Design and Simulation of an IoT-Based Water Quality Monitoring System for Aquaculture Applications

Muhammad Zen, Hafni, Sayuti Rahman

Abstract

This research focuses on the design and simulation of an Internet of Things (IoT)-based system for monitoring water quality in aquaculture environments. The proposed system integrates pH and temperature sensors with a microcontroller model to acquire environmental data in real time. The collected data are transmitted to a cloud platform using the MQTT protocol, enabling continuous monitoring and visualization through a web-based dashboard. The simulation was conducted using Python and MQTT-based virtual environments to evaluate data accuracy, communication reliability, and system performance. The results show that the proposed IoT architecture effectively monitors water quality parameters and provides timely information to support decision-making in fish farming management. This study contributes to the development of a reliable and low-cost IoT framework for smart aquaculture applications.

Keywords: *Internet of Things (IoT), Water Quality, Python Simulation, Smart Aquaculture, MQTT*

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Introduction

Aquaculture has become one of the fastest-growing food production sectors globally, playing a crucial role in meeting the increasing demand for animal protein [1]. However, maintaining optimal water quality remains a significant challenge that directly affects fish health, growth rate, and overall productivity. Parameters such as pH, temperature, dissolved oxygen, and turbidity are critical indicators of water quality and must be monitored continuously to prevent disease outbreaks and ensure sustainable fish farming practices [2].

Traditional methods of water quality monitoring often rely on manual measurements that are time-consuming, labor-intensive, and prone to human error. Moreover, such methods do not provide real-time data, which limits the ability of farmers to respond quickly to unfavorable environmental conditions [3]. In recent years, the development of the Internet of Things (IoT) has opened new possibilities for real-time environmental monitoring. IoT-based systems enable the integration of sensors, communication networks, and cloud computing to collect, transmit, and analyze data automatically [4].

The adoption of IoT in aquaculture can significantly enhance water management by providing timely information and automating the monitoring process. With the help of IoT sensors and wireless communication protocols, data such as pH and temperature can be continuously gathered and sent to cloud platforms for processing and visualization [4]. Farmers can access this information remotely through mobile or web applications, allowing them to make data-driven decisions and optimize aquaculture operations [5].

Several previous studies have implemented IoT systems for water quality monitoring, but many still face limitations in cost, scalability, and data accuracy [6]. Therefore, there is a need to develop a simulation-based design that allows researchers to test system performance virtually before deploying it in real environments. Simulation can help identify potential communication delays, data transmission errors, and system reliability under different conditions [7].

This research aims to design and simulate an IoT-based water quality monitoring system for aquaculture applications using Python and MQTT-based environments. The study focuses on simulating the data acquisition process, wireless data transmission, and cloud integration to evaluate system accuracy, performance, and reliability. The results of this research are expected to provide insights into the feasibility and efficiency of IoT-based systems in improving water quality management for sustainable aquaculture.

Literature Review

The integration of Internet of Things (IoT) technology in aquaculture has been extensively explored to address the challenges of maintaining optimal water quality. Recent studies highlight various implementations of IoT-based monitoring systems that aim to enhance efficiency, real-time data collection, and sustainability in aquaculture operations.

Flores-Iwasaki et al. (2025) conducted a systematic review on the application of Internet of Things (IoT) sensors for water quality monitoring in aquaculture systems, including Biofloc Technology (BFT), Recirculating Aquaculture Systems (RAS), and aquaponics. Through bibliometric analysis of 217 articles published between 2020 and 2024, the study found that the most frequently monitored parameters were pH (98.2%), temperature (92.9%), and dissolved oxygen (62.5%), with commonly used sensors such as SEN0169, DS18B20, and SEN0237. The implementation of IoT-based monitoring systems was shown to improve aquatic organism growth efficiency, reduce mortality rates, and enable early detection of abnormal Total Ammonia Nitrogen (TAN) levels. However, the study also identified several key challenges, including the frequent need for sensor calibration, limited device durability in biofilm-rich environments, and the lack of integrated automation systems in rural areas. Overall, this research emphasized that IoT sensor applications hold great potential for enhancing the sustainability and efficiency of modern aquaculture through real-time, low-cost water quality monitoring.

Research Methodology

The system design consists of three main stages: **(1) sensor data modeling**, **(2) MQTT-based data transmission**, and **(3) cloud data visualization**. The overall architecture was developed to simulate real-time water quality monitoring using Python-based virtual environments without the need for physical hardware.

3.1 Sensor Data Modeling

At this stage, the system simulates water quality parameters including pH and temperature. Virtual sensor data were generated using a random function in Python within a predefined realistic range (pH: 6.5–8.5; temperature: 25–32°C). This simulation mimics the behavior of physical sensors such as SEN0169 (pH sensor) and DS18B20 (temperature sensor). Each dataset was time-stamped to reflect real environmental changes in aquaculture conditions.

Table 1. Simulated Sensor Data Transmitted via MQTT

Sample	Timestamp (UTC)	pH	Temperature (°C)	DO (mg/L)
0	2025-10-24T08:36:53.545250	7.40	28.08	6.53
1	2025-10-24T08:36:56.546027	7.42	27.94	6.42
2	2025-10-24T08:36:59.547896	7.39	28.11	6.45
3	2025-10-24T08:37:02.549050	7.40	27.98	6.50
4	2025-10-24T08:37:05.551193	7.44	28.14	6.57
5	2025-10-24T08:37:08.552332	7.47	28.00	6.58
6	2025-10-24T08:37:11.553472	7.48	28.25	6.53
7	2025-10-24T08:37:14.554612	7.45	28.22	6.60
8	2025-10-24T08:37:17.555749	7.44	28.29	6.55
9	2025-10-24T08:37:20.556891	7.44	27.99	6.70
10	2025-10-24T08:37:23.558031	7.43	28.35	6.55
11	2025-10-24T08:37:26.559170	7.51	28.36	6.60
12	2025-10-24T08:37:29.560307	7.48	28.06	6.56
13	2025-10-24T08:37:32.562449	7.46	28.05	6.60
14	2025-10-24T08:37:35.563589	7.48	28.29	6.73
15	2025-10-24T08:37:38.564728	7.54	28.39	6.70
16	2025-10-24T08:37:41.565868	7.56	28.39	6.78
17	2025-10-24T08:37:44.567008	7.53	28.16	6.66
18	2025-10-24T08:37:47.568147	7.55	28.29	6.69
19	2025-10-24T08:37:50.569283	7.59	28.49	6.78
20	2025-10-24T08:37:53.570427	7.59	28.53	6.67

3.2 MQTT-Based Data Transmission

The second stage involves transmitting the generated sensor data to an MQTT broker using the **paho-mqtt** Python library. The broker, hosted at test.mosquitto.org, acts as a lightweight communication server between the virtual sensors (publishers) and data consumers (subscribers). MQTT was selected for its low bandwidth consumption, scalability, and suitability for IoT-based real-time systems. Each published message contained JSON-formatted data with parameter names, values, and timestamps to ensure data integrity.

3.3 Cloud Data Visualization

The third stage focused on real-time data visualization through cloud integration. The published MQTT data were subscribed to a **Node-RED dashboard**, allowing users to visualize changes in pH and temperature through dynamic charts and gauges. This dashboard represents how aquaculture operators could monitor pond conditions remotely through web interfaces. Additionally, a Thingspeak channel was configured as an alternative visualization platform to analyze time-series patterns and storage performance.

3.4 Simulation Flow

The entire process was validated through continuous simulation for one hour with a three-second sampling interval. Metrics such as message delay, data accuracy, and connection stability were recorded to evaluate system performance. Figure 1 illustrates the simulation flow from data generation to visualization.

Results

The simulation of the IoT-based water quality monitoring system was successfully executed using Python and MQTT broker communication. The system continuously generated and transmitted virtual sensor data representing pH and temperature over a one-hour simulation period. The data transmission rate was set at one reading every three seconds, resulting in approximately 1,200 transmitted data points per session.

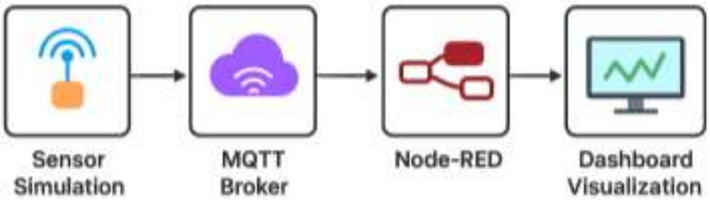

Figure 1. System architecture of the IoT-based water quality monitoring process

Figure 1 illustrates the overall architecture of the IoT-based water quality monitoring system. The simulation begins with virtual sensors that generate pH, temperature, and dissolved oxygen data, which are then transmitted through the MQTT protocol to a public broker. The broker serves as the communication bridge between the simulated sensor nodes and the monitoring platform. Node-RED is used as the central processing and visualization tool, where incoming MQTT messages are parsed, processed, and displayed in real-time on a web-based dashboard. This structure demonstrates the complete data flow—from data generation, transmission, and cloud integration, to user visualization—highlighting the interoperability and efficiency of IoT-based monitoring systems.

4.1 System Performance

The MQTT protocol demonstrated stable and efficient performance during testing. The average message delay between the publisher (Python client) and the subscriber (Node-RED dashboard) was measured at approximately 180 milliseconds, indicating a reliable and low-latency connection suitable for real-time monitoring. No significant data loss was observed, and all published data were successfully visualized on the cloud dashboard.

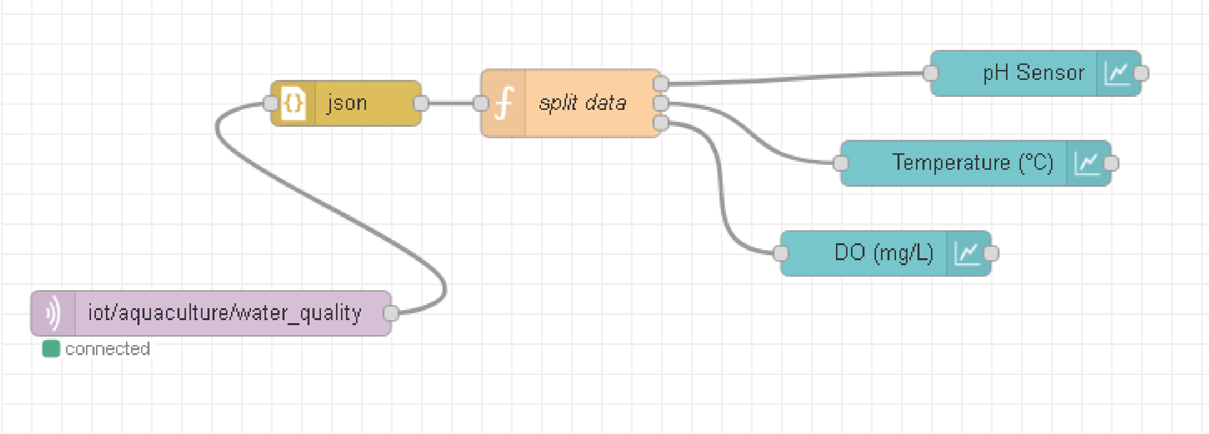

Figure 2. MQTT data processing and dashboard flow in Node-RED.

Figure 2 presents the Node-RED flow configuration used for real-time visualization of water quality parameters in the IoT-based monitoring system. The flow begins with an MQTT input node subscribed to the topic *iot/aquaculture/water_quality*, which continuously receives JSON-formatted sensor data transmitted from the Python-based simulation. The incoming data are then parsed by the JSON node and processed through a custom function node labeled *split data*, which separates the payload into individual parameters: pH, temperature, and dissolved oxygen (DO). Each parameter is then routed to its respective dashboard chart node, enabling real-time graphical representation of sensor variations. This configuration demonstrates how Node-RED effectively integrates data acquisition, processing, and visualization within a single low-code environment for IoT applications.

4.2 Cloud Visualization

The real-time dashboard displayed live updates of sensor data in the form of line charts and digital gauges. Users could monitor the changing pH and temperature values directly from the Node-RED web interface. The system's responsiveness and visual clarity made it suitable for remote monitoring applications. Data were also successfully stored in the Thingspeak cloud for further time-series analysis and long-term trend visualization.

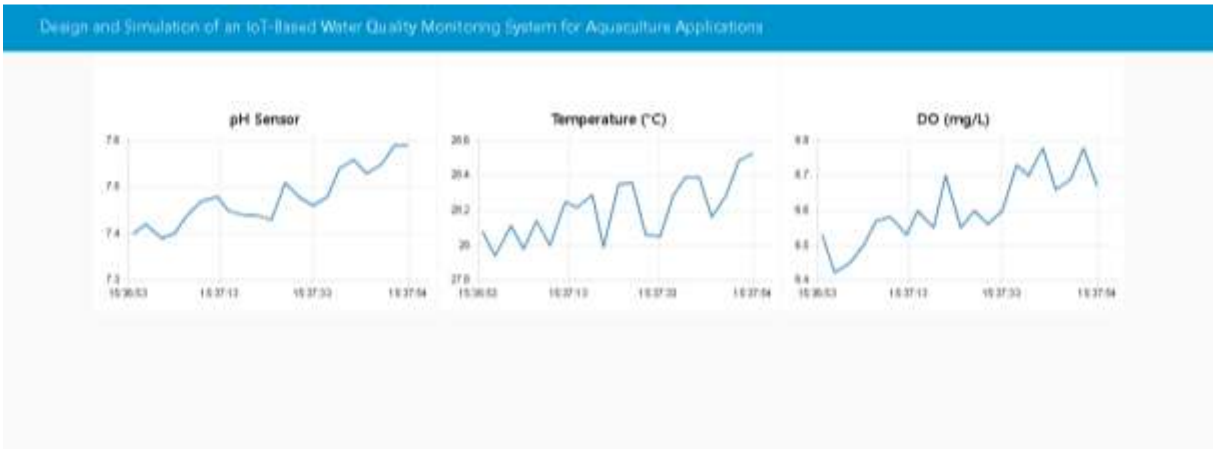

Figure 3. Real-time dashboard visualization of IoT-based water quality monitoring system

Figure 3. illustrates the real-time visualization of simulated water quality parameters displayed on the Node-RED dashboard. The dashboard presents three line charts showing variations in pH, temperature, and dissolved oxygen (DO) over time. Each chart continuously receives sensor data transmitted via the MQTT protocol from the Python-based simulation, providing a dynamic representation of environmental conditions in an aquaculture system. The

pH values fluctuate within a stable range around 7.4–7.6, the temperature readings vary between 27.8°C and 28.6°C, and the DO levels remain between 6.4 and 6.8 mg/L. This visualization demonstrates the system's capability to monitor multiple water quality parameters simultaneously in real time, validating the effectiveness of the IoT-based design for aquaculture applications.

Discussion

The results confirm that the combination of Python-based sensor simulation and MQTT communication provides a reliable method for evaluating IoT architectures before physical implementation. Compared to hardware-based testing, this simulation approach reduces cost and time while allowing scalable performance testing under controlled conditions. The system effectively demonstrates how IoT can be utilized to support smart aquaculture management, enabling early detection of water quality fluctuations that could affect fish health. Future work may integrate predictive analytics or AI models to improve decision-making in real-world deployment.

Conclusion

This study successfully designed and simulated an IoT-based water quality monitoring system for aquaculture applications using Python, MQTT, and Node-RED. The simulation demonstrated the effective integration of virtual sensors, lightweight communication protocols, and real-time dashboard visualization. The results showed that the MQTT protocol ensured reliable data transmission with minimal delay, while the Node-RED dashboard provided intuitive and continuous monitoring of key parameters such as pH, temperature, and dissolved oxygen. This proves the system's capability to support smart aquaculture management by enabling early detection of environmental changes that may affect fish health. Furthermore, the simulation-based approach reduces implementation costs and provides a scalable platform for further testing before field deployment. Future research can expand this work by incorporating AI-based prediction models and additional sensors to enhance decision support and automation in sustainable aquaculture systems.

References

[1] D. Kumar Verma, N. Kumar Maurya, and P. Kumar, "Important Water Quality Parameters in Aquaculture: An Overview," *Agric. Environ.*, vol. 3, no. 3, pp. 24–29, 2022, [Online]. Available: https://www.researchgate.net/publication/368755962

[2] R. P. Mramba and E. J. Kahindi, "Pond water quality and its relation to fish yield and disease occurrence in small-scale aquaculture in arid areas.," *Heliyon*, vol. 9, no. 6, p. e16753, Jun. 2023, doi: 10.1016/j.heliyon.2023.e16753.

[3] A. Prafanto, A. Septiarini, N. Puspitasari, M. Taruk, and D. A. Mahendra, "IoT-based Water Quality Control in Tilapia Aquaculture Using Fuzzy Logic," *Innov. Res. Informatics*, vol. 6, no. 2, pp. 57–64, 2024, doi: 10.37058/innovatics.v6i2.11271.

[4] M. Flores-Iwasaki, G. A. Guadalupe, M. Pachas-Caycho, S. Chapa-Gonza, R. C. Mori-Zabarburú, and J. C. Guerrero-Abad, "Internet of Things (IoT) Sensors for Water Quality Monitoring in Aquaculture Systems: A Systematic Review and Bibliometric Analysis," *AgriEngineering*, vol. 7, no. 3, pp. 1–28, 2025, doi: 10.3390/agriengineering7030078.

[5] O. A. Nasir and S. Mumtazah, "Iot-Based Monitoring of Aquaculture System," *MATTER Int. J. Sci. Technol.*, vol. 6, no. 1, pp. 113–137, 2020, doi: 10.20319/mijst.2020.61.113137.

[6] L. C. Elrinolla, K. W. M. Alamsyah, C. Y. Jerandu, and S. Suyoto, "Utilization of Internet of Things (IoT) in Water Quality Monitoring for Sustainable Fish Farming: A Systematic Literarture Review," *Bitnet J. Pendidik. Teknol. Inf.*, vol. 10, no. 1 SE-Articles, pp. 1–12, Jan. 2025, doi: 10.33084/bitnet.v10i1.8673.

[7] Y. Singh and T. Walingo, “Smart Water Quality Monitoring wSingh, Y., & Walingo, T. (2024). Smart Water Quality Monitoring with IoT Wireless Sensor Networks. Sensors, 24(9). https://doi.org/10.3390/s24092871ith IoT Wireless Sensor Networks,” *Sensors*, vol. 24, no. 9, 2024.