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Automated IoT-Based Water Quality Monitoring and Control with Fuzzy Logic for Intensive Aquaculture of Oreochromis niloticus †

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Abstract

The Bureau of Fisheries and Aquatic Resources Tilapia Industry Roadmap (2022–2025) emphasizes the need for technological innovation in Philippine aquaculture. We developed an automated IoT-based monitoring and control system for *Oreochromis niloticus* using fuzzy logic for the dynamic regulation of temperature, dissolved oxygen, pH, ammonia, total dissolved solids, and turbidity. The system integrates sensors and a web-based interface for real-time data access and management of aeration, filtration, and temperature. Experimental results show the improved stability of water quality, reduced fish mortality, and enhanced growth performance compared with conventional setups. The system demonstrates a practical and sustainable approach to intensifying tilapia aquaculture through smart automation.

Keywords: IoT; fuzzy logic; water quality monitoring; automated control system; intensive aquaculture

1. Introduction

The Bureau of Fisheries and Aquatic Resources (BFAR) Tilapia Industry Roadmap (2022–2025) identifies engineering and technological advancements as key to improving the efficiency and sustainability of tilapia production in the Philippines. It emphasizes upgrading infrastructure, accelerating engineering services, and promoting technology transfer in hatchery, nursery, and grow-out operations. Inspired by these initiatives, this study aims to assist Filipino fish farmers through expertise in instrumentation and control, applying IoT-based solutions for real-time water quality monitoring and management. This technology enhances resource use, reduces mortality, and increases production density [1].

Previous studies highlight limitations in existing IoT monitoring systems. One system controlled pH and water level using fuzzy logic but did not monitor ammonia, total dissolved solids (TDS), or dissolved oxygen (DO) [2]. Another system tracked pH, dissolved oxygen, temperature, and water hardness, with automatic aeration based on fuzzy rules, but actively controlled only DO while excluding ammonia and TDS [3]. Other prototypes monitored pH, dissolved oxygen, and temperature without IoT integration [4], or measured water level and turbidity with a liquid crystal display and water replacement functions but lacked IoT capability and broader parameter coverage [5]. Overall, these studies focused on monitoring but failed to integrate all critical parameters, including pH, ammonia, turbidity,

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dissolved oxygen, and TDS, into a single device [6]. Controlling only select parameters without considering their interdependence risks creating imbalanced conditions [7]. Therefore, developing a comprehensive monitoring and control system that encompasses all essential parameters is vital for advancing aquaculture sustainability [8].

We designed an IoT-enabled water monitoring and control system for tilapia aquaculture using fuzzy logic algorithms. The system monitors key water quality parameters, including time, date, ammonia, DO, TDS, turbidity, temperature, and pH. We also designed an automated control system with aeration, water replacement, and temperature regulation governed by fuzzy logic. The system is integrated into an IoT framework for real-time, internet-based monitoring and control and evaluated for fish growth and mortality, with the results compared with those of a conventional system.

2. Materials and Methods

The developed system follows an input–process–output framework to improve aquaculture management through IoT-based monitoring and control (Figure 1). pH, temperature, DO, turbidity, TDS, and ammonia are measured using sensors connected to a microcontroller for real-time data collection. A fuzzy logic algorithm guides automated processes, including aeration, filtration, temperature regulation, and water replacement, ensuring intelligent and adaptive control. The workflow enables wireless monitoring and provides a basis for comparing IoT-based and conventional systems. [3] Overall, the system enhances sensor accuracy, optimizes fish survival, and ensures efficient, data-driven aquaculture management accessible on the Internet (Figure 1).

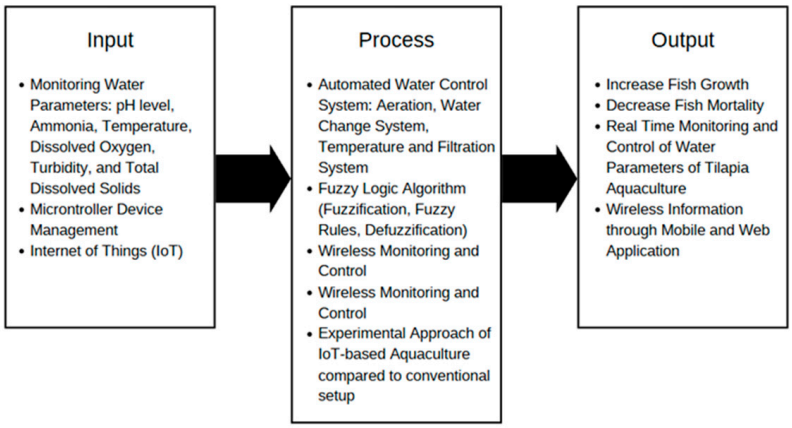


Figure 1. System workflow.

The system flowchart in Figure 2 illustrates the architecture of an IoT-based monitoring and control system for tilapia aquaculture integrated with fuzzy logic-based decision-making to maintain optimal culture conditions. The Arduino microcontroller with sensors continuously monitors pH, DO, temperature, ammonia, TDS, and turbidity, executing adaptive control actions such as heating, aeration, filtration, and water replacement. Fuzzy logic processes nonlinear sensor data to ensure balanced water quality, while all readings and control activities are transmitted to a web-based interface for real-time visualization and remote operation. This intelligent system enhances environmental stability, promotes tilapia growth and survival, and reduces manual intervention through automation [9] (Figure 2).

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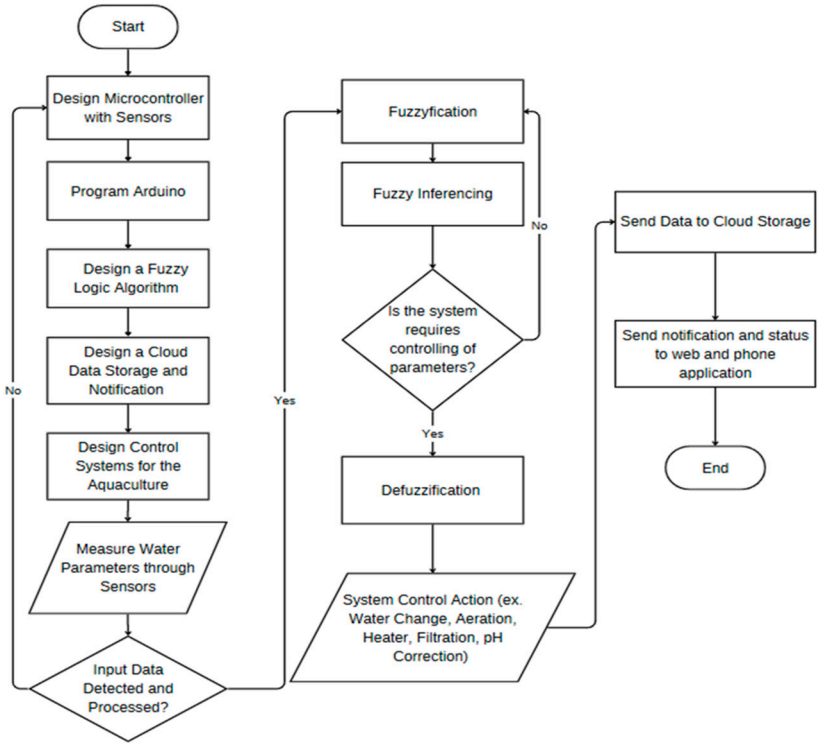
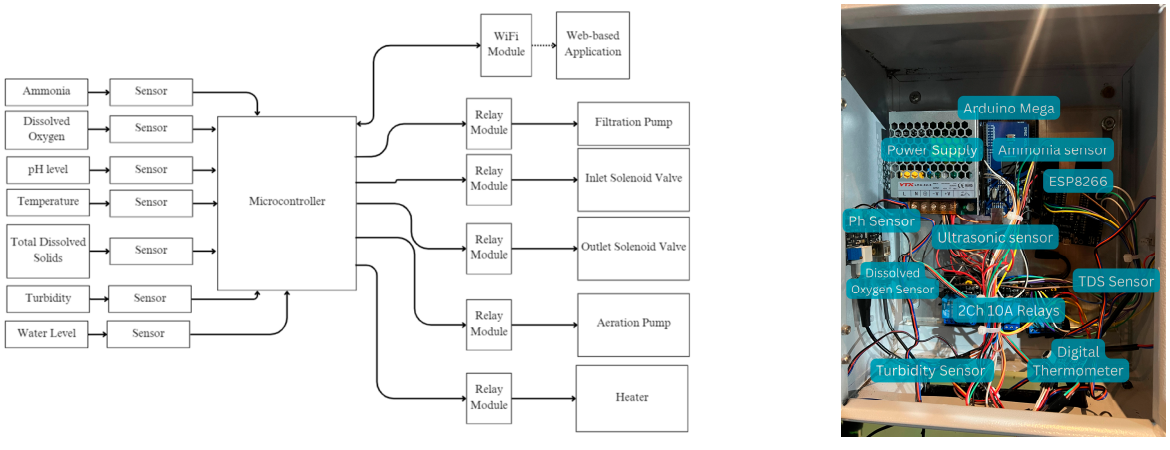


Figure 2. System process.

The automated IoT-based control system for tilapia aquaculture uses Arduino Mega with an ESP8266 WiFi module for real-time and remote monitoring (Figure 3). It integrates sensors for pH, turbidity, DO, ammonia, temperature, TDS, and water level to regulate the heater, aerator, filtration pump, and solenoid valves. Equipped with a multi-stage filtration unit (K1 media, sand, and activated charcoal) and web-based monitoring, the system ensures optimal water quality and efficient automated aquaculture management (Figure 3).



(**a**) (**b**)

Figure 3. (**a**) Block diagram of the program of the developed system; (**b**) Wiring connection of the IoT-based monitoring and control system illustrating the connection between the microcontroller, sensors, and actuators.

In the system, MATLAB's R2022a Fuzzy Logic Toolbox is employed to develop a Mamdani-based fuzzy inference system, designed to manage the nonlinear and uncertain nature of water quality conditions in tilapia aquaculture. We defined fuzzy sets and

membership functions for both input and output variables based on established aquaculture standards and real-time sensor data readings. A customized rule base was formulated using linguistic if–then statements that reflect optimal environmental conditions for tilapia culture. The system fuzzifies sensor inputs, processes them through logical rule evaluation, aggregates the outcomes, and defuzzifies the results to produce precise control actions. This intelligent decision-making framework ensures adaptive and accurate management of aquaculture parameters where conventional binary logic would be inadequate (Figure 4).

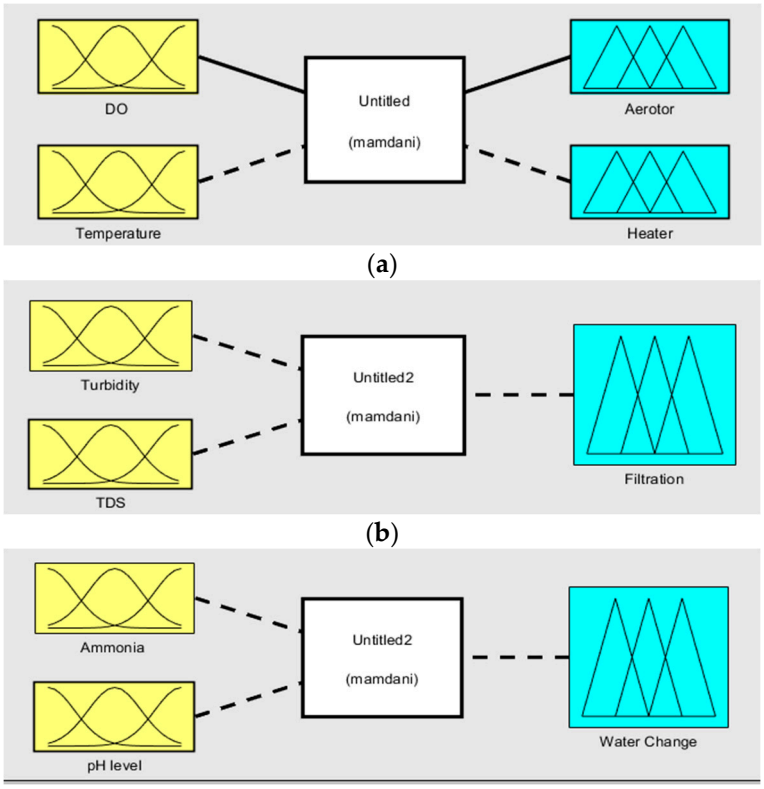


Figure 4. Fuzzy logic control structure showing the following: (**a**) temperature and DO regulating aerator and heater; (**b**) TDS and turbidity managing filtration; (**c**) pH and ammonia controlling automatic water replacement to maintain optimal aquaculture conditions.

3. Results

The three-week real-time monitoring recorded six key water parameters, namely temperature, DO, TDS, turbidity, pH, and ammonia, along with the growth performance and mortality of tilapia. Using a web-based application, the system continuously tracked these parameters to evaluate overall water quality and its influence on fish health, survival, and growth throughout the study period.

3.1. Water Parameter Sensor Data

The three-week data collection demonstrates the effective operation of the water quality sensors and control mechanisms. The real-time readings confirm that the sensors accurately monitored temperature, DO, turbidity, TDS, pH, and ammonia levels, while the automated heater, aerator, and filtration systems responded appropriately to maintain optimal water conditions throughout the monitoring period (Figure 5).

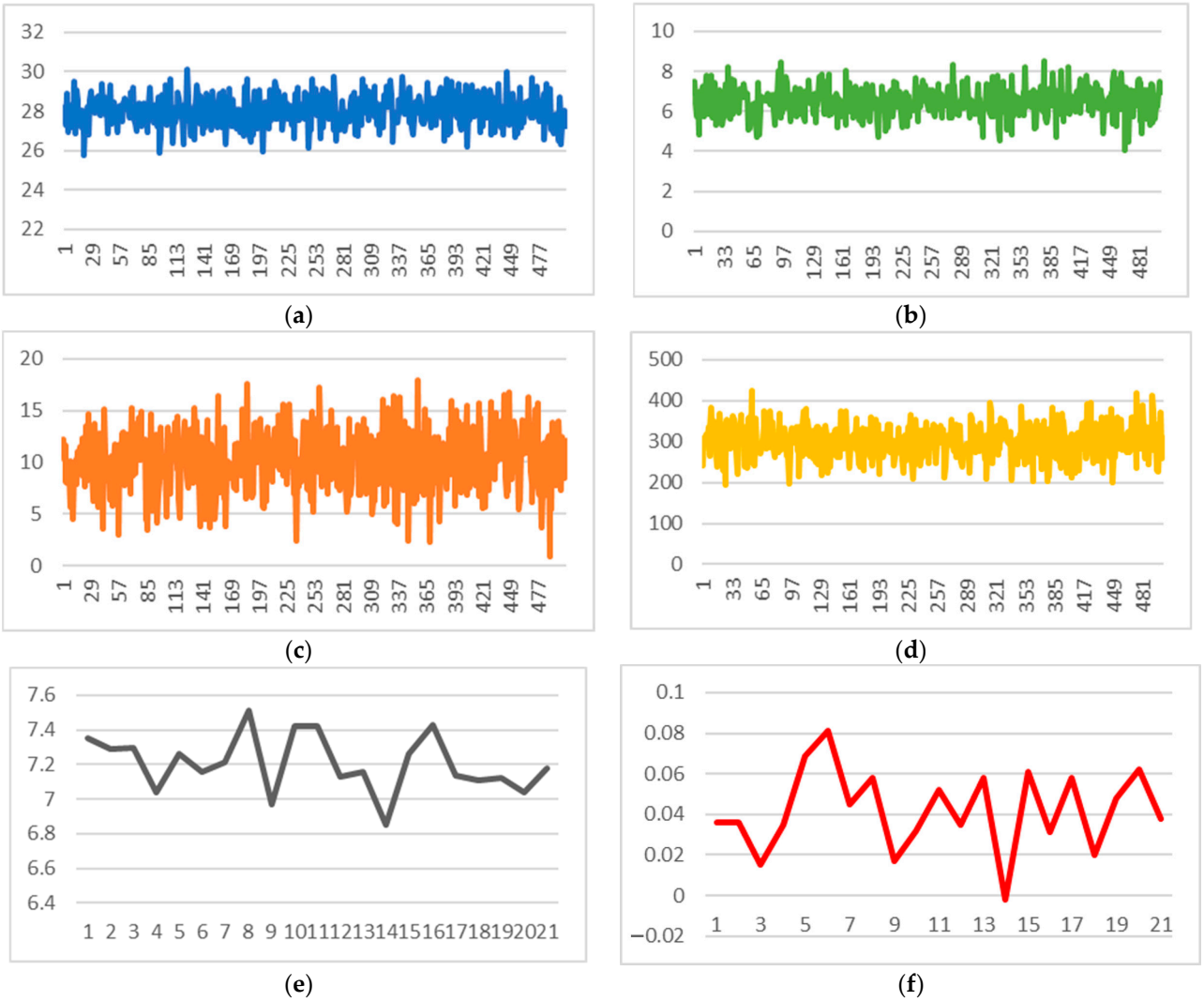


Figure 5. (**a**) Temperature; (**b**) DO; (**c**) Turbidity; (**d**) TDS; (**e**) pH; (**f**) Ammonia.

3.2. Web-Based Application

The web-based application displays real-time numerical readings of all water quality parameters along with their corresponding linguistic values generated through the fuzzy logic design. This interface enables users to easily interpret system status, monitor overall water quality, and observe automated control responses in real time (Figure 6).

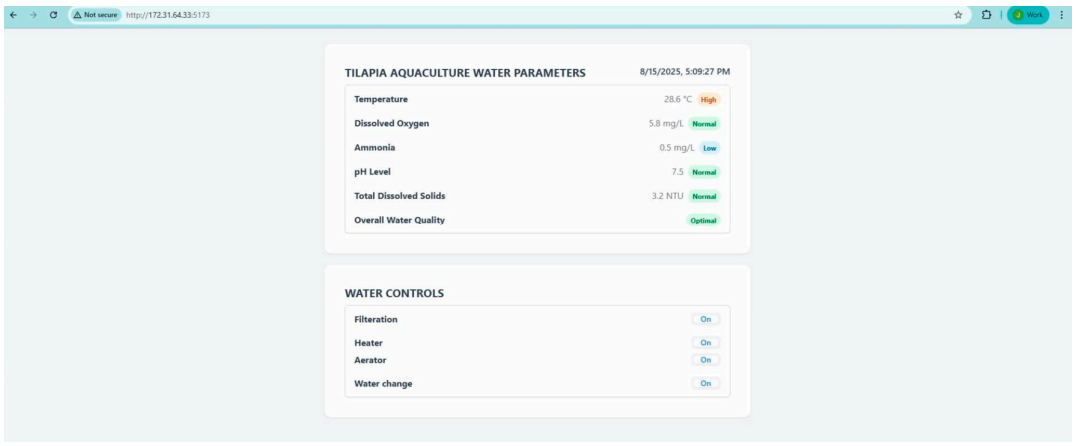


Figure 6. Accessible web-based application.

3.3. Fish Growth and Mortality

Table 1 presents the paired sample *t*-test results comparing fish growth under the Conventional Setup and the Automated Monitoring and Control System. The computed *t*-value (0.537) and *p*-value (0.611) reveal no significant difference, indicating comparable growth performance between the two systems.

Table 1. Paired sample *t*-test comparing the conventional setup and automated monitoring and control system in fish growth.

Data	Mean Weight	Standard Deviation	Test Statistic	*p* Value
Conventional setup	4.34	0.22286	0.536667	0.610803
Automated monitoring and control system	4.22	0.109977		

Table 2 shows the paired sample *t*-test comparing the survival rate between the conventional setup and the automated monitoring and control system. The results indicate that the automated system achieved a higher fish count (86) than the conventional setup (79). The computed *t*-value (4.302) and *p*-value (0.044) reveal a significant difference, suggesting that the automated system led to improved fish survival.

Table 2. Paired sample *t*-test comparing the conventional setup and automated monitoring and control system with survival rate.

Data	Fish Count	Standard Deviation	Test Statistic	*p* Value
Conventional setup	79	79	4.30265	0.044467
Automated monitoring and control system	86	43		

4. Discussion

The three-week real-time monitoring of the aquaculture system demonstrated the effectiveness of the IoT-based fuzzy logic control in maintaining optimal water quality for tilapia culture. The temperature ranged from 25.73 to 30.1 °C, remaining near the ideal range of 28–30 °C, with the heater automatically activating at around 26 °C to restore thermal balance. Dissolved oxygen levels varied between 4.06 and 8.5 mg/L, with the aerator triggering below the 5.5 mg/L threshold to maintain sufficient oxygenation and prevent hypoxic stress. Turbidity fluctuated from 0.87 to 17.98 nephelometric turbidity units (NTU), and TDS ranged from 193.89 to 424.92 mg/L; the filtration system automatically actuated when turbidity exceeded 30 NTU or TDS surpassed 350 mg/L, ensuring water clarity and ionic balance. Ammonia remained low (0.002–0.081 mg/L), and pH levels (6.5–7.51) stayed within the optimal range of 6.5–9.0, indicating stable conditions despite no water change during the period. The heater, aerator, and filtration controls consistently responded whenever parameters deviated from ideal levels, maintaining environmental stability. Hourly data readings confirmed that over 90% of monitored values remained within optimal thresholds, validating the system's reliability and precision in sustaining favorable water quality and supporting healthy tilapia growth with minimal mortality. The results indicate that while fish growth showed no significant difference between the conventional setup and the automated monitoring and control system, survival rate significantly improved under the automated setup. This suggests that automation may not directly affect growth performance but can enhance survival efficiency and overall system reliability.

We developed and evaluated an IoT-based automated monitoring and control system for intensive tilapia aquaculture using fuzzy logic. The system effectively maintained optimal water quality parameters, including temperature, DO, turbidity, TDS, pH, and ammonia, through real-time sensing and adaptive control, ensuring environmental stability throughout the culture period. Comparative analysis results revealed no significant difference in fish growth between the automated and conventional setups. However, the automated system achieved a significantly higher survival rate. These results demonstrate that integrating IoT and fuzzy logic technologies can enhance aquaculture management by improving survival efficiency, reducing manual intervention, and supporting sustainable fish production in alignment with BFAR's Tilapia Industry Roadmap (2022–2025).

Author Contributions: Conceptualization, A.S.G. and A.N.; methodology, A.S.G. and A.N.; software, A.S.G.; validation, A.S.G., A.N. and G.M.; formal analysis, G.M.; writing—original draft preparation, A.S.G. and A.N.; writing—review and editing, A.N.; visualization, A.N.; supervision, G.M. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Ethical review and approval were waived for this study because it is a purely technical/engineering application involving non-invasive monitoring under standard aquaculture practices, and it does not include any procedures that cause harm or stress to the animal subjects (*Oreochromis niloticus*). The study complies with the relevant guidelines of the Bureau of Fisheries and Aquatic Resources under the Department of Agriculture.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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