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DESIGN AND IMPLEMENTATION OF A SMART VERTICAL HYDROPONIC SYSTEM FOR URBAN FARMING

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I. ABSTRACT

The increasing population in urban areas and the continuous reduction of available agricultural land have created a need for efficient farming methods that can produce fresh food in limited spaces. Traditional farming depends heavily on soil quality, weather conditions, and large water consumption, which makes it difficult to sustain in many urban locations. Hydroponics offers an alternative cultivation method where plants are grown without soil by supplying nutrients directly through water. When this technique is combined with a vertical structure, it becomes more suitable for city environments because more plants can be grown in a smaller area. This project focuses on the design and implementation of a Smart Vertical Hydroponic System for urban farming using IoT technology. The system is developed using a vertical PVC tower structure with net pots for plant placement and a recirculating water system for nutrient delivery. An ESP32 microcontroller is used as the main control unit due to its built-in Wi-Fi capability and compatibility with sensor-based applications.

To monitor important operating conditions, the system uses a TDS sensor for measuring nutrient concentration, a water flow sensor for checking circulation, a water level sensor for reservoir monitoring, and a DHT11 sensor for temperature and humidity measurement. The sensor readings are transmitted through MQTT protocol to a backend server and displayed on a web dashboard for real-time monitoring and control.

The system supports both manual and automatic operation. Basic safety features such as low water level shutdown, no-flow alert, and pump control logic are included to improve reliability. The proposed model is intended as a low-cost, practical, and scalable solution for

homes, educational institutions, and small urban farming setups. It also demonstrates the effective use of IoT technology in modern agriculture.

II. INTRODUCTION

Agriculture has always been an essential part of human life, but in recent years it has faced several challenges such as reduction in cultivable land, irregular climate conditions, water scarcity, and increasing food demand. In urban areas, these challenges are more significant because open land for farming is limited and most people depend on food supplied from distant rural regions. Due to this, there is growing interest in alternative farming methods that can produce fresh crops in small spaces with better resource efficiency **[1], [9]**.

Hydroponics is a modern cultivation technique in which plants are grown without soil by using nutrient-rich water solutions. Instead of absorbing minerals from soil, plant roots directly receive the required nutrients through water. This method allows better control over plant growth conditions, reduces soil-related diseases, and uses less water when compared to conventional farming **[1], [2], [15]**. Because of these advantages, hydroponics is becoming popular for indoor farming, rooftop cultivation, greenhouses, and educational research projects.

Among different hydroponic models, vertical hydroponic systems are especially useful for urban farming. In this arrangement, plants are placed in multiple levels using towers or stacked structures, which helps in maximizing plant capacity within a small floor area **[1], [13]**. A vertical system can be installed in homes, balconies, terraces, schools, and commercial indoor spaces where horizontal land availability is low.

Although hydroponic farming offers many benefits, it also requires regular monitoring of important parameters such as nutrient concentration, water level, circulation flow, temperature, and humidity. If these conditions are not maintained properly, plant growth can be affected and system failures may occur **[2], [6]**. Manual monitoring of these values on a daily basis is time-consuming and may not always be accurate.

To overcome these issues, Internet of Things (IoT) technology can be integrated with hydroponics. IoT allows sensors, controllers, and online dashboards to work together for real-time monitoring and automation. Users can observe system performance remotely, receive alerts, and control devices such as pumps through a connected platform **[3], [9], [11]**.

In this project, a Smart Vertical Hydroponic System has been designed and implemented using ESP32, multiple sensors, MQTT communication, and a web dashboard. The objective is to create a practical and affordable urban farming solution that saves space, reduces water wastage, and simplifies plant maintenance through smart monitoring and control.

III. RELATED WORKS / LITERATURE REVIEW

In recent years, hydroponic farming has gained significant attention as an alternative agricultural method due to increasing urbanization, water scarcity, and declining cultivable land. After 2022, many researchers focused on integrating hydroponic systems with Internet of Things (IoT), automation, cloud dashboards, and artificial intelligence to improve productivity and reduce manual effort **[4], [8], [9]**.

Demir and Çiçek (2026) developed a low-cost IoT-based Nutrient Film Technique (NFT) hydroponic system using ESP32 and the MING stack. Their system used MQTT, InfluxDB, Node-RED, and Grafana for monitoring and control **[4]**.

Baraskar et al. (2025) proposed an AI-powered automated hydroponic system that integrated ESP32, MQTT broker, Firebase database, and NextJS dashboard **[8]**.

A 2025 implementation study on IoT-enabled nutrient and environmental monitoring for vertical hydroponic farming presented a real-time dashboard using ESP32 and cloud integration **[6]**.

Hasan et al. (2024) introduced an IoT-based greenhouse hydroponics system with remote monitoring and crop-specific parameter control **[5]**.

Bouzid et al. (2025) explored machine learning-based yield prediction in IoT-enabled indoor vertical hydroponic farms **[7]**.

Benyas (2025) studied the impact of IoT integration on water conservation in hydroponic systems **[15]**.

From the reviewed literature, it is clear that hydroponic research is moving toward automation, remote monitoring, and intelligent control. However, many available systems focus on commercial setups or use costly sensors and complex architectures. There is still a need for a practical, low-cost, student-level smart vertical hydroponic system using ESP32, TDS sensor, flow sensor, water level sensor, and dashboard monitoring.

IV. PROPOSED METHODOLOGY

The proposed methodology of this project is based on developing a practical smart vertical hydroponic system that can be used in urban areas where farming space is limited. The idea behind the system is to combine hydroponic cultivation with IoT technology so that plant growth conditions can be monitored continuously and controlled with less manual effort. Many small hydroponic setups fail because users are unable to check nutrient levels, water circulation, and environmental conditions regularly. This project has been planned to solve those common issues through a simple but effective implementation model.

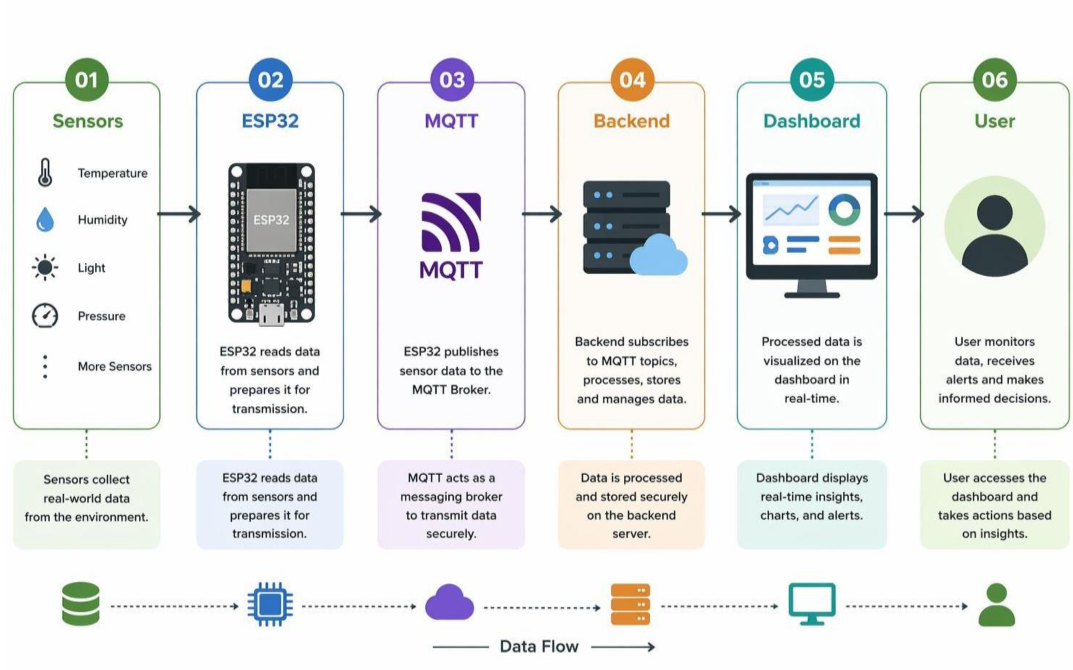

Figure 1: Proposed Methodology Diagram.

The first stage of the methodology involved understanding the basic needs of hydroponic farming. A healthy hydroponic system requires continuous water movement, proper nutrient concentration, sufficient water in the reservoir, and stable surrounding temperature. If any of these factors are ignored, plant growth can slow down or the system may stop functioning correctly. Therefore, the proposed model was designed to monitor these parameters in real time and provide quick response when abnormal conditions occur

To make the system suitable for homes and city environments, a vertical farming structure was selected instead of a horizontal one. In this design, plants are arranged vertically inside a

PVC pipe tower. Multiple openings are created on the pipe surface where net pots are inserted. Plants are placed inside these pots while their roots remain inside the tower. This arrangement allows many plants to be grown using a very small floor area. The vertical approach is especially useful for balconies, rooftops, terraces, classrooms, and indoor spaces where conventional farming is not possible **[1], [13]**

At the bottom of the tower, a nutrient reservoir tank is placed to store water mixed with plant nutrients. A 12V DC pump is connected to the tank and is used to push nutrient solution to the top of the tower. Once the water reaches the top, it flows downward due to gravity and passes through the root zones of all plants. During this flow, roots absorb the required nutrients and moisture. The remaining water returns to the tank and is reused again. This recirculation process reduces water wastage and makes the system more efficient than traditional soil farming **[1], [15]**

To make the setup intelligent and self-monitoring, several sensors are integrated into the system. A TDS sensor is used to measure the concentration of dissolved nutrients in water. This is important because plants need nutrients within a proper range. If nutrient concentration becomes too low, plant growth may become weak. If it becomes too high, roots may get damaged. By monitoring TDS values regularly, the user can maintain proper nutrient balance **[2], [6], [12]**

A water flow sensor is installed in the pipeline to verify whether water is circulating properly. In many hydroponic systems, the pump may turn on but water may not flow because of blockage, dry tank condition, or pump malfunction. In such cases, roots remain dry and plants may suffer quickly. The flow sensor helps detect this issue immediately **[6], [12]**

A water level sensor is placed inside the nutrient reservoir tank. Its purpose is to monitor the available water quantity. If the water level falls below the safe limit, the controller can stop the pump automatically. This prevents dry running, which can damage the motor and interrupt nutrient supply **[6], [12]**

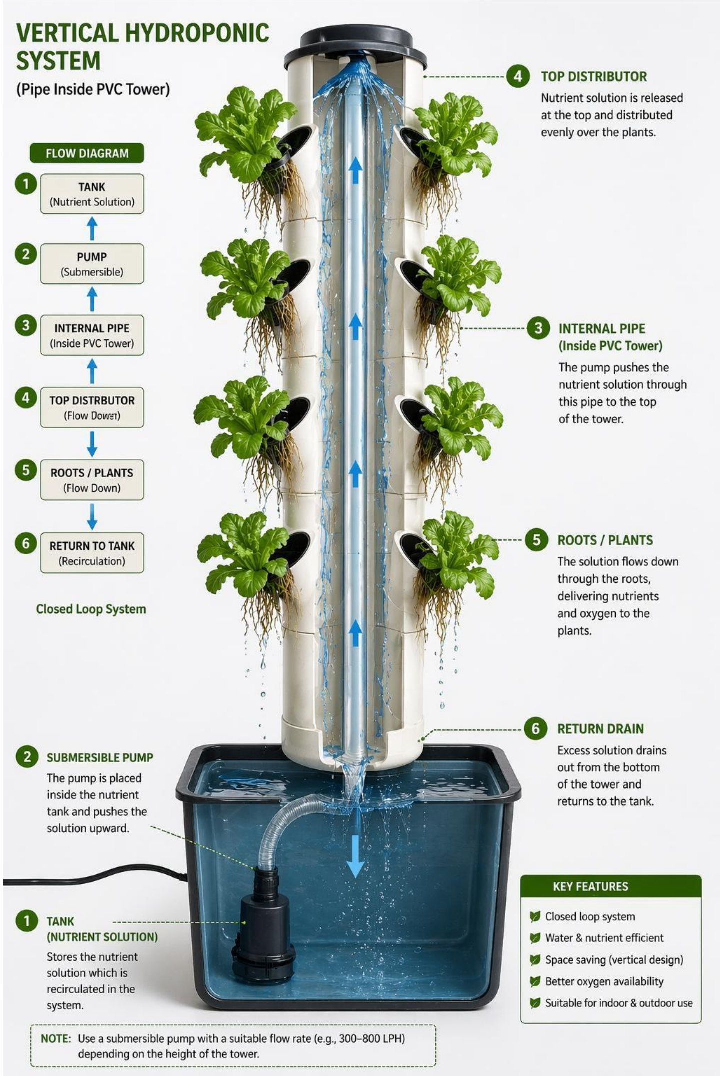

Figure 2: Vertical Hydroponic Farming Structure.

A DHT11 sensor is also included to measure surrounding temperature and humidity. Although it is a simple sensor, it gives useful environmental data because temperature and humidity directly affect evaporation rate and plant health. During hot weather, the system may need more frequent circulation

For controlling all these devices, ESP32 is selected as the main controller. This board was chosen because it has built-in Wi-Fi, multiple input/output pins, analog support, and sufficient processing capability for sensor-based projects. Using ESP32 also reduces the need for extra Wi-Fi modules. It acts as the brain of the complete system by reading sensor values, processing conditions, sending data online, receiving user commands, and controlling the pump through a relay module **[4], [9]** The relay module is an important part of the hardware methodology because the pump operates on 12V supply while ESP32 uses low-voltage logic signals. Direct connection between them is not safe. Therefore, the relay works as an electrically isolated switch. When ESP32 sends a signal, the relay activates and supplies power to the pump. This method ensures safe operation of both devices **[9], [11]**

For communication, the project uses Wi-Fi and MQTT protocol. MQTT was selected because it is lightweight, fast, and commonly used in IoT applications **[4], [9], [11]**. ESP32 publishes sensor data to the MQTT broker at regular intervals. The backend server receives this data, stores it in a database, and updates the web dashboard. In the same way, if the user sends a command from the dashboard, the backend forwards that command through MQTT and ESP32 receives it instantly.

The web dashboard is developed as the main monitoring and control interface. Instead of checking the physical system manually every day, the user can simply open the dashboard and observe live values such as nutrient concentration, water level, flow status, temperature, humidity, and pump condition. The dashboard also allows manual switching of the pump and can display historical graphs of sensor data. This makes the system easier to manage and more practical for daily use **[3], [5], [8]**

Automation logic is another important part of the methodology. The project is not limited to displaying data only; it also responds to certain conditions. For example, if the water level becomes too low, the system automatically stops the pump and generates an alert. If the pump is active but the flow sensor detects no movement, a fault notification can be shown. If temperature rises above the normal range, the system can increase water circulation intervals. If nutrient concentration drops, the dashboard can recommend nutrient refill. These simple automation rules reduce manual supervision and improve reliability **[6], [8]**

After assembly, the system is tested in multiple stages. First, all sensors are checked individually to confirm stable readings. Then the pump is tested to ensure water reaches the top of the tower and flows evenly downward. Wi-Fi and MQTT communication are verified by checking whether live data appears on the dashboard. Finally, safety conditions such as low water shutdown and no-flow detection are tested The complete operational cycle begins when power is supplied to the system. ESP32 connects to Wi-Fi, starts reading sensors, and activates the pump according to the selected mode. Water circulates through the tower, sensor data is continuously transmitted to the dashboard, and automation logic runs in the background. The user can monitor the system remotely and take action whenever required

Overall, the proposed methodology combines low-cost hardware, vertical farming design, sensor-based monitoring, cloud communication, and automation into one integrated solution. The system has been planned in such a way that it remains affordable, practical, and easy to upgrade in the future. It provides a strong foundation for urban farming, educational demonstration, and future research in smart agriculture.

V. SYSTEM DESIGN

The system design of the proposed project is developed by combining hydroponic farming hardware with an IoT-based monitoring and control platform. The main objective of the design is to create a compact, reliable, and easy-to-manage vertical farming system that can operate efficiently in urban environments. While designing the system, attention was given to space utilization, water circulation, sensor placement, electrical safety, remote accessibility, and future scalability.

The complete design can be divided into four major sections: the physical hydroponic structure, the sensing and control unit, the communication layer, and the user interface layer. All these sections work together as a single integrated system **[3], [9], [11]**

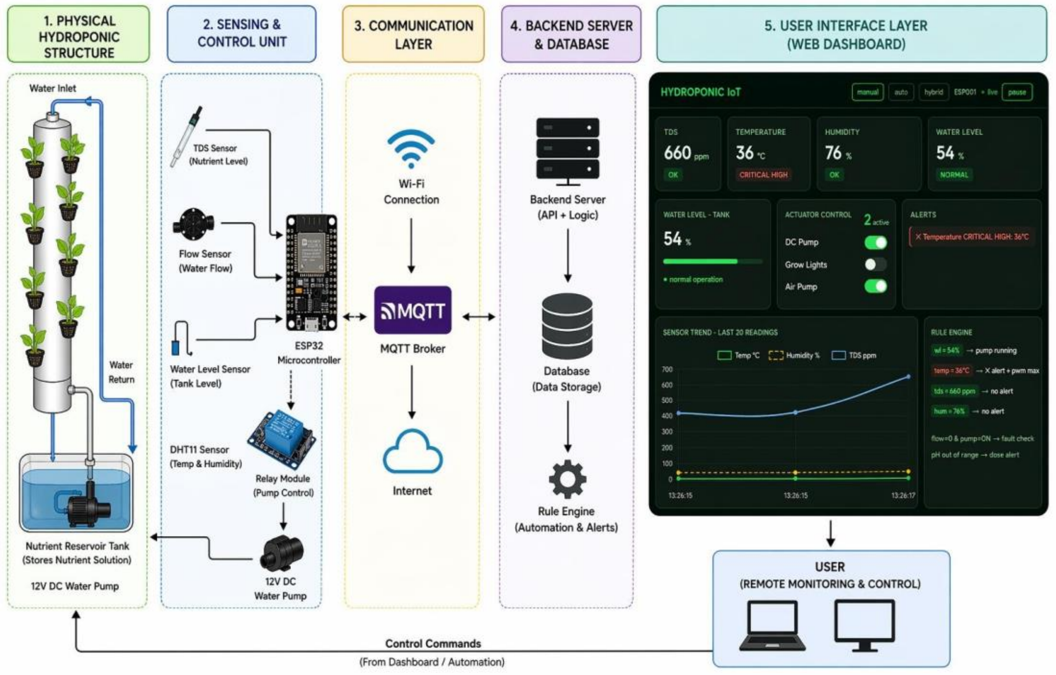

Figure 3: Smart Hydroponic System Architecture.

The physical farming section consists of a vertical PVC tower with multiple openings for plant holders. Net pots are inserted into these openings, and plants are placed inside them. The tower is mounted in a vertical position so that multiple plants can grow upward rather than occupying horizontal floor space. This makes the design suitable for balconies, terraces, rooftops, indoor rooms, and other small urban spaces. The vertical arrangement increases planting capacity while keeping the footprint small **[1], [13]**

At the bottom of the tower, a nutrient reservoir tank is placed. This tank stores water mixed with the required nutrients for plant growth. A 12V DC water pump is connected to the tank and acts as the main circulation unit. The pump sends nutrient water through a pipe to the top of the tower. Once the water reaches the top, it flows downward inside the PVC structure and passes through the root zones of all plants. After flowing through the tower, unused water returns to the reservoir tank, where it is recirculated again. This closed-loop design helps in reducing water wastage and improves nutrient efficiency **[1], [15]**

The sensing and control section is built around the ESP32 microcontroller. ESP32 acts as the central processing unit of the project and manages all sensor readings, communication tasks, and control decisions. It was selected because it provides built-in Wi-Fi, multiple GPIO pins, analog input support, and enough processing capability for real-time monitoring applications **[4], [9]**

Several sensors are connected to the controller to monitor the important conditions of the hydroponic system. A TDS sensor is used to check nutrient concentration in water. Since hydroponic plants depend entirely on dissolved nutrients, maintaining proper TDS values is essential for healthy growth. A water flow sensor is installed in the circulation line to confirm that water is moving properly whenever the pump is active. This helps in detecting blockages or pump failure. A water level sensor is placed in the reservoir tank to monitor available water quantity and prevent dry-run conditions. A DHT11 sensor is used to measure surrounding temperature and humidity, which can affect evaporation and plant growth **[2], [6], [12]**

To operate the pump safely, a relay module is included in the design. Since the pump runs on 12V supply and ESP32 works on low-voltage logic, direct connection is not suitable. The relay works as an electrically isolated switch controlled by ESP32. When the controller sends an output signal, the relay activates and supplies power to the pump **[9], [11]** The communication layer of the system is based on Wi-Fi and MQTT protocol. ESP32 connects to the local Wi-Fi network and sends sensor data to the MQTT broker at regular intervals. MQTT was selected because it is lightweight, fast, and suitable for IoT devices. The publish-subscribe model of MQTT makes communication reliable and efficient. Sensor data is transmitted from ESP32 to the backend system, while control commands from the dashboard are sent back to ESP32 through the same communication channel **[3], [4], [11]**

The backend section is designed to receive MQTT data, store readings in a database, process automation rules, and provide data to the dashboard. It acts as the bridge between the hardware and the user interface. Historical data can also be stored for future analysis, helping users understand nutrient trends, water usage, and environmental changes over time **[3], [5]**

The user interface layer is developed in the form of a web dashboard. This dashboard allows users to monitor live values such as TDS level, water flow status, reservoir level, temperature, humidity, and pump condition. The dashboard also provides manual control options for switching the pump ON or OFF. Graphical charts may be included to display historical trends of sensor readings. Since the dashboard is web-based, it can be accessed remotely through a browser on a laptop or smartphone **[3], [5], [8]**

From an operational point of view, the system is designed to support both manual and automatic modes. In manual mode, the user directly controls the pump through the dashboard. In automatic mode, the controller follows predefined logic. For example, if the water level becomes too low, the pump is turned OFF automatically. If the flow sensor detects no movement while the pump is running, an alert can be generated. If temperature rises, circulation frequency can be adjusted **[6], [8]**

The system design also considers maintenance and future expansion. Additional sensors such as pH, light intensity, dissolved oxygen, or camera modules can be added later without changing the complete architecture. Multiple hydroponic towers can also be connected to the same dashboard using separate device IDs

Overall, the system design combines agriculture hardware and modern digital control into a single compact platform. It is intended to be practical enough for real implementation while remaining simple enough for student-level development. The design supports efficient urban farming, continuous monitoring, reduced water wastage, and convenient user control

VI. HARDWARE IMPLEMENTATION

The hardware implementation of the proposed Smart Vertical Hydroponic System is one of the most important stages of the project because it converts the design concept into a working physical model. In this phase, all selected components are assembled, connected, and tested so that the hydroponic unit can perform real-time monitoring and water circulation. The implementation was planned in a way that uses easily available components, low-cost hardware, and a structure that can be maintained without difficulty

The complete hardware setup consists of three major parts: the hydroponic growing structure, the sensing and control circuit, and the water circulation mechanism. Each part has a specific role in the overall functioning of the system.

The main farming structure is built using a PVC pipe tower. PVC was selected because it is lightweight, durable, low-cost, and easy to cut or modify. Circular openings were created on the pipe surface at equal spacing so that net pots could be inserted properly. These net pots are used to hold the plants while allowing the roots to hang inside the pipe. The vertical tower is fixed securely in an upright position using a stable base support so that it remains balanced during operation **[1], [13]**

Figure 4: Hardware Setup of Vertical Hydroponic System.

A nutrient reservoir tank is placed below the tower. This tank stores water mixed with hydroponic nutrients required for plant growth. The size of the tank was selected according to the expected water demand of the tower. A lid or partial cover can be used to reduce contamination, evaporation, and dust entry. Since hydroponic systems depend on clean recirculating water, maintaining the reservoir is an important part of hardware implementation

A 12V DC water pump is installed inside or near the reservoir tank. The pump is connected to a pipe that carries nutrient solution to the top of the vertical tower. During testing, pump capacity was considered carefully because insufficient pump pressure may fail to lift water to the required height, while excessive flow may cause overflow or unstable distribution. Once activated, the pump pushes nutrient water upward, after which gravity allows the water to flow downward through the root zone and return to the tank **[1], [15]**

The control section of the hardware is built around the ESP32 microcontroller board. ESP32 is mounted on a PCB board or safe enclosure area to protect it from moisture and accidental wire damage. Since hydroponic systems involve water, keeping the controller away from wet surfaces is necessary. ESP32 acts as the central unit that receives sensor signals and controls the relay output **[4], [9]**

The TDS sensor is connected to the nutrient reservoir to measure dissolved solids in the water. Proper placement of this sensor is important because inaccurate readings may occur if the probe is placed near heavy turbulence or air bubbles. The probe is inserted into the nutrient solution at a stable position where readings remain consistent **[2], [6], [12]**

The water flow sensor is connected in-line with the pipe carrying water from the pump to the tower. This placement ensures that whenever the pump is running, the sensor can detect actual water movement. If the pump turns on but no flow is recorded, the system can identify possible blockage or pump failure **[6], [12]**

The water level sensor is mounted inside the reservoir tank. It is positioned at a suitable height to detect the minimum safe water level. When the level drops below the threshold, the controller can stop pump operation to prevent dry running. This simple implementation greatly increases pump life and improves reliability **[6], [12]**

The DHT11 sensor is mounted outside the reservoir and tower in an open area where air can circulate freely. It should not be placed directly near wet surfaces or under strong sunlight because such placement may affect temperature and humidity readings. This sensor provides surrounding environmental data which is useful for monitoring plant conditions

A relay module is used between the ESP32 and the 12V pump. Since the pump requires higher voltage and current than the controller can supply, the relay works as an electrically isolated switch. When ESP32 sends a digital signal, the relay energizes and completes the pump circuit. This arrangement protects the controller from direct high-load connection and allows safe automation **[9], [11]**

The electrical wiring of the project was implemented using jumper wires, connectors, and insulated joints. Special attention was given to loose connections because unstable wiring can lead to false sensor readings or sudden pump interruption. Heat shrink sleeves and proper insulation were used where required. Separate power lines were considered for the controller and pump to reduce electrical noise.

During implementation, waterproofing and safety were given importance because the project uses both water and electrical devices together. The controller and relay board were placed in a dry section, while pipe joints were checked for leakage. Sensor wires were routed neatly to avoid accidental pulling or contact with water.

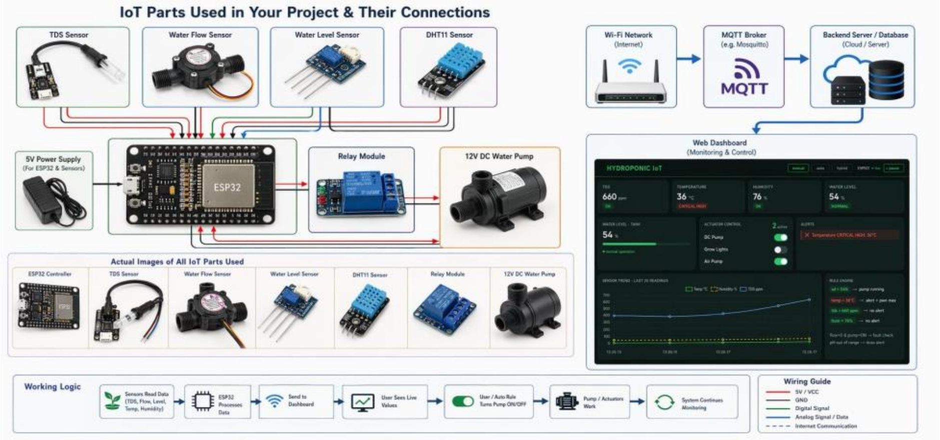

Figure 5: IoT Component Connection Diagram.

The hardware was assembled in modular form so that individual components can be replaced easily. For example, if the pump fails, it can be removed without disturbing the tower. Similarly, sensors can be recalibrated or replaced independently. This approach improves long-term maintenance

Initial hardware testing included checking pump operation, water lift height, downward flow consistency, sensor response, relay switching, and controller power stability. Each component was tested separately before integrating the full system. This reduced troubleshooting time during final assembly.

One practical observation during implementation is that pump size and pipe diameter must match the tower height. Another important observation is that sensor placement strongly affects reading accuracy. Therefore, calibration and physical positioning are essential steps, not just electrical connections.

Overall, the hardware implementation transforms the project from a theoretical design into a functional smart farming prototype. The selected components are economical, practical, and suitable for student-level development. At the same time, the hardware architecture is strong enough to support future upgrades such as pH sensors, grow lights, dosing pumps, or multiple tower units.

VII. SOFTWARE IMPLEMENTATION

The software implementation of the proposed Smart Vertical Hydroponic System was developed to provide real-time monitoring, remote control, and intelligent decision support through a web-based dashboard. The dashboard acts as the central interface between the user and the hydroponic hardware system.

Unlike basic monitoring systems that only display sensor readings, the developed dashboard includes live analytics, actuator control, rule-based automation, and alert generation. This makes the system more practical for daily use and closer to real smart farming applications **[3], [5], [8]**.

The dashboard was designed with a responsive dark-themed interface to improve visibility and readability. It can be accessed through a web browser and is suitable for laptop or desktop monitoring. Sensor data received from the ESP32 controller through MQTT communication is continuously updated on the dashboard **[3], [4], [11]**.

HYDROPONIC IoT

TDS 660 ppm OK

TEMPERATURE 36 °C CRITICAL HIGH

HUMIDITY 76 % OK

WATER LEVEL 54 % NORMAL

WATER LEVEL · TANK 54 %
● normal operation

ACTUATOR CONTROL 2 active
DC Pump ●
Grow Lights ○
Air Pump ●

ALERTS
✕ Temperature CRITICAL HIGH: 36°C

RULE ENGINE
wl = 54% → pump running
temp = 36°C → ✕ alert + pwm max
tds = 660 ppm → no alert
hum = 76% → no alert
flow=0 & pump=ON → fault check
pH out of range → dose alert

Figure 6: Smart Hydroponic Dashboard Interface.

The top section of the dashboard displays the current operating status of the hydroponic system. It includes selectable operating modes such as Manual Mode, Auto Mode, and Hybrid Mode. Manual mode allows direct user control of devices, Auto mode follows programmed logic, while Hybrid mode combines automation with user override options. The dashboard also displays device identity and live connection status.

The main monitoring area shows important real-time parameters through separate cards. These include TDS value in ppm, temperature in degree Celsius, humidity percentage, and water level percentage. Each card also contains health indicators such as OK, NORMAL, or CRITICAL HIGH depending on threshold conditions. This allows the user to quickly understand system status without checking raw values **[2], [6], [12]**.

A dedicated tank water level panel is included to visualize reservoir condition using a progress bar. This helps in identifying whether nutrient solution is sufficient for continued operation. If the level becomes critically low, automation logic can stop the pump to prevent damage **[6], [12]**.

The actuator control section allows switching connected devices such as DC pump, grow lights, and air pump. This makes the dashboard more advanced than standard hydroponic monitoring systems because it supports full control of farming hardware, not only data observation.

An alerts panel is integrated to notify abnormal conditions. During testing, the dashboard correctly displayed a critical high temperature warning at 36°C. This confirms that threshold-based alert logic is active and functioning properly **[6], [8]**.

The lower section contains a sensor trend graph showing the last readings of temperature, humidity, and TDS. Graphical representation helps the user understand whether values are stable, rising, or falling over time. This feature is useful for nutrient adjustment and environmental management **[3], [5]**.

Another intelligent feature is the Rule Engine panel. This section interprets sensor conditions and displays automated decisions such as:

Water level normal, pump running Temperature high, increase PWM speed TDS normal, no alert

Humidity normal, no alert

Flow = 0 with pump ON, fault check pH out of range, dosing alert

This indicates that the dashboard is not only visualizing data but also applying logical decision rules **[6], [8]**.

Dashboard Architecture

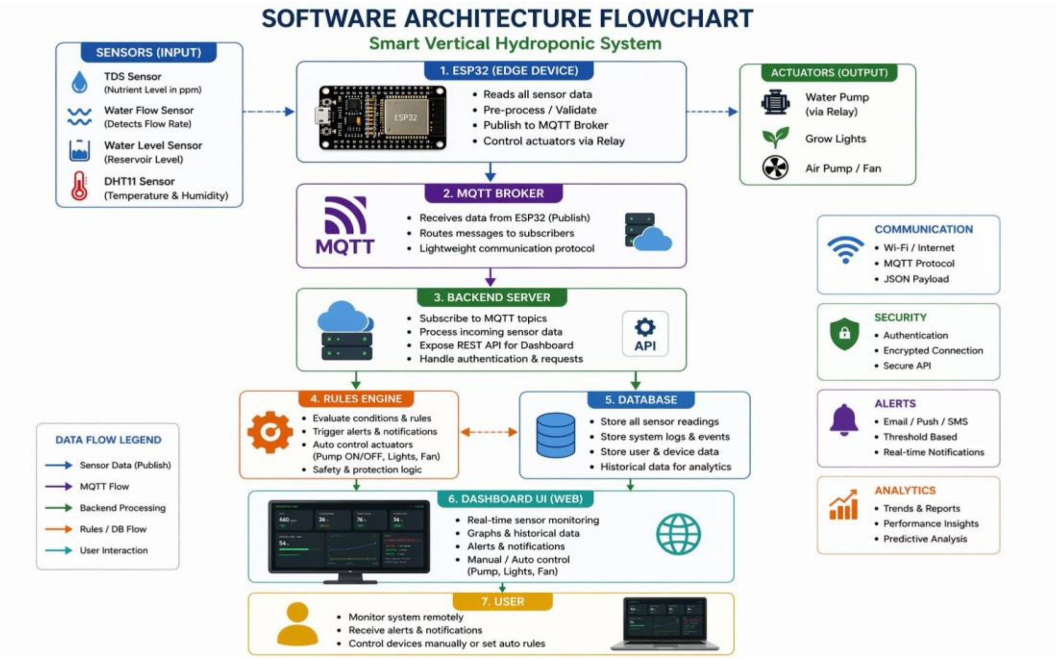

Figure 7: Software Architecture Flowchart Practical Benefits of Dashboard Implementation.

The developed dashboard reduces the need for manual inspection of the hydroponic unit. Users can monitor crop conditions, control devices, and receive alerts from a single screen. It improves convenience, system reliability, and operational efficiency **[3], [5], [8]**.

Overall, the software implementation transforms the hydroponic setup into a smart connected farming platform suitable for urban agriculture and future expansion.

VIII. RESULTS AND DISCUSSION

After completing the hardware assembly and software integration, the developed Smart Vertical Hydroponic System was tested to evaluate its overall performance. The purpose of testing was to check whether the individual modules such as the vertical tower, pump circulation system, sensors, ESP32 controller, MQTT communication, and dashboard were working properly when operated together as one system.

The first part of testing was related to the physical structure of the setup. The vertical PVC tower remained stable during normal operation and was able to hold the net pots properly. The spacing between the plant holders was found suitable for small leafy plants and herbs. One of the practical benefits observed during this stage was that the system occupied very little floor space compared to conventional pot-based gardening. This confirms that the design is suitable for urban areas where space is limited.

The water circulation mechanism was then tested using the 12V DC pump connected to the nutrient tank. During operation, the pump successfully lifted the nutrient solution to the top of the tower. Water then moved downward through the inner section of the pipe and reached the plant root zone. The remaining water collected back into the reservoir tank and could be reused again. This continuous circulation confirmed that the basic hydroponic flow system was functioning as expected.

During testing, it was observed that selecting the correct pump capacity is important. If the pump is too weak, water may not reach the top of the tower properly. If the pump flow is too high, unnecessary splashing or overflow may occur. After adjustment, the selected pump provided stable circulation for the prototype model.

The sensor modules were tested next. The TDS sensor was able to provide live nutrient readings on the dashboard. During one test cycle, the displayed value was around **660 ppm**, which indicated that the system was successfully reading and transmitting nutrient concentration data. This feature is useful because hydroponic plants depend entirely on dissolved nutrients, and regular monitoring helps maintain healthy growth conditions.

The environmental monitoring section also performed properly. The DHT11 sensor displayed surrounding temperature and humidity values on the dashboard. During one reading, the temperature reached **36°C** and humidity was around **76%**. Since the temperature crossed the preset limit, the dashboard automatically showed a critical high temperature warning. This result confirmed that the alert system was active and responding correctly to threshold conditions.

The water level sensor installed in the tank was also tested successfully. During operation, the dashboard displayed a water level value of approximately **54%**. This helped in estimating how much nutrient solution was available in the reservoir. Such monitoring is useful because it prevents sudden pump dry-run conditions and reminds the user when refilling is required.

The actuator control system was tested using the dashboard interface. Commands were sent to switch the DC pump and other connected outputs. The response from the system was quick and stable, showing that communication between the dashboard and ESP32 was functioning correctly. This proves that the system is not only monitoring data but also supporting remote device control.

The graph section of the dashboard showed recent changes in sensor readings over time. This feature was found useful during testing because it helped in understanding whether parameters were stable or gradually changing. Instead of checking single values repeatedly, the graph gives a clearer picture of system behavior.

The rule engine logic integrated into the dashboard also worked properly during trial runs. Based on the live sensor values, the system interpreted current conditions such as normal water level, running pump status, and high temperature warning. This made the system more intelligent than a simple display panel because it could provide condition-based feedback to the user.

Some practical observations were also noted during implementation. Sensor calibration is necessary for accurate long-term readings, especially for TDS measurement. Stable internet connection is required for uninterrupted dashboard updates. Wiring should be protected from moisture because the project combines electronics and water systems in the same setup. It was also observed that keeping the controller unit in a dry enclosure improves reliability.

A summary of the prototype performance is given below:

Parameter	Observation
Tower Stability	Stable during operation
Water Flow	Successful circulation
TDS Monitoring	Live values received
Temperature Alert	Triggered correctly
Water Level Reading	Working properly
Dashboard Control	Responsive
Graph Monitoring	Functional
Rule Engine	Active

Overall, the testing results show that the developed prototype is functioning successfully as a smart hydroponic model. The system was able to circulate nutrient water, monitor important parameters, generate alerts, and provide remote control through the dashboard. For a student-level implementation, the results were encouraging and demonstrate that the project can be further expanded into a larger smart farming solution in the future.

IX. CONCLUSION

The present work focused on the design and implementation of a Smart Vertical Hydroponic System developed for urban farming applications. The project successfully combined hydroponic cultivation with IoT technology to create a practical farming model that can be used in places where traditional agriculture is difficult due to limited space. By using a vertical tower structure, the system allows multiple plants to be grown within a small area, making it suitable for homes, balconies, rooftops, educational institutions, and indoor environments.

The implemented prototype integrated important hardware components such as ESP32, TDS sensor, water flow sensor, water level sensor, DHT11 sensor, relay module, and a 12V DC water pump. These components worked together to monitor nutrient concentration, water circulation, tank level, and environmental conditions. The use of ESP32 with built-in Wi-Fi enabled real-time communication between the hardware setup and the web dashboard through MQTT protocol.

The developed dashboard added significant value to the project by providing live sensor readings, graphical monitoring, alert notifications, and remote control options. Different operating modes such as Manual, Auto, and Hybrid mode improved flexibility for users. During testing, the system was able to circulate nutrient solution successfully, display real-time data, generate alerts for abnormal conditions, and respond to control commands.

One of the key achievements of this project is that it demonstrates how low-cost hardware and commonly available components can be used to build a functional smart farming system. The project also shows that hydroponics can be made more efficient and user-friendly when combined with automation and remote monitoring.

Overall, the developed system performed successfully as a student-level implementation prototype and provides a strong foundation for future improvements. It can be considered a useful step toward sustainable urban farming and smart agriculture solutions.

X. FUTURE SCOPE

Although the current prototype achieved its main objectives, several improvements can be added in future versions to increase efficiency, automation, and scalability.

One important enhancement would be the addition of a **pH sensor** for more accurate nutrient solution management. In hydroponics, pH plays a major role in nutrient absorption, and automatic pH monitoring would improve plant growth consistency.

The system can also be upgraded with an **automatic nutrient dosing mechanism** where nutrients are added to the reservoir based on TDS values. This would reduce manual maintenance and make the system more autonomous.

Another useful improvement would be the integration of **grow lights with timer control** for indoor farming applications. This would allow cultivation in areas with low natural sunlight.

A **mobile application** can be developed in future so that users can monitor the system and control devices directly from smartphones. Push notifications for alerts such as low water level or pump failure would improve convenience.

The project also has scope for **camera-based plant health monitoring** using image processing or artificial intelligence. Such a system could identify leaf discoloration, disease symptoms, or growth issues at an early stage.

For larger applications, multiple towers can be connected to a **centralized monitoring platform** where several hydroponic units are managed through one dashboard. This would be useful for commercial or institutional farming setups.

Future versions may also include **solar power backup systems** to reduce electricity dependency and improve sustainability.

With these improvements, the current prototype can be expanded into a complete intelligent farming platform capable of supporting larger-scale urban agriculture and commercial smart hydroponic production.

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