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Development of IoT-based Smart System for Environmental Control and Water Quality Monitoring in Plant Factory

Pengembangan Sistem Cerdas Berbasis IoT untuk Pengendalian Lingkungan dan Pemantauan Kualitas Air pada Plant Factory

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ABSTRACT

This study aims to design and implement an IoT-based environmental control and water quality monitoring system in a Plant Factory. This system supports concrete steps toward efficient, adaptive, technology-based smart farming by providing real-time monitoring and automatic control of environmental and water conditions. The research method involves designing hardware with sensors to monitor air temperature, humidity, light intensity, water temperature, pH, and TDS, as well as actuators in the form of fans for temperature control integrated with the Arduino Cloud IoT platform for real-time monitoring. The research shows that the sensor calibration results are below 5%, making them suitable for use. During testing, the developed system successfully monitored environmental parameters and water quality in real-time, with the fan capable of cooling the plant factory space below 30°C. However, challenges arose during sensor data verification, with discrepancies between LCD display readings and IoT data at certain times. Nevertheless, this IoT-based system effectively monitors data and controls temperature within the plant factory.

Keywords: environmental control; IoT; monitoring; plant factory; water quality

ABSTRAK

Penelitian ini bertujuan untuk merancang dan mengimplementasikan sistem pengendalian lingkungan dan pemantauan kualitas air berbasis IoT di dalam Plant Factory. Sistem ini mendukung langkah-langkah konkret menuju pertanian cerdas yang efisien, adaptif, dan berbasis teknologi dengan menyediakan pemantauan real-time dan pengendalian otomatis terhadap kondisi lingkungan dan air. Metode penelitian melibatkan desain hardware dengan sensor untuk memantau suhu udara, kelembapan, intensitas cahaya, suhu air, pH, dan TDS, serta aktuator berupa kipas untuk pengendalian suhu yang terintegrasi dengan platform Arduino Cloud IoT untuk pemantauan real-time. Hasil penelitian menunjukkan bahwa hasil kalibrasi sensor berada di bawah 5%, sehingga cocok untuk digunakan. Selama pengujian, sistem yang dikembangkan berhasil memantau parameter lingkungan dan kualitas air secara real-time, dengan kipas mampu mendinginkan ruang pabrik tanaman di bawah 30°C. Namun, tantangan muncul selama verifikasi data sensor, dengan ketidaksesuaian antara pembacaan layar LCD dan data IoT pada waktu tertentu. Meskipun demikian, sistem berbasis IoT ini secara efektif memantau data dan mengontrol suhu di dalam pabrik tanaman.

Kata kunci: *kualitas air; IoT; pemantauan; pengendalian lingkungan; plant factory*

INTRODUCTION

Rapid population growth and increasing food demand drive the development of more efficient and sustainable agricultural systems. Plant Factory is one of the innovative solutions in technology-based agriculture that enables crop production in a controlled environment (He et al., 2021; Liu et al., 2024). However, one of the main challenges in the plant factory system is maintaining water quality as a crucial factor in hydroponic plant growth. Uncontrolled water quality can lead to nutrient imbalance, growth of pathogenic microorganisms, and reduced crop yields. Therefore, a water quality monitoring system that can work in real-time and automatically is needed to improve the efficiency and effectiveness of plant factory management.

Various studies have been conducted to develop Internet of Things (IoT)-based monitoring systems in agriculture. (Dhanaraju et al., 2022; Gondchawar & Kawitkar, 2016; Kim et al., 2020; Quy et al., 2022). For example, research by Wang et al. (2021) developed an IoT system for hydroponic nutrition monitoring, while (De Side et al., 2025) Red node-based IoT was used to monitor the microclimate in the plant factory. However, most studies still have limitations regarding real-time integration of data from all aspects of the environment, especially in the plant factory, the use of the latest IoT system platforms, and the speed and accuracy in responding to sensor readings.

This research aims to design an IoT-based temperature control and water quality monitoring system in a plant factory that can work automatically and be integrated. The idea of device communication applied to precision agriculture emerges from the Internet of Things (IoT) development, which allows remote users to perform various monitoring activities. (Abdullah et al., 2023). In real-time, the system will use various sensors to measure environmental parameters such as temperature, humidity, light intensity, and water quality, such as pH, temperature, and electrical conductivity. The data read by the sensors will be collected and processed through the latest Arduino cloud platform with standardized protocols, such as MQTT, which ensures data transmission with high accuracy and efficiency. This protocol enables fast and accurate data communication between the device and the cloud. This system is expected to improve the efficiency of modern agriculture and contribute to developing more adaptive and intelligent IoT-based agricultural technology.

METHOD

The tools used in this research are ESP32 and Arduino UNO V3, DHT22 sensor, DS18B20 sensor, TDS sensor SEN0244, pH sensor 4502C, Arduino Cloud platform, jumper cable, 20x4 LCD, adapter, laptop Asus x455l core i3, and Arduino IDE software. While the material needed for hydroponic nutrition in the Plant Factory is used AB mix solution, the type of plant grown is pakcoy, at the age of 3 weeks after germination. Pakcoy has a short harvest period and is easy to cultivate. Figure 1 presents the scheme of the intelligent monitoring system built in the plant factory.

This research was conducted in several stages: Preparing hydroponic plants in the plant factory, assembling the monitoring system, programming and connecting the hydroponic nutrient basin monitoring system, observing the results of monitoring system testing, and conducting data analysis. Figure 2 shows the intelligent monitoring system installed in the plant factory. The simultaneous use of Arduino Uno and ESP32 microcontrollers is due to the limited number of pins on the ESP32, necessitating the addition of pins from the Arduino Uno, particularly the use of the SDA and SCL pins for the LCD.

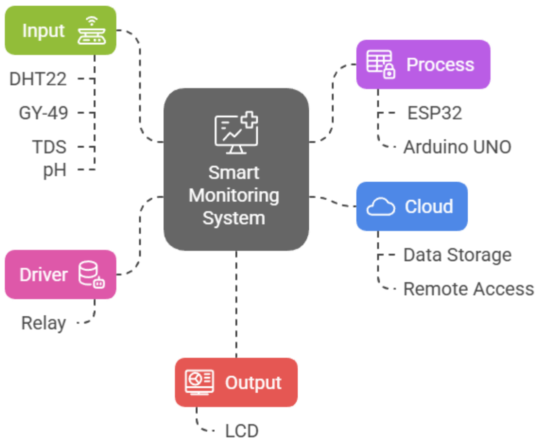

Figure 1. Factory block diagram of an intelligent monitoring plant

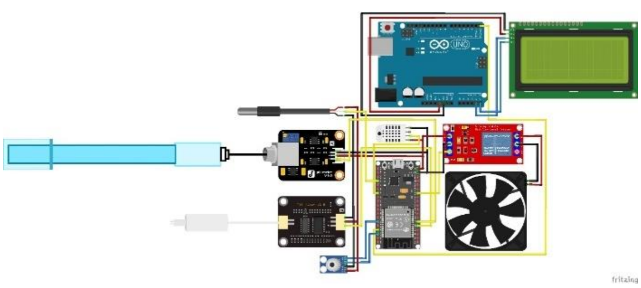

Figure 2. Control and monitoring system for the factory plant.

Table 1. Control and monitoring system components

No	Components	Function
1	DHT22	Sensors for temperature and humidity monitoring
2	GY-49	Sensor for light intensity monitoring
3	TDS meter	Sensors to monitor nutrient content
4	pH meter	Sensor to monitor acid content
5	DS18B20	Sensor to monitor water temperature due to its waterproof nature
5	Relay	Components for connecting and disconnecting the current
6	ESP32	Send data to the cloud
7	Arduino UNO	Activate the LCD via pins A4 and A5
8	LCD 20x4	As a display tool
9	Adaptor DC 12 V	Power supply source

Before the final design is implemented, each component in the system is tested first to ensure it can function correctly. Each component has its function, as shown in Table 1.

Each sensor must be calibrated with a standard measuring instrument, namely HTC-2 to measure temperature and humidity, a lux meter to measure light intensity, pH liquid (4, 7, 10), and TDS liquid (100, 500, 1500 ppm). After that, calculate the error value. The equation used to calculate the error value uses the mean absolute percentage error (MAPE) (Clements et al., 2016):

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right| x100\% \quad (1)$$

Description: yi = observation value to i; $\hat{y}_i$= expected value to i; n = number of observations.

If the error is less than 10%, the model fit is perfect, while a range from 10 to 20% indicates a good fit, and 20 to 30% an acceptable level. A MAPE above 30% implies poor model accuracy and disqualifies the model from practical use (Piekutowska et al., 2021).

Plant Factory Preparation

The plant factory (Figure 3) is made using a 3 x 3 cm square iron frame with a size of 1.5 m x 0.8 m x 2 m (p x l x t), arranged with three levels, and each level has three hydroponic gutters. Each gutter has six planting holes irrigated with the NFT (Nutrient Film Technique) system.

Instead of sunlight, the system uses a 120 cm long Fultrum brand LED grow light (18 W, wavelength 450 nm and 650 nm) to help the plants photosynthesize. The lights are set to run for 15 hours daily (07.00 am until 10.00 pm), exceeding the regular 12 hours of sunlight to optimize photosynthesis.

Monitoring and Control System Preparation

The monitoring and control system is designed to collect data every 5 minutes daily, which is sent to the cloud. Generally, the monitoring and control system consists of input in the form of sensors and data processing in ESP32 and Arduino UNO, then the data is sent and stored in the cloud through the Arduino cloud platform. The data results will be displayed on the 20 x 4 LCD layer, and the control system response will be an exhaust fan. The flow chart in

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Figure 3. Plant factory

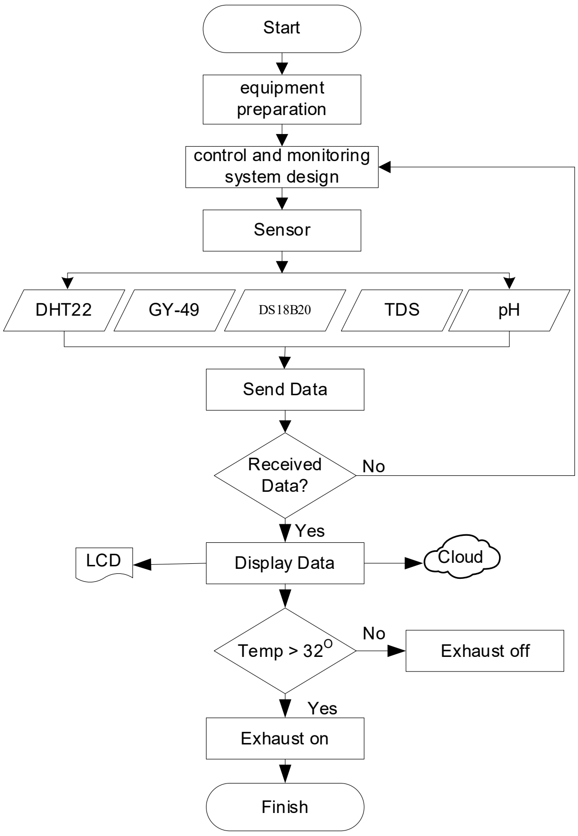

Figure 4. Flowchart of the plant factory control system

RESULT AND DISCUSSION

In this research, an environmental control system and water quality monitoring have been successfully implemented. This system is made in a panel box measuring 220 mm x 150 mm x 75 mm. The following tool design results are presented in Figure 5.

Sensor calibration

Before the system is applied in the plant factory, all sensors must be calibrated to ensure they can work properly. The calibration procedure compares the reference value with the value read by the sensor 5 times. Then, the error value is sought using the MAPE approach. The sensor calibration results can be seen in Table 2.

From the sensor calibration results, it is obtained that the entire sensor has an MAPE value below 5%, meaning that it has a high accuracy value so that it can be used for data collection.

System testing

The next step is testing the monitoring and control system, which is carried out to ensure that each installed component can work according to the instructions given. This test includes readings from each sensor displayed on the LCD, relay testing, and testing the data transfer system through the Arduino Cloud platform. One of the primary advantages of the Arduino Cloud is the facilitation of real-time data acquisition and management (Habibuddin et al., 2024).

Figure 6 shows the results of testing the system, which can work correctly. All sensors can be read on the LCD every 5 minutes, and visualization of sensor reading graphs from Arduino Cloud can also be displayed on desktops and mobile phones (Figure 7).

On the Arduino cloud web page, the display consists of several components that can be seen, including (1) temperature display, (2) pH display, (3) light intensity display, (4) nutrient content display (PPM), (5) button display for remote temperature control, and (6) graph display. Not all components can be displayed on the web page because the free version only displays a maximum of 5 parameters. The control system uses a 12-volt DC fan as an actuator to dissipate excess heat in the plant factory. The DHT22 sensor sends temperature data to the ESP32, which becomes a reference for further action. ESP32 sends a signal to the relay to activate or deactivate the DC fan actuator according to the previously determined set point. If the room temperature in the plant factory exceeds 32 ^{o}C, the fan will turn on and off if the temperature falls below 30 ^{o}C. Table 3 shows the performance of the DC fan using relays to regulate the temperature inside the plant factory. From the test results, the highest temperature was recorded during the day, ranging from 33 to 33.3 °C. The control system is set to turn on the fan when the temperature exceeds 32 °C. The temperature cannot drop below 32 °C even when the fan runs. The hot environmental conditions during the day further complicate the temperature's lowering process.

The morning temperature in the plant factory was the lowest at 28.2 ^{o}C and the highest at 29.2 ^{o}C. The average temperature in the morning is 28.2 ^{o}C. During the day, the temperature increased with the lowest value being 33 ^{o}C and the highest value being 33.3 °C, with an average of 33.14 ^{o}C. In the afternoon, the temperature tends to drop, with the lowest value of 32.2 ^{o}C and the highest value of 32.5 ^{o}C, with an average of 32.42 ˚C. The temperature and relative humidity were both negatively related. (Chowdhury et al., 2021). This is in line with the statement (Wu et al., 2020) Which states that temperature is inversely proportional to humidity. In the morning, the minimum humidity value was 80.7% and the maximum was 84.6%, averaging 82.14%. In the afternoon, the lowest humidity was 64.3% and the highest was 65.9%, averaging 65.14%. The afternoon conditions showed that the minimum humidity was 72.7% and the maximum was 76.4%, averaging 74.25%.

From this data, it can be concluded that the microclimate in the plant factory is still ideal for the growth of vegetable plants, which on average have growing conditions with temperatures of 28 ^{o}C to 33 ^{o}C and humidity ranging from 70% to 85% (Chia & Lim, 2022; Ferrante & Mariani, 2018). The next sensor tested is the GY-49 sensor, which is used to measure the amount of light intensity in lux units.

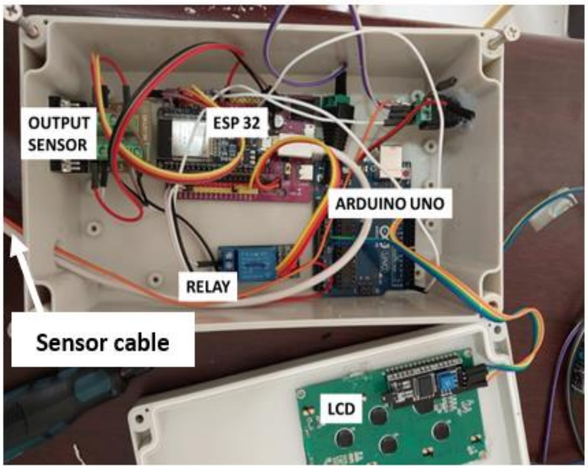

Figure 5. Results of the assembly of the plant factory control and monitoring system components

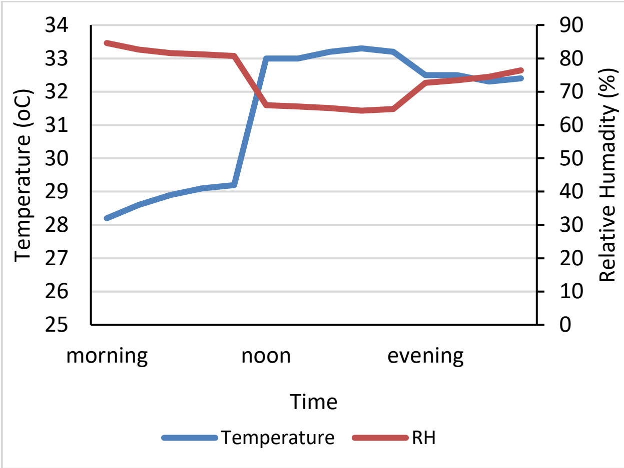

Figure 8. DHT22 sensor testing

Figure 6. Monitoring and control system test results

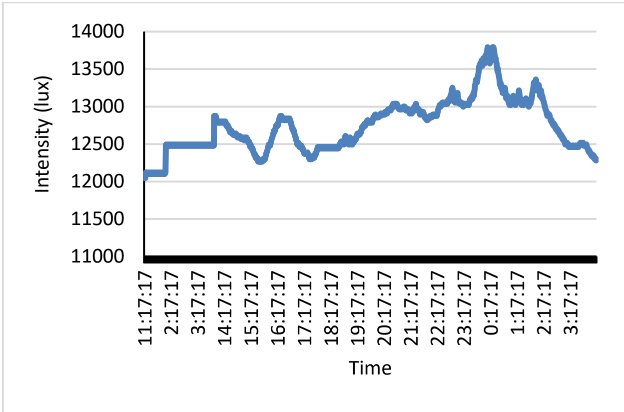

Figure 9. GY-49 Sensor testing

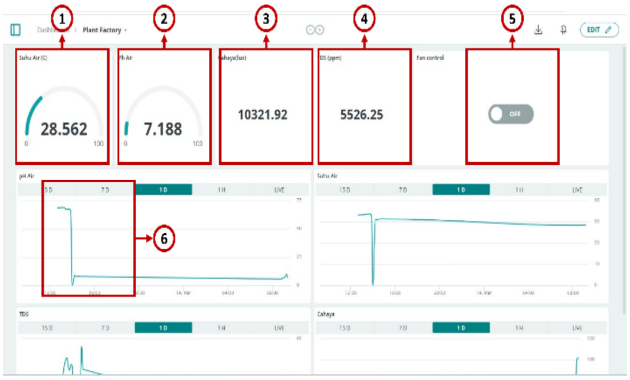

Figure 7. Arduino cloud dashboard display via desktop

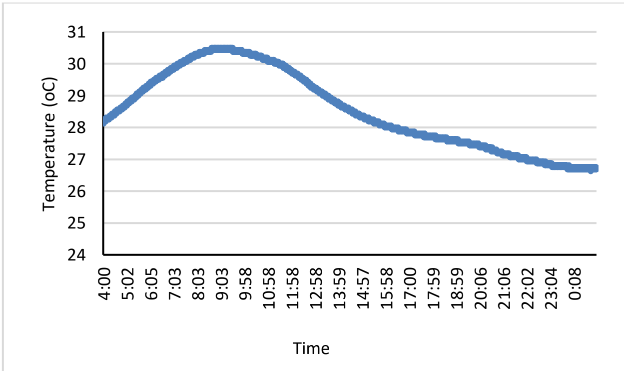

Figure 10. Water temperature sensor testing

Testing climate sensor components

Testing the environmental sensor component involves air temperature, humidity, and light intensity parameters. The calibrated sensors were then used to monitor the climatic conditions around the plant factory. Figure 8 shows the DHT22 sensor readings for monitoring air temperature and humidity.

Figure 9 shows that the GY-49 sensor can read the light intensity value with a max value of 13792 lux, a min value of 12046 lux, and an overall average reading of 12741.4875 lux. At night, light intensity tends to be higher. PLN's electrical voltage is more stable at night due to lower electricity consumption than daytime (Amirullah et al., 2024). The light source used in this study comes from a grow light lamp that is constantly lit for 15 hours daily from 07.00 am to 10.00 pm. After that, the lights will turn off. The use of 15 hours is based on the biological conditions of plants to carry out photosynthesis. The longer the light source is given, the longer the plants will continue to photosynthesize. This method has a good impact because production can be increased. However, it should also be noted that plants require a dark reaction or do not need light to convert carbon dioxide (CO_2) into glucose (sugar) (Buchanan, 2016; Putra et al., 2025).

Table 2. Sensor calibration test

Sensor	Repetition	Reference	Sensor	MAPE (%)
DHT22 Humidity (%)	5	80	78	2.5
DHT22 Temperature (^oC)	5	30	29.5	1.67
GY-49 (lux)	5	27787.5	26743.13	3.76
pH	5	7.0	6.8	2.86
TDS (ppm)	5	1382	1362	1.45

Table 3. Performance of DC fans in controlling temperature

Date	Time	Temperature (^oC)	Fan Performance
11/13/2024	07.00.12	28.2	OFF
11/13/2024	07.05.08	28.6	OFF
11/13/2024	07.10.08	28.9	OFF
11/13/2024	07.15.03	29.1	OFF
11/13/2024	07.20.08	29.2	OFF
…...	…...	…..	….
11/13/2024	12.00.01	33	ON
11/13/2024	12.05.05	33	ON
11/13/2024	12.10.06	33.2	ON
11/13/2024	12.15.06	33.3	ON
11/13/2024	12.20.03	33.2	ON
11/13/2024	17.00.00	32.5	ON
11/13/2024	17.05.06	32.5	ON
11/13/2024	17.15.11	32.3	ON
11/13/2024	17.20.03	32.4	ON
…...	…..	…..	…..
11/14/2024	07.00.03	28.9	OFF
11/14/2024	07.05.11	29.5	OFF

Testing water quality sensor components

Water quality monitoring in this research involves observing water temperature, nutrient levels, and pH. Real-time water observation is critical to ensure that plants get clean water, have the right nutrient content, and are free from harmful substances that can hinder their growth and productivity. (Bhateria & Jain, 2016). The water temperature sensor is a waterproof sensor used to monitor water temperature. This sensor has a temperature reading range of -55°C to +125°C (Trevathan & Schmidtke, 2022). The water temperature conditions in the nutrient basin of the plant factory are presented in Figure 10.

Water temperature is crucial in the hydroponic system implemented in the plant factory because it can affect plant metabolism, nutrient absorption, and overall plant health. The water temperature recorded in the DS18B20 sensor averages 28.53 ^oC. This temperature is considered high for plant needs because it can reduce oxygen levels in the water (Mishra, 2023). Therefore, in the field implementation, the water basin is conditioned using a pump with a water flow like a drop to produce adequate O_2 for the plants (Figure 11).

This water temperature monitoring system is beneficial for monitoring water conditions in nutrient reservoirs in the plant factory, so that preventive measures can be taken if it is found that water conditions are not what plants need.

Testing was also carried out on the pH sensor. This sensor is critical in maintaining water quality and ensuring plants get the proper nutrients in optimal conditions, avoiding poisoning, reducing stress, and increasing the efficiency and yield of plant growth. (Abd El-Hack et al., 2022). Figure 12 shows the testing of the pH sensor directly applied to the nutrient basin.

The test results showed pH readings in the range of 6.6 to 7.1. According to Trientini et al., (2023)The ideal pH for hydroponic nutrient solutions is between 5.5 and 6.5. An improper pH can cause nutrients to be poorly absorbed by plant roots, which can stunt growth and cause nutritional problems. Future research needs to include nutritional control to stabilize pH levels.

The last sensor used in water quality testing is the TDS meter sensor. This sensor measures the amount of total dissolved solids in a liquid. The basis of the TDS sensor reading is to measure the resistance or electrical conductivity of the liquid. Then, based on an internal algorithm and conversion factor, the meter will convert this resistance/conductivity value into an estimated TDS value. The TDS value is usually displayed in units of parts per million (ppm) or milligrams per liter (mg/L) (Setyobudi & others, 2023). The TDS value is tested during the test, as shown in Figure 13.

From the sensor test results, it can be seen that the sensor value during measurement ranges from 1100 ppm to 1265 ppm. The TDS sensor readings were unstable due to the uneven mixture of liquid A and B, and the constantly rippling water was also a contributing factor. An additional stirrer is needed for future research. In this test, the TDS value was kept at around 1200 ppm because according to Shareef et al., (2024), for vegetable crops, the standard nutrient requirement is 1200 ppm. If the plants show signs of nutrient deficiency (slow growth, yellowing leaves) or excess nutrients (burning leaf tips), you may need to adjust the PPM concentration to maintain nutrient stability (Kelana et al., 2025).

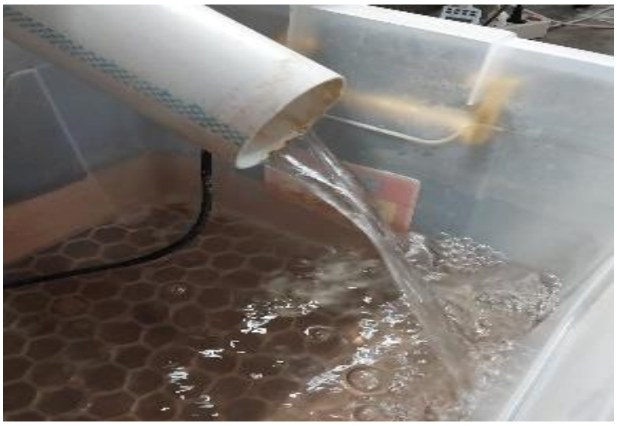

Figure 11. Waterfalls to increase O_2 levels in water

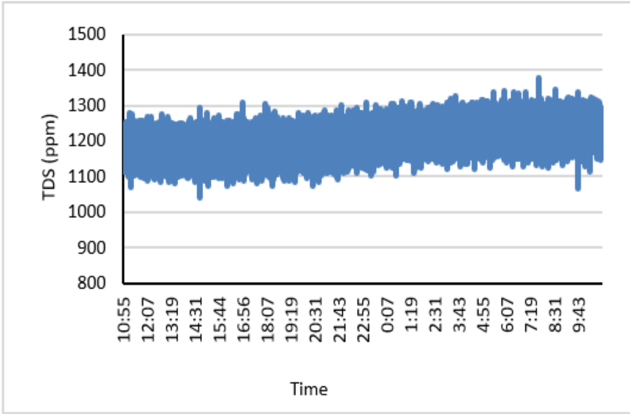

Figure 13. TDS meter sensor testing

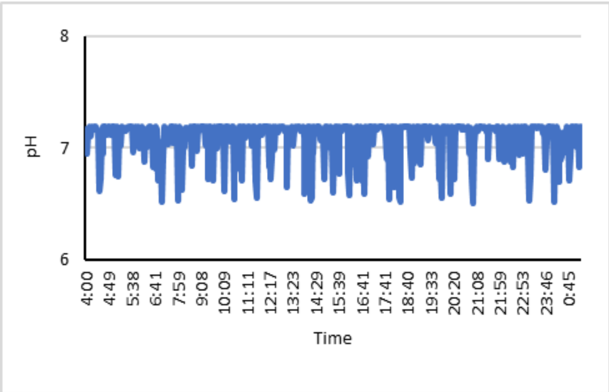

Figure 12. pH sensor testing

Figure 14. Pakcoy plant

Plant growth

The average growth of pakcoy greens in the plant factory showed a average plant height of 13.75 cm, 44 leaves, a canopy area of 204.74 cm^2, a root length of 19.23 cm, and a average wet weight of 45.37 grams. Overall, the plants grew optimally, as indicated by the number of leaves, root length, and wet weight of the plants in general. Figure 14 shows the growth of pakcoy 40 days after transplanting.

CONCLUSIONS

According to the research objectives, this research successfully designed and implemented an IoT-based system for environmental control and water quality monitoring in a plant factory. In real-time, the system effectively monitors important parameters such as air temperature and humidity, light intensity, water temperature, pH, and TDS, and is equipped with automatic temperature control. The data collection and remote monitoring automation system enables faster and more informed decision-making, optimizes growing conditions, and contributes to increased productivity and resource efficiency. This research is to support smart agriculture in the future. The optimal growth of pakcoy in a plant factory is shown by its height of 13.75 cm, 44.33 leaves, 19.23 cm roots, and weight of 20.27 grams. For future research to be comprehensive, environmental parameters and water quality must be controlled automatically, such as temperature and humidity, pH, and water nutrients.

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