Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 3, Issue 4, 2025

# DEVELOPMENT AND PERFORMANCE ANALYSIS OF AN IOT-ENHANCED SMART VERTICAL FARMING SYSTEM FOR SUSTAINABLE URBAN AGRICULTURE

**Faiq Said[*1], Muhammad Azhar[2], Sajid Khan[3], Sahibzada Naveed Inayat Ullah[4], Farhan Ali[5], Muhammad Ayub Khan[6]**

[*1]*Department of Mechanical Engineering, University of Engineering & Technology, Mardan 23200, Pakistan*
[2]*Department of Mechanical Engineering, HITEC University, Taxila Cantt, Rawalpindi 47080, Pakistan*
[3]*Department of Computer Science, University of Engineering and Technology, Mardan, Pakistan*
[4,5,6]*Department of Mechanical Engineering, University of Engineering & Technology, Peshawar 25120, Pakistan*

[*1]engr.faiq.said@uetmardan.edu.pk

**DOI:** https://doi.org/10.5281/zenodo.15286308

**Keywords**
Smart agriculture, automated irrigation, vertical hydroponics, Internet of Things-based farming, and sustainable food production.

**Article History**
Received on 10 March 2025
Accepted on 10 April 2025
Published on 26 April 2025



**Corresponding Author: ***
**Faiq Said**

**Abstract**
*This study presents the design, fabrication, and performance evaluation of an advanced IoT-integrated domestic vertical farming system, combining hydroponics and automation to achieve optimal efficiency in urban agriculture. The system incorporates a 12V, 15W pump with a flow rate of 10 L/min and a pressure head of 2.10 m, operating at 4.22 W with an efficiency of 78%, ensuring minimal energy consumption while maintaining effective irrigation. The ESP32/Node MCU microcontroller-controlled temperature, humidity, water level, and total dissolved solids (TDS) sensors used in IoT-enabled monitoring showed remarkable accuracy, with sensor accuracy variances of ±2% for water and nutrient levels and ±3% for temperature and humidity. A consistent temperature of 34.2°C and humidity of 43% were recorded by real-time monitoring, and a quick reaction time of less than five seconds was guaranteed by automated irrigation and nutrient delivery. By providing a user-friendly interface for remote control and real-time data presentation, the Arduino Cloud dashboard improves system usability. Because it is affordable and scalable, its remarkable vertical farming performance which includes improved resource use, less manual labor, and enhanced crop growth makes it a great choice for sustainable urban agriculture.*

## INTRODUCTION

Vertical farming, a contemporary technique for cultivating crops on stacked tiers in controlled settings, protects crops from weather, conserves water, gets rid of pesticides, and makes the most of available space, allowing for the production and installation of fresh food locally and year-round anyplace [1]. Vertical farming is a technique that conserves soil and land resources, lowers freshwater use, and enables crops to be cultivated indoors under controlled circumstances [2]. Vertical farming has other advantages for environmental sustainability as well, though when compared to traditional farming techniques, it also makes it possible to significantly lower the volume of freshwater usage while at the same time providing higher yields [3]. The term "vertical farming" was first coined by the geologist Gilbert Ellis Bailey in 1915, though he gave the term an entirely different meaning, suggesting to farm deeper into the soil by using explosives to reach the depths of root growth [4]. Vertical farming varies in form and purpose, including layered structures, rooftop farms, and multistorey buildings. While some view it as a niche practice, others see it as vital for sustainable urban food systems and future food security [5, 6]. Vertical farming overcomes seasonal limits, enabling high yields and quality crops even in tough climates. Despite high costs, it strengthens food security and marks progress toward sustainable food systems [7-9].

Various hydroponic methods have been developed, with the ebb–flow system being one of the most widely used cultivation systems in commercial vertical farms [10]. Vertical farming is widely implemented in East and Southeast Asia, with examples like Smart Farm in China, Nuvege Plant Factory in Japan, Sky Green Farms in Singapore, and Next on in South Korea, demonstrating its role in sustainable urban agriculture. Additionally, vertical farming helps address the growing competition for limited land and water resources between food and energy production, highlighting its importance in future food systems [11, 12]. The growing global population is significantly influencing food demand. It is projected that the world's population, which was about 7.7 billion in 2019, could reach approximately 9.7 billion by 2050 and 10.9 billion by 2100 [13]. Greenhouses and vertical farms are key controlled environment agriculture systems with distinct advantages. Greenhouses, typically located outside cities, rely on solar radiation, while vertical farms use artificial lighting and operate in urban areas, reducing food miles, $CO_2$ emissions, and supply chain waste [14, 15].

Gurung et al. reported that hydroponic systems reduce water consumption by 95%, while aeroponic systems achieve a 98% reduction. Vertical farming increases yield by 10–15 times per square meter; however, high energy demands remain a challenge, with LED lighting accounting for 60% of total operational costs. The capital investment required ranges from $1,500 to $3,000 per square meter, limiting large-scale adoption. Integrating renewable energy sources could potentially reduce costs by 30%, improving the economic feasibility of vertical farming [16]. Yapp et al. conducted a qualitative study using semi-structured interviews with urban farmers in Penang, Johor, and Sabah to analyze challenges in hydroponic vertical farming. The study identified five primary obstacles: regulatory constraints, where farmers face complex government policies despite subsidies; financial limitations, with capital access difficulties restricting expansion; operational barriers, including infrastructure and maintenance costs; environmental challenges, such as climate variability affecting yields; and market volatility, with fluctuating demand impacting profitability. To mitigate these challenges, Yapp et al. propose integrating global financial blockchain networks and agro-tokens while expanding agro-lending initiatives, aligning with Malaysia's goal of enhancing urban farming for food security and price stability [17].

Mim et al. investigated AI's potential in agriculture, emphasizing how it may enhance automation, resource efficiency, and crop monitoring. They highlighted the advantages of predictive analytics, precision farming, and AI-IoT synergy. Adoption is hampered by issues including exorbitant prices, complicated technology, worries about data privacy, and legal restrictions [18]. The work by Kaiser et al. on vertical farming systems (VFS) places a strong emphasis on resource efficiency and crop physiology through dynamic environmental management. They contend that cost may be decreased without sacrificing biomass output by adapting light intensity to power costs. Predictive crop models for climatic setpoints and sensor-driven feedback systems are also highlighted [19].

According to Saad et al., Urban Smart Vertical Farming (USVF), which combines IoT and AI, can promote food security and achieve the target of a 60% increase in food production by 2050. Given the estimated 9.6 billion people on the planet, USVF provides a scalable solution that can be adjusted to fit metropolitan settings. The study examined a range of USVF topologies, automation strategies, and management difficulties, highlighting problems such as high technology costs and social acceptance. Although USVF maximizes space and minimizes human labor, obstacles including limited resources and intricate control systems prevent widespread use. To increase viability, the authors suggest improvements in automation and system efficiency [20]. Light usage efficiency (LUEinc) in vertical farms, greenhouses, and open-field lettuce growing were examined by Jin et al. Based to their findings, vertical farming produces the highest LUEinc (0.55 $gmol^{-1}$), outperforming greenhouse lettuce (0.39 $gmol^{-1}$) and field-grown lettuce (0.23 $gmol^{-1}$). If conditions are right, vertical farming can provide up to 700 kg of lettuce per square meter annually. The study employs a comparative approach to assess resource efficiency and productivity by computing LUEinc across multiple expanding systems [21].

According to a research by Martin et al. on growing-service systems (GSS) in urban agriculture, modular vertical farms optimize plant development through automation and digital monitoring. While B2C models enable customers to produce fresh food with continuous support services, B2B models concentrate on leases or subscriptions [22]. Using Kuwait as a case study, Abdullah et al. investigated the advantages of controlled environment agriculture (CEA) in Gulf Cooperation Council nations. According to the study, if Kuwait installed 15 $km^2$ of indoor farms or less than 0.1 $km^2$ of vertical farms, it would no longer need to import vital vegetable commodities. The study emphasized the significance of suitable setting, legislative support, and regulatory frameworks for indoor agriculture [23]. Using heat load models and raytracing software for system efficiency and daylight distribution, Ng and Foo's work on solar-based vertical farming discovered that tilting trays by 20° boosts crop productivity and sun irradiance without requiring more energy [24].

Using the Internet of Things and big data analytics, Shrivastava et al. have created an automated robotic system for vertical hydroponic gardening. This technique maximizes crop yields by removing the need for soil and cultivation time. IoT sensors ensure ideal growth conditions by automating water and fertilizer supply and monitoring plant health. This intelligent agricultural technology lowers expenses and labor requirements while increasing production [25].

Shrivastava et al. use big data analytics and the Internet of Things to propose an automated robotic system for vertical hydroponic farming. This technique reduces the amount of area and time needed for cultivation by replacing physical labor and poor soil quality in traditional agriculture. For optimum development, regulated nutrient solutions and rockwool are utilized, while IoT sensors are employed to automate water and fertilizer supply and monitor plant health. By using less area and better water management, vertical hydroponics further increases efficiency. The study emphasizes how smart farming technologies may boost output while reducing expenses and manpower requirements [26]. Wood et al. investigated how Singapore's food security, urbanization, and environmental issues might be addressed through vertical farming. The study emphasizes how urban farming has become more cost-effective and efficient because to hydroponics, aeroponics, and aquaponics, which allow for high-yield production in constrained areas. Through both governmental and private investments in advanced farming systems, especially in high-rise buildings, Singapore has achieved notable strides in vertical farming. Land scarcity and a complicated regulatory environment, however, continue to be major obstacles. Despite current physical and policy limitations, the results highlight the promise of vertical farming as a sustainable urban food production approach [27]. In order to maximize plant development, Chowdhury et al. created an automated vertical hydroponic system that integrates IoT technologies for real-time environmental parameter monitoring and control. The solution improves operational efficiency via real-time data display and SMS notifications. The study recommends using machine learning to enhance performance and flexibility even more. This method, which was created as an affordable indoor farming solution, could lessen dependency on imported produce, especially in the Arab world. It is advised that future studies compare hydroponically produced plants with conventional field crops in order to evaluate sustainability and production [28].

In their comparison of vertical East/West bifacial systems with conventional North/South monofacial solar farms, Riaz et al. showed that vertical bifacial farms can use less PV arrays to obtain comparable energy output and PAR levels. Reduced land use, less disruption to farm equipment, enhanced resilience to soiling, and possible cost savings are some benefits of these systems. The results demonstrate the potential of vertical bifacial technology to maximize land efficiency and operational resilience in agrivoltaics applications, highlighting its feasibility in sustainable agriculture and energy generation [29]. The environmental advantages of combining vertical farms with nearby industry and buildings were examined by Martin et al. Their results show that residual heat utilization and by-products like discarded grains and $CO_2$ from brewers can significantly reduce energy use and GHG emissions. Resource trade-offs were noted, even though tactics like local distribution and the usage of biofertilizer had less of an impact. The study highlights the importance of synergies in improving energy and material efficiency using a systems analysis method, urging more research on practical application [30].

Existing research on vertical farming primarily focuses on large-scale commercial systems with high operational costs and complex automation, making them less feasible for domestic applications. Additionally, prior studies often lack precise quantification of system responsiveness, energy efficiency, and resource utilization, limiting their practical applicability for small-scale urban agriculture. This research addresses these gaps by developing a cost-effective, IoT-enhanced domestic vertical farming system that integrates real-time monitoring and automated control. The system achieves optimized pump performance (12V, 15W, 10 L/min), ensuring efficient nutrient delivery, while sensor accuracy remains within <3% for temperature and humidity and <2% for water and nutrient levels. The system demonstrates a rapid response time of <5 seconds to environmental fluctuations, significantly improving operational stability. By leveraging IoT for continuous monitoring and automation, this study presents a scalable and energy-efficient solution tailored for urban households, enabling sustainable food production with minimal manual intervention. The findings contribute to the advancement of smart agriculture by providing a practical and resource-efficient framework for integrating hydroponics with IoT technology.

## 2. Materials and Methods

### 2.1 System Design and Framework

Together with the design, the manufacturing process included such stages as developing precise concepts of the individual components of the system and then integrating all the elements of the project. Piping layout and the design of vertical layers, Figure 1 were significant regarding the flow of the fluid and stability of the units. Pipes were expected to meet flow and pressure characteristics that would accommodate the water needs while layers in the vertical direction were arranged in such a manner that held the plant and provided equal distribution of water. These pipes form the primary structure of the hydroponic system, serving as channels for nutrient solution flow and support for the plants. The pipes specification and material for the component are in Table 1 and Table 2 respectively.

**Table 1. Pipes Specification**

| SPECIFICATION | VALUE |
|---|---|
| Length | 1220m |
| Outer Diameter | 101.6mm |
| Hole Diameter | 58mm |
| Wall Thickness | 6.35mm |
| Density | 1330 kg/m³ |

**Table 2. Component Material**

| COMPONENT | MATERIAL |
|---|---|
| Stand | Carbon Steel/Mild Steel |
| Nozzle | Plastic/Metal |
| Pipe End Capes | PVC |
| Water Tank | Plastic or Non-Corrosive Material |

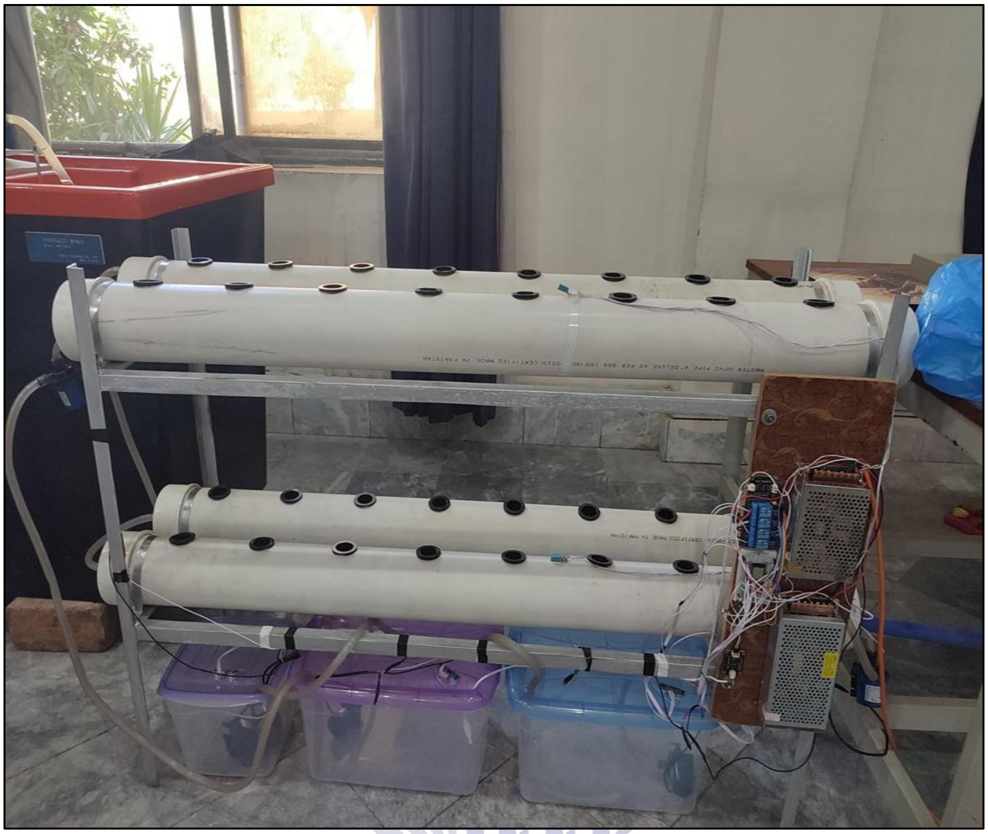

Figure 1. Vertical Pipes and Layers

The manufacturing phase included creating context of the designed components by selecting correct or suitable Material and practicing on them. Next came the integration, who's all the components and various assemblies were connected to make up the entire technical system and then tested to ensure that all worked properly and pertinent interfaces aligned appropriately. The Pipes can be prepared using the Length and Diameter as described in Table 1 by using cutting and drilling method. After that any debris should be removed ensuring smooth operation and preventing blockage. The stand is assembled using welding operation for a stable frame. The nutrient and water tank should be placed in a convenient place for and easy access and maintenance. Ensure they are positioned to allow for gravity-fed or pump-assisted flow into the PVC pipes. These pipes are connected to the tanks using nozzles and connectors. Sensors and Microcontrollers are installed at an appropriate location within the system to monitor the environmental conditions, flow, and other aspects. The Electrical Connection of this assembly is composed of the following components shown in Table 3.

Table. 3 Electrical Connections

| NAME | VALUE |
|---|---|
| Power Supply | 12V DC |
| Voltage Regulator | LM7805 Regulator |
| Relay | 5-Pin Relay |
| Wiring | $1mm^2$ |

Other Process include the Planting and addition of nutrition in the disposable glasses. After that PVC pipes is placed in the PVC Pipes. Then the Nutrient tank is filled with well-balanced nutrient solution suitable for Plants. For a hydroponic system to be effective, long-lasting, and simple to maintain, careful planning and execution are necessary. Using the parts given and these detailed instructions, you may create a robust and effective hydroponic system. Because it provides a controlled environment for optimal plant growth and is expandable or adaptable to specific needs, this system guarantees flexibility and response to changing demands.

### 2.2 Fluid Mechanics and Water Flow Management

In vegetal filter strips (VFS), hydraulic principles play a significant role in regulating the effectiveness and efficiency of water flow. This flow can be visualized to ensure even coverage and prevent over- or under-irrigation. Using hydraulic calculations based on crop requirements and system architecture, the right pumps must be chosen to provide constant pressure and flow rates. Water storage systems use hydraulic principles to ensure water availability and regulate variations in supply or demand. Knowledge of flow rates is essential for nutrition distribution and system efficiency. Fluid dynamics in bends, valves, and structures are also studied to reduce energy loss, reduce wear on equipment, and improve performance. Hydraulics integration in vertical farming systems promotes sustainable urban farming, reduces waste, and maximizes resources.

To ensure stiff water flow for irrigation then it is important to understand where water flows. For flow analysis of water through a system pipe constructed of steel and concrete, Computational Fluid Dynamics (CFD) software like ANSYS Fluent was employed. The simulation outcome delivered complex information on the flow of the fluid and pressure variations within CFD and helped in identifying ways to align the design for least resistance and best results. Pump, Figure 2, selection is crucial in Order to provide the required flow rate and the pressure that's why the correct selection of the suitable pump is so important. This was done under the assessment of the discharge rate the irrigation system needed for the vegetable production in vertical farming and the position of the water storage tank. Based on these characteristics, the pump was chosen. To measure and, therefore, better visualize the flow rate of water, flow meters Figure 3 were incorporated. These meters helped to record numerical results and, at the same time, visual representation due to the necessity to check the system effectiveness and water distribution.



**Figure 2. Pump**

**Figure 3. Flow Meter**

### 2.3 Computer-Aided Design (CAD)

A comprehensive description of the vertical farming system was made using the CAD tool with the aim of generating accurate 3D models. Among the models in designing were the structure of the building as well as the pipes and different parts. The use of tools like Creo, AutoCAD, SolidWorks CATIA, Unigraphics and I- DEAS were used to create the 3D model of the whole project as shown in Figure 4. Such designs contained every dimensional parameter and size reference required to build the subject structure. Formats enabled configuration and simulation of the system in a building before constructing it physically.

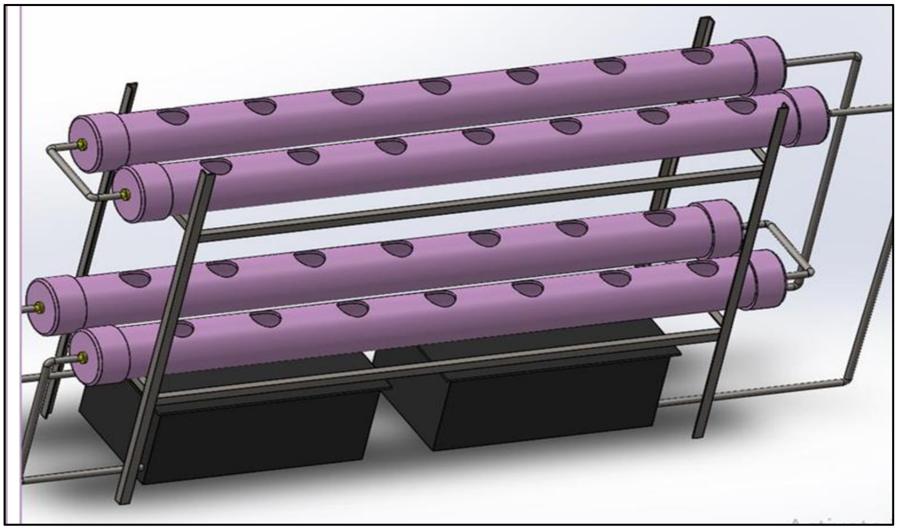

Figure 4. CAD Model of Vertical Farming

**2.4 Instrumentation and Control Systems (Arduino and Sensors)**

Sensors and Controlled System have facilitated the accurate monitoring and regulation of factors such as temperature, humidity, and light to optimize crop growth conditions. Consequently, farmers are able to attain higher yields and improved quality while reducing resource consumption and environmental impact. Some of the studied sensors were Temperature, Humidity, Light, Moisture and Nutrient Sensor. An Arduino micro controller was used in this project to record information from these sensors as well as regulating the action of other automated systems such as the lighting, irrigation and air conditioning systems. Application commands, sensor control, and signal gathering were managed by software specifically made for the Arduino microcontroller platform. With the help of this code, the system was able to adapt the parameters for the optimal plant growth and receive instructions from the continuously changing environmental situation.

**2.5 Data Collection, Analysis, and Visualization**

**2.5.1 Data Collection**

In order for operators to maximize growth and spot trends, sensor data was gathered and archived for further study. This knowledge was applied to guarantee sustainable agricultural methods and enhance agriculture processes. When the ESP32 microcontroller was linked to an Adafruit MQTT broker and a Wi-Fi network, lightweight Message

Queuing Telemetry Transport (MQTT) was produced. The port and data from the MQTT broker were used to setup the ESP32, which sent data from relevant sensors every five minutes. Increased agricultural productivity and less resource waste resulted from this, leading to more productive and ecologically friendly farming practices.

**2.5.2 Data Analysis**

Temperature, humidity, light levels, and nutrient concentrations are the six key plant development factors that the research sought to evaluate for stability. Sensor accuracy, system latency, and algorithms' capacity to anticipate and respond to environmental changes were all taken into account when assessing the system's response to changes. Plant growth rates, health indicators, automated system responsiveness, and environmental parameter stability were additional criteria. Based on sensor readings and threshold values, Adafruit IO's logic operations regulate lights and pumps. For example, the system may control brightness or turn on air conditioning if the temperature climbs over a predetermined point.

**2.5.3 Hardware Design**

It is composed of several subparts which have control and monitoring of the environmental conditions, as well as nutrients present in a vertical farming system. The microcontroller of the Hardware is composed of Three Microcontrollers shown in Figure 5 and its details are mentioned in Table 4.

**Table. 4 Hardware Component**

| Hardware Components | Details |
|---|---|
| Pump | 12V DC |
| Temperature Sensor | LM35/ds18b20 |
| Humidity Sensor | DHT11 |
| TDS Sensor | Water Quality Sensor |
| Level Sensor | SEN136B5B |
| Microcontroller | ESP32 |
| Power Supply | 12A, 12V DC |
| Voltage Regulator | Mosfet Arduino Shield |
| Push Button | Generic |
| Relays | SPDT 12V DC |
| Mosfet Modules | 12-36V |

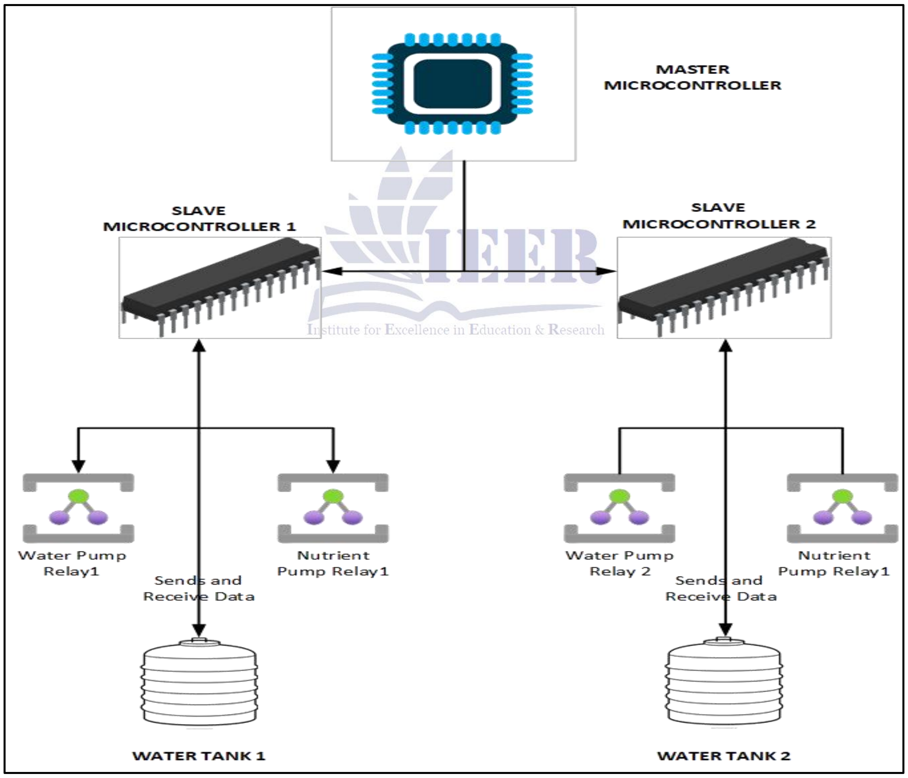


**Figure 5. Microcontrollers Waypoint**

The sensor part comprises of water level, temperature, humidity, Total Dissolved Solids (TDS), among others. The Water Level Sensors are utilized in order to keep check on the water and nutrient which are present in the tanks. There are four level sensors Figure. 6 that are Level Sensor 1-a and Level Sensor 1-b. The other two sensors are, Level Sensor 2-a and Level Sensor 2-b. Each Sensors are connected to their Respective Tanks. For the system to operate safely and optimally, it is also essential to monitor the temperature often at various points, particularly along horizontal lines. It is simpler to proactively identify anomalies or inefficiencies thanks to the temperature sensors on these lines, which offer data in real time. Regular comparison of data across these horizontal lines may effectively monitor temperature swings and quickly identify possible issues, ensuring that the system runs within the intended parameters. Additionally, keeping the temperature steady and suitable is essential for efficiency and avoiding damage or risks brought on by exceptionally high or low temperatures. An efficient system management procedure must include routine sensor data evaluations and inspections (Figure 7).

Because humidity sensors track and modify moisture levels, they are crucial for preserving ideal plant development conditions. By enabling precise temperature controls and irrigation system management, they help avoid overwatering and low humidity. They enhance agricultural operations and indoor gardens by maximizing resource use and promoting sustainable practices. Sensors for total dissolved solids (TDS) monitor the cleanliness and safety of water for use in drinking water, agricultural, and industrial activities. For plants to be healthy and productive, both sensors are essential. Using signals from the robots' microcontrollers, the relays function as switches to regulate the pumps.

**Table. 5 Relays and Their Use**

| Relays | Uses |
|---|---|
| Water Pump Relay 1 | Control Pump for Water Tank 1 |
| Water Pump Relay 2 | Control Pump for Water Tank 2 |
| Nutrient Pump Relay 1 | Control Pump for Nutrient Tank 1 |
| Nutrient Pump Relay 2 | Control Pump for Nutrient Tank 2 |

Pumps make it easier for plants to receive nutrients and water, which promotes better plant growth. The selection of a suitable pump is essential to ensure the desired flow rate and pressure. The pump selected for this project is a 12V, 15-watt pump, which provides the flexibility to increase the size of the model by adding up to four more layers using the same components. This pump is cost-effective, ensuring that the overall cost of the model does not increase significantly, while also allowing for scalability to meet higher production demands There are two types of pumps Figure. 10, Nutrient and Water Pump. These Pump are used to control Nutrient Tank and Water Tank respectively.

**Figure 6. Level Sensor**

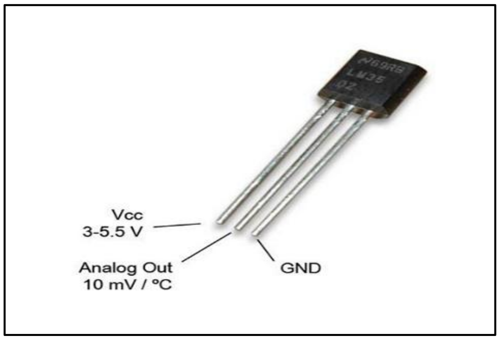


**Figure 7. LM35 Temperature Sensor**

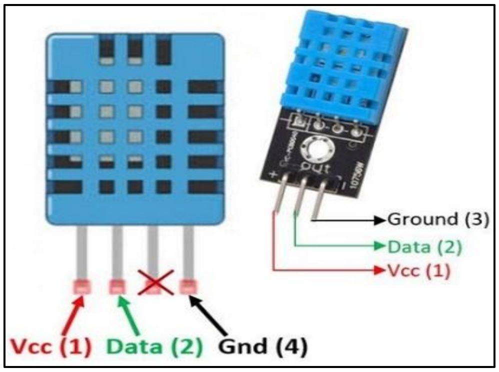


Figure 8. Humidity sensor - DHT11

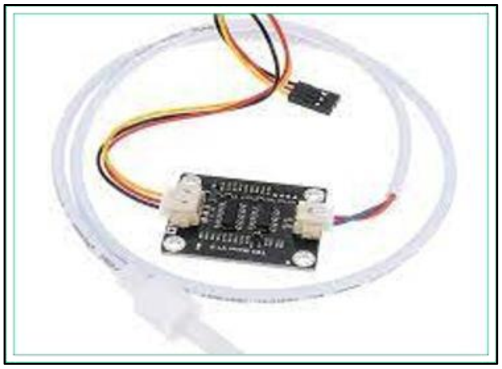

Figure 9. TDS Sensor

Figure 10. Pump

**2.5.4 Software Design**

This extends considerable flexibility to the monitoring and control of the system through the cloud and can be done remotely. In the world of IoT Vertical Farming, utilizing cloud data visualization presents significant transformative benefits. Cloud solutions increase production and efficiency by allowing farmers to remotely monitor and control every part of farming. These systems use a variety of Internet of Things sensors to collect data in real time on plant health, temperature, light levels, and soil moisture. This vast amount of data is processed in the cloud and shown in user-friendly dashboards so that farmers can quickly access important trends and insights. As illustrated in Figure. 11, these data visualization tools help with accurate monitoring by alerting users to possible problems before they become more serious. For instance, the cloud system can quickly notify the farmer if a sensor detects abnormal temperature levels, enabling immediate remedial action. Furthermore, cloud-based control allows farmers to remotely modify environmental conditions, going beyond mere monitoring.

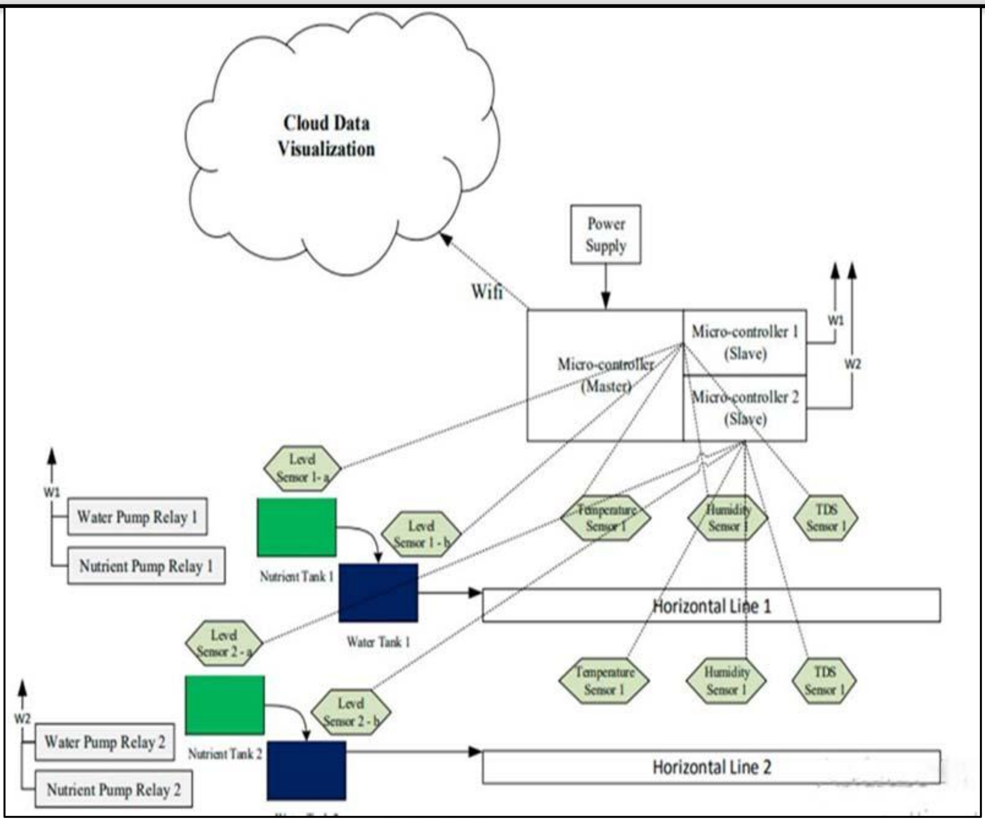


Figure 11. Data Visualization

### 2.6 Experimental Setup and Testing Procedures

A cloud-based architecture can be used to visualize the data. Data transmission and reception are made possible by the core microcontroller's Wi-Fi connection to the cloud. This setup allows for real-time remote monitoring and management of the agricultural system. Encryption techniques are used to safeguard data security and privacy during transmission between the microcontroller and the cloud. Sensors continuously monitor the water/nutrient levels and environmental conditions. As slaves, the microcontrollers collect sensor data and send it to the master microcontroller. In order to maintain ideal growing conditions, the master microcontroller uses the sensor data to send commands to the relays to switch on or off the pumps. When specific thresholds are exceeded, the system is configured to notify users via email or SMS, requiring prompt action. Users can remotely monitor the system and make required modifications by using sensor data that is sent to the cloud for real-time viewing and analysis. The cloud platform archives historical data, allowing users to examine trends and patterns over time. This facilitates enhanced decision-making for future farm management strategies. With its simple controls and graphical display of the farming system's condition, the user-friendly design makes it easy to interact with the cloud platform shown in figure 12.

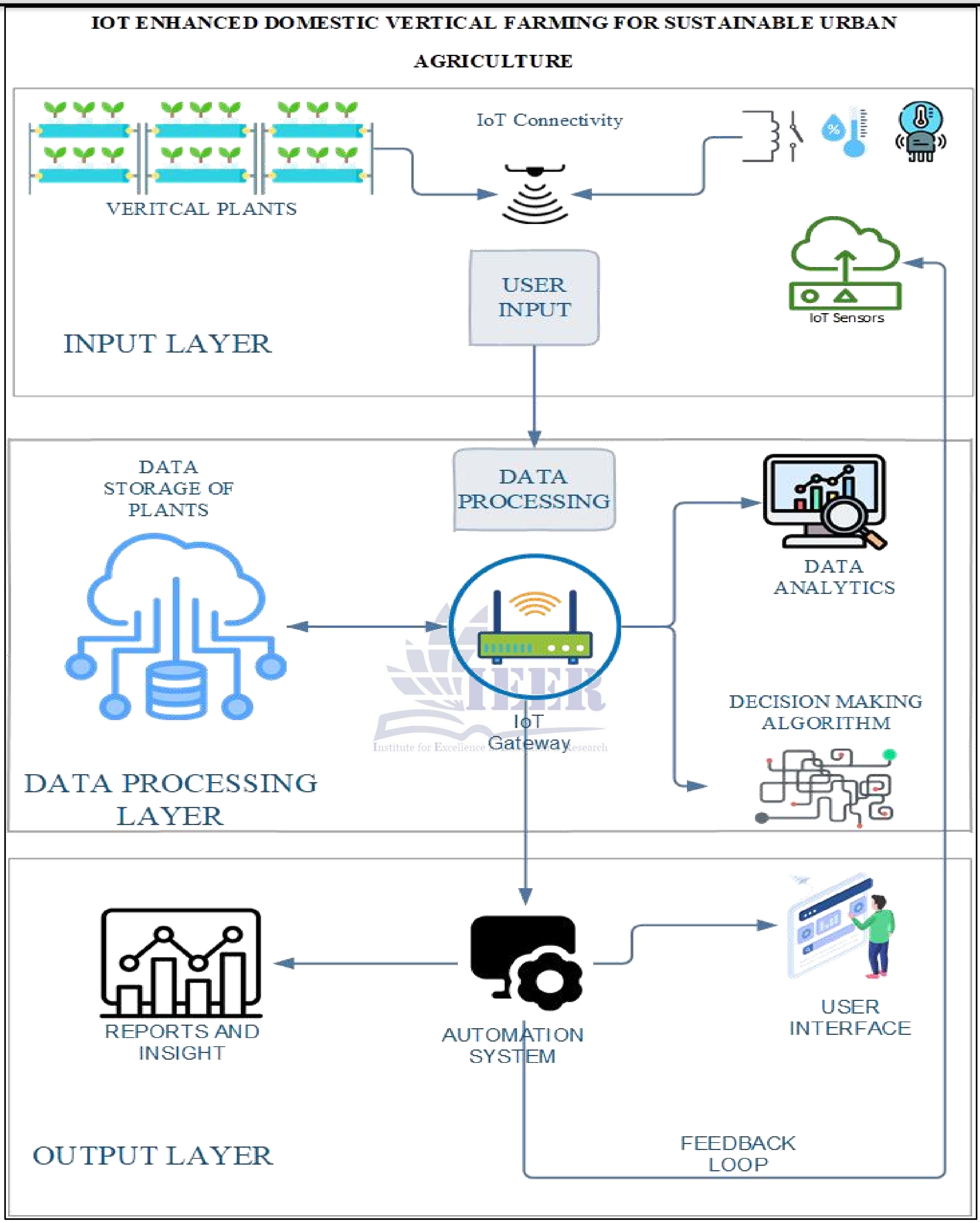


Figure 12. Work Process of IoT Vertical Farming

### 3. Fabrication Process

The fabrication of the IoT-enhanced domestic vertical farming system involved the systematic assembly of mechanical, electrical, and IoT components to create a functional hydroponic setup. The process is outlined in the following subsections.

### 3.1 Structural Components

The structural components of the system included PVC pipes shown in figure 13 and a steel stand shown in figure 14. The PVC pipes, with an outer diameter of 101.6 mm and a wall thickness of 6.35 mm, were cut to a length of 1220 mm. Holes of 58 mm diameter were drilled at uniform intervals along the pipes to accommodate plant holders. The pipes were thoroughly cleaned to ensure smooth nutrient flow and prevent blockages. The steel stand, constructed from carbon or mild steel, was welded into a stable frame to support the PVC pipes. To enhance durability and prevent corrosion, the stand was coated with rust-proof paint.

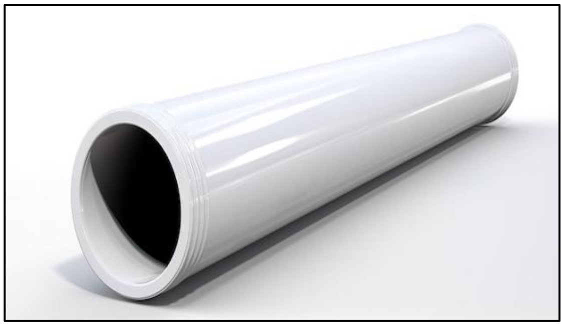

**Figure 13. PVC Pipe**

**Figure 14. Steel stand**

### 3.2 Hydroponic System Assembly

The hydroponic system was assembled by integrating the structural components with functional elements. PVC pipe end caps shown in figure 15 were secured using watertight glue to prevent leaks. Nutrient and water tanks shown in figure 16, made of non-corrosive materials, were positioned to facilitate gravity-fed or pump-assisted flow. Nozzles were installed along the PVC pipes to ensure even distribution of the nutrient solution shown in figure 18. Transparent glasses filled with coco peat or foam shown in figure 17 were placed in the drilled holes to serve as plant holders, and lettuce seeds were planted in these holders.

**Figure 15. End cap**

**Figure 16. Nutrient Tank**

**Figure 17. Coco peat/foam**

**Figure 18. Fertilizer for Nutrient solution**

### 3.3 IoT Integration

The system was enhanced with IoT devices for real-time monitoring and control. Sensors were installed to measure temperature (LM35/DS18B20), humidity (DHT11/DHT22), total dissolved solids (TDS), and water level (SEN136B5B/HC-SR04). These sensors were connected to an ESP32 or Node MCU micro-controller for data collection and system control. The electrical setup included a 20A 12V DC power supply, with voltage regulation provided by an LM7805 regulator. Relays and switches were installed to control pumps and other components, ensuring efficient operation shown in figure 19.

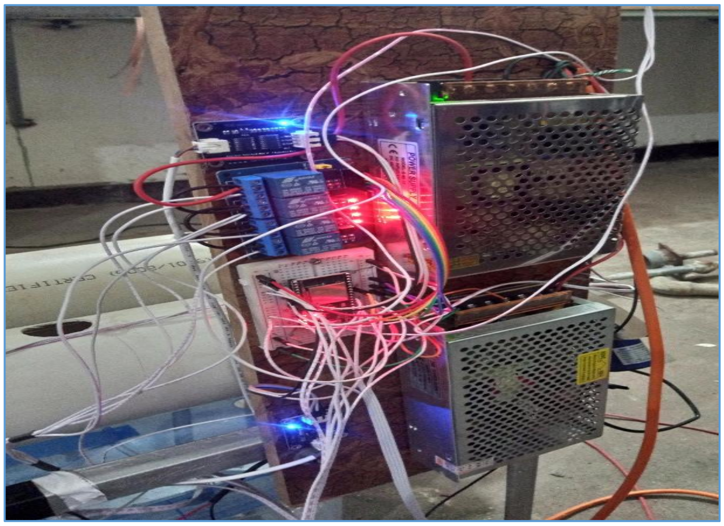

Figure 19. IoT Integration Schematic for the Hydroponic System

## 4. Results and Discussion

### 4.1 System Dimensions and Hydroponic Calculations

For the hydroponic system to work at its best and maintain structural integrity, the physical measurements shown in Table 6 and related computations were crucial.

Table 6. Structural Specifications and Hydroponic System Dimensions

| Property | PVC Pipe Value |
|---|---|
| Outer Diameter (OD) | 101.6 mm |
| Wall Thickness (WT) | 6.35 mm |
| Inner Diameter (ID) | 99.6 mm |
| Length | 1.22 m |



#### 4.1.1 Cross-Sectional Area of PVC Pipe

The cross-sectional area (A) was calculated using the formula shown in Table 7.

Table 7. Cross-Sectional Area Calculation of PVC Pipe

| Calculation | Formula | Result |
|---|---|---|
| Area of PVC Pipe | $A = \pi (OD / 2)^2 - \pi(OD - 2\times WT / 2)^2$ | $A = 1.900 \times 10^{-3}\ m^2$ |

#### 4.1.2 Volume of PVC Pipe

The calculation for PVC pipe volume is shown in Table 8.

Table 8. PVC pipe volume calculations

| Calculation | Formula | Substitution | Result |
|---|---|---|---|
| Volume of PVC Pipe | Volume = Area × Length | Volume = $1.900 \times 10^{-3} \times 1.22$ | Volume = $0.000193\ m^3$ |

#### 4.1.3 Weight of PVC Pipe and Water

The calculation for Weight of PVC Pipe and Water is shown in Table 9.

ISSN (e) 3007-3138 (p) 3007-312X Volume 3, Issue 4, 2025


**Table 9. Weight Estimation of PVC Pipe and Contained Water**

| Calculation | Formula | Substitution | Result |
|---|---|---|---|
| Weight of PVC Pipe | $W_{PVC}$ = Volume ×Density | $W_{PVC}$ = 0.000193 ×1330 | $W_{PVC}$ = 0.256 kg |
| Weight of Water | $W_{Water} = V_{water} \times D_{water}$ | $W_{Water}$ = 0.009505 × 997 | $W_{Water}$ = 9.47 kg |
| Total Weight | $W_{Total} = W_{PVC} + W_{Water}$ | $W_{Total}$ = 0.256 + 9.47 | $W_{Total}$ = 9.732 kg |

### 4.2 Pumping System Analysis

A 12V, 15-watt pump was selected based on system requirements, offering cost-effectiveness and scalability. It supports a flow rate of 10 L/min, sufficient for irrigation across all layers.

#### 4.2.1 Velocity and Power Calculations

The calculations for Velocity and Power are shown in Table 10.

**Table 10. Presents the pump's velocity and power requirements for the system**

| Parameter | Formula | Value | Unit |
|---|---|---|---|
| Velocity (v) | $v = Q / A$ | 0.8 | m/s |
| Pressure Head (h) | From system measurements | 2.10 | m |
| Power (P) | $P = \gamma Q h / \eta p$ | 4.22 | W |

Where:

- $Q = 0.00016\ m^3$
- $A = 0.00029\ m^2$
- $\gamma = 9810\ N/m^3$ (specific weight of water)
- $h = 2.10$ m (pressure head)
- $\eta_p = 0.78$ (pump efficiency)

### 4.3 IoT System Performance Metrics

The IoT-based domestic vertical farming system was evaluated based on key performance metrics, including real-time monitoring, system responsiveness, accuracy, and energy efficiency.

#### 4.3.1 Real-Time Data Monitoring

Key parameters were tracked in real-time by the IoT system; the temperature was 34.2°C, the humidity averaged 43%, the water levels were tracked for effective irrigation, and the nutrient levels were adjusted to guarantee the best possible plant growth shown in figure 20, 21a and 21b.



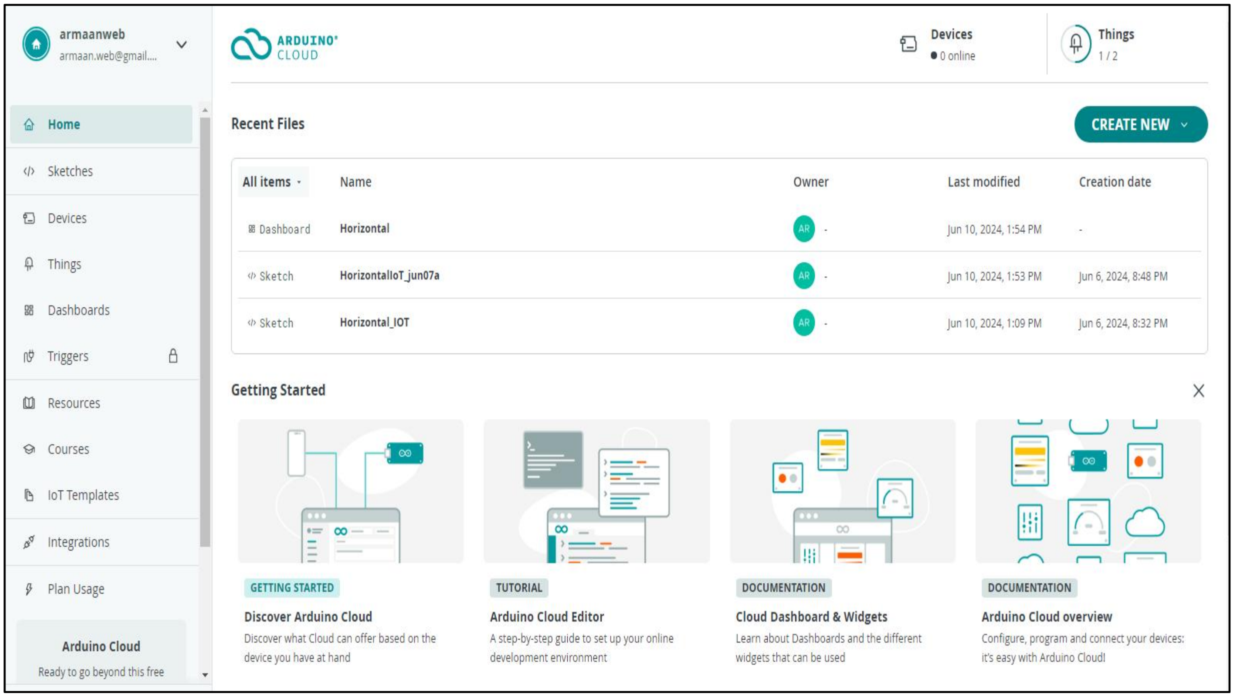


**Figure 20. Arduino Cloud Interface for IoT Device Management**

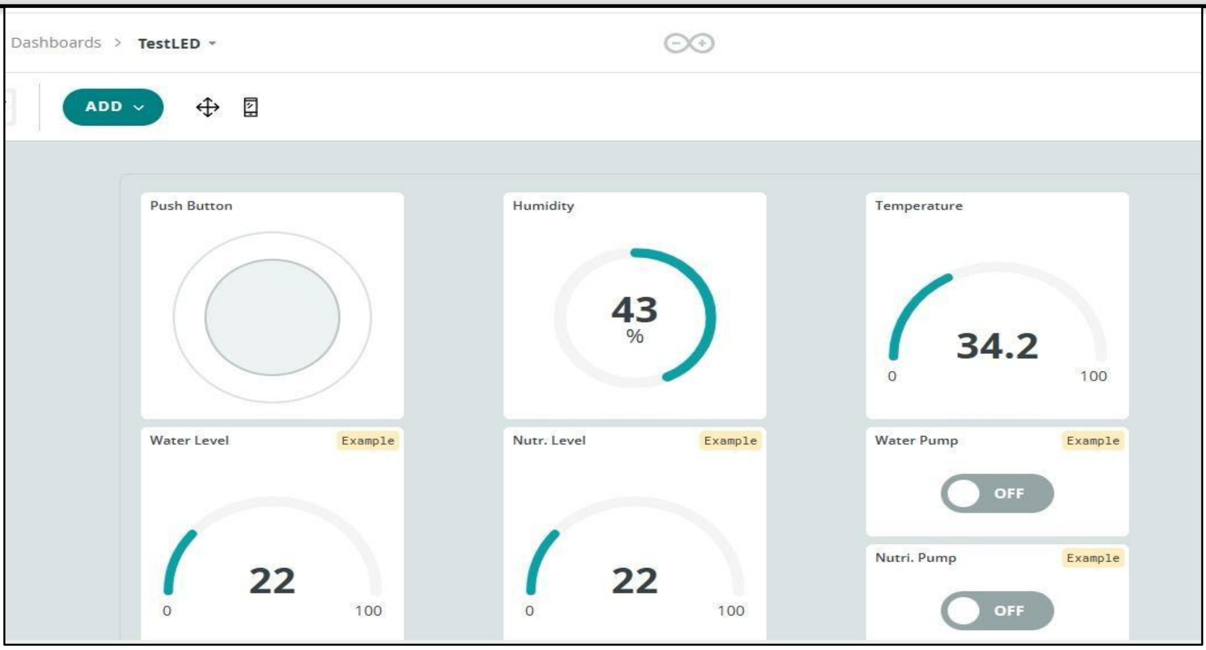


Figure 21a. Real-Time Data Monitoring and Visualization of Key Parameters

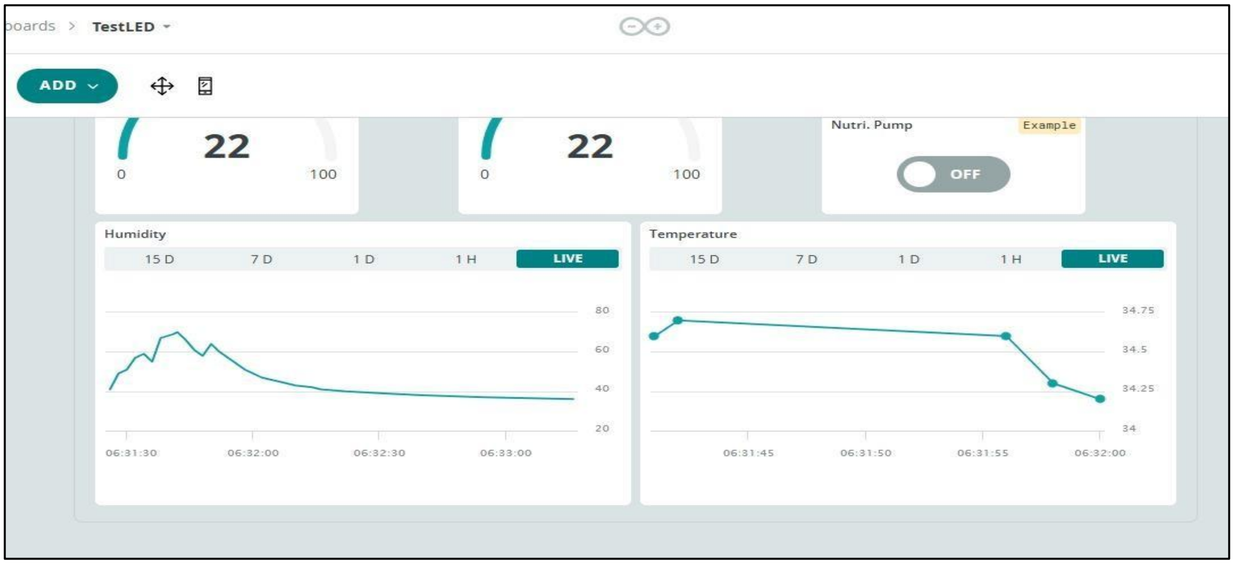


Figure 21b. Real-Time Data Monitoring and Visualization of Key Parameters

**4.3.2 System Responsiveness**

When the water levels fell below a predetermined threshold, the system's water pump activated, reacting quickly to variations in the water levels. With an average on/off response time of less than five seconds, it operated efficiently. In a similar manner, the nutrient pump functioned according to preset parameters, guaranteeing timely and reliable nutrient delivery for the best possible plant growth.

**4.3.3 Accuracy and Reliability**

Sensors showed a variance of less than 3% for temperature and humidity, and less than 2% for water and nutrient levels, indicating high reliability.

**4.3.4 User Interface**

The dashboard displayed real-time data with easy-to-interpret graphical representations of key metrics shown in Table 11. Alerts were sent via mobile app for critical parameters such as water level and temperature.

**Table. 11 Performance Evaluation Summary**

| Metric | Description | Performance Level |
|---|---|---|
| Temperature | Monitored with ±1°C variance. | Excellent |
| Humidity | Average 43% with ±5% accuracy. | Very Good |
| Water Level | Responsive water level monitoring. | Excellent |
| Pump Response Time | Water and nutrient pumps responded within 5 seconds. | Excellent |
| System Interface | Real-time data display on dashboard and app. | Very Good |

### 4.4 Interpretation of Data and Insights

With a weight of 9.732 kg, the system is easy to install and physically efficient, using just 4.22 W of power for watering. Using dependable sensors to monitor water, temperature, humidity, and nutrient levels, it also integrates the Internet of Things for effective plant development and resource management.

## 5. Conclusion

The study evaluated system responsiveness, sustainability, real-time monitoring, and energy usage while effectively combining automation and hydroponics to develop a home vertical growing system for sustainable urban agriculture.

**Key conclusions include:**

- Every layer was effectively irrigated using a 12V, 15-watt pump with a 10 L/min flow rate, keeping the velocity at 0.8 m/s and the pressure head at 2.10 m to ensure low energy consumption.
- With sensor accuracy of ±2% for water and nutrient levels and ±3% for temperature and humidity owing to automatic changes, real-time monitoring revealed ideal plant development conditions at 34.2°C and 43% humidity.
- By responding to variations in water and nutrient levels in less than five seconds, the gadget guaranteed constant watering and ideal fertilizer delivery.
- Through data visualization, real-time notifications for important indicators, and an intuitive interface that ensures simple operation and efficient system control, the Arduino Cloud made remote monitoring possible.
- IoT-driven automation improved urban agriculture efficiency by reducing manual work, maximizing water and nutrient use, and reducing costs and scalability.

Future developments in urban food production might include AI-based optimization, more crop diversity, and adaptive automation. Meanwhile, IoT-integrated vertical farming provides a technologically sophisticated and resource-efficient method of producing urban food.



## 6. REFERENCES

1. Oh, S. and C. Lu, Vertical farming-smart urban agriculture for enhancing resilience and sustainability in food security. The Journal of Horticultural Science and Biotechnology, 2023. **98**(2): p. 133-140.
2. Rathor, A.S., et al., Empowering vertical farming through IoT and AI-Driven technologies: A comprehensive review. Heliyon, 2024.
3. Kalantari, F., et al., Opportunities and challenges in sustainability of vertical farming: A review. Journal of Landscape Ecology, 2018. **11**(1): p. 35-60.
4. Bailey, G.E., Vertical farming. 1915: Lord Baltimore Press.
5. Petrovics, D. and M. Giezen, Planning for sustainable urban food systems: an analysis of the up-scaling potential of vertical farming. Journal of Environmental Planning and Management, 2022. **65**(5): p. 785-808.
6. Van Gerrewey, T., N. Boon, and D. Geelen, Vertical Farming: The Only Way Is Up? Agronomy 2022, 12, 2. 2021, s Note: MDPI stays neutral with regard to jurisdictional claims in published ....
7. Beacham, A.M., L.H. Vickers, and J.M. Monaghan, Vertical farming: a summary of approaches to growing skywards. The

Journal of Horticultural Science and Biotechnology, 2019. **94**(3): p. 277-283.
8. Ares, G., Methodological issues in cross-cultural sensory and consumer research. Food Quality and Preference, 2018. **64**: p. 253-263.
9. Farhangi, M., et al., The role of urban agriculture technologies in transformation toward participatory local urban planning in rafsanjan. Land, 2021. **10**(8): p. 830.
10. Hosseini, H., et al., Nutrient use in vertical farming: Optimal electrical conductivity of nutrient solution for growth of lettuce and basil in hydroponic cultivation. Horticulturae, 2021. **7**(9): p. 283.
11. Shamshiri, R.R., et al., A., HI; Weltzien, C.; Ahmad, D.; Shad, ZM Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. Int. J. Agric. Biol. Eng, 2018. **11**: p. 1-22.
12. Manos, D.-P. and G. Xydis, Hydroponics: are we moving towards that direction only because of the environment? A discussion on forecasting and a systems review. Environmental Science and Pollution Research, 2019. **26**(13): p. 12662-12672.
13. Kaur, G., P. Upadhyaya, and P. Chawla, Comparative analysis of IoT-based controlled environment and uncontrolled environment plant growth monitoring system for hydroponic indoor vertical farm. Environmental Research, 2023. **222**: p. 115313.
14. Vatistas, C., D.D. Avgoustaki, and T. Bartzanas, A systematic literature review on controlled-environment agriculture: How vertical farms and greenhouses can influence the sustainability and footprint of urban microclimate with local food production. Atmosphere, 2022. **13**(8): p. 1258.
15. Despommier, D., Farming up the city: the rise of urban vertical farms. Trends in biotechnology, 2013. **31**(7): p. 388-389.
16. Gurung, L., et al., Vertical farming in urban agriculture: Opportunities, challenges, and future directions. Big Data Agric, 2024. **6**: p. 89-95.
17. Yapp, E.H.T., et al., Urban farming: the challenges of hydroponic and vertical farming in Malaysia. Cogent Food & Agriculture, 2025. **11**(1): p. 2448601.
18. Mim, M.I., F. Sultana, and M.R. Hasan, AI-Powered Autonomous Farming: The Future of Sustainable Agriculture. European Journal of Theoretical and Applied Sciences, 2025. **3**(1): p. 11-31.
19. Kaiser, E., et al., Vertical farming goes dynamic: optimizing resource use efficiency, product quality, and energy costs. Frontiers in Science, 2024. **2**: p. 1411259.
20. Saad, M.H.M., N.M. Hamdan, and M.R. Sarker, State of the art of urban smart vertical farming automation system: Advanced topologies, issues and recommendations. Electronics, 2021. **10**(12): p. 1422.
21. Jin, W., et al., Light use efficiency of lettuce cultivation in vertical farms compared with greenhouse and field. Food and Energy Security, 2023. **12**(1): p. e391.
22. Martin, M. and M.J. Bustamante, Growing-service systems: new business models for modular urban-vertical farming. Frontiers in Sustainable Food Systems, 2021. **5**: p. 787281.
23. Abdullah, M.J., Z. Zhang, and K. Matsubae, Potential for food self-sufficiency improvements through indoor and vertical farming in the gulf cooperation council: Challenges and opportunities from the case of Kuwait. Sustainability, 2021. **13**(22): p. 12553.
24. Larsen, D.H., et al., Response of basil growth and morphology to light intensity and spectrum in a vertical farm. Frontiers in Plant Science, 2020. **11**: p. 597906.
25. Shrivastava, A., et al., Automatic robotic system design and development for vertical hydroponic farming using IoT and big data analysis. Materials Today: Proceedings, 2023. **80**: p. 3546-3553.
26. de Oliveira, F.B., et al., Lean principles in vertical farming: A case study. Procedia CIRP, 2020. **93**: p. 712-717.

27. Wong, C., J. Wood, and S. Paturi, Vertical farming: an assessment of Singapore City. Etropic: electronic journal of studies in the tropics, 2020. **19**: p. 228-248.
28. Chowdhury, M.E., et al., Design, construction and testing of IoT based automated indoor vertical hydroponics farming test-bed in Qatar. Sensors, 2020. **20**(19): p. 5637.
29. Riaz, M.H., et al., Module technology for agrivoltaics: Vertical bifacial versus tilted monofacial farms. IEEE Journal of Photovoltaics, 2021. **11**(2): p. 469-477.
30. Martin, M., T. Weidner, and C. Gullström, Estimating the potential of building integration and regional synergies to improve the environmental performance of urban vertical farming. Frontiers in Sustainable Food Systems, 2022. **6**: p. 849304.

.