Digitalization of Automatic Monitoring and Control for Aquaculture Based on Internet of Things

Roytua Daud Siringoringo[1], Tiara Hande Dias Kusumaningrum[2], Ilham Sayekti[3], Sri Kusumastuti
[1],[2]Program Studi Sarjana Terapan Teknologi Rekayasa Elektronika
[3],[4]Jurusan Teknik Elektro, Politeknik Negeri Semarang
E-mail: roytua00@gmail.com, tiarahande231001@gmail.com, ilham.sayekti@polines.ac.id, kuzumastuti@gmail.com

***Abstract*— Fish pond management is highly dependent on water quality parameters such as temperature, pH level, and water level. In practice, monitoring and controlling these parameters are often performed manually, resulting in inefficiency and delayed response to environmental changes. This study presents the design and implementation of an Internet of Things-based monitoring and control system for fish pond maintenance. The system utilizes an ESP32 microcontroller integrated with a DS18B20 temperature sensor, a pH sensor, and an HC-SR04 ultrasonic sensor. The control method combines automatic and manual control. In automatic mode, the ESP32 activates the water pumps, aerator, and feeder based on predefined sensor thresholds, while in manual mode, control commands are issued through the Node-RED dashboard and transmitted to the ESP32 via the MQTT protocol. Experimental results show that the system achieved average percentage errors of 3.83% for temperature measurement, 2.56% for pH measurement, and 2.70% for water level measurement, while all actuators responded reliably to user commands through real-time communication. The developed system provides an effective and practical solution to improve efficiency and accessibility in aquaculture management.**

Keywords—automatic control, ESP32, fish pond monitoring, Internet of Things, Node-RED.

I. INTRODUCTION

Aquaculture plays a significant role in supporting food security and economic development, particularly in freshwater fish farming. The productivity and sustainability of aquaculture activities are strongly influenced by water quality conditions such as temperature, pH level, and water level, which directly affect fish metabolism, growth rate, and survival [1], [2]. Improper water quality management can lead to stress, disease, and increased mortality rates in fish ponds.

In many small and medium scale aquaculture operations, pond monitoring and equipment control are still performed manually. This conventional approach requires continuous human presence and often results in delayed responses to environmental changes. Several studies have reported that manual monitoring practices reduce efficiency and increase the risk of water quality deterioration due to inconsistent observation and control [3], [4].

These limitations highlight the need for a more systematic and technology-driven approach to aquaculture maintenance. Recent advances in IoT technology have encouraged the adoption of intelligent aquaculture systems that integrate environmental sensors, wireless communication, and online monitoring platforms. Such systems enable continuous observation of water quality conditions, reduce manual inspection, and support timely decision-making for maintaining a stable aquaculture environment [16].

The rapid development of Internet of Things technology has enabled the integration of sensors, microcontrollers, and communication networks to support real time environmental monitoring. IoT based systems allow continuous data acquisition, remote access, and improved decision making based on actual field conditions [5]. In the context of aquaculture, IoT has been widely applied to monitor water quality parameters and improve operational efficiency [6], [7].

However, many existing IoT based aquaculture systems focus primarily on monitoring functions without providing sufficient flexibility in device control. In practical applications, fish farmers often require manual intervention to operate pumps, aerators, and feeders based on situational needs and experience. Systems that lack flexible control mechanisms may limit practical usability in real pond environments [8].

This research proposes the digitalization of an automatic monitoring and control system for aquaculture maintenance based on Internet of Things technology. The system integrates an ESP32 microcontroller with temperature, pH, and water level sensors to monitor pond conditions in real time. A Node-RED-based dashboard, developed using an open-source flow-based programming tool that supports Rapid Event Development, is implemented to visualize sensor data and enable remote manual control of pond-supporting equipment. Node-RED accelerates the development of event-driven applications by enabling visual workflow creation that responds to real-time events, such as sensor readings and user commands, while transmitting control commands to the ESP32 via the MQTT communication protocol.

II. MATERIALS AND METHODS

This research employs a system development and experimental evaluation approach to design, implement, and validate an Internet of Things based monitoring and control system for aquaculture maintenance. This approach is commonly used in the development of IoT based monitoring systems because it allows structured system design followed by direct performance evaluation in real environments [1], [2].

The methodology emphasizes the integration of sensing devices, embedded control units, communication networks, and user interfaces. Each system component is designed, implemented, and tested individually before being evaluated as part of an integrated system. This ensures that system performance can be analyzed both at component level and system level.

Experimental testing is conducted to evaluate sensor accuracy, control responsiveness, and communication reliability. The evaluation results are then used as the basis

for performance analysis and discussion in subsequent sections.

A. Research Methodology

The research methodology consists of several sequential stages, including system requirement analysis, system design, implementation, testing, and evaluation. This structured methodology ensures that the developed system meets functional requirements and operates reliably in aquaculture environments [3].

System requirement analysis is conducted to identify key parameters that influence aquaculture maintenance. Based on literature studies and field observations, water temperature, pH level, and water level are selected as the primary monitoring parameters due to their significant impact on fish health and pond stability [4], [5].

Following requirement analysis, system design and implementation are carried out. The final stage involves experimental testing and performance evaluation to verify system functionality, accuracy, and reliability under real operating conditions.

B. System Architecture

The system architecture is designed based on a layered Internet of Things concept consisting of sensing, processing, communication, and application layers. This architecture model is widely adopted in IoT system development to support modularity, scalability, and flexible system expansion [6]. The overall architecture of the proposed system is illustrated in Fig. 1.

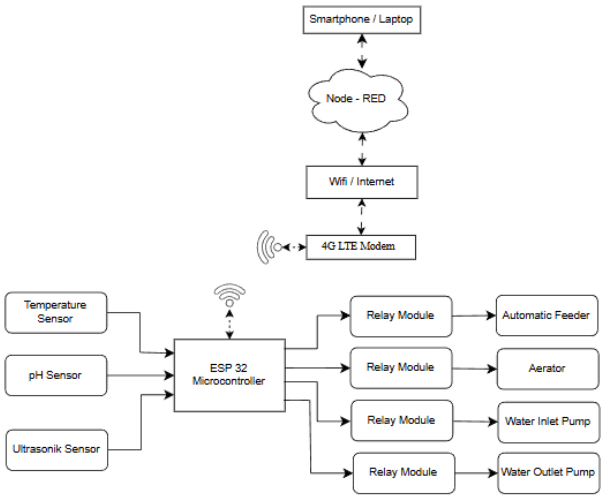


Fig 1. Block diagram of the proposed IoT-based aquaculture monitoring and control system.

The sensing layer is responsible for acquiring environmental data from the fish pond using multiple sensors, including a temperature sensor, pH sensor, and ultrasonic sensor for water level measurement. These sensors continuously monitor pond conditions and provide real-time data required for water quality evaluation and system control.

The processing layer is managed by an ESP32 microcontroller, which functions as the central control unit of the system. The ESP32 processes sensor data, executes control logic, and determines actuator operation based on user commands received from the monitoring platform. The microcontroller is also responsible for handling data communication with external networks.

The communication layer utilizes a 4G LTE modem to provide internet connectivity, enabling data transmission between the ESP32 microcontroller and the Node-RED server through a WiFi and internet network. Sensor data are transmitted to the server for monitoring purposes, while control commands from users are sent back to the ESP32 for execution. This bidirectional communication supports real-time monitoring and remote control functionality.

The application layer is implemented using a Node-RED based dashboard that can be accessed through smartphones or laptops. This dashboard visualizes sensor data in real time and provides control interfaces for operating actuators. Actuator control is implemented through relay modules connected to the ESP32, which drive devices such as an automatic feeder, aerator, water inlet pump, and water outlet pump. The integrated operation of these layers enables effective monitoring and control of fish pond conditions based on Internet of Things technology.

C. Hardware Design

Hardware system is centered on the ESP32 microcontroller due to its integrated Wi-Fi capability, sufficient processing performance, and support for both digital and analog inputs. The ESP32 has been widely used in IoT applications because of its reliability and low power consumption [7]. Recent studies have further confirmed the effectiveness of ESP32 as a hardware platform for IoT-based aquaculture monitoring systems. Besides offering integrated Wi-Fi connectivity and low power consumption, ESP32 enables reliable real-time data acquisition and transmission from environmental sensors to web-based monitoring platforms. These capabilities make ESP32 a cost-effective and practical solution for implementing continuous monitoring and control systems in aquaculture applications [15].

Water temperature is measured using a DS18B20 digital temperature sensor that operates using a one-wire communication protocol. This protocol reduces wiring complexity and improves signal stability. The waterproof design of the sensor allows continuous immersion in pond water without affecting measurement accuracy [8].

Water pH is measured using an analog pH sensor equipped with a signal conditioning module. The module amplifies and stabilizes the low-level voltage generated by the pH probe before being read by the ESP32 analog-to-digital converter. Water level measurement is performed using an HC-SR04 ultrasonic sensor mounted above the water surface, which calculates distance based on ultrasonic wave propagation [9].

Actuators such as water inlet pumps, water outlet pumps, an aerator, and an automatic feeder are controlled using a four-channel relay module. The relay module provides electrical isolation between low-voltage control circuits [10] and high-power loads, ensuring safe system operation [11].

D. Power Supply Configuration

The power supply system is designed to provide stable electrical power to both control and actuation components. An AC power source is converted into regulated DC

voltages using a power supply unit to meet system requirements.

Higher voltage levels are allocated to actuators such as pumps and aerators, while lower regulated voltages are supplied to the ESP32, sensors, and relay control circuits. This separation reduces electrical interference and improves system stability.

Electrical isolation between control and actuation circuits is maintained to protect sensitive electronic components from voltage surges and electrical noise, which is essential for long-term system reliability [12].

E. Software Design

Software system includes embedded programs running on the ESP32 microcontroller and a monitoring and control application built with Node-RED. Embedded programs handle initialization of sensors, continuous data acquisition, execution of control algorithms, and management of communication protocols. Additional functions include error detection, data buffering, and logging to ensure reliable operation under varying pond conditions.

Sensor readings are gathered at scheduled intervals and transmitted to the monitoring platform for real-time visualization and analysis. The software continuously monitors incoming control commands from the Node-RED dashboard and triggers corresponding actuator operations through the relay module, ensuring timely response to user inputs.

Node-RED serves as the application layer and primary user interface, providing interactive dashboards that display sensor data trends, system status, and alerts. It also offers manual control widgets for pumps, aerators, and feeders, allowing users to intervene when necessary. Node-RED is favored in IoT applications for its modularity, ease of integration with various devices, and support for rapid development of custom workflows [13].

F. Communication and Data Transmission

Communication between the ESP32 and the monitoring platform is established using an internet-based client-server communication model, where the ESP32 acts as a client that periodically sends sensor data and receives control commands from the server.

This communication approach is widely adopted in IoT systems because it allows real-time data exchange with minimal latency, ensures scalability for multiple devices, and supports remote monitoring from any location with internet access [14]. The system also implements error-checking mechanisms and retransmission protocols to maintain data integrity in case of network interruptions.

Sensor readings and actuator status information are transmitted in a structured data format, such as JSON, to ensure consistency, readability, and ease of processing by the server. Each data packet includes timestamped measurements, device identifiers, and status flags, which facilitate accurate logging and historical analysis. Lightweight data packets are used to minimize network overhead, reduce transmission delays, and support continuous monitoring without overloading the communication channel.

On the server side, Node-RED continuously listens for incoming data streams, parses the structured packets, and routes the information to appropriate dashboard components for visualization. The platform also manages command queues for actuators, ensuring that user inputs are executed in the correct sequence. This mechanism enables reliable bidirectional communication between the control unit and the user interface, allowing real-time feedback, alert notifications, and synchronized control of multiple devices within the aquaculture system.

G. Control Strategy

The control strategy implemented in this system is designed to integrate automated monitoring with flexible user intervention to maintain optimal pond conditions. The system continuously tracks water temperature, pH, and water level, and can automatically activate actuators such as pumps, aerators, and feeders when sensor readings exceed predefined thresholds. This ensures that critical environmental parameters remain within safe ranges without requiring constant human supervision.

In parallel, the Node-RED dashboard provides users with the ability to manually control or adjust actuator operations in real time. Users can override automatic actions, schedule operations, or fine-tune system responses based on their observations and experience. This combination of automation and human oversight enhances operational flexibility and allows for adaptive management of the aquaculture environment.

When a command is issued through the dashboard, it is transmitted to the ESP32 microcontroller, which promptly executes the corresponding action via the relay module. The system continuously updates the dashboard with the latest sensor readings and actuator statuses, providing accurate, real-time feedback. This bidirectional communication ensures that user inputs and system responses remain synchronized, minimizing the risk of conflicting actions or delays.

Furthermore, the control logic includes safety and reliability mechanisms, such as limiting the duration of actuator operation, preventing simultaneous conflicting commands, and incorporating fail-safe responses in case of sensor anomalies. This hybrid control approach is particularly effective in aquaculture settings, where water quality can fluctuate rapidly and human judgment is crucial for responding to unexpected conditions, thereby safeguarding fish health and maintaining system efficiency [15].

H. System Operation

The proposed Internet of Things based aquaculture monitoring and control system operates through a structured workflow that integrates sensing, communication, monitoring, and control processes. The system operation is designed to support two main operating modes, namely automatic operation mode and manual operation mode, allowing flexibility in system management based on operational requirements.

At the initial stage, the system performs an initialization process. When the system is powered on, the ESP32 microcontroller initializes all connected sensors, including the temperature sensor, pH sensor, and ultrasonic sensor, as

well as the relay modules used to control actuators. The system then attempts to establish a connection with the Node-RED server through the internet network. If the connection is not successfully established, the system repeatedly retries until a stable connection is achieved or a predefined timeout condition is met. This process ensures reliable communication before normal system operation begins.

1) Automatic Operation Mode

In automatic operation mode, the system performs monitoring and control actions based on sensor readings and predefined logic. The operational flow of the automatic mode is illustrated in Fig. 2. After a successful connection to the server is established, the ESP32 continuously reads environmental parameters from the sensors, including water temperature, pH level, and water level.

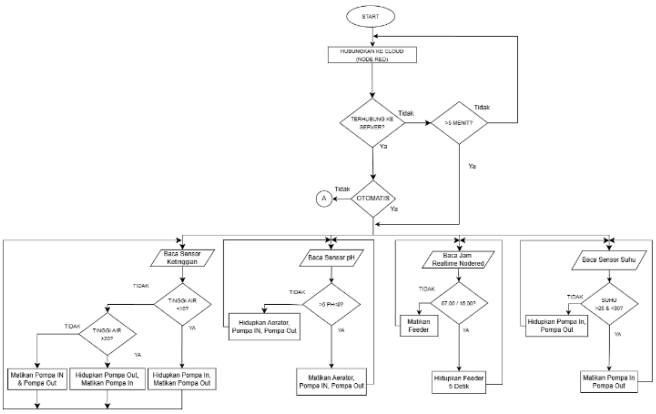


Fig 2. Flowchart of automatic operation mode of the proposed IoT-based aquaculture monitoring and control system.

The temperature sensor data are first evaluated to determine whether the measured temperature exceeds the predefined threshold. If the temperature is higher than the allowable range, the system activates the aerator to improve water conditions. If the temperature remains within the acceptable range, the system proceeds to evaluate the pH sensor data. When the pH value falls outside the predefined safe range, corrective actions are initiated according to the control logic.

Following temperature and pH evaluation, the system reads the water level using the ultrasonic sensor. The measured water level is compared with predefined upper and lower threshold values. If the water level is detected to be below the minimum threshold, the system activates the water inlet pump to increase the water volume. Conversely, if the water level exceeds the maximum threshold, the water outlet pump is activated to reduce excess water. These control actions ensure that the pond water level remains within the desired operating range.

In addition to sensor-based control, the automatic mode also supports scheduled operations. The system reads the current time and compares it with predefined feeding schedules. When the scheduled feeding time is reached, the automatic feeder is activated for a specified duration and then turned off automatically. This scheduling mechanism ensures consistent feeding without requiring manual intervention.

2) Manual Operation Mode

The manual operation mode allows users to directly control system actuators through the Node-RED monitoring dashboard. The operational flow of the manual mode is illustrated in Fig. 3. In this mode, the ESP32 receives control commands issued by the user via the dashboard interface.

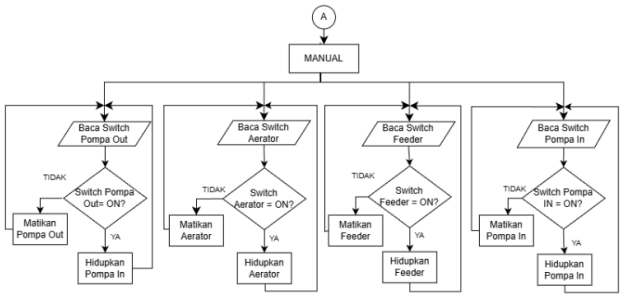


Fig 3. Flowchart of manual operation mode of the proposed IoT-based aquaculture monitoring and control system.

For each actuator, including the water inlet pump, water outlet pump, aerator, and feeder, the system continuously reads the corresponding switch status from the dashboard. When a switch is set to the ON state, the ESP32 activates the associated relay module to turn on the actuator. Conversely, when the switch is set to the OFF state, the actuator is deactivated. This process allows users to manually override automatic control actions and operate the system devices according to situational needs.

The manual operation mode is particularly useful for system testing, maintenance activities, and specific operational adjustments that require direct user intervention. The system ensures that the actuator status displayed on the dashboard is always synchronized with the actual device condition in the field.

3) Continuous System Loop

During normal operation, the system continuously repeats the processes of sensing, data transmission, monitoring, and control execution in a loop. This continuous loop enables real-time monitoring of pond conditions and responsive control actions in both automatic and manual modes. The integrated workflow ensures stable and efficient system operation, supporting practical aquaculture maintenance through Internet of Things technology.

The overall operational workflow of the proposed system, including both automatic and manual modes, is summarized in Fig. 2 and Fig. 3, which illustrate the detailed control logic and decision-making processes implemented in the system.

I. Testing and Evaluation Procedure

This section describes the procedures used to assess the performance of the monitoring and control system without presenting actual results. System testing is planned to evaluate the accuracy of sensor measurements, the responsiveness of actuators, and the reliability of communication between devices. Sensor evaluation involves comparing readings with reference instruments under

controlled conditions to determine measurement consistency and stability.

Actuator testing is designed to measure response times and operational reliability when control commands are issued from the Node-RED dashboard. Each actuator is subjected to repeated trials to ensure that the system can consistently execute commands as intended.

Communication testing outlines the methods for assessing data transmission stability between the ESP32 microcontroller and the Node-RED platform under normal network conditions. The overall system evaluation focuses on continuous operation, data integrity, and user accessibility, providing a framework for the results that will be presented in the following section.

III. Results and Discussion

This section presents the results of system implementation and testing of the proposed Internet of Things based aquaculture monitoring and control system. The discussion focuses on sensor performance, actuator response, communication reliability, and overall system functionality under real operating conditions.

A. Results Overview

This section provides a comprehensive overview of the experimental results obtained from the evaluation of the proposed Internet of Things based aquaculture monitoring and control system. The assessment emphasizes multiple aspects of system performance, including the accuracy and precision of sensor measurements, the responsiveness and reliability of actuators, the stability and efficiency of communication protocols, and the overall integration and functionality of the system components.

The experimental results are systematically organized according to each functional module of the system. Temperature sensing performance is analyzed to determine the sensor's ability to track environmental changes accurately over time. pH sensor measurements are evaluated to assess consistency and sensitivity under varying water conditions. Water level detection is examined to verify the precision and repeatability of ultrasonic measurements. Actuator response is measured to ensure timely and reliable operation of pumps, aerators, and feeders. Additionally, the monitoring interface and communication system are assessed for data transmission stability, latency, and user interface effectiveness, ensuring that the system can support real-time remote monitoring and control.

Each component's performance is discussed in detail, highlighting observed trends, deviations, and potential sources of error. Temperature and pH sensors are compared against reference instruments to quantify measurement accuracy, while water level sensors are evaluated for repeatability under different pond conditions. Actuator tests focus on response times and operational consistency, providing insight into the system's ability to maintain optimal aquaculture conditions automatically.

The structured approach allows for a thorough examination of both individual component performance and the overall system behavior. By analyzing the interactions between sensors, actuators, and the communication network, the study identifies strengths and limitations of the integrated system. This comprehensive evaluation provides a clear understanding of how each module contributes to the overall functionality and reliability of the aquaculture monitoring and control system.

All results presented in this section are derived from the testing procedures described in Section II-H, with detailed numerical data provided in tables and figures. The discussion emphasizes the effectiveness, reliability, and practical applicability of the proposed system in real-world aquaculture environments, offering insights into potential improvements, optimization strategies, and considerations for scaling the system for larger or more complex aquaculture operations.

B. Mathematical Formulation

Mathematical formulations are used to evaluate the performance of the proposed monitoring system by quantifying the difference between sensor measurements and reference instruments. These formulations provide an objective basis for analyzing sensor accuracy and system reliability in aquaculture applications.

The measurement error is calculated by determining the difference between the sensor reading and the reference value, as expressed in (1):

$$e = X_s - X_r \quad \text{.....(1)}$$

where e represents the measurement error, X_s is the value measured by the sensor, and X_r is the reference value obtained from a calibrated instrument.

To evaluate sensor accuracy in a relative manner, the percentage error is calculated using (2):

$$Error\ (\%) = |X_s - X_r| / X_r \times 100\% \quad \text{.....(2)}$$

This formulation is used to assess how closely the sensor readings match the reference measurements under various testing conditions. The percentage error provides a normalized metric that allows comparison across different measurement ranges and sensor types.

For repeated measurements, the average error value is calculated to represent overall sensor performance, as shown in (3):

$$E_avg = (1 / n) \sum |X_s - X_r| \quad \text{.....(3)}$$

where E_avg denotes the average error and n represents the number of measurement samples. This average value is used to evaluate measurement consistency and stability during testing.

The above formulations are applied to the temperature sensor, pH sensor, and water level sensor data presented in the subsequent sections. The calculated error values serve as the basis for performance analysis and discussion of system accuracy in real aquaculture environments.

C. Temperature Sensor Performance Analysis

The performance of the DS18B20 temperature sensor was evaluated to determine its accuracy and stability in measuring pond water temperature. The evaluation was

conducted by comparing sensor readings with a calibrated reference thermometer under the same environmental conditions. Measurements were taken repeatedly to observe consistency and to minimize the influence of random fluctuations.

The measurement error for each data sample was calculated using (1), while the percentage error was determined using (2). These calculations provide a quantitative basis for evaluating the deviation between the sensor measurements and the reference values. Furthermore, the average error was calculated using (3) to represent the overall accuracy of the temperature sensor during the testing period.

Table I presents the comparison between the DS18B20 temperature sensor readings and the reference thermometer values, including the calculated error and percentage error.

TABLE I. COMPARISON OF DS18B20 TEMPERATURE SENSOR AND REFERENCE MEASUREMENTS

No	Temperature (°C)	Reference Temperature (°C)	Error Absolut (°C)	Error (%)
1	18,67	19,30	0,63	3,26
2	23,45	22,80	0,65	2,85
3	25,09	24,20	0,89	3,68
4	28,89	27,70	1,19	4,29
5	31,23	29,80	1,43	4,80
6	27,53	26,40	1,13	4,28
7	24,98	24,10	0,88	3,65
Total	–	–	**6,80**	**26,81**
Average	–	–	**0,97**	**3,83**

Based on the data presented in Table I, the DS18B20 sensor demonstrates stable temperature measurements with relatively small deviations from the reference instrument. The observed errors remain within acceptable limits for freshwater aquaculture applications, where minor temperature variations do not significantly affect fish health. The consistency of the readings across multiple measurements indicates that the sensor is suitable for continuous real-time monitoring of pond water temperature.

These results confirm that the DS18B20 temperature sensor can reliably support the temperature monitoring function of the proposed system and provide accurate input data for aquaculture maintenance and decision making.

D. pH Sensor Performance Analysis

The performance of the pH sensor was evaluated to assess its accuracy, repeatability, and suitability for monitoring water acidity in aquaculture environments. The evaluation was carried out by comparing the pH sensor readings with reference pH values obtained from a standard measurement instrument under controlled conditions. Multiple measurements were performed to observe sensor response to variations in water acidity.

The measurement error for each data sample was calculated using (1), while the percentage error was determined using (2). These calculations provide a quantitative measure of the deviation between the sensor output and the reference pH values. In addition, the average error was calculated using (3) to evaluate the overall accuracy and consistency of the pH sensor during the testing process.

Table II shows the comparison between the pH sensor readings and the reference pH values, including the calculated error and percentage error.

TABLE II. COMPARISON OF TEMPERATURE SENSOR AND REFERENCE MEASUREMENTS

No	pH Sensor	Reference pH	Error Absolut	Error (%)
1	4,5	4,7	0,20	4,26
2	5,6	5,8	0,20	3,45
3	7,1	7,0	0,10	1,43
4	8,7	8,5	0,20	2,35
5	9,2	9,1	0,10	1,10
6	8,1	7,9	0,20	2,53
7	6,9	7,1	0,20	2,82
Total	–	–	**1,20**	**17,94**
Average	–	–	**0,17**	**2,56**

Based on the data presented in Table II, the pH sensor is able to detect changes in water acidity with acceptable accuracy for aquaculture monitoring purposes. Although slight deviations between sensor readings and reference values are observed, these deviations remain within tolerable limits for freshwater fish pond applications. The consistency of the measurements across repeated trials indicates stable sensor performance.

The results demonstrate that the pH sensor can effectively support real-time monitoring of water quality and provide reliable input data for decision making related to aquaculture maintenance. This performance confirms the suitability of the pH sensor for integration into the proposed Internet of Things based monitoring and control system.

E. Water Level Measurement Analysis

Water level measurement performance was evaluated using the HC-SR04 ultrasonic sensor to determine its accuracy and repeatability in detecting pond water level variations. The evaluation was conducted by comparing the distance measured by the ultrasonic sensor with manually measured reference distances under identical conditions. Multiple measurements were performed to observe consistency and to minimize the influence of environmental disturbances.

For each measurement, the error value was calculated using (1), while the percentage error was determined using (2). These calculations provide a quantitative assessment of the deviation between the ultrasonic sensor measurements and the reference values. In addition, the average error was calculated using (3) to evaluate the overall accuracy of the water level measurement system.

Table III presents the comparison between the HC-SR04 ultrasonic sensor measurements and the reference water level values, including the calculated error and percentage error.

TABLE III. COMPARISON OF WATER LEVEL MEASUREMENT (HC-SR04) AND REFERENCE MEASUREMENTS

No	Measured Water Level (cm)	Reference Water Level (cm)	Absolute Error (cm)	Error (%)
1	14,8	15,3	0,5	3,27

No	Measured Water Level (cm)	Reference Water Level (cm)	Absolute Error (cm)	Error (%)
2	18,2	18,7	0,5	2,67
3	20,2	19,6	0,6	3,06
4	23,6	24,1	0,5	2,07
5	25,3	24,6	0,7	2,85
6	22,9	23,5	0,6	2,55
7	19,9	20,4	0,5	2,45
Total	–	–	**3,9**	**18,92**
Average	–	–	**0,56**	**2,70**

Based on the data presented in Table III, the ultrasonic sensor is able to detect water level changes consistently with acceptable accuracy for aquaculture monitoring applications. Minor deviations observed during testing are primarily influenced by surface turbulence and environmental noise. However, these deviations remain within tolerable limits and do not significantly affect the overall monitoring function.

The results confirm that the HC-SR04 ultrasonic sensor is suitable for continuous monitoring of water level variations in fish ponds and can reliably support water volume management within the proposed Internet of Things based monitoring and control system.

F. Actuator Response and Control Performance

The performance of actuators in the proposed system, including water inlet pumps, water outlet pumps, aerators, and automatic feeders, was evaluated to determine response time, operational reliability, and consistency during system operation. Actuator testing was conducted by issuing control commands through the Node-RED dashboard and observing the system response under normal operating conditions.

For each actuator, response time was measured as the time interval between the command being sent from the monitoring interface and the actual activation or deactivation of the device. Multiple trials were performed to assess consistency and to identify potential delays or irregular behavior. The evaluation also considered the stability of actuator operation during repeated switching.

Table IV summarizes the response time and operational performance of each actuator during system testing.

TABLE IV. ACTUATOR RESPONSE TIME AND OPERATIONAL PERFORMANCE

No	Time	Temp-erature (°C)	pH	Water Level (cm)	Water Inlet Pump	Water outlet Pump	Aerator	Feeder
1	06.00	19.57	7.2	10.5	ON	ON	OFF	OFF
2	08.30	23.3	4.8	11.7	ON	ON	OFF	OFF
3	10.15	24.1	7.4	9.1	OFF	OFF	OFF	OFF
4	12.40	26.3	6.9	15.7	OFF	OFF	OFF	OFF
5	07.00	22.1	7.1	10.8	ON	ON	OFF	ON
6	15.00	25.3	6.8	12.9	ON	ON	OFF	ON
7	16.30	24.4	7.3	11.0	OFF	OFF	OFF	OFF
8	17.45	23.9	6.5	12.5	OFF	OFF	OFF	OFF
9	19.50	22.2	7.0	12.2	OFF	OFF	OFF	OFF

The experimental results indicate that all actuators respond promptly to control commands with minimal delay. Repeated testing shows consistent operation without unexpected activation or failure. The response times observed are suitable for real-time aquaculture maintenance, where timely actuation is essential to maintain optimal pond conditions.

These results confirm that the actuator control mechanism implemented in the proposed system is reliable and effective. Integration with the Node-RED dashboard enables responsive and user-friendly control of pond equipment, supporting both monitoring and manual control functions in the aquaculture management system.

G. Communication and Monitoring System Performance

The performance of the communication and monitoring system was evaluated to assess data transmission reliability, update frequency, and dashboard responsiveness. This evaluation focuses on the ability of the system to deliver real-time sensor data and actuator status information from the ESP32 microcontroller to the Node-RED monitoring platform through an internet connection.

During system testing, sensor data including temperature, pH level, and water level were transmitted continuously to the Node-RED server. The monitoring dashboard successfully displayed updated data values in real time, allowing users to observe pond conditions remotely. Data transmission remained stable throughout the testing period, with no significant data loss or communication interruption under normal network conditions.

Control commands issued from the Node-RED dashboard were transmitted back to the ESP32 microcontroller and executed promptly. The synchronization between monitoring data and actuator status updates was maintained consistently, ensuring that the information displayed on the dashboard accurately reflected the actual system condition. This bidirectional communication confirms that the system supports effective remote monitoring and control.

Figure 4 shows the Node-RED monitoring dashboard used during system testing.

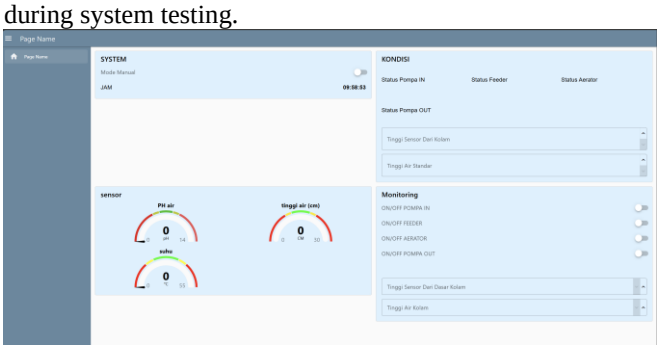


Fig 4. Node-RED based monitoring dashboard.

The results demonstrate that the communication and monitoring subsystem operates reliably and provides an intuitive user interface. This performance supports the practical implementation of the proposed Internet of Things

based aquaculture monitoring and control system, enabling users to monitor and manage pond conditions efficiently from a remote location.

H. Overall System Discussion

The overall evaluation results indicate that the proposed Internet of Things based aquaculture monitoring and control system operates reliably and in accordance with its design objectives. The integration of sensing devices, control actuators, the ESP32 microcontroller, and the Node-RED monitoring platform functions cohesively, enabling continuous data acquisition, real-time visualization, and responsive control.

The experimental results demonstrate that the temperature, pH, and water level sensors provide stable and sufficiently accurate measurements for freshwater aquaculture applications. Although minor deviations from reference measurements are observed, the calculated error values remain within acceptable ranges and do not significantly affect system performance. These characteristics indicate that the sensor subsystem is suitable for supporting data-driven decision making related to water quality management.

Actuator performance analysis confirms that water pumps, aerators, and automatic feeders respond promptly to control commands transmitted through the monitoring dashboard. The observed response times and consistent operational behavior indicate that the control mechanism is capable of meeting real-time operational requirements in aquaculture environments, where timely actuation is essential to maintaining optimal pond conditions.

Furthermore, the communication and monitoring subsystem exhibits stable data transmission and reliable dashboard updates throughout the testing process. The Node-RED based interface provides clear visualization of sensor data and actuator status, as well as intuitive manual control functionality. This capability enhances system usability and reduces the need for continuous on-site supervision.

Overall, the results confirm that the proposed system effectively integrates monitoring and control functionalities into a unified Internet of Things framework. The system offers a practical and efficient solution for small to medium scale freshwater aquaculture operations by improving monitoring efficiency, control flexibility, and accessibility through remote digital interfaces.

IV. Conclusion

This study successfully designed, implemented, and evaluated an Internet of Things-based monitoring and control system for freshwater aquaculture using an ESP32 microcontroller integrated with temperature, pH, and water level sensors, as well as a Node-RED dashboard for real-time monitoring and remote control. Experimental results showed average percentage errors of 3.83% for temperature measurement, 2.56% for pH measurement, and 2.70% for water level measurement, while all actuators responded reliably to control commands through stable real-time communication. These results demonstrate that the proposed system is capable of providing accurate monitoring, responsive control, and improved operational efficiency for small- to medium-scale aquaculture applications. Future work may focus on implementing more advanced automatic control algorithms, integrating additional water quality parameters, and incorporating predictive data analysis to further enhance system performance.

References

[1] Direktorat Produksi dan Usaha Budidaya, *Buku Saku Budidaya Ikan Lele Sistem Bioflok*, Jakarta, Indonesia, 2017, pp. 13–14, 35–36.M. Imaduddin and Sapri, "Pengaruh suhu air terhadap pertumbuhan ikan lele," Jurnal Perikanan, vol. 9, no. 2, pp. 45–52, 2017.

[2] A. Nurhidayat, "Analisis pengaruh kualitas air terhadap pertumbuhan ikan air tawar," Jurnal Ilmu Perikanan, vol. 13, no. 1, pp. 1–9, 2021. https://doi.org/10.29406/jr.v9i2.2969

[3] R. Pratama, N. Salsabila, and Suprapto, "Pengaruh pH air terhadap tingkat kelangsungan hidup ikan lele," Jurnal Akuakultur Indonesia, vol. 20, no. 2, pp. 89–98, 2021.

[4] M. Rizal, dkk., *Konsep dan Implementasi Internet of Things*, Yayasan Kita Menulis, 2023. [Online]. Available: https://www.researchgate.net/publication/372393866_Konsep_dan_Implementasi_Internet_of_Things. Accessed: Jan. 18, 2026.

[5] L. Maghfiroh, E. Prasetyo, and A. Wibowo, "Penerapan Internet of Things (IoT) pada sistem monitoring dan kontrol lingkungan," Jurnal Teknologi Informasi dan Komputer, vol. 7, no. 1, pp. 33–41, 2021.

[6] A. Musyrifah, R. Pramudya, and H. Nugroho, "Implementasi sensor ultrasonik pada sistem monitoring ketinggian air berbasis mikrokontroler," Jurnal Sistem Instrumentasi, vol. 10, no. 1, pp. 15–23, 2024.

[7] A. Ibrahim, B. Santoso, and D. Lestari, "Karakteristik sensor pH analog pada sistem monitoring kualitas air," Jurnal Instrumentasi dan Sensor, vol. 8, no. 2, pp. 101–109, 2023.

[8] Dallas Semiconductor, "DS18B20 programmable resolution 1-Wire digital thermometer datasheet," Dallas Semiconductor, USA, 2015.

[9] DFRobot, "Analog pH sensor meter kit documentation," 2019. [Online]. Available: https://www.dfrobot.com. Accessed: Jan. 10, 2026.

[10] Espressif Systems, "ESP32 series datasheet," Espressif Systems, Shanghai, China, 2023.

[11] Rachmad, A., Setiawan, E., Hasbullah, A.W. (2024). Recognition of the sound of the Lonchura Maja bird and the threat of house sparrows using Edge Impulses based on a custom deep neural network to protect rice plants. Ingénierie des Systèmes d'Information, Vol. 29, No. 5, pp. 1755-1762. https://doi.org/10.18280/isi.290509

[12] Node-RED, "Node-RED documentation," 2024. [Online]. Available: https://nodered.org. Accessed: Jan. 12, 2026.

[13] A. Kadir, Panduan Praktis Internet of Things (IoT) untuk Pemula. Yogyakarta, Indonesia: Andi Offset, 2018.

[14] D. Setiawan, B. Prakoso, and R. Hartono, "Perancangan sistem monitoring kualitas air berbasis mikrokontroler dan internet," Jurnal Teknologi Elektro, vol. 9, no. 1, pp. 55–63, 2020.

[15] A. Suwardono, F. E. Prahesti, E. M. Indrawati, and M. A. J. Ashofa, "IoT Based Catfish Farm Monitoring with ESP32 Microcontroller and DS18B20 Sensor," *Jurnal Sains dan Teknologi*, vol. 13, no. 3, pp. 508–516, 2024. [Online]. Available: https://doi.org/10.23887/jstundiksha.v13i3.85996

[16] O. O. Olanubi, T. T. Akano, and O. S. Asaolu, "Design and development of an IoT-based intelligent water quality management system for aquaculture," Journal of Electrical Systems and Information Technology, vol. 11, no. 15, 2024. [Online]. Available: https://doi.org/10.1186/s43067-024-00139-z.