Iot-Based Hydroponic Monitoring System For Pakcoy Cultivation Using The Nutrient Film Technique (NFT)

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Article history: Received January 10, 2026| Revised April 29, 2026| Accepted April 30, 2026

***Abstract* – The rapid reduction of agricultural land in urban areas necessitates the development of efficient and scalable farming systems. This study aims to develop an IoT-based monitoring and control system for hydroponic pakcoy cultivation using the Nutrient Film Technique (NFT), with a focus on improving environmental stability and supporting sustainable urban farming. The proposed system integrates multiple sensors, including pH, Total Dissolved Solids (TDS), water temperature, air temperature, and humidity sensors, with Arduino Uno and ESP32 microcontrollers. The system enables real-time data acquisition, cloud-based monitoring via Firebase, and automatic control of nutrient conditions using threshold-based mechanisms. The accuracy of the system was evaluated using the Mean Absolute Percentage Error (MAPE) method by comparing sensor readings with standard instruments. The results show that all sensors achieved excellent accuracy, with MAPE values of 1.36% for water temperature, 2.15% for air temperature, 1.38% for humidity, 5.52% for pH, and 7.82% for TDS. Furthermore, the system successfully maintained key hydroponic parameters within optimal ranges (pH 5.5–6.5 and TDS 1050–1400 ppm), which are essential for nutrient availability and plant growth. This stability reduces environmental fluctuations and minimizes plant stress, thereby supporting more consistent growth conditions for pakcoy cultivation. In addition, the implementation of real-time monitoring and automated control reduces manual intervention and improves operational efficiency in urban hydroponic systems. These findings demonstrate that the proposed IoT-based system not only provides accurate environmental monitoring but also contributes to improving the reliability and efficiency of hydroponic farming, making it a promising solution for sustainable urban agriculture.**

Keywords: IoT-based hydroponics; Nutrient Film Technique (NFT); pakcoy; sensor accuracy; urban farming; precision agriculture.

I. INTRODUCTION

The rapid reduction of agricultural land in Indonesia
The rapid reduction of agricultural land in Indonesia poses significant challenges to food security and sustainable farming systems. Rapid urbanization, industrial expansion, and residential development have accelerated the conversion of productive agricultural land into non-agricultural uses, thereby reducing domestic food production capacity and increasing dependence on external supply chains [1]. This structural transformation not only affects food availability but also threatens long-term agricultural sustainability, particularly in densely populated urban regions. Consequently, innovative agricultural approaches are required to ensure efficient food production within limited spaces while maintaining environmental balance and crop quality.

In response to these challenges, hydroponics has emerged as a viable alternative to conventional soil-based agriculture. Hydroponics is a soilless cultivation technique in which plants receive essential nutrients through water-based solutions, allowing for precise control over nutrient delivery and environmental conditions [2]. This method is particularly suitable for urban environments, where land availability is constrained, as it enables vertical farming and high-density crop production. Compared to traditional agriculture, hydroponics offers several advantages, including improved water-use efficiency, reduced reliance on pesticides, and higher productivity per unit area [3]. Additionally, controlled environment agriculture (CEA) systems, such as hydroponics, have been shown to significantly enhance resource efficiency and crop consistency under varying environmental conditions [4].

Among various hydroponic techniques, the Nutrient Film Technique (NFT) is widely adopted due to its efficient use of water and nutrients. In this system, a thin film of nutrient-rich solution continuously flows over plant roots, ensuring adequate oxygen supply and nutrient absorption. Despite its efficiency, the performance of NFT systems is highly sensitive to environmental and nutrient parameters, including pH, Total Dissolved Solids (TDS), water temperature, ambient temperature, and humidity. Variations in these parameters can significantly influence nutrient solubility, root oxygen availability, and plant metabolic processes, ultimately affecting crop yield and quality [5] [6]. For instance, unstable pH levels can lead to nutrient lockout, while inappropriate TDS concentrations may cause osmotic stress, both of which negatively impact plant growth.

Conventional hydroponic management typically relies on manual monitoring using handheld instruments. While effective on a small scale, this approach is time-consuming, labor-intensive, and prone to human error, particularly in continuous or large-scale operations. Moreover, manual measurements are often limited in frequency, making it difficult to capture dynamic environmental changes in real time. These limitations highlight the need for automated monitoring systems that can provide continuous, accurate, and real-time data.

The integration of Internet of Things (IoT) technology has been widely proposed as a solution to enhance hydroponic system management. IoT-based systems utilize interconnected sensors, microcontrollers, and communication networks to collect and transmit real-time data to cloud-based platforms, enabling remote monitoring and control [7] [8]. Recent advancements in smart agriculture have demonstrated the potential of IoT in optimizing irrigation, climate control, and nutrient management [9]. Furthermore, IoT systems support data-driven decision-making, which is a key component of precision agriculture, allowing farmers to respond quickly to environmental changes and improve resource efficiency.

Despite these advancements, several critical limitations remain in existing IoT-based hydroponic systems. First, many studies focus primarily on monitoring functions without integrating adaptive or automated control mechanisms, limiting their effectiveness in maintaining optimal conditions under dynamic environments [10]. Second, most systems rely on static threshold values for parameters such as pH and TDS, which do not account for crop-specific requirements or environmental variability. Third, the accuracy and reliability of sensors are often not rigorously validated against standard measurement instruments, raising concerns about data credibility in real-world applications [11]. Additionally, existing research is predominantly conducted in controlled or temperate environments, which may not reflect the challenges faced in tropical regions.

These limitations are particularly relevant in tropical areas such as Pontianak, Indonesia, which is characterized by high humidity levels and consistently elevated temperatures throughout the year. Such environmental conditions can accelerate nutrient solution instability, reduce dissolved oxygen levels in NFT systems, and increase plant stress due to enhanced transpiration rates. High temperatures also affect nutrient solubility and microbial activity in the solution, potentially leading to rapid changes in water quality. However, there is still limited research addressing the implementation of IoT-based hydroponic systems under these specific climatic conditions, highlighting a significant research gap.

Furthermore, pakcoy (Brassica rapa L.) is a widely cultivated leafy vegetable with high economic value and increasing market demand in Indonesia. It has a relatively short growth cycle and is suitable for hydroponic cultivation; however, it is highly sensitive to variations in pH and nutrient concentration. Even minor deviations from optimal conditions can lead to reduced leaf quality, slower growth, and lower yield. Therefore, maintaining stable environmental and nutrient parameters is essential for achieving optimal production. Despite its importance, there is limited research focusing on IoT-based systems specifically designed for pakcoy cultivation under tropical NFT conditions.

Based on these considerations, this study aims to develop an IoT-based monitoring and control system for hydroponic pakcoy cultivation using the NFT method. The proposed system is designed to monitor key parameters in real time, including pH, TDS, water temperature, ambient temperature, and humidity, while automatically adjusting nutrient conditions to maintain optimal ranges. The system integrates sensors, microcontrollers, and a Firebase-based cloud platform to enable real-time data visualization and remote system control.

The contributions of this study are threefold. First, it proposes a cost-effective IoT system tailored for pakcoy cultivation in NFT hydroponic systems under tropical environmental conditions. Second, it evaluates sensor accuracy through validation against standard measurement instruments, ensuring data reliability. Third, it demonstrates the integration of cloud-based platforms for real-time monitoring and decision-making in hydroponic farming systems.

The novelty of this research lies not only in the application of IoT technology but also in its contextual adaptation to tropical climates, its emphasis on sensor validation, and its focus on crop-specific optimization for pakcoy cultivation. This study is expected to contribute to the development of more adaptive, reliable, and scalable smart farming systems, thereby supporting sustainable urban agriculture and enhancing regional food security.

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II. Method

This study employs a quantitative research method, focusing on numerical data that can be measured and analyzed statistically. The primary objective is to design, implement, and evaluate an IoT-based hydroponic monitoring system for Pakcoy cultivation using the Nutrient Film Technique (NFT). The research method consists of several stages, including error measurement using the Mean Absolute Percentage Error (MAPE), hardware and software design, system implementation, and validation through comparison with standard measuring instruments.

A. System Architecture

The proposed system consists of three main layers:

1. Sensing Layer
   Collects real-time data using sensors:
   - pH sensor
   - TDS sensor
   - Water temperature sensor
   - Air temperature and humidity sensor (DHT)
2. Processing Layer
   - Arduino Uno processes sensor data
   - ESP32 handles wireless communication
3. Application Layer
   - Cloud platform (Firebase) for data storage
   - Web-based dashboard for visualization and monitoring

Data flows from sensors → Arduino → ESP32 → cloud → user interface.

B. Hadware Design

The hardware system is designed based on the integration of sensors, microcontrollers, communication modules, and actuators, as illustrated in Figure 3.

The system utilizes an Arduino Uno as the main data acquisition and control unit, while the ESP32 is employed as a Wi-Fi communication module for transmitting data to the cloud platform.

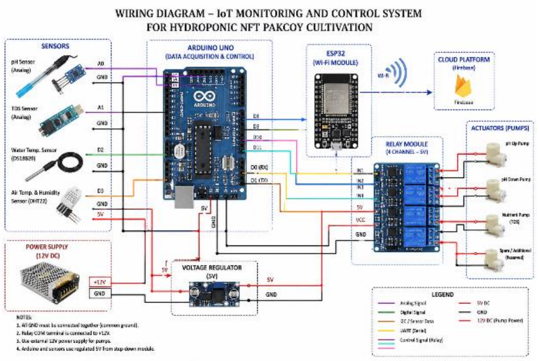


Figure 3. Wiring diagram of the IoT-based monitoring and control system for hydroponic NFT pakcoy cultivation.

The complete wiring configuration of the system is presented in Figure 3, which illustrates the interconnection between sensors, Arduino Uno, ESP32, relay module, and actuators, including power distribution and communication pathways

D. Hydroponic Structure Design

he hydroponic cultivation system is based on the NFT (Nutrient Film Technique) method, where nutrient-rich water circulates continuously for 24 hours. The structural design includes:

1. PVC pipes for nutrient channels.
2. Reservoir tanks for nutrient storage.
3. Water pumps for circulation.
4. Net pots and rockwool as plant holders.

Figures 3 and 4 present the physical hydroponic frame and NFT design model.

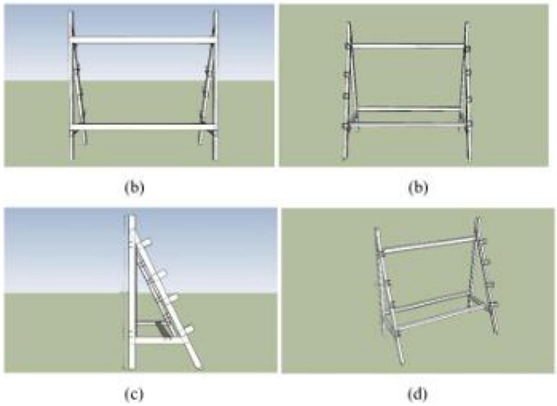


Figure 3. Hydroponic Frame Design Without Pipes (a) Rear View (b) Front View (c) Side View (d) Perspective View

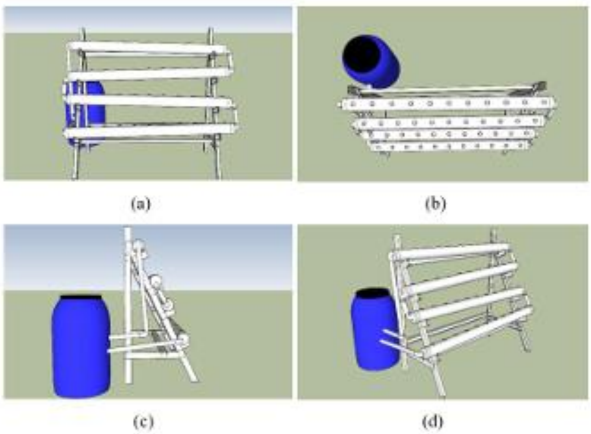


Figure 4. NFT Hydroponic Design (a) Front View (b) Top View (c) Side View (d) Perspective View

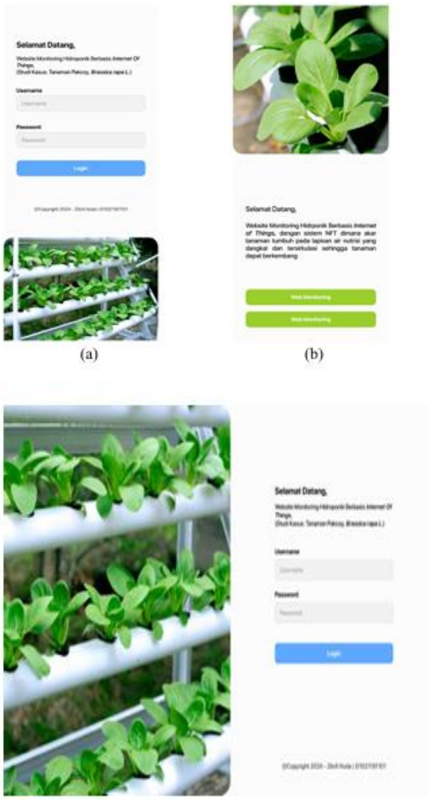
E. *Software Design*

The software system consists of:

1. Embedded Programming
   - Arduino IDE is used to program both Arduino Uno and ESP32
   - Functions include:
     - Sensor data acquisition
     - Data filtering and conversion
     - Threshold-based decision making
     - Serial communication
2. Cloud Integration
   - Firebase is used as a real-time database

- ESP32 sends data via Wi-Fi using HTTP/REST API

3. User Interface
   - Web dashboard displays:
     - Real-time parameter values
     - Historical data visualization
     - System status (pump ON/OFF)

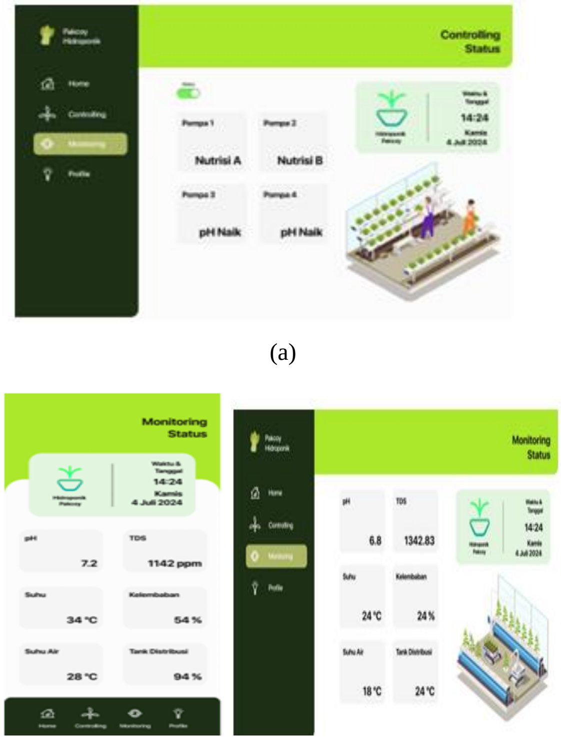


(a) (b)

Figure 5. Hydroponic Monitoring Website Display on Desktop: (a) Login Page (b) Main Page

(a) (b)

Figure 6. Pump Control Display via Mobile Website: (a) ON Status (b) OFF Status



(a)

(b) (c)

Figure 7. Data Display on Hydroponic Monitoring Website: (a) Control Data on Desktop, (b) Monitoring Data on Mobile, (c) Monitoring Data on Desktop

F. Control Mechanism

The system applies a threshold-based automatic control strategy.

1. Optimal Parameter Ranges (Pakcoy Hydroponics)
   - pH: 5.5 – 6.5
   - TDS: 1050 – 1400 ppm
   - Water temperature: 20 – 28°C
   - Humidity: 60 – 80%
2. Control Logic
   - If pH < 5.5 → activate pH up pump
   - If pH > 6.5 → activate pH down pump
   - If TDS < 1050 ppm → activate nutrient pump
   - Pumps stop automatically when values return to optimal range

This mechanism ensures continuous adjustment of nutrient conditions without manual intervention.

G. System Testing

System testing is carried out to evaluate the accuracy of the sensors and the stability of IoT communication. Measurements from the developed device are compared against standard instruments (Table 1), including:

- Digital Thermo-Hygrometer (temperature & humidity).
- Multiparameter Water Quality Meter (pH, TDS, EC, salinity, water temperature).

The test results are analyzed using MAPE to quantify measurement accuracy.

G. Variables and Data Collection

The main variables observed include:

1. Ambient temperature and humidity (DHT22).
2. Water temperature (DS18B20).
3. Water pH (pH sensor).
4. Total Dissolved Solids (TDS sensor).
5. System accuracy compared with standard instruments.

H. *Plant Cultivation Procedure*

The cultivation process uses Pakcoy (Brassica rapa L.) with the following procedure:

1. Seeds are germinated for two weeks in a nursery tray.
2. Seedlings are transferred to the NFT system with rockwool and net pots as media.
3. Nutrient solution uses **AB Mix**, adjusted with pH up/down solutions to maintain pH 5.5–6.5.
4. Growth is observed for ±4 weeks, with weekly measurement of plant height and leaf development.

I. Accuracy Evaluation Model

To evaluate system accuracy, the Mean Absolute Percentage Error (MAPE) method is used.

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{Y_t^1 - \widehat{Y}_t}{Y_t^1}\right| \times 100\%$$

Y_t^1 = value from standard instrument

Y_t = value from IoT system

n = number of observations

MAPE Interpretation:

< 10% → Excellent accuracy

10–20% → Good accuracy

20–50% → Acceptable

50% → Poor accuracy

III. RESULT AND DISCUSSION

A. System Implemtantion an Interface

The hydroponic monitoring system was developed The developed IoT-based hydroponic monitoring system was successfully implemented to observe and control key environmental parameters in pakcoy cultivation using the NFT method. The system integrates an Arduino Uno for data acquisition, an ESP32 for wireless communication, and a Firebase-based web platform for real-time monitoring.

All sensor data—including air temperature, humidity, water temperature, pH, and TDS—are displayed both on a 20×4 LCD and a web-based dashboard. The interface also enables actuator control, including nutrient pumps and pH adjustment systems

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(a) (b)

Figure 8. Monitoring Interface (a) interface on desktop (b) interface on mobile

B. Sensor Accuracy Evaluation (MAPE Analysis)

Sensor accuracy was evaluated using the Mean Absolute Percentage Error (MAPE) method by comparing IoT sensor readings with standard instruments.

Table 1. Summary of MAPE Results

Sensor	MAPE (%)	Category
Water Temperature (DS18B20)	1.36	Excellent
Air Temperature (DHT22)	2.15	Excellent
Humidity (DHT22)	1.38	Excellent
pH Sensor	5.52	Excellent
TDS Sensor	7.82	Excellent

All sensors achieved MAPE values below 10%, indicating excellent accuracy

1. Water Temperature

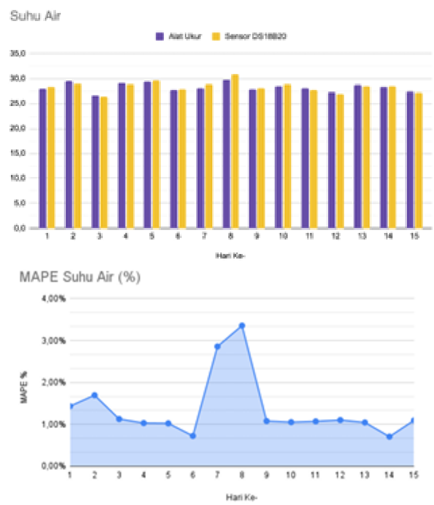

Figure 9 Comparison of Water Temperature Measurements Using DS18B20 Sensor and Water Thermometer, and MAPE Analysis of Measurement Results.

The DS18B20 sensor achieved a MAPE of 1.36%, demonstrating high precision. Stable water temperature is essential in NFT systems as it affects dissolved oxygen and nutrient solubility.

2. Air Temperature and Humadity

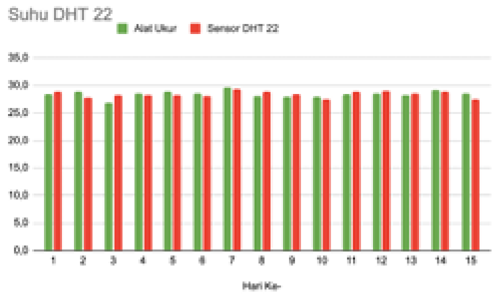

Figure 10 presents the comparison and MAPE graphs for DHT22.

The DHT22 sensor achieved:

- 2.15% (temperature)
- 1.38% (humidity)

These parameters are critical for transpiration and photosynthesis.

3. PH Measurment

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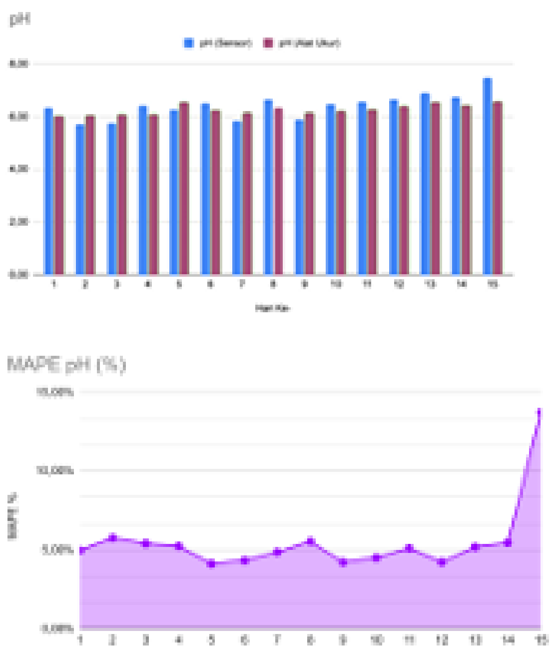

Figure 11. shows the pH comparison.

The pH sensor achieved 5.52% MAPE. Stable pH ensures nutrient availability and prevents deficiencies.

4. TDS Measurement

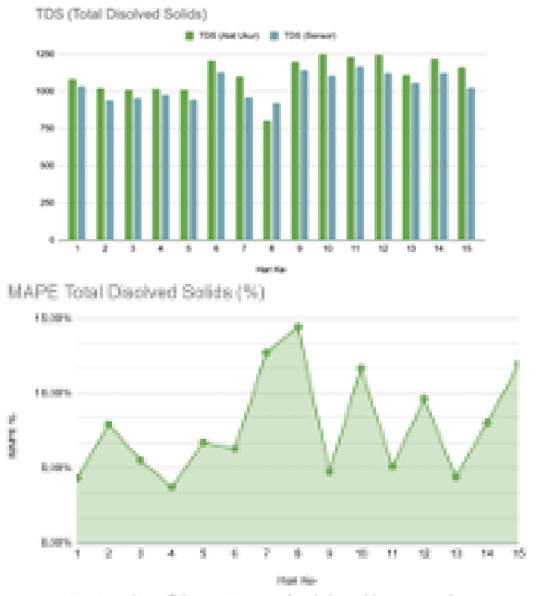

Figure 12. Comparison Graph of TDS Sensor and TDS Meter Measurements and MAPE Analysis

The TDS sensor achieved 7.82% MAPE. This confirms reliable nutrient concentration monitoring

The stability of environmental and nutrient parameters monitored by the IoT-based system plays a critical role in determining the growth performance of pakcoy cultivated using the Nutrient Film Technique (NFT). In this study, the system consistently maintained key parameters within their optimal ranges, particularly pH (5.5–6.5) and Total Dissolved Solids (TDS) (1050–1400 ppm), which are widely recognized as essential for leafy vegetable cultivation.

From a physiological perspective, pH stability directly influences nutrient solubility and availability in the hydroponic solution. When the pH remains within the optimal range, essential macro- and micronutrients such as nitrogen (N), phosphorus (P), potassium (K), iron (Fe), and magnesium (Mg) are more readily absorbed by plant roots. In contrast, deviations from this range can lead to nutrient lockout or toxicity, which negatively affects plant metabolism and growth. The results of this study indicate that the automated control system successfully minimized such fluctuations, thereby supporting a more stable nutrient uptake process.

Similarly, the regulation of TDS values ensures that the concentration of dissolved nutrients remains within a range that supports optimal plant growth without causing osmotic stress. Low TDS levels can result in nutrient deficiencies, leading to stunted growth and pale leaves, whereas excessively high TDS levels may cause salt accumulation and inhibit water absorption due to osmotic imbalance. The observed consistency in TDS levels throughout the monitoring period suggests that the system effectively maintained nutrient equilibrium, which is crucial for sustaining plant vigor.

In addition to nutrient parameters, environmental conditions such as air temperature, humidity, and water temperature also contribute significantly to plant physiological processes. Stable air temperature supports optimal photosynthetic activity, while appropriate humidity levels regulate transpiration rates and prevent excessive water loss. Water temperature, on the other hand, affects dissolved oxygen levels in the nutrient solution, which is essential for root respiration. The low MAPE values obtained from the DS18B20 and DHT22 sensors indicate that these environmental parameters were monitored with high accuracy, allowing the system to maintain a favorable microclimate for plant growth.

Observationally, the pakcoy plants cultivated under this system exhibited several indicators of healthy growth. These include uniform leaf coloration (indicating adequate chlorophyll production), consistent leaf expansion, and the absence of visible symptoms of nutrient deficiency such as chlorosis or necrosis. The uniformity of plant morphology across the cultivation system suggests that environmental conditions were evenly distributed and effectively controlled.

Furthermore, the integration of real-time monitoring and automatic control reduces the likelihood of delayed corrective actions, which are common in manual hydroponic management. By continuously adjusting pH and nutrient levels, the system prevents prolonged exposure to suboptimal conditions, thereby minimizing plant stress. This continuous feedback loop is a key advantage of IoT-based hydroponic systems, as it enhances system responsiveness and overall cultivation efficiency.

Although direct quantitative measurements of plant yield (such as biomass or harvest weight) were not included in this study, the stability of critical growth parameters and the observed plant conditions strongly indicate that the system contributes positively to plant development. These findings are consistent with the principles of precision agriculture, where maintaining optimal environmental conditions through continuous monitoring leads to improved crop performance and resource efficiency.

In summary, the results demonstrate that the accuracy and stability of the IoT-based monitoring system are not only significant from an engineering perspective but also have direct implications for plant health and productivity. The ability to maintain optimal nutrient and environmental conditions in real time represents a crucial step toward the development of intelligent and sustainable hydroponic farming systems.

C. Evaluation of Data Recording in an IoT-Based Hydroponic Monitoring System for Pakcoy

The overall data recording analysis of the hydroponic monitoring system, involving the DS18B20 water temperature sensor, DHT22 for ambient temperature and humidity, pH sensor, and TDS sensor, reveals a complex dynamic in hydroponic environmental monitoring. A comparative assessment between data generated by automatic sensors and manual measurement tools highlights significant differences in the level of detail and data dynamics. Automatic sensors provide a wider range of data, reflecting their capability to detect environmental variations in real-time and their higher sensitivity to minor changes. This is specifically evident in the broader humidity range and more dynamic water distribution and temperature variations recorded by the sensors.

Table 2. Comparative Data Recording Using Manual Measurement Tools

No	Water Temp (°C)	Ambient Temp (°C)	Humidity (%)	pH	TDS (ppm)	Tank Distribution (%)
1	27.9	28.4	85	6.02	1081	99
2	29.5	28.8	88	6.06	1022	96
3	26.6	26.8	80	6.09	1011	93
4	29.1	28.6	82	6.09	1018	90
5	29.3	28.8	81	6.54	1011	87
6	27.6	28.6	79	6.22	1207	84
7	28	29.6	84	6.15	1100	80
8	29.8	28.1	78	6.31	804	98
9	27.8	28	80	6.15	1200	93
10	28.5	27.9	77	6.2	1250	92
11	28	28.4	90	6.25	1230	91
12	27.2	28.5	82	6.37	1246	86
13	28.7	28.2	83	6.54	1108	81
14	28.3	29.2	84	6.4	1220	76
15	27.4	28.5	81	6.55	1163	81
16	28.4	27.7	80	6.5	1180	85
17	27.5	32.7	86	6.45	1190	83
18	28.2	31.5	75	6.48	1175	84
19	27.8	30.8	78	6.52	1185	82
20	29.8	33.1	70	6.06	1402	71
21	30	31.4	76	6.1	1300	58
22	29.5	30.4	70	6.2	1250	46
23	35.3	36.5	72	7.45	925	34
24	34.2	30.5	73	7.3	771	66
25	33	33.4	74	7.35	800	54
26	32.5	32.4	71	7.4	820	44
27	30.5	31.3	75	7.38	810	38
28	34	32.4	70	7.42	830	33

Conversely, manual measurement data tend to show higher stability and lower fluctuations. According to Jensen (2005), manual measurements are limited by sampling frequency and instrument resolution, which explains this stability. However, manual data remain essential for verification and calibration of sensor systems, ensuring that real-time data accurately represent actual environmental conditions.

Table 3. Comparative Data Recording Using IoT Sensors

No	DB18B20 (Water Temp °C)	DHT22 (Ambient Temp °C)	Humidity (%)	pH	TDS (ppm)	Tank Distribution (%)
1	28.3	28.9	86	6.32	1034	98
2	29	27.8	89	5.71	941	97
3	26.3	28.3	79	5.76	955	98
4	28.8	28.2	83	6.41	980	89
5	29.6	28.2	83	6.27	943	86
6	27.8	28.1	78	6.49	1131	85
7	28.8	29.3	85	5.85	960	81

8	30.8	28.8	79	6.66	920	97
9	28.1	28.4	82	5.89	1143	93
10	28.8	27.4	76	6.48	1104	91
11	27.7	28.9	91	6.57	1167	91
12	26.9	29	83	6.64	1126	85
13	28.4	28.5	84	6.88	1059	82
14	28.5	28.9	85	6.75	1122	75
15	27.1	27.4	82	7.45	1024	81
16	28	28.8	82	6.79	1132	85
17	28	31.8	83	6.12	1116	83
18	27.7	30.8	75	6.23	1139	83
19	28.3	31.9	79	5.73	1175	81
20	29.3	33.3	80	6.45	1121	69
21	31	32.6	76	7.81	879	57

Tables 2 and 3 facilitate a comparative analysis between real-time data acquired by automatic sensors and manual measurements, highlighting unique characteristics of each method in representing environmental conditions. Automatic sensors, through high-frequency sampling, capture a more dynamic and broader data spectrum and demonstrate superior sensitivity to microclimatic changes, particularly in humidity variation, temperature fluctuations, and water distribution. Manual data provide a more static representation due to inherent limitations in sampling and resolution.

A clear difference between the two methods is observed in TDS and water distribution. Sensor data show smaller TDS fluctuations but greater variation in water distribution, whereas manual tools show higher TDS values with more stable distribution. Both methods, however, provide consistent pH readings within the ideal range, indicating stable nutrient solutions.

The integration of automatic sensors and manual verification strengthens system reliability and ensures accurate, real-time monitoring, in line with principles of precision agriculture, which emphasize the importance of combining automated sensing with periodic manual calibration to optimize plant growth conditions.

The research on the IoT-based hydroponic system for pakcoy cultivation demonstrates that the developed monitoring system was successfully implemented and operates effectively in tracking critical growth parameters. The testing results show that all sensors achieved ac-ceptable levels of accuracy, with water temperature ranging from 2–3%, pH from 4–5.86%, TDS from 4–9.17%, ambient temperature and humidity from 2–4.6%, and tank distribution from 1–3%. Such precision enables hydroponic parameters to be consistently maintained within optimal ranges, which is essential for ensuring stable growth conditions for pakcoy. Additionally, the system facilitates remote monitoring and reduces reliance on manual in-spections, thereby improving operational efficiency and providing greater flexibility for hy-droponic farmers. Although direct measurements of harvest outcomes were not included in this study, the system is designed to maintain nutrient conditions within scientifically rec-ommended optimal ranges. As a result, it can support a stable hydroponic environment, indi-rectly minimizing growth disturbances and enhancing overall plant productivity

IV. CONCLUSION

This study successfully developed and implemented an IoT-based monitoring and control system for hydroponic pakcoy cultivation using the Nutrient Film Technique (NFT). The system integrates multiple sensors, including pH, Total Dissolved Solids (TDS), water temperature, air temperature, and humidity sensors, with microcontrollers and a cloud-based platform to enable real-time monitoring and automatic control of environmental and nutrient conditions.

The accuracy evaluation using the Mean Absolute Percentage Error (MAPE) method shows that all sensors achieved excellent performance, with error values below 10%. This indicates that the system provides reliable and precise measurements, making it suitable for real-time hydroponic applications. In addition to accuracy, the system demonstrated effective control performance by maintaining key parameters within optimal ranges, particularly pH (5.5–6.5) and TDS (1050–1400 ppm), which are essential for supporting nutrient availability and plant growth.

The stability of these parameters contributes directly to maintaining favorable growing conditions, as reflected in the observed healthy characteristics of pakcoy plants, including uniform leaf color, consistent growth patterns, and the absence of visible nutrient deficiency symptoms. These findings highlight that the integration of IoT technology not only improves monitoring efficiency but also plays a significant role in enhancing environmental stability and supporting plant development in hydroponic systems.

Furthermore, the implementation of real-time monitoring combined with automatic control reduces dependence on manual intervention and enables faster system response to environmental changes. This improves operational efficiency and supports the application of precision agriculture principles in urban farming environments.

Despite these promising results, several aspects can be further developed to enhance system performance and scalability. Future research may focus on integrating machine learning algorithms to enable predictive and adaptive nutrient control, thereby improving decision-making accuracy under dynamic environmental conditions. In addition, the incorporation of renewable energy sources, such as solar power systems, can increase energy efficiency and support sustainable farming practices. The development of mobile-based applications may also improve accessibility and user interaction, while expanding the system to accommodate multiple crop types could increase its practical applicability. Finally, integrating automated plant growth analysis, such as leaf area detection or biomass estimation, would provide a more comprehensive evaluation of the relationship between environmental control and crop productivity.

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