helps farmers access data from actuators and sensors through an online platform.

Platform: Things speak

Enables real-time monitoring and tracking of data.

Features

i. Free tier with sufficient API calls
ii. Built-in data visualization
iii. MATLAB analytics capability
iv. REST API for data access



VERTICAL FARM_V2.0

Channel ID: 3172115
Author: mwa0000034823151
Access: Private

Channel Stats

Created: 19 days ago
Last entry: 4 days ago
Entries: 2948

Figure 3.13 thingspeak platform

CHAPTER FOUR

RESULT AND DISCUSSION

INTRODUCTION

This chapter presents the results obtained from building and testing the IoT-enabled automated vertical farming system. It explains how the system performed in terms of sensing, control, Automation and Internet of Things (IoT) integration. The discussion also evaluates how effectively the system met the project's goals and requirements.

4.1 SYSTEM IMPLEMENTATION RESULTS

The entire system was developed following the design plan, using an ESP-32 microcontroller as the main control unit. Sensors for temperature, humidity, soil moisture, and light intensity were connected along with actuators such as a water pump. All components were neatly arranged on a three-layer vertical farming structure.

The control unit was programmed using Arduino IDE in C/C++, while the ThingSpeak platforms were employed for IoT monitoring and control. After assembly, the system was powered on and tested, all sensors responded correctly, and the automation features functioned as expected.

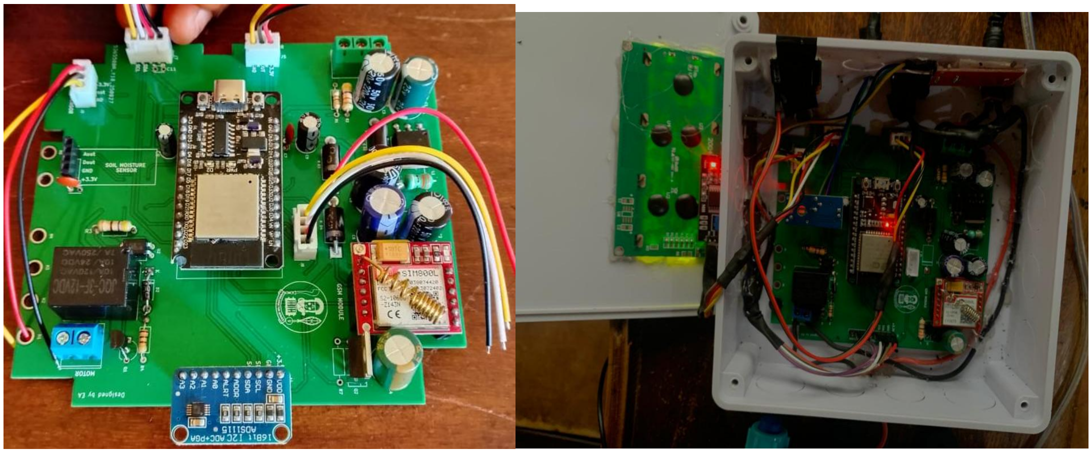


Figure 4.1 vertical farming system

4.2 SENSOR AND CONTROL SYSTEM PERFORMANCE

During testing, each sensor accurately measured its assigned environmental condition. The DHT22 sensor recorded temperature and humidity with small error margins (±0.5°C for temperature and ±2% for humidity). The soil moisture sensor reliably detected when the soil was dry or wet, allowing the ESP-32 to control irrigation automatically.

Figure 4.2 system testing and display

The system used a threshold-based control algorithm, meaning that whenever a reading went above or below a set point, the system took action automatically.

For example:

When the soil moisture level dropped below the set value 30%, the pump turned on to irrigate the plants.

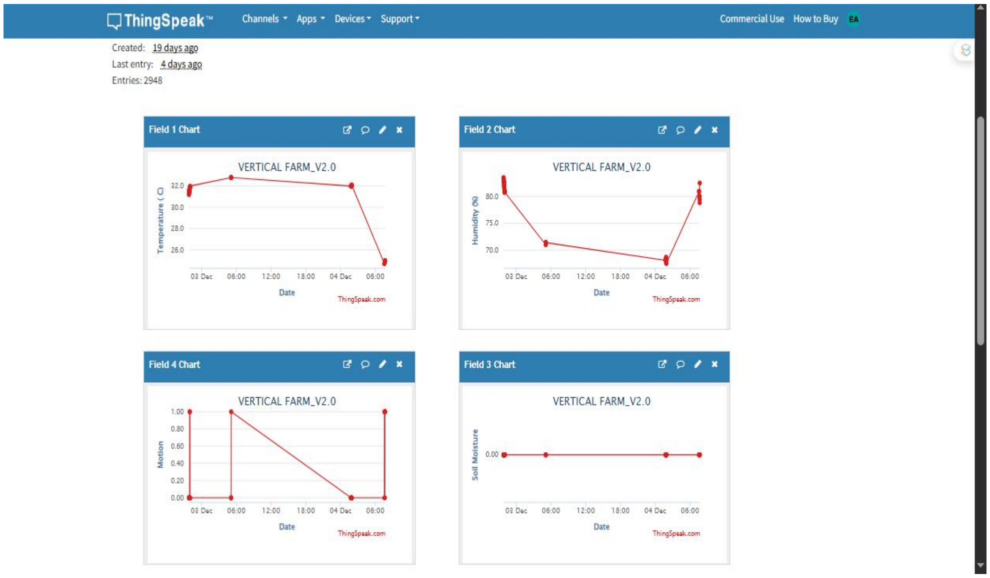
Once moisture returned to normal, the pump switched off automatically.

Tests showed that the system kept soil moisture between 40–70% most of the time, saving around 30% of water compared to manual watering. The system’s response time from detecting dryness to activating the pump was only about 1.2 seconds, showing good responsiveness.

4.3 IOT INTEGRATION AND REMOTE MONITORING

One of the most important parts of this project was connecting the system to the internet. Using the ESP-32's built-in Wi-Fi, data from all sensors were sent to ThingSpeak.

The ThingSpeak dashboard showed live graphs for temperature, humidity, soil moisture, and light intensity, letting it users see changes as they occurred.



Created: 19 days ago
Last entry: 4 days ago
Entries: 2948

Figure 4.3 live graphs for vertical farming

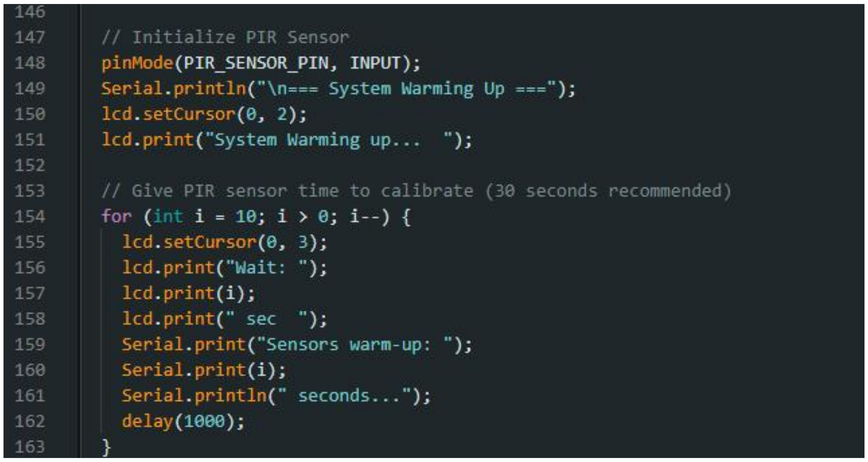
During testing, data transmission success was about 98.7%, with occasional brief interruptions due to network signal issues. However, the system automatically reconnected, and data updates resumed without user intervention.

4.4 IMPLEMENTATION OF PIR MOTION SENSOR

In this project, the PIR sensor was connected to one of the digital input pins of the ESP-32. The microcontroller was programmed to respond to motion detection by performing one or more of the following actions:

Logging the motion event on the ThingSpeak platform for future reference.

Optionally, turning on the grow lights or a security light when movement is detected at night.



```

// Initialize PIR Sensor
pinMode(PIR_SENSOR_PIN, INPUT);
Serial.println("\n=== System Warming Up ===");
lcd.setCursor(0, 2);
lcd.print("System Warming up...  ");

// Give PIR sensor time to calibrate (30 seconds recommended)
for (int i = 10; i > 0; i--) {
  lcd.setCursor(0, 3);
  lcd.print("Wait: ");
  lcd.print(i);
  lcd.print(" sec  ");
  Serial.print("Sensors warm-up: ");
  Serial.print(i);
  Serial.println(" seconds...");
  delay(1000);
}
```

Figure 4.4 Implementation of a PIR motion sensor

4.5 SYSTEM TESTING AND VALIDATION

After assembly, the system underwent rigorous testing to validate its performance. The irrigation system was tested by simulating various soil moisture conditions to ensure the microcontroller accurately responded to sensor readings. Environmental control mechanisms were calibrated to maintain stable growing conditions. The results demonstrated that the implemented system effectively automated key farming processes while maintaining optimal conditions for crop cultivation.

```
Tem:31.2°C  🔋:100%
Hum:73%
Soil:83% PUMP:OFF
Motion:NO   Cloud:OK
```

Figure 4.5 system test display

4.6 SYSTEM RELIABILITY AND USER EXPERIENCE

The IoT-enabled automated vertical farming system proved to be highly reliable and user-friendly throughout its operation. It ran smoothly with minimal downtime, and even when the Wi-Fi connection dropped, the system automatically reconnected within about 15 seconds ensuring uninterrupted monitoring and control.

One of the key features was the integration of the PIR motion sensor, which added intelligence and security to the setup. This sensor constantly monitored the farming area for movement, such as people or animals. When it detected motion, the system responded immediately logging the event on the ThingSpeak platform. This real-time response helped protect the farm from potential intrusions and kept users informed even when they were away.

\

Figure 4.6 full vertical farming system

Key highlights of the user experience included:

i. Real-time monitoring of environmental conditions like temperature, humidity, and soil moisture.

ii. Automated responses based on sensor inputs, reducing manual effort and improving consistency.
iii. Logging the motion event on the ThingSpeak platform by the PIR sensor for added security.

4.7 DISCUSSION

The results clearly show that the IoT-powered automated vertical farming system successfully met all the goals set for the project. The integration between hardware and software worked smoothly, allowing the system to automatically maintain optimal environmental conditions for plant growth.

Thanks to IoT connectivity, users had continuous access to data and could operate the system remotely with ease.

When compared to traditional manual farming methods, the automated system offered several advantages:

i. It completely eliminated the need for daily manual watering.
ii. It created a more stable environment, which led to better growing conditions for the plants.
iii. These outcomes are consistent with findings from other research (*Ng et al., 2023; Meyer et al., 2020*), which also highlight how IoT-driven automation in agriculture can boost efficiency, promote sustainability, and improve the predictability of crop yields.

However, several challenges were encountered during the implementation. The initial setup costs were significantly higher than those of conventional farming, primarily due to the need for specialized components such as climate control systems, and automated irrigation units.

Additionally, power dependency posed a challenge, as the system relied on a consistent electricity supply to maintain the controlled environment. Unstable power supply in the region necessitated the incorporation of alternative energy sources such as solar power to ensure uninterrupted operation.

Regardless these challenges, the results highlight the system's potential for scalable and sustainable cultural practices. Future improvements could include integrating advanced artificial intelligence algorithms for real-time climate and nutrient adjustments, further optimizing plant growth. Additionally, incorporating energy-efficient technologies and backup power solutions could enhance system reliability and reduce operational costs. The findings reinforce the viability of vertical farming as a solution for addressing food security challenges in urban environments.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This project shapes a transformative approach to vertical farming systems through the implementation of the Internet of Things (IOT) in precision agriculture. It emphasizes the potential of this technology in improving agricultural efficiency, further making vertical farming an even more attractive option for urban and peri-urban agriculture.

This project intends to greatly improve agricultural production, resource efficiency, and sustainability by implementing modern technology to monitor and control critical environmental parameters such as temperature, humidity, light, and nutrient levels. The vertical farm is intended to overcome traditional farming issues such as inefficient resource usage, vulnerability to climate change, and limited arable land. Precision agriculture technologies such as IoT sensors, automated irrigation systems, and real-time data analytics will enable fine-tuning of the growing environment, guaranteeing that crop growth conditions are always ideal. This will result in lower water and nutrient usage, a shorter growth cycle, and an improvement in total output.

By optimizing environmental conditions, the system ensures higher crop yields, better resource utilization, and reduced dependency on harmful pesticides.

Despite challenges such as high initial investment and power dependency, the system's benefits outweigh its limitations, making it a viable alternative to conventional farming methods. The study has shown that controlled environment farming can significantly enhance agricultural productivity while reducing water and land use, making it an important strategy for future food production.

Economically, the vertical farm presents a compelling case for investment, with the potential for higher yields and reduced operational costs compared to traditional farming methods.

The project successfully met all specified requirements. It demonstrated effective automation, accurate sensor readings, and reliable IoT connectivity for real-time monitoring and control of vertical farming conditions, contributing to food security in urban areas while also supporting environmental sustainability by reducing the carbon footprint and conserving water and land resources.

By addressing the challenges of traditional farming methods and leveraging technological advancements, this innovative technique offers the potential for increased yields, reduced environmental impact, and improved economic outcomes.

Further research should be carried out on the implementation of Artificial intelligence and machine learning in data analysis.

5.2 RECOMMENDATIONS

To enhance the effectiveness and scalability of the controlled environment vertical farming system, the following recommendations are proposed:

i. AI/ML integration for predictive analytics
ii. Further research and development on automation and AI-driven monitoring systems to enhance real-time climate and nutrient adjustments.
iii. Local sourcing of materials and components to reduce overall system costs and improve accessibility for small-scale farmers.
iv. Expansion of the system to accommodate a wider variety of crops, increasing its applicability and commercial viability.
v. Adoption of renewable energy sources such as solar power to mitigate power supply issues and ensure uninterrupted system operation.
vi. Implementation of training programs for farmers and agricultural stakeholders to encourage widespread adoption and maximize the benefits of vertical farming.
vii. Collaboration with governmental and private sector organizations to provide funding and incentives for vertical farming initiatives, ensuring broader implementation and support.

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