ISSN 2355-3286

Design of a Nutrient and Environment Monitoring IoT Device in Vertical Hydroponic System

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Accepted April 19, 2025
Approved June 16, 2025

***Abstract*—This study presents the design and performance evaluation of an Internet of Things (IoT)-based nutrient and environmental monitoring device for vertical hydroponic farming. The system employs multiple sensors to measure pH, Total Dissolved Solids (TDS), nutrient temperature, air temperature, and air humidity. Data is transmitted via ESP32 and integrated with the Arduino IoT Cloud, enabling real-time monitoring through a web dashboard and IoT Remote mobile application. A 10-day testing period was conducted to compare sensor outputs against standard calibrator references. The device demonstrated minimal bias (e.g., 0.20 for pH, 0.51 °C for nutrient temperature) and high precision (100.00%) across all parameters. Accuracy ranged from 92.33% (TDS) to 98.24% (nutrient temperature), while error rates were relatively low (e.g., 1.76% for nutrient temperature and 7.67% for TDS). These findings validate the system's reliability and consistency, supporting its potential for scalable implementation in precision-controlled, real-time monitoring applications within urban agriculture.**

***Index Terms*—IoT Device; Vertical Hydroponic; Nutrient and Environment Monitoring; Sensors; Real-time Data; Arduino IoT Cloud.**

I. INTRODUCTION

The global agricultural sector is currently transforming due to increasing pressures from urbanisation, climate change, and the rising demand for sustainable food systems. Conventional soil-based agriculture has become less viable in urban environments, prompting the adoption of alternative cultivation methods such as hydroponics. This soil-less system offers efficient utilisation of water and nutrients while enabling year-round crop production, making it highly suitable for urban farming initiatives [1].

However, the success of hydroponic systems largely depends on the accurate and continuous monitoring of nutrient concentrations and environmental parameters. Manual monitoring techniques or the use of standalone sensors are still commonly applied, despite their limitations in providing real-time integration, automated feedback, and system responsiveness [2]. This is particularly problematic in vertically integrated and large-scale hydroponic setups, where system precision monitoring farming is essential to maintain optimal plant growth.

According to the Food and Agriculture Organization (FAO), conventional agriculture achieves less than 50% water use efficiency, whereas vertical hydroponic systems can exceed 95%, but only under precise microclimatic and nutrient control [3], [4]. Furthermore, reports from Indonesia's National Research and Innovation Agency (BRIN) highlight the rapid growth of urban farming initiatives, although technical challenges in monitoring and system responsiveness continue to hinder their sustainability [5], [6]. These trends emphasise the urgent need for integrated, cost-effective, and adaptive systems for smart nutrient and environmental management in hydroponic agriculture [5].

Several recent studies have attempted to address this need. Sulaiman et al. (2025) conducted a review on pH and EC control systems in hydroponics, stressing the necessity for real-time nutrient monitoring using cloud platforms [1]. Rofiansyah et al. (2025) developed an image-based IoT hydroponic system, but the absence of sensor validation through statistical analysis limited its accuracy [2]. Simanungkalit et al. (2023) proposed an IoT-enabled vertical hydroponic system focused on hardware deployment yet lacked integration with cloud analytics and benchmarking tools [6]. Meanwhile, Oton and Iqbal (2021) implemented a low-cost SCADA solution using ESP32 and Arduino IoT Cloud, although not in the context of agriculture [7]. Noviardi (2022) introduced an Arduino IoT Cloud-based aquaponic model; however, it lacked synchronization across multiple sensor inputs and did not evaluate data accuracy against reference standards [8].

Sneineh and Shabaneh introduced an ESP32-based hydroponic IoT system, but it lacked quantitative evaluation of sensor error effects on nutrient balance and plant growth [9]. Moreover, Yuan et al. pointed out that the disconnection between sensor accuracy metrics (e.g., RMSE, precision) and actionable agronomic decisions remains a significant research gap in smart agriculture systems [3]. This gap underscores that mere data collection is insufficient without rigorous validation and its translation into effective nutrient management strategies. In vertical hydroponics, even minor inaccuracies in nutrient monitoring can disrupt root absorption efficiency, impact photosynthetic activity and biomass accumulation [10], [11], [12], [13].

Advancements in Internet of Things (IoT) technologies have enabled smart farming solutions that combine microcontrollers, digital sensors, and cloud-based platforms for remote and real-time monitoring [7], [14], [15]. Among available platforms, Arduino IoT Cloud stands out for its secure ESP32 compatibility, built-in sketch programming, and support for real-time mobile access via IoT Remote [7]. It offers advantages over other platforms, such as Blynk [16], ThingSpeak [17], Antares [18] or MongoDB [19], which often require complex backend configuration or lack native mobile applications.

While previous studies have demonstrated the efficacy of IoT frameworks in hydroponic and soil-based cultivation, few have addressed the real-time synchronisation between nutrient dynamics (pH and TDS) and environmental parameters (air temperature and humidity) in mist-based vertical hydroponic setups [8], [20], [21]. Although prior research shows promise, most systems are limited in scope, lacking integration between sensors, real-time synchronisation, user-accessible dashboards, and performance validation. These gaps present critical barriers to deploying scalable and responsive hydroponic monitoring systems. A recent review of smart nutrient management technologies further underscores the need for IoT systems that combine multi-sensor input, cloud automation, and adaptive control frameworks specific to crop environments [22].

This study proposes the design and implementation of an IoT-based monitoring device specifically for vertical hydroponic systems, fully integrated with the Arduino IoT Cloud platform. The proposed system incorporates TDS, pH, water temperature, air temperature, and humidity sensors, all interfaced with an ESP32 microcontroller. A real-time dashboard enables remote visualisation and control of system parameters. To ensure reliability and measurement accuracy, the sensor readings will be compared with a calibrated reference instrument to calculate bias, precision, accuracy, and error, thereby enabling comprehensive performance validation of the monitoring system [16], [22].

By filling a methodological and technological research gap, this study offers a comprehensive framework for smart vertical hydroponic monitoring that is responsive, accurate, and cost-effective. It also aligns with the objectives of the United Nations Sustainable Development Goals (SDGs), particularly in enhancing sustainable agriculture and promoting resilient infrastructure for urban food production systems [23], [24].

The paper is organised as follows: Section I introduces the research background and objectives. Section II discusses system architecture, component configuration, and calibration procedures. Section III presents experimental results and system performance evaluation. Finally, Section IV concludes with key findings and provides recommendations for future system development.

II. Methods

This study employed a design and implementation approach that integrates hardware and software components in a real-time Internet of Things (IoT)-based monitoring system for vertical hydroponic agriculture. The methodology was structured into four main stages, as outlined below:

A. System Architecture & Design

The proposed IoT system is designed to monitor nutrients and environmental conditions in an vertical hydroponic setup. It integrates both hardware and software components to support real-time monitoring and automation. The hardware includes one microcontroller, five sensors, two actuators, and a display. The software includes a web dashboard and a mobile interface. The system interconnection is illustrated in Fig. 1.

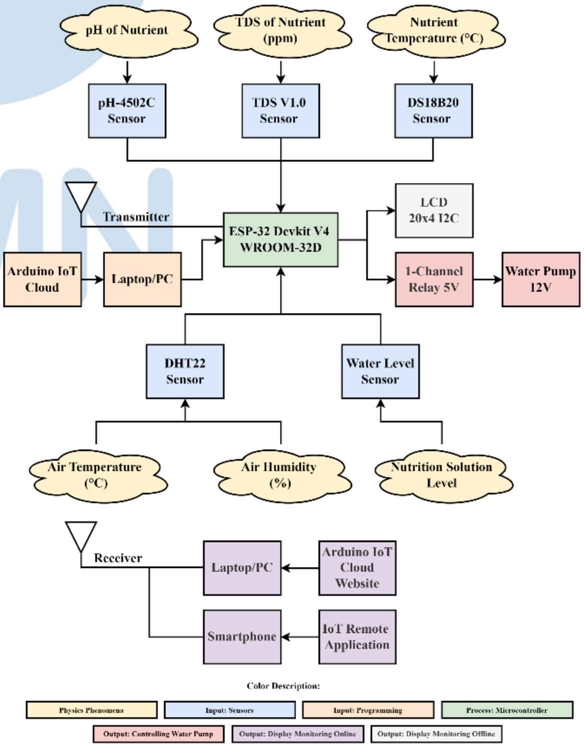

Fig. 1. Block Diagram of The IoT Device Interconnection

The system uses the ESP32 WROOM-32D as the main controller. This microcontroller receives, processes, and transmits data to the Arduino IoT Cloud via Wi-Fi. It supports wireless data transmission, enabling cloud-based monitoring. Each sensor has a specific function. The pH-4502C sensor measures the pH of the nutrient solution, which affects nutrient uptake. The TDS V1.0 CHN sensor detects total dissolved solids, showing the strength of the nutrient concentration. These values help in adjusting the fertilizer according to plant needs.

The DS18B20 sensor measures the nutrient solution temperature. It is waterproof and has high accuracy (±0.5°C), making it ideal for liquid monitoring. Temperature affects root metabolism and oxygen solubility. The DHT22 sensor records air temperature and humidity. These factors are important for controlling transpiration and preventing plant stress. A water level sensor checks the height of the solution in the reservoir. If the level is low, the system sends alerts or activates the pump. This prevents dry-run damage and ensures continuous nutrient flow.

A 5-volt single-channel relay acts as a switch to control the 12V water pump. The pump transfers the solution from a 20-liter tank to the vertical hydroponic pipes. An LCD 20x4 display with I2C shows real-time data from the sensors in numeric and text format. On the software side, the Arduino IoT Cloud is used to upload the program and build the web dashboard. The IoT Remote app is used to build the mobile dashboard interface. All hardware components are wired into a single IoT device unit, as illustrated in Fig. 2.

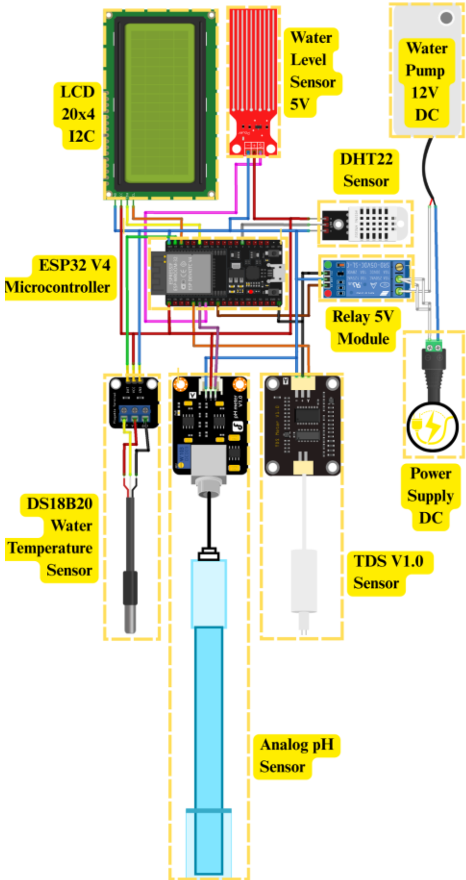

Fig. 2. Schematic Diagram of The IoT Device

Both hardware and software components form an integrated environmental and nutrient monitoring system that enables real-time, cloud-based data acquisition via Arduino IoT Cloud.

B. System Programming & Algorithm

The code for the IoT device was developed and compiled using the Sketch menu on the Arduino IoT Cloud web platform. The program initializes each sensor, acquires data, converts analogue signals into digital values, and transmits the processed results to the Arduino IoT Cloud via Wi-Fi using compatible libraries. Figure 3 illustrates the code compilation process executed through the Arduino IoT Cloud interface.

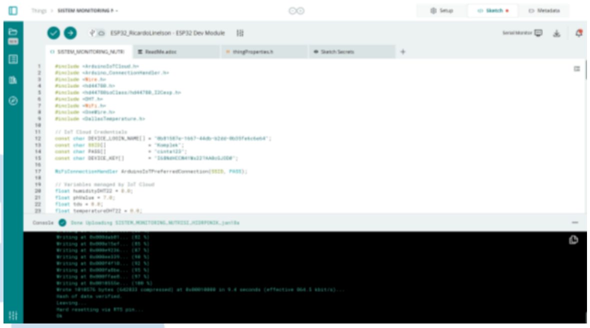

Fig. 3. Code Compilation Process

As shown in Fig. 4, the device was successfully flashed with the compiled program. This was verified through a confirmation message displayed on the serial monitor, indicating that the code upload and cloud connectivity were successful. The serial output included the following key messages as described in Fig. 4. These messages confirm that the device established a Wi-Fi connection, synchronised with the Arduino IoT Cloud, and began updating sensors data in real-time.

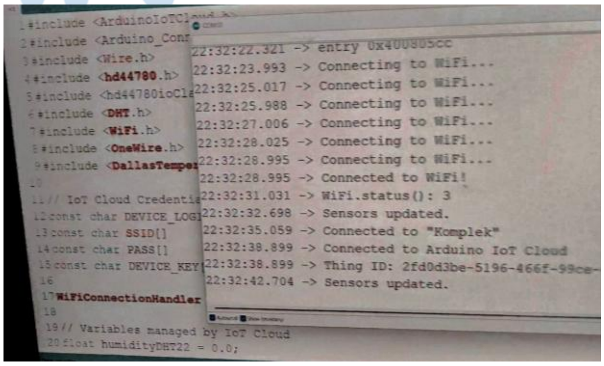

Fig. 4. Result on Serial Monitor

To illustrate the logical workflow of the system, Figure 5 presents a flowchart detailing the core algorithm implemented in the microcontroller. The system begins by initializing all sensors and proceeds to sequentially read environmental and nutrient-related parameters. Each sensor value undergoes basic validation and calibration routines before being transmitted to the Arduino IoT Cloud for real-time monitoring and data logging.

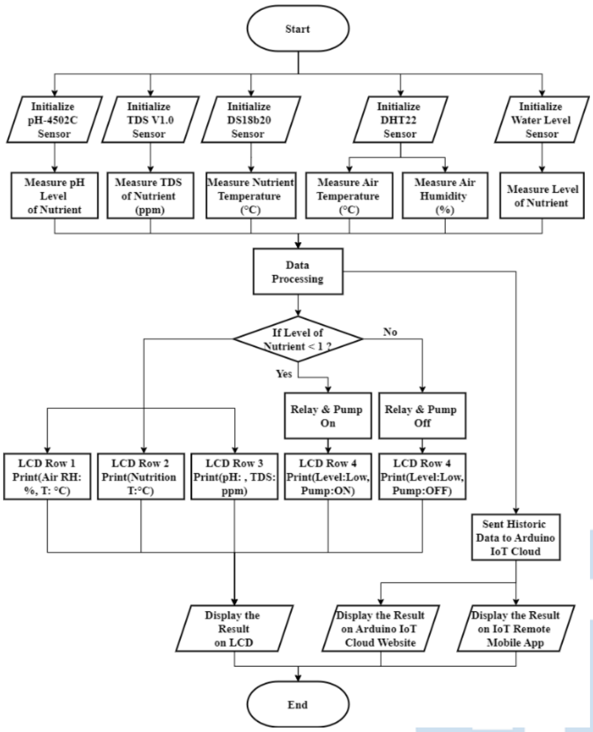

Fig. 5. Flowchart of the Code Algorithm

Conditional logic is embedded within the system to control the actuator, specifically a relay module that regulates the nutrient pump based on sensor thresholds. A binary trigger mechanism (digital 0 or 1) governs the relay's activation state. The water level sensor is strategically installed at a height of 20 cm from the base of the nutrient reservoir, corresponding to approximately 5 litres of solution. When the sensor detects the presence of nutrient solution (binary signal: 1), the system deactivates the pump to prevent overflow or unnecessary circulation. Conversely, when the sensor detects the absence of liquid (binary signal: 0), the relay is triggered to activate the pump and restore the appropriate fluid level in the system. This control logic ensures automated nutrient regulation within the vertical hydroponic environment, enhancing operational efficiency and reducing the risk of human error or pump dry-run damage.

C. System Cloud Connectivity

In Fig. 7, the device status history on the cloud dashboard indicates consistent uptime and communication. Cloud connectivity ensures that sensor readings are regularly updated and stored on a centralised server for visualisation and logging.

Fig. 6. Device Status History

D. Setting Dashboard

To visualize sensor data remotely, a dashboard was built using the Arduino IoT Cloud interface. The configured dashboard allows users to monitor environmental and nutrient parameters and also control actuators remotely. The dashboard design is mobile responsive, ensuring accessibility across different devices and user interfaces. Each monitored variable was assigned to a corresponding widget on the platform, such as real-time gauges and line charts as shown in Fig. 9.

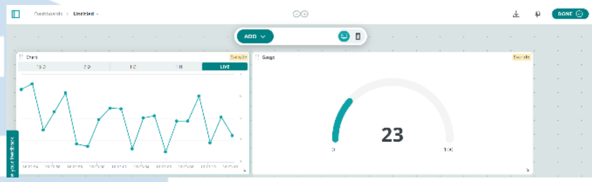

Fig. 7. Dashboard Setting

E. Sensor Data Validation Test

The readings from the five main sensors on the IoT device were compared against three calibrator instruments to assess measurement accuracy. The pH-4502C sensor was validated using a digital pH meter. The TDS V1.0 sensor was compared with a TDS-3 meter. The DS18B20 sensor was validated using an external thermometer probe on the HTC-2. The DHT22 sensor was used to measure air temperature and humidity, which were compared against the internal thermometer and hygrometer on the HTC-2, respectively.

The validation test was conducted over a period of 10 days. Due to the calibrator instruments lacking automatic logging features, measurements were taken manually three times per day at 8 AM, 1 PM, and 6 PM. The daily average was calculated from these three samples for both the IoT device and the calibrator tools. Consequently, 10 average data points were obtained for each sensor.

The collected data was processed and analysed using descriptive statistical methods. Sensor data were compared to reference values using standard equations to calculate precision, accuracy, bias, and error [22], [25]. as shown below:

$$Precision = 100\% \left(1 - \frac{\sigma}{\bar{x}}\right) \quad (1)$$

$$Accuracy = 100\% \left(1 - \frac{|Bias| + 3\sigma}{x_{real}}\right) \quad (2)$$

$$|Bias| = |x_{real} - \bar{x}| \quad (3)$$

$$Error = 100\% \left(\frac{|Bias| + 3\sigma}{x_{real}}\right) \quad (4)$$

In these equations, $\bar{x}$ denotes the average value obtained from the sensor measurements. σ refers to the standard deviation indicating data dispersion. x_{real} represents the reference value obtained from the calibrator device. $|Bias|$ (3) determines the absolute value of bias between the measured value ($\bar{x}$) and actual value (x_{real}). Precision (1) reflects the consistency of repeated measurements. Accuracy (2) measures the accuracy by accounting for both bias and associated uncertainty. Error (4) calculates the relative error in percentage, comparing the deviation to the actual reference value.

III. Result and Discussion

The results of this research encompass four main areas of analysis: (1) the design outcome of the IoT-based monitoring device, (2) the visualization output of the real-time monitoring dashboard, (3) the validation results of sensor data accuracy and performance, and (4) the identified potentials for system improvements, including future integration with predictive analytics and automation frameworks.

A. IoT Device Design

The designed IoT device is positioned at the front side of the reservoir to allow users easy access to view real-time monitoring data on the LCD screen. A vertical pipe is installed above the reservoir, featuring several holes that serve as planting spots for hydroponic crops. This vertical pipe is directly connected to the reservoir, functioning to collect and return the nutrient solution that flows down from the top, driven by the water pump. The final design of the IoT device is shown in Fig. 8.

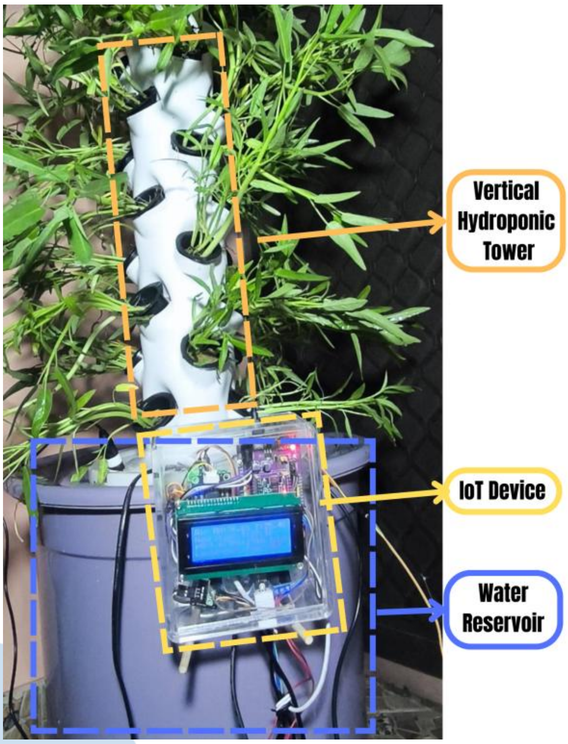

Fig. 8. IoT Device Result

B. Dashboard Monitoring Display

From a functionality standpoint, Arduino IoT Cloud offers up to 10 widgets in the free version, enabling more comprehensive monitoring of variables such as pH, TDS, nutrient temperature, air temperature, and humidity. In contrast, Blynk limits free users to only 4 widgets, without built-in data export, and historical data access is constrained by cloud storage capacity. ThingSpeak, Antares, and MongoDB, while flexible, lack native mobile applications and require separate backend integration or manual query configuration, thus increasing development complexity. Furthermore, data in Arduino IoT Cloud is stored for 1 day, but can be exported manually prior to expiration, offering a balance between free-tier limitations and usability.

The monitoring data history is presented using five gauges and five-line charts arranged on a single dashboard interface. The five monitored variables include Potential of Hydrogen (pH), Total Dissolved Solids (ppm), Nutrient Temperature (°C), Air Temperature (°C), and Air Humidity (%). The dashboard display is accessible via laptop, PC, or mobile phone through the Arduino IoT Cloud website, as shown in Fig. 9.

Fig. 9. Dashboard on Website Arduino IoT Cloud

Additionally, Arduino IoT Cloud provides a mobile application called IoT Remote, which can be downloaded from app stores. The IoT Remote app facilitates easier access to the monitoring dashboard by allowing users to open it directly from the application. The mobile dashboard display via IoT Remote is illustrated in Fig. 10.

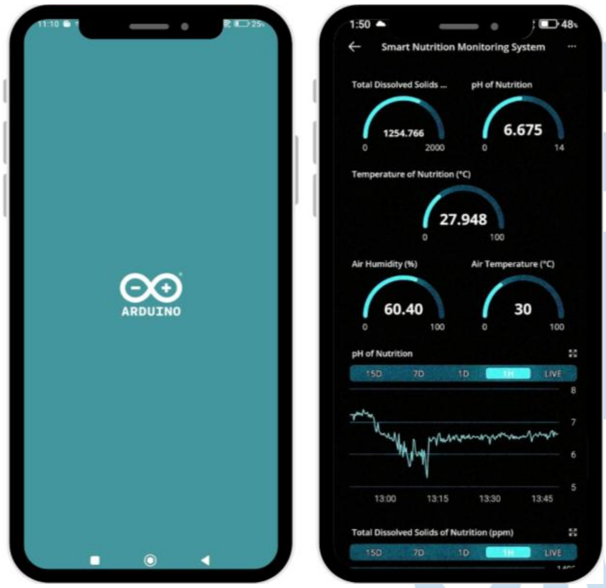

Fig. 10. Dashboard on IoT Remote Mobile App

C. *Device Sensor Reading Performance*

The detailed measurement results from each monitoring sensor were analysed to determine the percentage of precision, accuracy, and error of the IoT device readings compared to the reference values obtained from calibrator instruments. The comparative performance outcomes over a 10-day testing period are presented in Table I.

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
Nutrient Temperature (°C)	29.03	28.52	0.51	100.00	98.24	1.76
Air Temperature (°C)	29.61	28.22	1.39	100.00	95.33	4.67
Air Humidity (%)	73.10	68.78	4.32	100.00	94.08	5.92

The mean device readings for each variable closely approximate the actual values, demonstrating relatively low bias, indicating that the sensors in the system provide accurate readings within acceptable margins. For instance, the bias in pH readings is only 0.20, and for nutrient temperature, it is 0.51, both of which are minimal discrepancies, ensuring the reliability of the device.

In terms of precision, all measurements show values close to 100%, with the highest being 100.60% for pH, TDS, and nutrient temperature. This indicates that the device is highly consistent in producing readings that align closely with the actual values, which is crucial for ensuring stable performance in an IoT monitoring system. However, while precision is consistently high, the accuracy and error percentages demonstrate slight deviations, especially in TDS, air temperature, and air humidity. For example, TDS has an accuracy of 92.33% and an error of 7.67%, suggesting a moderate discrepancy between the device's readings and the actual values.

The error percentage for all variables varies, with the lowest error observed in nutrient temperature (1.76%) and the highest in air humidity (5.92%). These discrepancies in error could be due to sensor calibration issues, environmental factors, or limitations in the sensor technology. While the system performs well within acceptable limits, the higher errors in variables like air temperature and humidity indicate that further calibration and fine-tuning of the sensors may be needed for more precise monitoring, especially in variable environmental conditions. Therefore, continuous calibration and periodic validation against reference instruments are recommended to improve overall device performance and reliability.

To further illustrate the measurement results of each monitoring sensor in comparison to the calibrator readings, scatter chart visualizations are provided in Fig. 11 through Fig. 15.

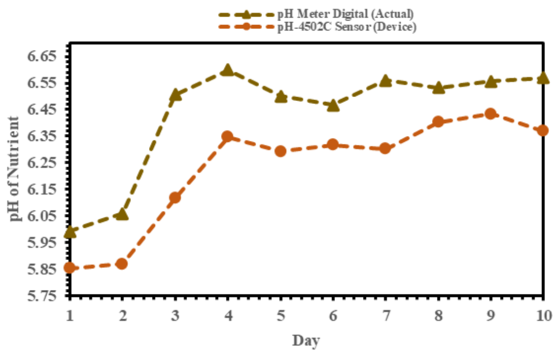

Fig. 11. Chart of pH Actual Values and Device Reading Value

ISSN 2355-3286

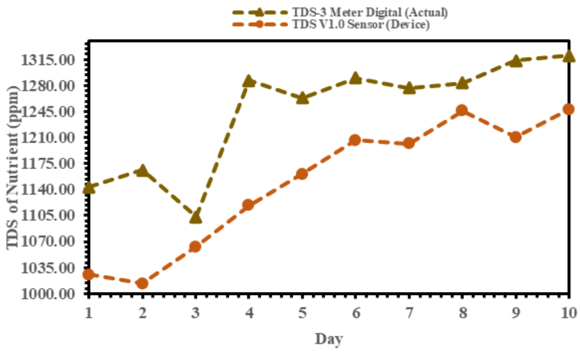

Fig. 12. Chart of TDS Actual Values and Device Reading Value

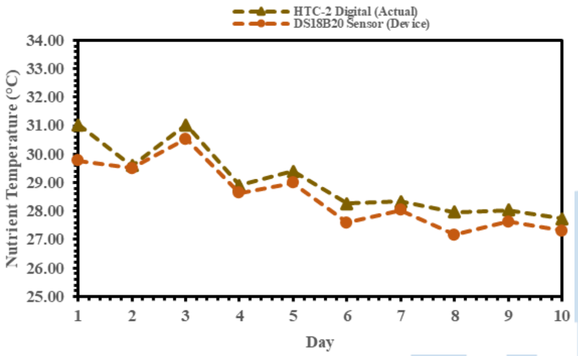

Fig. 13. Chart of Nutrient Temperature Actual Values and Device Reading Value

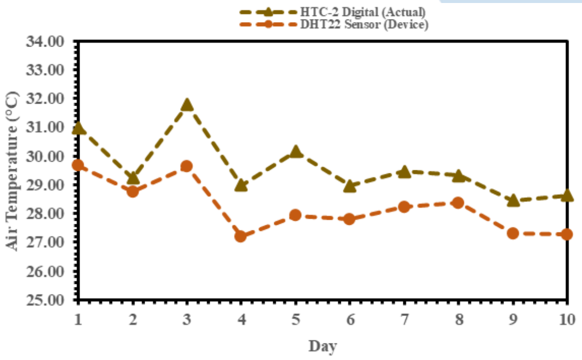

Fig. 14. Chart of Air Temperature Actual Values and Device Reading Value

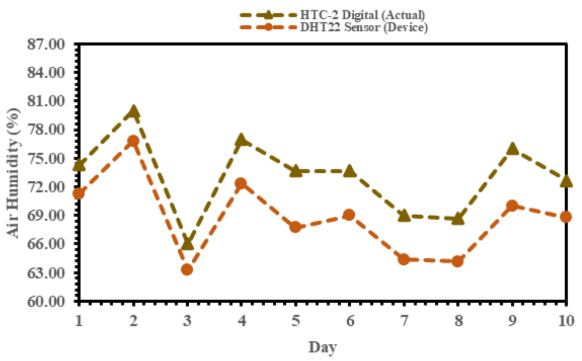

Fig. 15. Chart of Air Humidity Actual Values and Device Reading Value

D. Potentials of System Improvements

In future development stages, the integration of machine learning algorithms could enable predictive analytics for nutrient dosing and environmental adjustments. By collecting and analysing historical sensor data such as pH, TDS, nutrient temperature, air temperature, and humidity, supervised models such as random forest, support vector machines, or LSTM (Long Short-Term Memory) neural networks could be trained to forecast nutrient requirements or detect anomalies in the microclimate environment. Similar techniques have proven effective in predictive irrigation scheduling and fertigation management in precision agriculture contexts [26], [27], [28], [29], [30]. This would enable a closed-loop system with automated actuation based on real-time prediction rather than threshold-based rules.

IV. CONCLUSION

This research presents the design and performance evaluation of an IoT-based nutrient monitoring system for vertical hydroponic planting. The system demonstrated high reliability, with mean device readings closely aligning with actual values, indicating low bias (e.g., 0.20 for pH and 0.51 for nutrient temperature). Precision values for all variables were found to exceed 100%, signifying consistency in the system's readings. However, the accuracy results revealed slight discrepancies, particularly in Total Dissolved Solids (TDS) (92.33%) and air humidity (94.08%), with error percentages ranging from 1.76% (nutrient temperature) to 7.67% (TDS).

The real-time monitoring dashboard, accessible via PC, laptop, or mobile application, provides users with an intuitive interface for efficient data visualization and analysis. Despite some minor deviations in accuracy, the device demonstrated sufficient performance for reliable nutrient and environmental monitoring in hydroponic systems.

Future studies should focus on further refining sensor calibration and reducing error margins, particularly in variables such as air temperature and humidity. Incorporating advanced sensor technologies or machine learning algorithms could enhance the system's accuracy and adaptability, thereby improving the precision and robustness of IoT-based agricultural monitoring systems.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to Universitas Multimedia Nusantara for the financial support and research facilities provided. These contributions were instrumental in the successful completion of this research.

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