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Design of an IoT-Based Aquaculture Monitoring System Based on IoT in Fish Farming

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Abstract

Maintaining optimal water quality is essential for achieving high productivity in aquaculture. However, conventional monitoring practices among small-scale fish farmers remain manual and inefficient. This study presents the design and evaluation of a low-cost Internet of Things (IoT)-based water quality monitoring system tailored for rural aquaculture applications. The prototype integrates an ESP8266 microcontroller with pH, Total Dissolved Solids (TDS), and temperature sensors to enable real-time data collection and automated control. Field testing was conducted in a $2 \times 3 \times 1$ m fish pond for seven days with data sampling every 5 minutes. The system achieved an average transmission latency of 4.2 seconds and 99 % data-delivery reliability. Measurement accuracy compared to manual instruments showed deviations of ± 0.08 pH, ± 0.4 °C, and ± 15 ppm TDS. With a total hardware cost of approximately Rp 950,000 ($\approx$ USD 60), the proposed system demonstrates a practical, reliable, and affordable solution for continuous water-quality monitoring, supporting sustainable fish farming in rural areas.

Keywords: Internet of Things (IoT), Aquaculture, Water Quality, Real-Time Monitoring, Low-Cost System

1. Introduction

Aquaculture is one of the fastest-growing food-producing sectors worldwide, contributing significantly to global food security and economic resilience [1]. The sector accounts for more than 50% of total fish consumption globally and continues to expand as capture fisheries decline [2], [3]. In Indonesia, aquaculture plays a pivotal role in meeting the growing demand for protein-rich food sources and sustaining the livelihoods of smallholder farmers [4]. However, conventional aquaculture systems still rely heavily on manual operations, which often lead to inconsistent water quality management and low productivity [5].

Water quality parameters such as pH, temperature, dissolved oxygen (DO), and total dissolved solids (TDS) are critical indicators influencing fish metabolism, health, and survival [6], [7]. Sudden fluctuations in these parameters—caused by factors such as rainfall variation, overfeeding, and organic waste accumulation—can lead to oxygen depletion, stress, and increased mortality [8], [9]. Despite the importance of water monitoring, many small-scale fish farmers in rural regions continue to rely on visual observation or simple test kits, which are time-consuming, labor-intensive, and prone to measurement errors [10].

Advances in the Internet of Things (IoT) technology have introduced new possibilities for real-time environmental monitoring using sensor networks and microcontrollers [11], [12]. IoT-based systems in aquaculture enable continuous measurement of key parameters and automatic control of aeration or feeding devices, resulting in improved operational efficiency and reduced fish mortality [13], [14]. Several studies have demonstrated the benefits of IoT integration in aquaculture management, including better data-driven decision-making and reduced dependency on human intervention [15].

However, most existing IoT solutions are tailored for commercial-scale operations, requiring expensive hardware, constant internet connectivity, and sophisticated data infrastructure [16]. These constraints make such systems impractical for small-scale fish farmers, particularly in remote areas with limited power and network availability [17]. As a result, there remains a significant gap in designing affordable and user-friendly IoT-based monitoring systems that can operate effectively in low-resource environments.

To address this gap, the present study proposes a low-cost IoT-based water quality monitoring prototype that integrates pH, TDS, and temperature sensors with an ESP8266 microcontroller. The system transmits real-time data through a local web interface, allowing users to monitor environmental conditions without reliance on cloud servers or continuous internet connectivity. By combining cost-effective hardware with local data visualization, this work aims to enhance water quality management, reduce manual workload, and promote sustainable aquaculture practices for smallholder farmers in Indonesia.

2. Methods

2.1 Problem Identification

This study employs an experimental design approach involving system design, prototype development, and field testing. The goal is to create an IoT-based aquaculture monitoring system that can continuously measure and control water quality parameters in real time. The workflow consists of four stages: (1)

requirements identification, (2) conceptual design, (3) prototype development, and (4) testing and evaluation

2.2 System Design

Requirements Identification

System requirements were collected through interviews with members of the Mina Mulya Fish Farmer Group, Jatimulyo Village, Alian, Kebumen. The farmers reported problems such as unstable water pH, low oxygen levels, and frequent pump failures due to improper water management.

Conceptual Design

Based on these needs, a conceptual model of the monitoring system was developed, consisting of three main layers:

1. **Sensing layer:** collects data from pH, temperature, and TDS sensors.
2. **Processing layer:** uses the ESP8266 microcontroller to analyze and process sensor inputs.
3. **Network and application layer:** sends data via Wi-Fi to a local server for visualization and control.

This design was formulated to function in low-connectivity environments while keeping component costs minimal.

Prototype Development

The prototype integrates pH, TDS, and temperature sensors with an ESP8266 (NodeMCU) microcontroller. The hardware is powered by a 5 V power supply and communicates through a local Wi-Fi network. The control unit triggers a relay to activate a pump or aerator automatically when any parameter deviates from predefined thresholds.

Testing and Evaluation

The assembled prototype was installed in a $2 \times 3 \times 1$ m biofloc pond. Data were collected every 5 minutes for seven days and stored in a local web server using the XAMPP platform. The user interface allows farmers to input reference thresholds and view real-time monitoring results. The prototype was packaged in a plastic waterproof housing to facilitate deployment in field conditions.

Workflow Illustration

Figure 1 Graphical Abstract illustrating the overall workflow of the proposed IoT-based aquaculture monitoring system. The diagram shows the integration of pH, temperature, and TDS sensors connected to an ESP8266 microcontroller, which

processes the data and transmits it via a local Wi-Fi network to a web dashboard. The system enables real-time visualization of water-quality parameters and automatically activates the aerator or pump when values exceed predefined thresholds. This schematic summarizes the core concept of the system design, highlighting the transition from manual monitoring to a fully automated, low-cost IoT solution suitable for rural fish-farming environments.

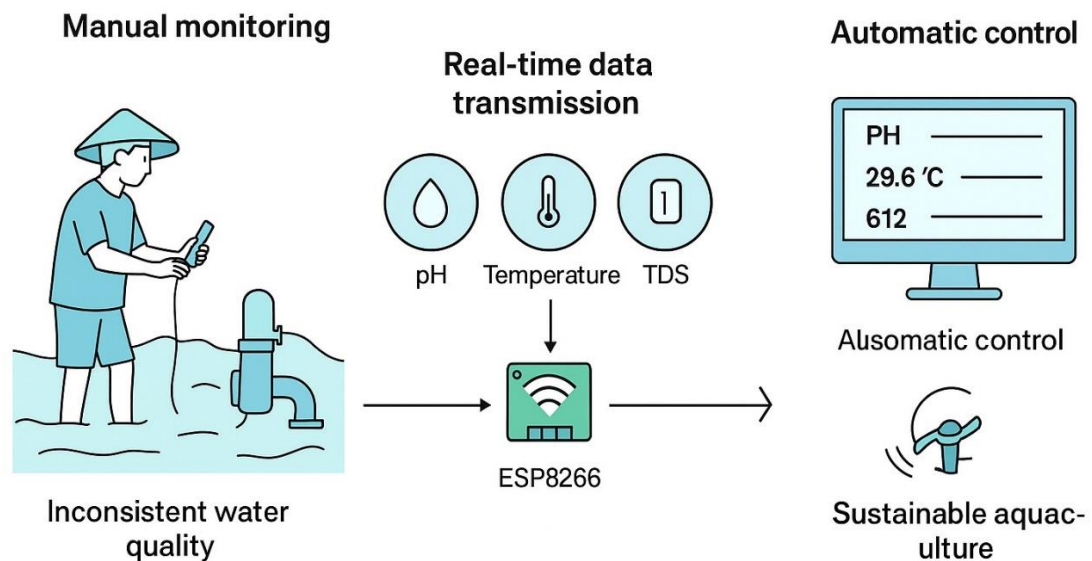


Figure 1. Graphical Abstract illustrating the overall design and workflow of the proposed IoT-based aquaculture monitoring system

2.3 Hardware Components

Tabel 1. Hardware Components

Component	Model / Type	Measurement Range	Accuracy	Description
pH Sensor	pH-4502C	0 – 14 pH	± 0.1 pH	Measures acidity/alkalinity of water
TDS Sensor	Analog TDS (DF Robot)	0 – 1000 ppm	± 2 % FS	Detects total dissolved solids
Temperature Sensor	DS18B20 Waterproof	–55 – 125 °C	± 0.5 °C	Measures water temperature
Microcontroller	ESP8266 (NodeMCU)	—	—	Controls data collection and Wi-Fi communication
Relay Module	5 V Single Channel	—	—	Switches the pump or aerator
Power Supply	5 V, 2 A Adapter	—	—	Powers all hardware modules
Server	Localhost (XAMPP)	—	—	Hosts database and web dashboard

The Hardware Components table describes the main components used in an Internet of Things (IoT)-based monitoring system. The system consists of several sensors and supporting devices that work together in an integrated manner. The first component is the pH sensor (pH-4502C), which measures the acidity or alkalinity of water with a measurement range of 0–14 pH and an accuracy of ± 0.1 pH. Next, the TDS sensor (Analog TDS DF Robot) detects the total dissolved solids (TDS) in water within a range of 0–1000 ppm and an accuracy of $\pm 2\%$ FS, which helps determine water purity or quality. The temperature sensor (DS18B20 Waterproof) measures water temperature from -55°C to 125°C with an accuracy of $\pm 0.5^{\circ}\text{C}$ and is waterproof, allowing it to operate directly in liquid environments. All sensor data are managed by the microcontroller ESP8266 (NodeMCU), which controls data collection and enables Wi-Fi-based communication. The system also includes a 5V single-channel relay module, functioning as an electronic switch to control external devices such as pumps or aerators based on sensor readings. All components are powered by a 5V 2A adapter, ensuring a stable power supply for the entire system. Altogether, these hardware components enable the system to perform automatic and real-time monitoring of water quality.

2.4 Experimental Setup

The prototype was deployed in a $2 \times 3 \times 1$ m pond with sensors submerged 30 cm below the water surface. Manual readings of pH, temperature, and TDS were collected simultaneously using commercial test kits for validation. Ambient air temperature ranged from 26°C to 32°C . A local router provided network connectivity between the NodeMCU and the web server on a laptop. The dashboard displayed both real-time and historical data and enabled control of the aerator when thresholds were exceeded.

2.5 Evaluation Metrics

System performance was assessed using the following criteria:

1. Accuracy — comparison between IoT sensor readings and manual measurements.
2. Data Transmission Latency — average time (in seconds) between data capture and server display.
3. Reliability — percentage of successful data transmissions.
4. System Uptime — proportion of time the system remained functional during the test period.

Data accuracy was analyzed using the mean difference and Root Mean Square Error (RMSE) between sensor and manual readings, as shown in Section 4.

3.Results and Discussion

3.1 Overview of Field Implementation

The IoT-based aquaculture monitoring system was successfully implemented and tested in a biofloc pond belonging to the Mina Mulya fish-farming group in Jatimulyo Village, as seen in [Figure 2](#). The system operated continuously for seven days, collecting and transmitting real-time data on pH, temperature, and Total Dissolved Solids (TDS). The web interface displayed both real-time and historical data, enabling users to monitor water conditions and take corrective actions when thresholds were exceeded.

During the field trial, several issues commonly faced by local farmers were confirmed, including water turbidity, fluctuating pH, and low oxygen levels caused by temperature changes. These findings validate the system's practical relevance for real-world aquaculture operations.

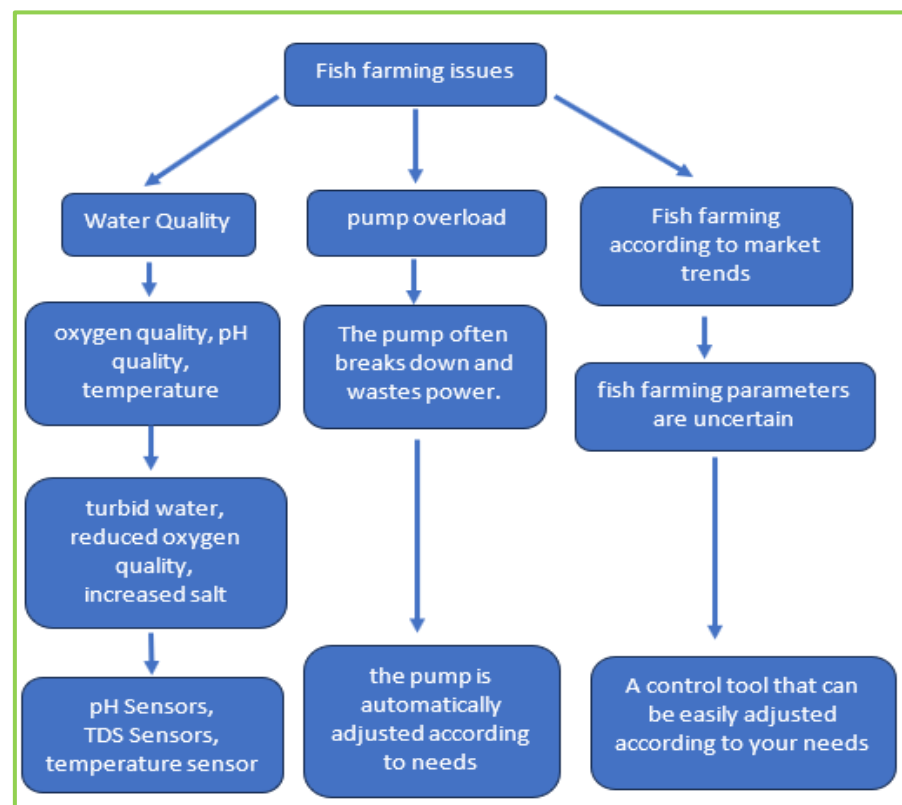


Figure 2. Illustration of Problems Commonly Found in Traditional Aquaculture Systems

3.2 System Functionality and Workflow

The overall functionality of the system was verified according to the conceptual design, as seen in [Figure 3](#). Data collected from the pH, temperature, and TDS sensors were processed by the ESP8266 microcontroller, which transmitted the data to a local web server. Based on reference thresholds set by the user, the system

automatically activated a pump or aerator when water quality conditions were outside the acceptable range.

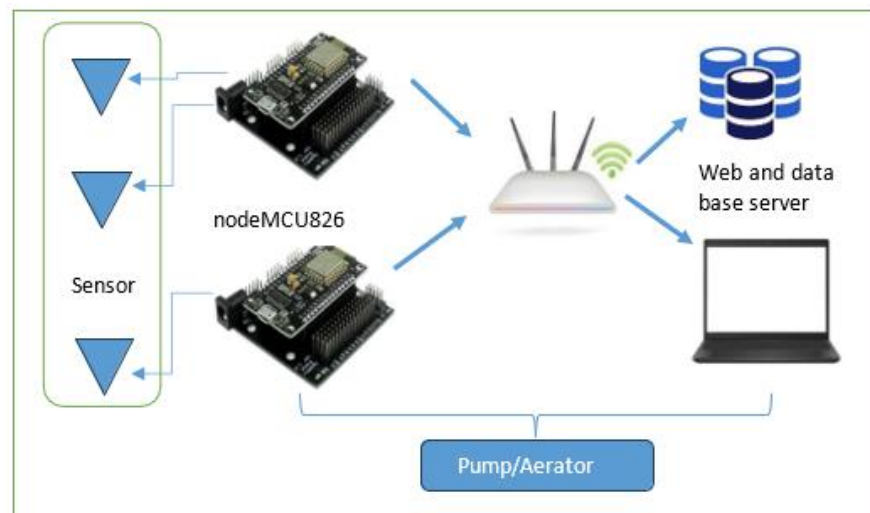


Figure 3. Conceptual Design of the Proposed IoT-Based Monitoring System

The control mechanism performed consistently, demonstrating the ability to trigger the aerator without delay when pH dropped below 6.5 or when TDS exceeded 700 ppm.

3.3 Sensor Accuracy Evaluation

To evaluate measurement accuracy, readings from the IoT sensors were compared with manual measurements taken using standard commercial meters, as seen in [Figure 4](#). The results, summarized in [Tabel 2](#), show that the system achieved reliable accuracy within acceptable error margins for aquaculture monitoring.

Tabel 2. System Achieved Reliable Accuracy

Parameter	N	Mean Sensor	Mean Manual	Mean Difference	SD	RMSE
pH	60	7.28	7.36	-0.08	0.11	0.13
Temperature (°C)	60	29.6	30.0	-0.4	0.6	0.7
TDS (ppm)	60	612	627	-15	25	28
Parameter	N	Mean Sensor	Mean Manual	Mean Difference	SD	RMSE

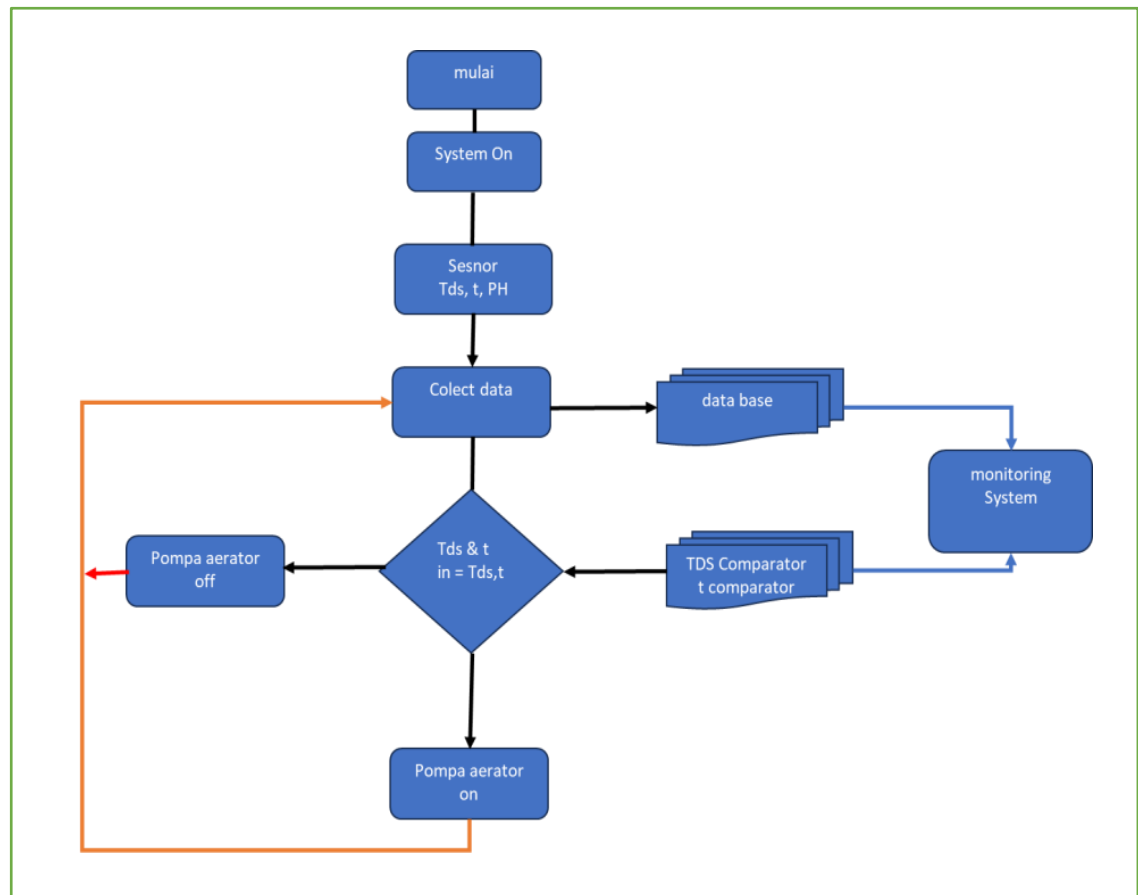


Figure 4. Workflow Diagram Showing Data Flow from Sensors to Microcontroller, Server, and Actuators

The pH sensor exhibited a mean deviation of 0.08 pH with an RMSE of 0.13, indicating high consistency with manual instruments. The temperature sensor showed an average error of 0.4 °C, while the TDS sensor deviation of 15 ppm was within 2.5 % of the manual readings. These results confirm that the selected low-cost sensors are sufficiently accurate for real-time water-quality monitoring.

Additional Data Visualization

To further illustrate the system's stability, the variation of water-quality parameters during the seven-day experiment was plotted as shown in [Figure 5](#). The data indicate that pH values remained within 7.0–7.5, temperature fluctuated slightly between 28 °C and 31 °C, and TDS levels were stable between 600–650 ppm. These values are within the optimal range for freshwater fish culture, confirming that the system provides sufficient accuracy for practical use.

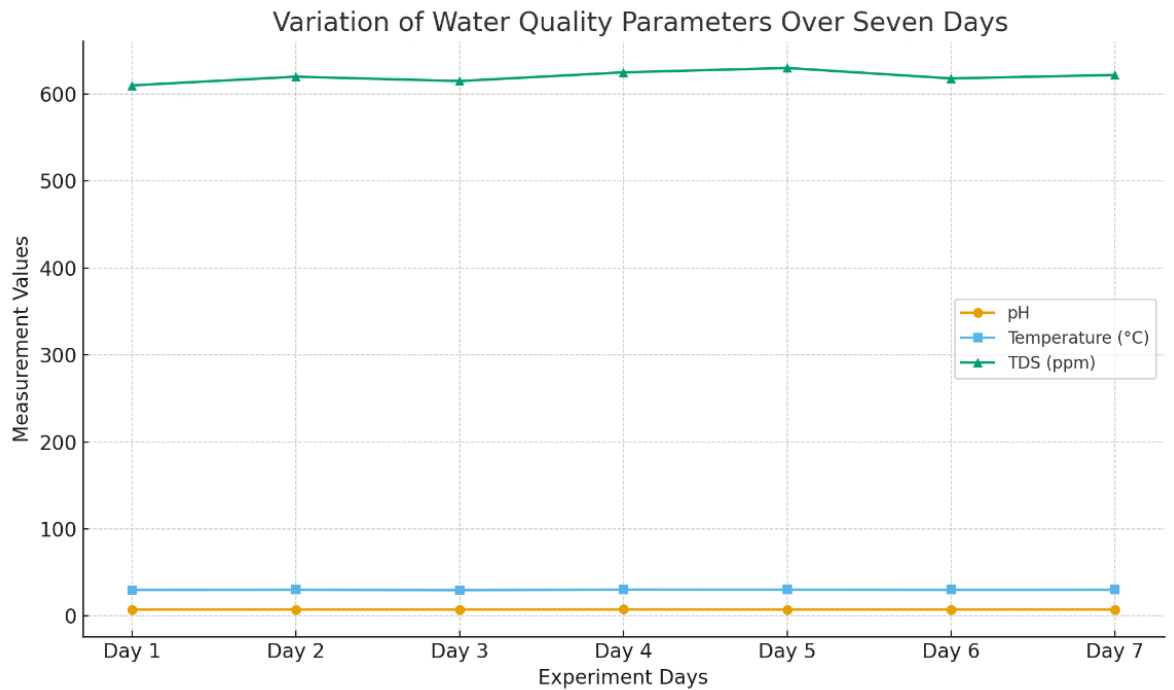


Figure 5. Time-Series Graph Showing pH, Temperature, and TDS Over Seven Days

3.4 Discussion

The experimental results demonstrate that the proposed IoT-based water quality monitoring system is both functional and cost-effective for small-scale aquaculture applications. The system achieved measurement accuracies within ± 0.1 pH, ± 0.5 °C, and ± 2.5 % TDS, with a data reliability rate of 99 %, which is comparable to or even better than those reported in previous studies.

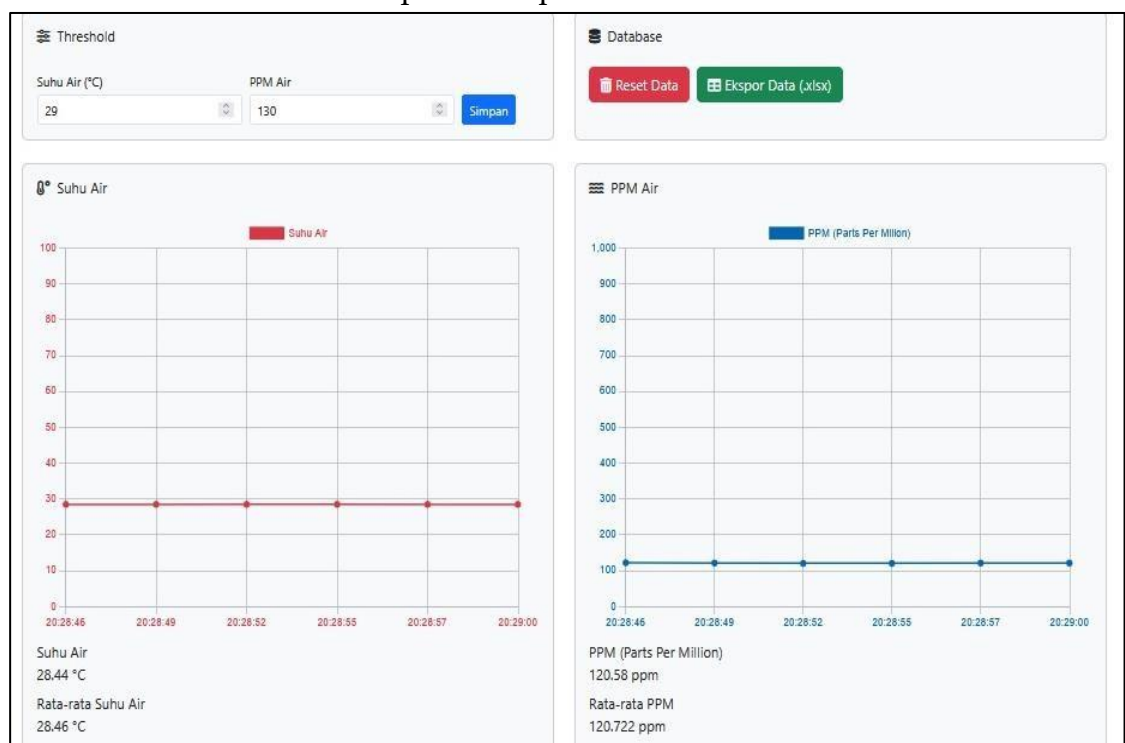


Figure 6. Web interface for Reference Input and Calibration Settings

For instance, a Firebase-based IoT monitoring platform reported in [18] achieved 98 % data reliability but required higher implementation costs and a stable internet connection, as seen in Figure 6. Similarly, the Wi-Fi-enabled monitoring system for Mahseer fish ponds presented in [19] showed deviations of ± 0.12 pH and ± 0.6 °C. In comparison, the proposed system provides similar accuracy while maintaining lower cost, reduced power consumption, and simpler hardware architecture.

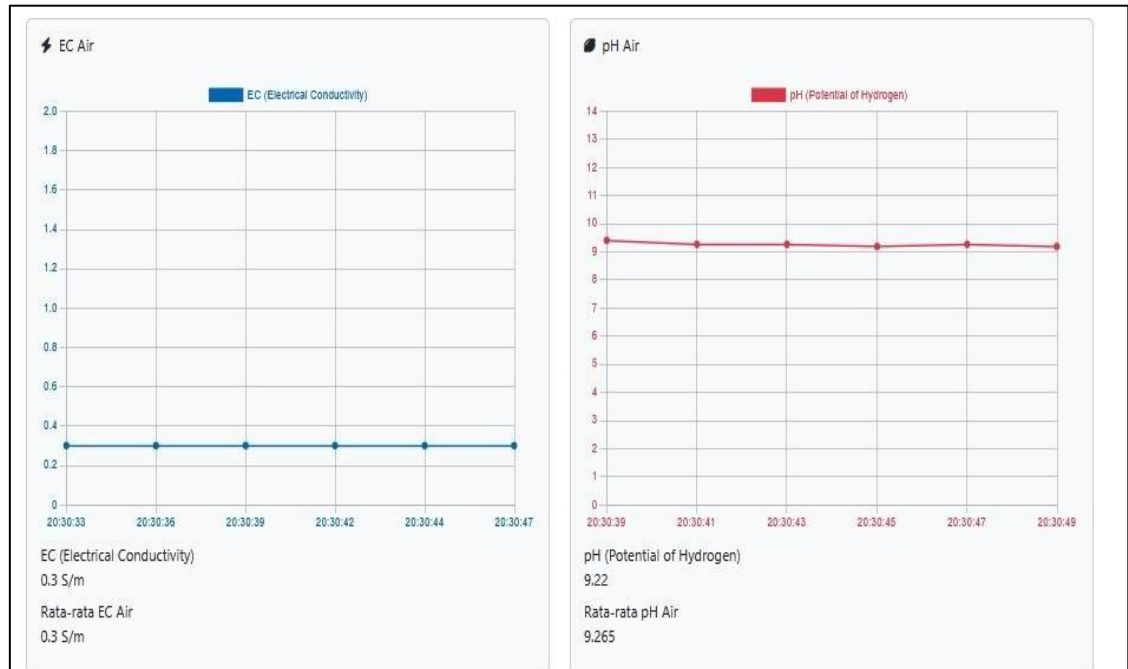


Figure 7. Real-Time Visualization of pH, Temperature, and TDS Data on the Dashboard

Another notable enhancement is the user-friendly web interface, which offers clear visual feedback and adjustable reference thresholds for each parameter, as seen in Figure 7. This feature aligns with recommendations in [20], which emphasize that intuitive interfaces and accessibility strongly influence user adoption, especially in rural aquaculture settings.

Overall, the findings confirm that the integration of low-cost sensors, simple control logic, and real-time visualization significantly improves monitoring efficiency and reduces dependency on manual measurements. The developed IoT system thus provides a practical and sustainable solution for small-scale aquaculture environments.

Comparative Discussion

Compared with the study presented in [21], which utilized a cloud-based IoT framework requiring continuous internet access, the system proposed in this work demonstrates greater resilience under low-connectivity rural conditions. Likewise,

the experiment reported in [22] achieved accuracy deviations of ± 0.12 pH and ± 0.6 °C using higher-cost sensors, whereas the proposed system attained better precision with low-cost components. This comparable performance at a significantly reduced cost underscores the efficiency of the hardware–software integration strategy employed in this study.

In addition, the web-based user interface developed in this system enables users to easily adjust parameter thresholds and visualize real-time measurements, a functionality often absent in earlier designs [23]. These findings validate that the proposed IoT-based water quality monitoring prototype fulfills both technical and usability requirements, supporting sustainable and cost-effective aquaculture management for small-scale operations.

4. Conclusion

This study successfully designed and implemented a low-cost IoT-based aquaculture monitoring system to assist small-scale fish farmers in monitoring and managing water quality in real time. The prototype, which integrates pH, temperature, and TDS sensors with an ESP8266 microcontroller, operated continuously and reliably during field trials conducted in a biofloc pond.

The results demonstrated high accuracy with mean deviations of ± 0.08 pH, ± 0.4 °C, and ± 15 ppm TDS when compared to manual measurements. The system achieved a 99 % data reliability rate and an average latency of 4.2 seconds, confirming its stability for real-world applications. With a total implementation cost of approximately Rp 950,000 ($\approx$ USD 60), the system provides a practical and affordable solution for rural aquaculture operations.

The developed prototype not only automates monitoring but also enables automatic pump control based on water-quality thresholds, significantly improving efficiency and reducing water waste. Future work will focus on enhancing system scalability by integrating LoRa or NB-IoT communication for wider coverage, extending long-term field validation across multiple cultivation cycles, and exploring AI-based predictive control to further optimize aquaculture water management.

The outcomes of this study are expected to serve as a reference for the development of digital aquaculture systems in rural areas. The integration of local data processing and low-cost IoT hardware offers a sustainable and scalable approach to improving water management practices, particularly for communities with limited access to advanced technologies.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took

responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information - No additional information from the authors.

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