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IoT Enable Nutrient and Environmental Monitoring for Hydrophobic Cultiration

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***Abstract* - This study focuses on the design and performance evaluation of an Internet of Things (IoT)–based device for monitoring nutrients and environmental conditions in vertical hydroponic farming. The system uses several sensors to measure pH, Total Dissolved Solids (TDS), nutrient solution temperature, air temperature, and air humidity. Sensor data are transmitted using an ESP32 microcontroller and integrated with the Arduino IoT Cloud, allowing real-time monitoring through a web dashboard and a mobile IoT Remote application.**

A 10-day experimental test was conducted to compare sensor readings with standard calibration instruments. The results show low bias values, such as 0.20 for pH and 0.51 °C for nutrient temperature, along with very high precision (100%) for all measured parameters. Accuracy values ranged from 92.33% for TDS to 98.24% for nutrient temperature, while error percentages remained relatively low, with 1.76% for nutrient temperature and 7.67% for TDS. These results confirm the reliability and consistency of the proposed system, indicating its suitability for scalable, real-time monitoring applications in precision-controlled urban agriculture environments.

Keywords - IoT device, vertical hydroponics, nutrient and environmental monitoring, sensors, real-time data, Arduino IoT Cloud.

I. INTRODUCTION

The global agricultural sector is undergoing major changes due to rapid urbanization, climate change, and the increasing demand for sustainable food production. Traditional soil-based farming faces several challenges in urban areas, which has led to the growing adoption of alternative cultivation methods such as hydroponics. Hydroponic farming eliminates the need for soil and allows efficient use of water and nutrients, while also supporting continuous, year-round crop production. These advantages make hydroponics particularly suitable for urban farming systems [1].

However, the success of hydroponic cultivation strongly depends on accurate and continuous monitoring of nutrient levels and environmental conditions. Many existing systems still rely on manual monitoring or standalone sensors, which have limitations in real-time integration, automation, and system responsiveness [2]. These limitations become more critical in vertical and large-scale hydroponic installations, where precise control is essential to maintain optimal plant growth conditions.

According to the Food and Agriculture Organization (FAO), conventional agriculture typically achieves less than 50% water-use efficiency. In contrast, vertical hydroponic systems can achieve efficiencies above 95%, but only when precise control of microclimatic and nutrient conditions is maintained [3], [4]. Reports from Indonesia's National Research and Innovation Agency (BRIN) also highlight the rapid growth of urban farming initiatives, while pointing out that monitoring limitations and slow system responses remain major challenges to long-term sustainability [5], [6]. These findings underline the urgent need for integrated, low-cost, and adaptive monitoring systems for smart hydroponic agriculture.

Several studies have attempted to address these challenges. Sulaiman et al. (2025) reviewed pH and electrical conductivity control systems in hydroponics and emphasized the importance of real-time, cloud-based nutrient monitoring [1]. Rofiansyah et al. (2025) proposed an image-based IoT hydroponic system; however, the lack of statistical sensor validation reduced confidence in its accuracy [2]. Simanungkalit et al. (2023) introduced an IoT-based vertical hydroponic system focused mainly on hardware implementation, but without cloud analytics or benchmarking tools [6]. Oton and Iqbal (2021) developed a low-cost SCADA system using ESP32 and Arduino IoT Cloud, though not for agricultural use [7]. Similarly, Noviardi (2022) proposed an Arduino IoT Cloud–based aquaponic system but did not address multi-sensor synchronization or accuracy validation [8]. Other studies also lack quantitative evaluation of sensor errors and their impact on nutrient balance and plant growth [9].

Recent research further highlights a major gap between sensor accuracy metrics (such as precision and RMSE) and their practical use in agricultural decision-making [3]. In vertical hydroponic systems, even small errors in nutrient monitoring can affect root absorption, photosynthesis, and overall plant biomass [10]–[13]. Therefore, reliable data collection must be combined with rigorous validation and meaningful interpretation.

Advances in IoT technology have enabled smart farming systems that integrate microcontrollers, sensors, and cloud platforms for real-time remote monitoring [7], [14], [15]. Among available platforms, Arduino IoT Cloud offers secure

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ESP32 compatibility, integrated programming tools, and native mobile access through the IoT Remote application. Compared to platforms such as Blynk, ThingSpeak, Antares, or MongoDB, Arduino IoT Cloud requires less backend configuration and provides easier mobile integration [16]–[19].

Although previous studies demonstrate the potential of IoT in agriculture, few systems provide synchronized, real-time monitoring of both nutrient parameters (pH and TDS) and environmental conditions (air temperature and humidity) in mist-based vertical hydroponic systems [8], [20], [21]. Most existing solutions lack full sensor integration, real-time dashboards, and comprehensive performance validation, which limits scalability and practical deployment.

This study proposes the design and implementation of an IoT-based monitoring system specifically developed for vertical hydroponic farming and fully integrated with Arduino IoT Cloud. The system combines pH, TDS, nutrient temperature, air temperature, and humidity sensors with an ESP32 microcontroller. A real-time dashboard enables remote visualization of system conditions. Sensor performance is validated by comparing readings with calibrated reference instruments, allowing the calculation of bias, precision, accuracy, and error. By addressing both technical and methodological gaps, this work provides a reliable, cost-effective framework for smart vertical hydroponic monitoring and supports sustainable urban agriculture in line with the United Nations Sustainable Development Goals (SDGs) [22]–[24].

The remainder of this paper is organized as follows. Section II describes the system design, architecture, and methodology. Section III presents the experimental results and performance analysis. Section IV concludes the paper and outlines directions for future research.

II. METHODS

This research adopts a design-and-implementation methodology that integrates both hardware and software components into a real-time IoT monitoring system for vertical hydroponic farming. The overall methodology is divided into four main stages.

1) *A. System Architecture and Design*

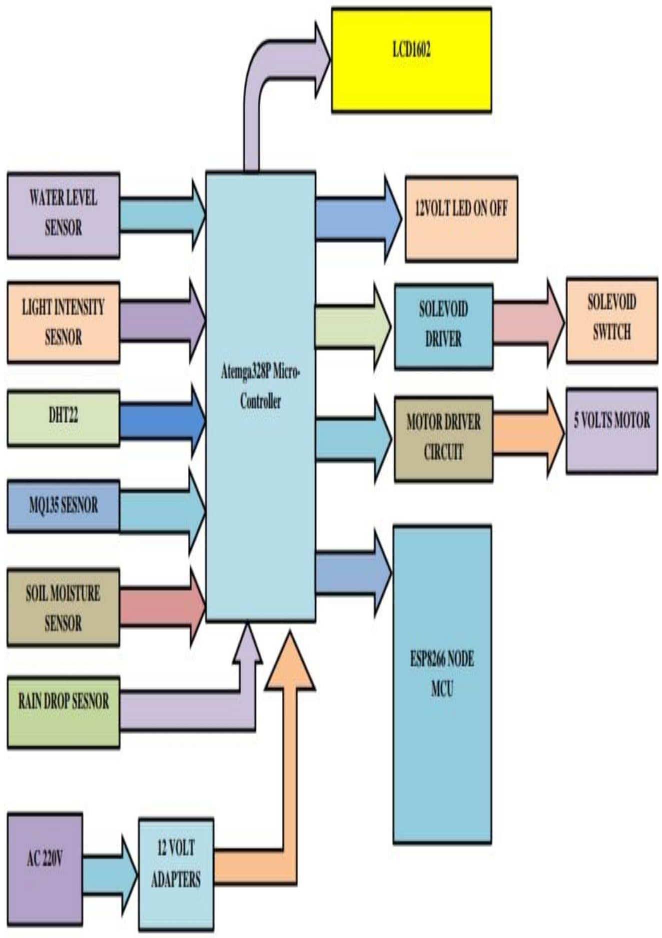
The proposed IoT system is designed to monitor nutrient and environmental conditions in a vertical hydroponic setup. It integrates hardware components with cloud-based software to enable real-time monitoring and automation. The hardware consists of one microcontroller, five sensors, two actuators, and a display unit, while the software includes a web-based dashboard and a mobile interface.

The ESP32 WROOM-32D microcontroller serves as the main processing unit. It collects data from the sensors, processes the readings, and transmits them to the Arduino IoT Cloud via Wi-Fi. The pH-4502C sensor measures the acidity or alkalinity of the nutrient solution, which directly affects nutrient absorption. The TDS V1.0 sensor measures the concentration of dissolved nutrients, helping determine fertilizer strength.

The DS18B20 waterproof temperature sensor measures nutrient solution temperature with high accuracy (±0.5 °C), which is critical for root metabolism and oxygen availability. The DHT22 sensor measures air temperature and humidity, both of which influence transpiration and plant stress. A water level sensor monitors the nutrient solution level in the reservoir to prevent pump dry-run conditions and ensure continuous nutrient circulation.

A 5 V single-channel relay controls a 12 V water pump that transfers nutrient solution from a 20-liter tank to the vertical hydroponic pipes. An LCD 20×4 display with I2C interface shows real-time sensor data in text and numerical form. All components are integrated into a single IoT device unit and connected to the Arduino IoT Cloud for real-time data acquisition.

2) *B. System Programming and Algorithm*



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The device firmware was developed and compiled using the Arduino IoT Cloud platform. The program initializes all sensors, reads sensor data, converts analog signals into digital values, and transmits the processed data to the cloud using Wi-Fi-compatible libraries.

After successful code compilation and upload, system operation was verified using serial monitor messages that confirmed Wi-Fi connectivity, cloud synchronization, and real-time data updates. The system workflow follows a structured algorithm in which sensor data are collected sequentially, validated, and calibrated before transmission to the cloud.

Control logic is implemented to operate the relay module based on sensor thresholds. The water level sensor is installed 20 cm above the reservoir base, corresponding to approximately 5 liters of solution. When the sensor detects sufficient nutrient solution, the pump is turned off. When the level drops below the threshold, the pump is activated to restore the solution level. This automated control mechanism improves efficiency and prevents pump damage.

C. System Cloud Connectivity

The Arduino IoT Cloud dashboard provides continuous device status updates and ensures stable communication between the IoT device and the cloud server. Sensor readings are updated in real time and stored for visualization and data analysis.

D. Dashboard Configuration

A remote monitoring dashboard was created using the Arduino IoT Cloud interface. The dashboard allows users to view sensor readings and remotely control actuators. It is responsive across multiple devices, including PCs, laptops, and smartphones. Each sensor variable is assigned to appropriate widgets such as gauges and line charts, enabling clear and intuitive visualization.

E. Sensor Data Validation

Sensor readings were validated by comparing them with standard calibration instruments over a 10-day testing period. The pH sensor was compared with a digital pH meter, the TDS sensor with a TDS-3 meter, and the DS18B20 temperature sensor with an external thermometer probe. Air temperature and humidity readings from the DHT22 sensor were compared with reference measurements from an HTC-2 device.

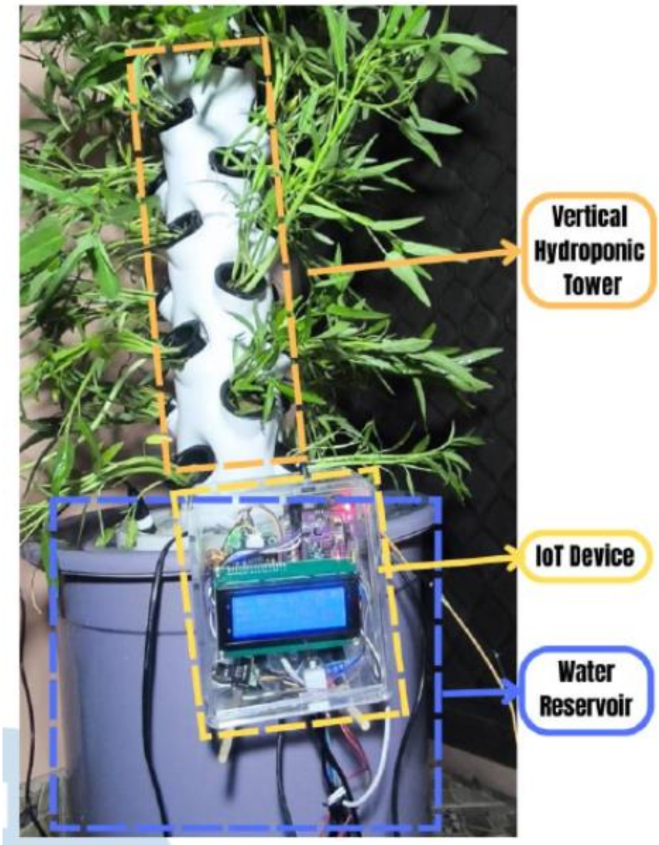
Measurements were taken manually three times per day at 8 AM, 1 PM, and 6 PM due to the lack of automatic logging in the calibrators. Daily averages were calculated, resulting in 10 data points per sensor. Performance metrics including precision, accuracy, bias, and error were calculated using standard statistical equations [22], [25].

III. RESULTS AND DISCUSSION

The results of this study are presented in four main parts: IoT device design, dashboard visualization, sensor performance evaluation, and future system improvement potential.

3) A. IoT Device Design

The IoT device is installed at the front of the nutrient reservoir to allow easy access to real-time data displayed on the LCD screen. A vertical pipe mounted above the reservoir contains multiple planting holes and allows nutrient solution to circulate back into the reservoir. This design supports efficient nutrient reuse and compact vertical farming.3



B. Dashboard Monitoring Display

Fig. 9. Dashboard on Website Arduino IoT Cloud

Arduino IoT Cloud provides up to 10 widgets in its free version, enabling comprehensive monitoring of multiple parameters. Compared to other platforms, it offers simpler configuration, native mobile support, and balanced usability within free-tier limitations. The dashboard displays pH, TDS, nutrient temperature, air temperature, and humidity using gauges and line charts, accessible through web browsers or the IoT Remote mobile application.

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Fig. 10. Dashboard on IoT Remote Mobile App

C. Sensor Reading Performance

Performance analysis shows that the mean sensor readings closely match the reference values, indicating low bias across all parameters. For example, pH and nutrient temperature biases were only 0.20 and 0.51, respectively. Precision values were near or equal to 100%, demonstrating consistent sensor performance.

TABLE I. DEVICE SENSOR READING PERFORMANCE

Variable	Mean Actual Value	Mean Device Reading	|Bias| ()	Precision (%)	Accuracy (%)	Error (%)
Potential of Hydrogen (No unit)	6.43	6.23	0.20	100.00	96.84	3.16
Total Dissolved Solids (ppm)	1244.60	1149.43	95.17	100.00	92.33	7.67

Accuracy values ranged from 92.33% for TDS to 98.24% for nutrient temperature, while error percentages remained within acceptable limits. Higher errors in TDS and air humidity may be caused by environmental factors or sensor limitations. Overall, the system performs reliably, though periodic recalibration is recommended to further improve accuracy.

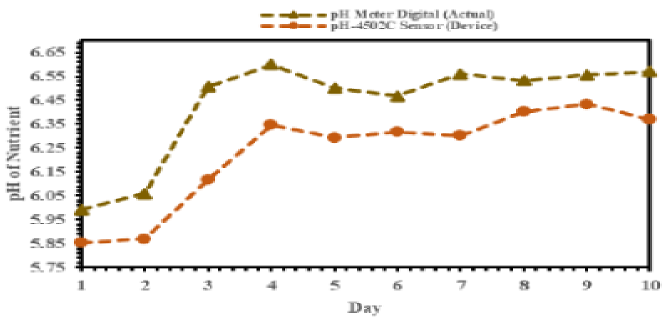

Fig. 11. Chart of pH Actual Values and Device Reading Value

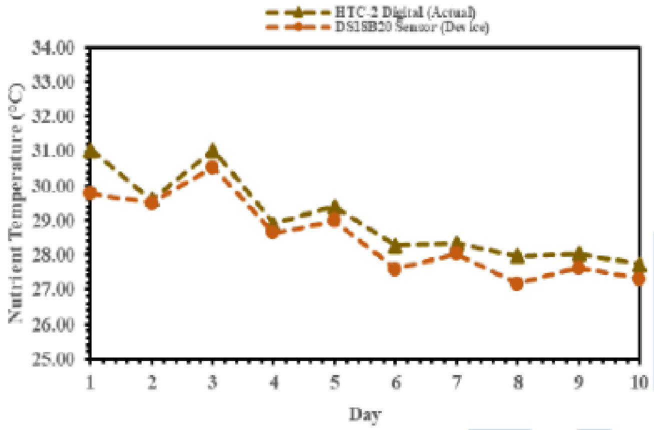

Fig. 13. Chart of Nutrient Temperature Actual Values and Device Reading Value

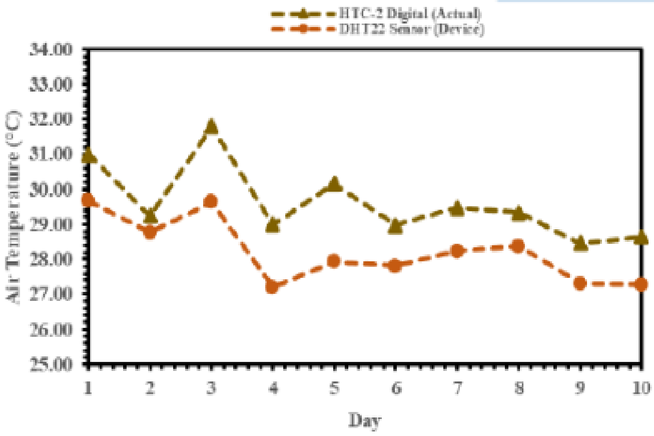

Fig. 14. Chart of Air Temperature Actual Values and Device Reading Value

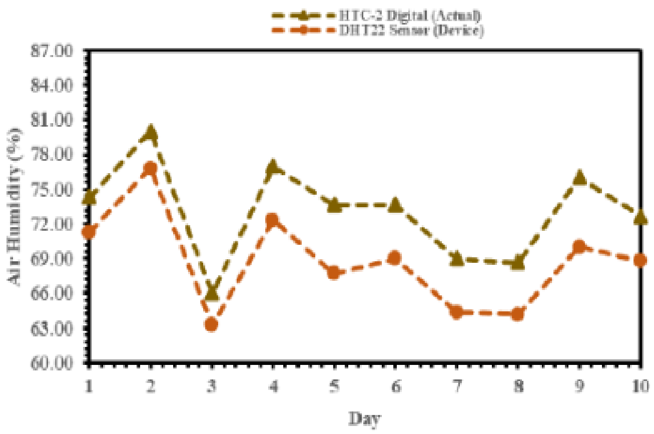

Fig. 15. Chart of Air Humidity Actual Values and Device Reading Value

1) D. Potential System Improvements

Future enhancements may include integrating machine learning techniques for predictive nutrient control and environmental optimization. Historical sensor data could be used to train models such as random forests, support vector machines, or LSTM networks to forecast nutrient needs and detect anomalies. This would enable a closed-loop, predictive control system instead of simple threshold-based operation.

IV. CONCLUSION

This study successfully designed and evaluated an IoT-based nutrient and environmental monitoring system for vertical hydroponic farming. The system demonstrated high reliability, with low bias and excellent precision across all measured parameters. Although slight accuracy deviations were observed, particularly in TDS and air humidity, the overall performance remains suitable for practical hydroponic applications.

The real-time dashboard provides an intuitive interface for monitoring and analysis across multiple devices. Future work should focus on improved sensor calibration, advanced sensing technologies, and predictive analytics to enhance system accuracy and adaptability.

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