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Design and Implementation of an Automated IoT System for Real-Time Water Quality Management in Aquaculture

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Abstract

Aquaculture plays a critical role in global food production, but traditional water quality monitoring methods are often inefficient, expensive, and incapable of real-time analysis. This paper presents the development and implementation of an IoT-based Aquaculture Water Quality Monitoring and Control System designed specifically for red tilapia farming. The system integrates multiple sensors to measure key water quality parameters, including temperature, pH, total dissolved solids (TDS), electrical conductivity (EC), turbidity, and water level. A key technical contribution of this work is the dual-configuration design featuring both open-loop and closed-loop architectures, in which the closed-loop system introduces an automated water-replacement mechanism capable of stabilizing water quality parameters without human intervention. Data are transmitted in real time through the ThingSpeak platform, allowing for continuous monitoring and analysis. Two system configurations were tested: an open-loop system for monitoring and a closed-loop system with automated water quality adjustments. Results showed that the closed-loop system significantly improved water stability, with an 80% survival rate of red tilapia compared to a 20% survival rate in the open-loop system. This study demonstrates the effectiveness of IoT-based automation in aquaculture, ensuring better water management, improved fish health, and increased sustainability.

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I. INTRODUCTION

Aquaculture, the farming of aquatic organisms such as fish, shellfish, and algae, has become a cornerstone of global food security, providing a sustainable source of protein to meet the growing demands of an increasing population [1]. With wild fish stocks under pressure from overfishing, habitat destruction, and climate change, aquaculture has emerged as a viable alternative to supplement seafood production [2]. However, the success of aquaculture operations heavily depends on maintaining optimal water quality, as it directly impacts the health, growth, and survival of aquatic species [3]. Poor water quality can lead to stress, disease outbreaks, and even mass mortality, resulting in significant economic losses for farmers [4,5].

Traditional methods of monitoring water quality in aquaculture systems often rely on manual sampling and laboratory analysis, which are time-consuming, labor-intensive, and lack real-time capabilities. These methods are insufficient for detecting sudden changes in water parameters, such as pH fluctuations, temperature spikes, or increases in ammonia levels, which can have immediate and detrimental effects on fish health [6]-[8]. Moreover, the lack of continuous monitoring can lead to delayed corrective actions, further exacerbating the risks to aquatic life [9] [10].

To address these challenges, modern aquaculture systems are increasingly adopting advanced technologies such as the Internet of Things (IoT), sensor networks, and automation to enable real-time monitoring and control of water quality [11]. IoT-based systems allow for the seamless integration of sensors, microcontrollers, and cloud platforms by providing farmers with continuous access to critical data and enabling them to implement an automated feedback mechanism to maintain optimal conditions. These systems not only improve the efficiency and accuracy of water quality management but also reduce the reliance on manual labor, making aquaculture operations more sustainable and cost-effective [12].

The motivation for this study comes from the growing need for innovative solutions to enhance the sustainability and productivity of aquaculture, particularly in the face of environmental challenges such as floods, pollution, and climate change [13]. For instance, in 2021, severe floods in Malaysia caused significant damage to aquaculture farms, resulting in losses of over RM12.1 million and affecting hundreds of farmers [14][15]. Such events highlight the importance of developing resilient and adaptive systems capable of ensuring the stability of aquaculture operations even under adverse conditions.

This study focuses on the design and implementation of an Aquaculture Water Quality Monitoring and Control System specifically for red tilapia farming. Red tilapia is a widely cultivated species due to its hardiness, fast growth rate, and high market demand. However, like all aquatic species, red tilapia requires specific water quality conditions to thrive, including a pH range of 6.5–8.5, a temperature range of 25–28°C, low levels of turbidity range of 0–30 NTU and a total dissolved solids (TDS) range of 5–300ppm [16]-[21]. Deviations from these optimal conditions can lead to stress, reduced growth rates, and increased susceptibility to diseases [22].

The scope of this project focuses on creating a system that monitors and manages water quality for red tilapia farming. The research encompasses two setups: an open-loop system for real-time monitoring and a closed-loop system with automated controls to stabilize water quality. Both systems integrate several sensors and an ESP32 microcontroller to monitor and measure important water parameters such as pH, temperature, turbidity, TDS, and water level at 20-minute intervals. The closed-loop system includes automated control mechanisms that respond to water quality changes, such as activating water pumps to adjust pH levels, turbidity, and water temperature, ensuring they remain within the ideal range for red tilapia.

This study demonstrates the potential of IoT-based automation in revolutionizing aquaculture water quality management. By providing continuous monitoring and automated controls, the proposed system provides a reliable, user-friendly, and cost-effective solution to help farmers maintain a healthy and sustainable aquaculture environment. The findings of this study contribute to the growing body of knowledge on smart aquaculture systems and pave the way for future advancements in the field.

In conclusion, unlike existing IoT-based aquaculture systems that primarily focus on passive monitoring, the proposed system introduces a novel dual-configuration architecture that not only performs real-time multi-parameter monitoring but also incorporates an automated closed-loop water-replacement mechanism. This distinguishes it from existing IoT aquaculture systems by actively correcting water quality deviations and enhancing survival outcomes in small-scale red tilapia farms.

II. METHODOLOGY

The methodology of this project outlines the design, development, and evaluation process of an Aquaculture Water Quality Monitoring and Control System for red tilapia farming. The approach focuses on creating two system configurations namely, an open-loop system for real-time monitoring and a closed-loop system with automated control mechanisms. The system integrates advanced technologies, including IoT, sensors, and microcontrollers to monitor critical water quality parameters such as temperature, pH, TDS, turbidity, and water level.

Data are collected through various sensors and transmitted via an ESP32 microcontroller to the ThingSpeak platform for monitoring and historical trend analysis. For the closed-loop system, the methodology includes automated actuators to respond to deviations in water quality parameters, ensuring the aquatic environment remains within optimal conditions.

The microcontroller components include two ESP 32 boards, a water temperature sensor (DS18B20), a TDS sensor, a pH sensor (E-201C), an ultrasonic sensor (HC-SR04), a turbidity sensor (SEN0189), three relay modules, two water pumps, two power adapters, two panel boxes and a breadboard.

Maintaining optimal water quality is crucial in aquaculture systems to support the health and growth of aquatic species. This project monitors critical parameters such as TDS (Total Dissolved Solids), pH, water level, turbidity, and temperature as they affect water chemistry, clarity, and physical conditions. To improve sensor sensitivity, several rounds of calibration were conducted to ensure accurate and reliable readings.

i. pH Value

$$\mathrm{pH} = -5.7426(\mathrm{V}) + 21.806 \quad (1)$$

where:
pH = pH level
V = output voltage

ii. TDS and EC

$$\mathrm{TDS} = 46.097(\mathrm{V})^3 - 88.4\,(\mathrm{V})^2 + 296.23(\mathrm{V}) \quad (2)$$

$$\mathrm{EC} = \mathrm{TDS} \times 2 \quad (3)$$

where:
TDS = Total dissolved Solids in ppm
V = output voltage
EC = Electrical conductivity

iii. Turbidity (Tu)

$$\mathrm{Tu} = 0.220994475(9050 - \mathrm{ADC}) \quad (4)$$

where:
Tu = turbidity in NTU
ADC = analogue value.

iv. Temperature

$$T = \frac{\mathrm{ADC}}{16} \quad (5)$$

where:
T = temperature in ℃
ADC = analogue value

For the PH value, the expression of V refers to the pH sensor output voltage measured by the ESP32 ADC and is taken within the 0–3.3 V input range of the microcontroller. The pH probe (E-201C) was calibrated using a two-point procedure with standard buffer solutions (pH 4.01 and pH 7.00) to determine the linear conversion coefficients (slope and intercept), temperature-compensated using the DS18B20 readings, and recalibrated weekly or after visible sensor fouling to compensate for sensor drift.

The coefficients used in Equations (2) and (3) are derived from the manufacturer’s calibration curve for the TDS/EC sensor module, which relates output voltage to ionic concentration, and were further validated in this study by measuring standard calibration solutions of known conductivity (84 µS/cm, 1413 µS/cm, and 12.88 mS/cm) to confirm linearity and adjust the conversion factors where necessary

In a standard aquaculture farm, several water quality parameters must be monitored including ammonia, nitrite, nitrate, electrical conductivity, water level, salinity, turbidity, TDS, carbon dioxide, and pH levels as those parameters directly influence the health, growth, and productivity of red tilapia. However, this project focuses on monitoring pH level, temperature, dissolved solids, electrical conductivity, water level, and turbidity of the water in an aquaculture farm for red tilapia fish. Table 1 shows the ideal water quality parameter for red tilapia farming.

Table 1
Ideal Condition for Red Tilapia Fish

Parameter	Optimal Range
Temperature	25°C to 28°C
pH Value	6.5 to 8.5
Turbidity	Less than 30 NTU
TDS	Between 5 ppm and 300 ppm
Electrical Conductivity	Between 10 µs/cm and 600 µs/cm
Water Level	Less than 75% of the height of tank or less than 36.75cm.

To ensure reliable measurement accuracy, each sensor underwent multi-point calibration using manufacturer-recommended procedures and reference standard solutions, such as pH calibration at 4.00, 7.00, and 10.00 buffers, and TDS/EC calibration using certified conductivity standards to minimize drift and improve repeatability across the monitoring period. No additional water treatments or conditioning were applied during the experiment beyond routine filtration already present in the system

The flowchart for this project illustrates the step-by-step process of an Aquaculture Water Quality Monitoring System. It begins with sensors collecting water parameters such as temperature, pH, TDS, turbidity, and water level readings. The data is transmitted to the ESP32 microcontroller, which processes the information and uploads it to the ThingSpeak platform for visualization. In the closed-loop design, the system uses feedback to control water pumps for automated actions, ensuring efficient water quality management and maintaining safe conditions for the fish. Figure 1 shows the flow chart for open loop system and Figure 2 shows the flow chart of the closed loop system.

In the closed-loop configuration, the control logic activates the water pumps whenever any parameter exceeds its predefined threshold, for example pH falling below 6.5 or rising above 8.5, turbidity surpassing 30 NTU, or TDS exceeding 300 ppm. The ESP32 continuously compares real-time sensor readings against these limits and automatically performs a 40% water replacement to restore conditions to the ideal range.

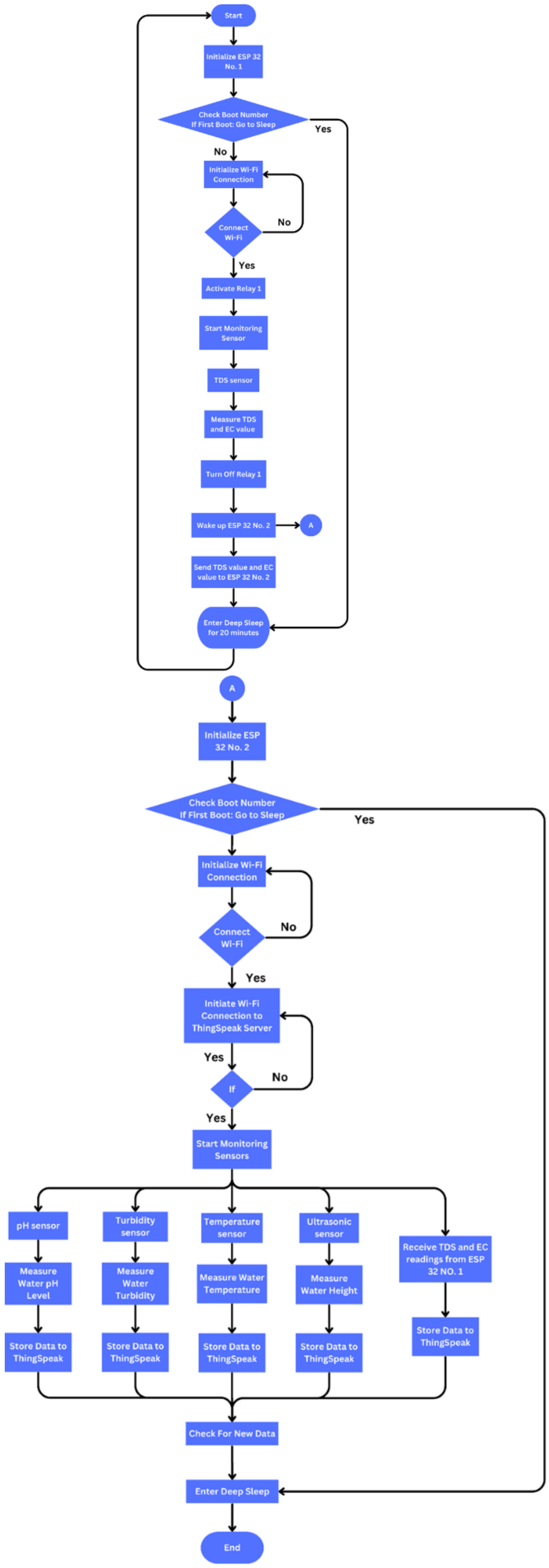

Figure 1. Flow Chart of an Open-Loop Aquaculture Water Quality Monitoring and Control System

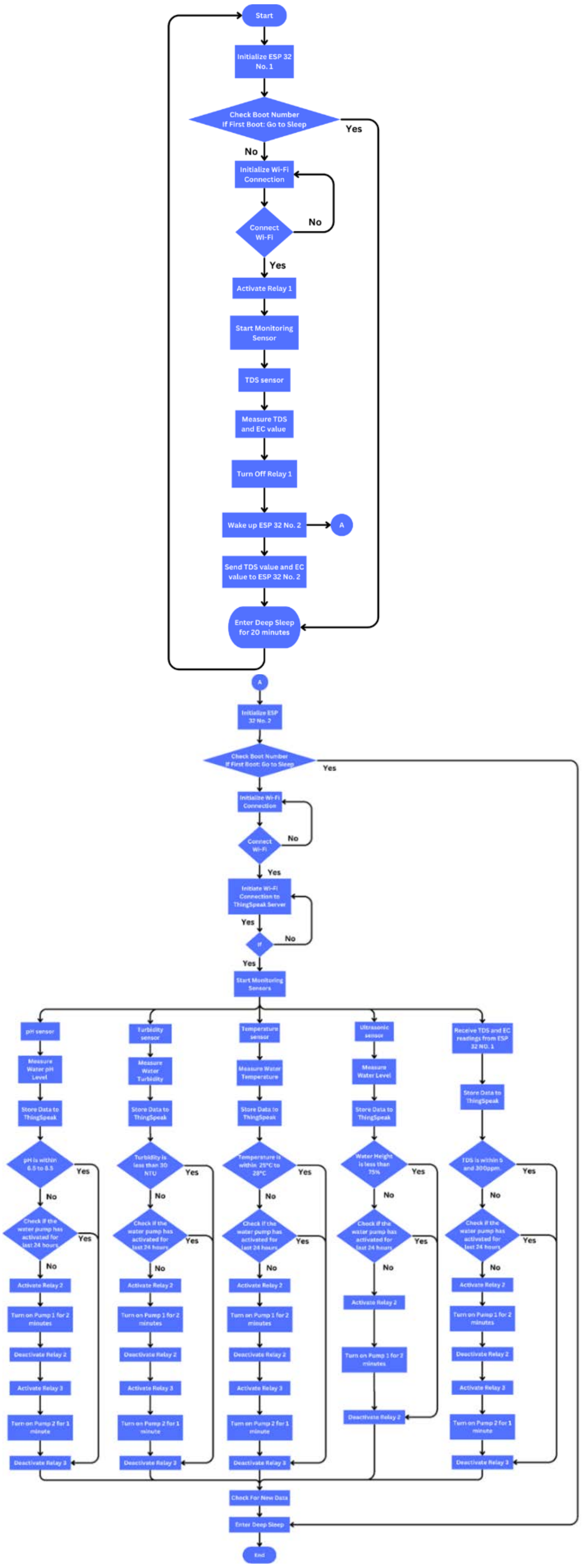

Figure 2. Flow Chart of a Closed-Loop Aquaculture Water Quality Monitoring and Control System

The aquaculture installations consists of 15 red tilapias housed in a circular water tank measuring 49 cm in height and 91 cm in diameter. The system also includes an air pump, live aquatic plants (Windelov Fern and Java Fern), an LED light, a biological filter (comprising a sponge filter, corals and bio-rings), 1/2 -inch and 1-inch PVC pipes, a hose, and a net.

Figure 3. Circuit Design

Figure 4. Hardware Setup

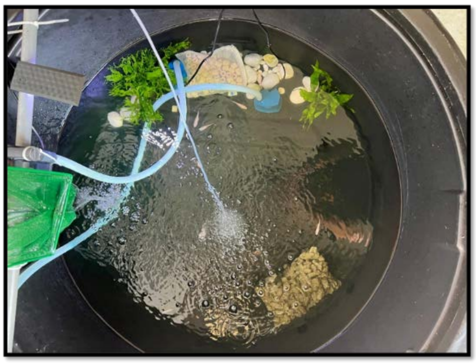

Figure 5. Aquaculture Tank

III. RESULT AND DISCUSSION

This report provides a detailed analysis of the systems' functionalities, advantages, and limitations in the context of the Aquaculture Water Quality Monitoring and Control System. Both systems were implemented for 9 to 11 days with 15 fish and approximately 160 liters of water in the tank. The fish were fed once daily, except for Saturday and Sunday. Furthermore, a 20-minute interval sampling method was used, collecting a total of 72 data points each day to assess the effectiveness of monitoring water quality parameters. The closed-loop system was implemented 5 days after the completion of the open-loop system. The average water quality parameters were calculated and analyzed using Microsoft Excel. By implementing both open-loop and closed-loop systems in a controlled aquaculture environment, the study aims to identify the strengths and weaknesses of each approach in real-world applications.

A. Open-Loop Control System

Table 3
Daily Average Water Quality Parameters in an Open-Loop Aquaculture System

Day	Temperature (°C)	pH Value	TDS (ppm)	EC (μS/cm)	Turbidity (NTU)	Water Level (cm)
1	26.45	7.45	256.00	512.00	6.86	25.87
2	26.40	7.37	260.76	521.52	9.46	25.96
3	26.13	7.25	268.44	536.88	12.3	26.03
4	26.70	6.98	289.68	579.36	15.38	25.82
5	26.99	6.76	297.00	594.00	19.44	26.06
6	26.37	6.67	305.87	611.76	24.01	26.15
7	26.52	6.48	314.65	629.30	27.80	26.17
8	26.18	6.33	334.28	668.56	31.84	26.12
9	26.23	5.97	355.68	711.36	35.34	26.02

$$\text{Survival Rate of Red Tilapia} = \frac{3}{15} \times 100\% = 20\%$$

i. Temperature

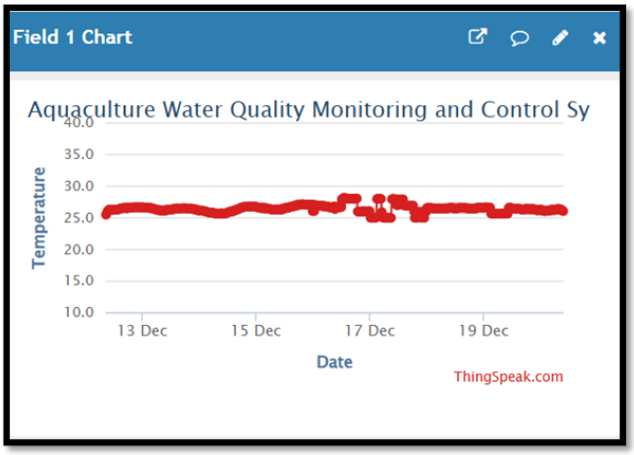

Figure 6. Temperature Variation in an Open-Loop Aquaculture System for 9 Days

This trend demonstrates that the system maintains a relatively stable temperature environment within the range of 25°C to 28°C. The observed temperature range is well-suited for the health and growth of red tilapia fish, as it falls within their optimal range. Since the temperature remains consistent without significant fluctuations, the system does not require additional heating mechanisms to maintain this ideal range.

ii. pH Value

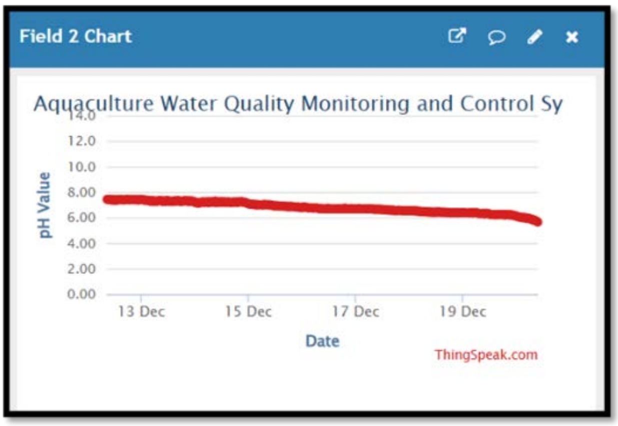

Figure 7. pH Variation in an Open-Loop Aquaculture System for 9 Days

The pH value slowly drops from 7.45 on Day 1 to 5.97 on Day 9, meaning the water becomes more acidic over time. This could happen because of waste from the fish, uneaten food, or organic matter breaking down in the water. Since the system did not perform any water changes for 9 days, these substances built up, making the water more acidic.

iii. Total Dissolved Solids (TDS)

Figure 8. TDS Variation in an Open-Loop Aquaculture System for 9 Days

This increase reflects the accumulation of dissolved substances such as minerals, ammonia, nitrate and waste byproducts, likely due to fish metabolic activity, uneaten food, and decaying organic matter. In an open-loop system without regular water changes, these substances accumulate over time, increases TDS concentration.

iv. Electrical Conductivity (EC)

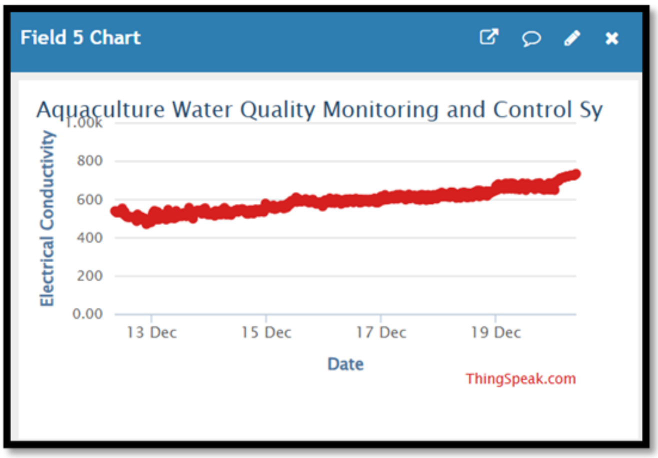

Figure 9. EC Variation in an Open-Loop Aquaculture System for 9 Days

Electrical Conductivity (EC) is approximately twice the total dissolved solids (TDS) value [23]. This trend indicates a rising concentration of dissolved ions in the water, such as salts, minerals, and other charged particles. The increase in EC is likely due to the accumulation of fish waste, uneaten feed, and other organic matter, which release ions as they decompose, thereby raising conductivity levels.

v. Turbidity (Tu)

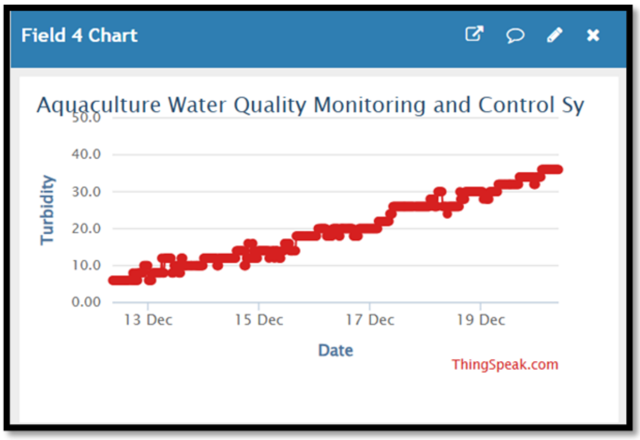

Figure 10. Tu Variation in an Open-Loop Aquaculture System for 9 Days

This gradual rise indicates the accumulation of suspended particles, organic matter, uneaten feed, and fish waste in the water. Even though the system is equipped with filtration, these substances will also build up which leads to reduced water clarity. If turbidity exceeds recommended levels, it can stress aquatic organisms and degrade water quality.

vi. Water Level

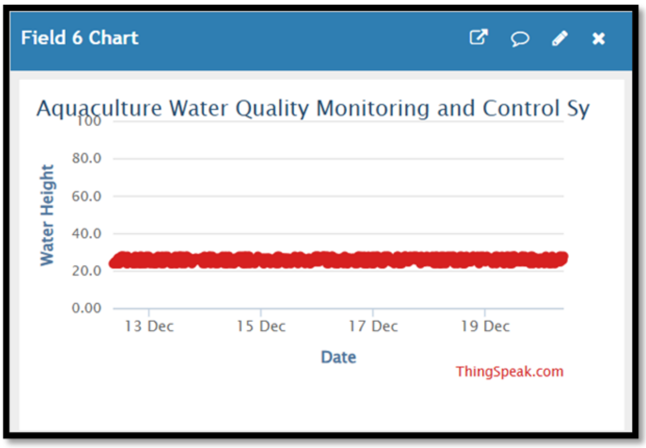

Figure 11. Water LevelVariation in an Open-Loop Aquaculture System for 9 Days

The water level remains consistent with minimal fluctuations, ranging from 25.82 cm to 26.17 cm. This consistency ensures stable living conditions for the red tilapia.

B. Closed-Loop Control System

The survival rate increased from 20% in the open-loop system to 80% in the closed-loop system, as determined through direct observation rather than statistical analysis. This limitation arises from the small sample size used in the experiment, which restricted the application of formal statistical inference. A larger sample size and longer test duration would allow for comprehensive statistical analysis to enhance the reliability of the survival rate results

Table 4
Daily Average Water Quality Parameters in a Closed-loop Aquaculture System

Day	Temperature (°C)	pH Value	TDS (ppm)	EC (μS/cm)	Turbidity (NTU)	Water Level (cm)
1	26.16	7.74	244.37	488.73	5.33	25.33
2	25.30	7.67	248.72	497.44	5.90	25.30
3	25.68	7.62	253.04	506.07	7.50	25.39
4	26.20	7.48	279.92	559.83	11.55	25
5	26.18	7.60	250.65	501.31	8.04	25.11
6	26.06	7.42	254.38	508.76	9.53	25.11
7	25.78	7.38	269.31	535.62	12.51	24.58
8	26.11	7.50	256.05	512.11	12.79	24.14
9	26.82	7.30	259.84	519.68	10.00	24.29
10	26.73	7.09	267.67	535.3	12.79	22.90
11	26.48	7.06	270.87	514.75	15.48	23.6

$$\text{Survival Rate of Red Tilapia} = \frac{12}{15} \times 100\% = 80\%$$

i. Temperature

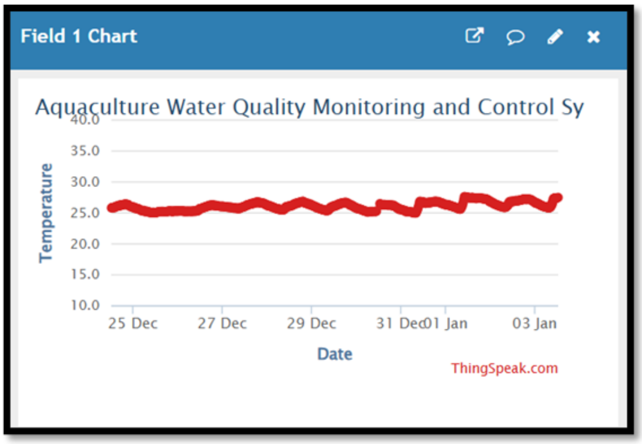

Figure 12. Temperature Variation in a Closed-Loop Aquaculture System for 11 Days

This trend demonstrates that the system maintains a relatively stable temperature environment within the range of 25°C to 28°C. This stability suggests that the aquaculture system is well-designed to maintain optimal temperature conditions, essential for sustaining red tilapia fish in the closed-loop setup.

ii. pH Value

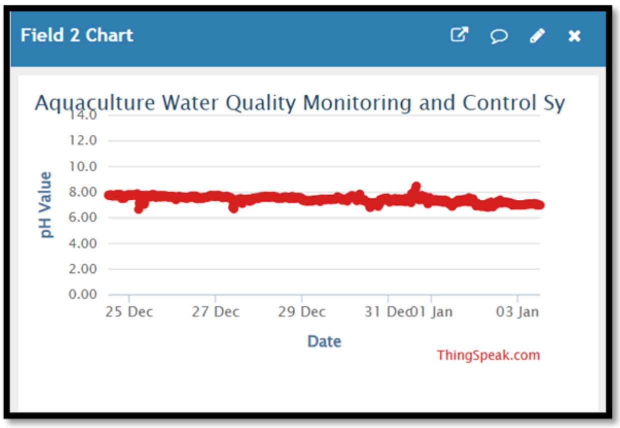

Figure 13. pH Variation in a Closed-Loop Aquaculture System for 11 Days

The trend shows a gradual decline in pH over the observed period, with minor fluctuations. The pH level decreases steadily from Day 1 to Day 4, reaching 7.48, then fluctuates slightly before dropping further to 7.06 on Day 11. This fluctuation is due to the system performing an automatic 40% water change on Day 5, which temporarily restored water neutrality.

iii. Total Dissolved Solids (TDS)

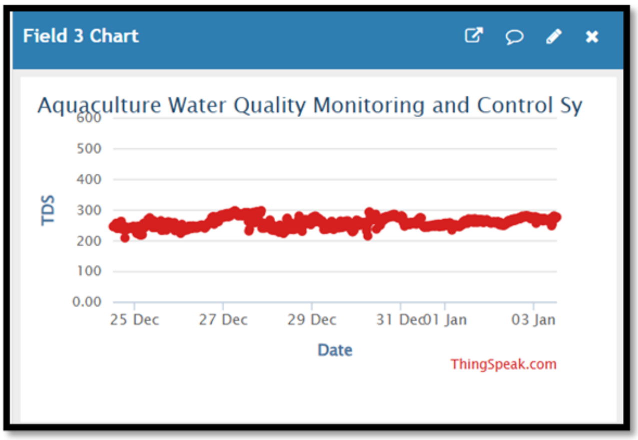

Figure 14. TDS Variation in a Closed-Loop Aquaculture System for 11 Days

The TDS levels range from 244.37 ppm on Day 1 to 270.87 ppm on Day 11, remaining within the ideal range of 5 ppm to 300 ppm. On most days, TDS shows a gradual increase due to feeding, fish waste, and other system activities. However, a significant drop from 279.92 ppm on Day 4 to 250.65 ppm on Day 5 likely resulted from a water change triggered by the system to maintain water quality. These water changes prevent excessive buildup of dissolved solids, which can negatively impact the health of red tilapia. This controlled variation indicates the system's ability to maintain a balanced environment by ensuring the water quality remains suitable for red tilapia. Stable TDS levels within the ideal range are critical for their growth, osmoregulation, and overall well-being.

iv. Electrical Conductivity (EC)

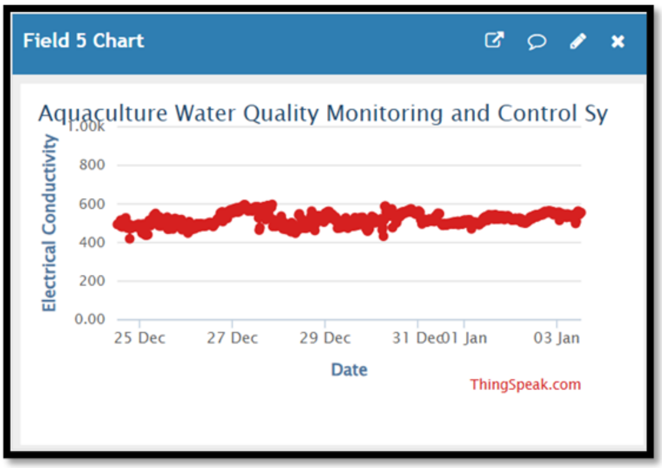

Figure 15. EC Variation in a Closed-Loop Aquaculture System for 11 Days

The fluctuations throughout the monitoring period stayed within the ideal range of 10 µS/cm to 600 µS/cm, indicating that the system maintains acceptable water quality conditions for aquaculture activities.

v. Turbidity (Tu)

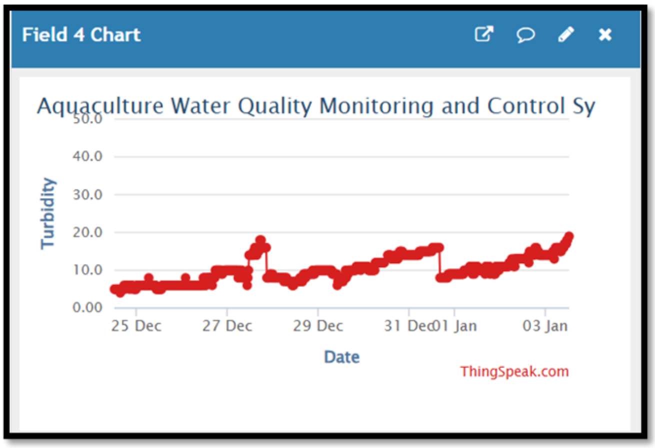

Figure 16. Tu Variation in a Closed-Loop Aquaculture System for 11 Days

The trend shows a gradual increase in turbidity from Day 1 to Day 4 with a maximum at 11.55 NTU on Day 4. This rise is likely due to an accumulation of suspended solids and organic waste from fish excretion, uneaten feed, and microbial activities. After Day 4, turbidity temporarily decreases to 8.04 NTU on Day 5, likely due to a 40% water replacement. However, turbidity then increases again, reaching to 12.79 NTU on Day 8 before slightly fluctuating and stabilizing at 15.48 NTU on Day 11. Although still below the critical threshold of 30 NTU, a weekly 40% water change is recommended to control suspended particles.

vi. Water Level

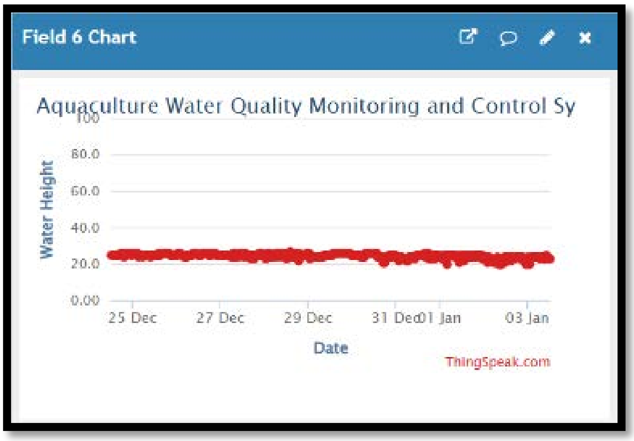

Figure 17. Water Level Variation in a Closed-Loop Aquaculture System for 11 Days

The water level ranges from 25.33 cm on Day 1 to a minimum of 23.6 cm on Day 11, showing a gradual decline over the monitoring period. These variations may result from evaporation, sensor error, minor filtration loss, and the closed-loop system's operations. Maintaining a consistent water level is critical for ensuring the water is always staying within the ideal range.

These parameters namely, pH, TDS, EC, turbidity, water level, and temperature were selected because they represent the most responsive and influential indicators of red tilapia health, affecting physiological stress, metabolic activity, water clarity, and overall tank stability. They are therefore essential for early detection of deteriorating water conditions in small-scale aquaculture systems.

Other parameters such as ammonia, nitrate, or dissolved oxygen were not included in the current prototype due to sensor availability and budget limitations. This phase focused on designing a cost-effective IoT-based monitoring and control system. The total cost of the prototype was approximately RM360, demonstrating that an effective water quality monitoring solution can be developed at low cost. The main objective of the study was to demonstrate the feasibility and functionality of a low-cost aquaculture water quality system using essential parameters such as pH, temperature, turbidity, TDS, EC, and water level.

Table 5 shows the estimated power consumption for the developed aquaculture system. The total monthly energy per month is 4.98 kWh which will cost between RM 1.10 and RM 3.00 per month, depending on usage pattern. Based on this estimated cost, scalability for commercial application is possible.

Table 5
Estimated Daily Average Power Consumption of the Aquaculture System

Component	Power (W)	Runtime/day	Energy/day (Wh)
2 × ESP32	1.0	24 h	24 Wh
Sensors & relays	1.0	24 h	24 Wh
Air pump	2.0	24 h	48 Wh
LED light	5.0	12 h	60 Wh
2 × water pumps	10.0	1 h	10 Wh
Total	166 Wh/day = 0.166 kWh/day.		

C. Comparison between Open-Loop and Closed-Loop System

The comparison between open-loop and closed-loop aquaculture systems shows critical differences in their effectiveness at maintaining water quality and ensuring the survival of red tilapia. The open-loop system relies on manual water changes, as it lacks a feedback mechanism. Over time, this results in the accumulation of dissolved solids, increased turbidity, and declining pH levels, making the water unsuitable for the fish.

This setup does not have any system to change the water, leading to a gradual decline in water conditions over time. As waste and other impurities build up in the water, it becomes less suitable for fish survival. The pH levels tend to drop, the turbidity increases, and the total dissolved solids (TDS) such as ammonia and nitrates start to accumulate. These poor conditions impair red tilapia survival and growth. As a result, the survival rate of red tilapia in this system is very low, at only 20% with 3 fish remaining at the end of the project on Day 11, even though this system includes aquatic plants and beneficial bacteria intended to remove ammonia and nitrates in the water. Overall, this system is less effective and not ideal for long-term fish farming, as it does not provide a stable or healthy environment for the fish. It cannot detect sudden changes in water quality and depends entirely on manual intervention.

Moreover, the closed-loop aquaculture system is far more effective at maintaining water quality and supporting the health of the red tilapia. This system includes a feedback mechanism that can detect water quality parameters and perform 40% of water replacement when those parameters fall outside optimal conditions. This allows the closed-loop system to ensure that key water parameters such as pH, turbidity, TDS, EC, temperature and water level stay within the ideal range for red tilapia. As a result, the system creates a more stable and controlled environment for the fish to live in.

The closed-loop system also uses water more efficiently, as it does not rely on constant water replacement like the open-loop system. This makes it a more sustainable option for fish farming. With water quality consistently maintained within the ideal range conditions, the fish in this system are healthier and have a much higher survival rate of 80% with 12 fish remaining at the end of the project on Day 11. Some fish deaths may be attributed to bacterial infections from the open-loop system, as the closed-loop system was implemented five days after the open-loop trial. The closed-loop system is clearly the better choice for aquaculture, as it provides a safer and more reliable environment for the fish while also conserving resources. It is more suitable for long-term fish farming and offers better results in terms of fish survival and overall productivity.

Table 6
Statistical Summary of Water Quality Parameters in the Open-Loop System (9 Days)

Parameter	Mean	Std Dev	Variance
Temperature (°C)	26.44	0.27	0.074
pH	6.81	0.50	0.252
TDS (ppm)	298.04	33.68	1134.65
EC (µS/cm)	596.08	67.37	4538.68
Turbidity (NTU)	20.27	10.10	102.06
Water Level (cm)	26.02	0.12	0.015

Table 7
Statistical Summary of Water Quality Parameters in the Closed-Loop System (11 Days)

Parameter	Mean	Std Dev	Variance
Temperature (°C)	26.14	0.45	0.199
pH	7.44	0.22	0.050
TDS (ppm)	259.53	11.01	121.26
EC (µS/cm)	516.33	20.40	416.25
Turbidity (NTU)	10.13	3.21	10.30
Water Level (cm)	24.61	0.81	0.652

A statistical analysis of the available data is shown in Table 6 and Table 7. The variance and standard deviation of each parameter confirm that the closed-loop system exhibited substantially higher stability. Parameters such as pH, turbidity, TDS and EC show markedly lower variance compared to the open-loop system, demonstrating the effectiveness of automated corrective actions in maintaining optimal water conditions.

The 20% survival in the open-loop system and 80% survival in the closed-loop system correlate strongly with water quality. The open-loop setup allowed pH to drop, TDS/EC and turbidity to accumulate, and fish to experience stress from deteriorating conditions, with no corrective actions. In contrast, the closed-loop system maintained stable parameters through automated water-change events, preventing harmful buildup and reducing fish stress, which contributed to significantly higher survival rates.

IV. CONCLUSION AND FUTURE WORK

The development and implementation of an Aquaculture Water Quality Monitoring and Control System in this project have demonstrated its potential as a reliable and efficient tool for ensuring water safety and sustainability. Through the use of sensors integrated with an ESP 32 microcontroller and a cloud-based monitoring platform such as ThingSpeak, the project demonstrated the feasibility of real-time water quality monitoring and data logging for continuous management of the fish tank. This closed-loop system enables users to monitor water quality conditions on the ThingSpeak platform and receive early alerts for potential pollution sources. The system also performs corrective actions such as pumping out the dirty water and refilling with clean water. This approach enables better control of water quality, reducing risks associated with unfavorable conditions such as high turbidity or imbalanced pH, which are common in open-loop systems.

The comparison between open- and closed-loop systems is compelling, and when factors such as lower long-term energy use, reduced labor and water change costs, and the ease of scaling automated feedback controls to larger or multiple tanks are considered, the closed-loop system offers a more sustainable, economical, and scalable solution for aquaculture operations.

In addition, the system is subject to several practical limitations, including potential sensor drift over long-term operation, dependence on a stable power supply during critical monitoring periods, and the need for periodic maintenance and recalibration to ensure continued accuracy and reliability.

Overall, the system successfully improved water stability and management efficiency, leading to a significant increase in fish survival from 20% in the open-loop setup to 80% in the closed-loop configuration, demonstrating its effectiveness in maintaining healthier aquaculture conditions.

For future work, there are several potential areas for further exploration and development. One significant direction could involve expanding the system's capabilities to monitor additional water quality parameters such as dissolved oxygen, ammonia, or nitrate levels, which are also critical for fish health and growth. A longer test duration and larger sample size would enhance the robustness and generalizability of the findings. To address this, future trials will be conducted over extended production cycles with a larger number of fish.

Another potential area for development involves scaling the system for larger aquaculture setups or adapting it for different fish species or aquatic animals. The scalability of the system could be enhanced to allow for broader adoption in commercial aquaculture operations. Additionally, exploring solar power could reduce operational costs and make it more environmentally sustainable. This would allow the system to remain operational during power outages, ensuring oxygen supply to aquatic organisms and uninterrupted monitoring and control.

Future research could also explore the integration of AI-based predictive analytics to anticipate water quality fluctuations before they occur, as well as investigate system scalability for commercial-scale aquaculture operations to validate its performance in larger and more complex environments.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of the paper.

AUTHOR CONTRIBUTION

All authors contributed equally to the conception and design of the study, data collection and testing, analysis, and manuscript preparation.

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