Available online at http://iorajournal.org/indx.php/orics /index

Operations Research: International Conference Series

e-ISSN: 2722-0974
p-ISSN: 2723-1739

Vol. 6, No. 3, pp. 129-136, 2025

Implementation of a Web-Based Water Quality Control System for Koi Ponds Using Mamdani Fuzzy Logic and the Laravel Framework

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Abstract

This study proposes a web-based water quality control system for koi ponds by integrating Mamdani fuzzy logic with the Laravel framework. The system employs pH, TDS, and temperature sensors connected to an ESP32 microcontroller to monitor water conditions in real time. Sensor inputs are processed through a fuzzy logic controller, which automatically regulates water treatment by activating pumps for acid or base solutions. A web application developed with Laravel provides a responsive interface that displays real-time data and records historical trends for further analysis. Experimental validation demonstrates that the system achieves high accuracy and reliable control performance, ensuring stable water quality within the optimal range for koi cultivation. By combining IoT-based monitoring with intelligent decision-making, this research offers a practical contribution to improving aquaculture efficiency and reducing fish mortality.

Keywords: Koi pond water quality, Mamdani fuzzy logic, IoT-based monitoring, ESP32 microcontroller, Web application (Laravel)

1. Introduction

Koi fish (Cyprinus carpio koi) are ornamental species with high aesthetic and economic value, widely cultivated in Indonesia. However, their health and growth are highly sensitive to water quality, particularly parameters such as pH, temperature, and total dissolved solids (TDS). When pH falls below 6.5 or rises above 8.0, fish become more vulnerable to diseases and ammonia accumulation, often resulting in high mortality rates (Gunawan et al., 2023). Similarly, inappropriate TDS or temperature levels can significantly disrupt fish development (Kurniawan et al., 2023; Yulianto & Handayani, 2022).

Traditional monitoring methods, including analog thermometers and litmus paper, remain widely used but are limited in providing real-time and accurate information (Putra et al., 2022). As a result, farmers often respond reactively to water quality issues, increasing the risk of production losses. This highlights the urgent need for an intelligent, automated monitoring and control system capable of maintaining optimal water conditions continuously.

In addressing this problem, the integration of Internet of Things (IoT) technology with fuzzy logic provides a promising solution. IoT devices such as the ESP32 microcontroller enable real-time data acquisition and wireless transmission, while Mamdani fuzzy logic offers reliable decision-making in handling nonlinear and uncertain parameters (Mamdani & Assilian, 1975; Zadeh, 1965). Previous studies have demonstrated the potential of fuzzy logic in aquaculture applications, yet many systems lack a comprehensive platform that supports both control and accessible data visualization (Setiawan et al., 2023).

To fill this gap, this study implements a web-based water quality control system that integrates IoT sensors with Mamdani fuzzy logic, supported by the Laravel framework. Laravel was selected because of its modular architecture, efficient database integration, and ability to provide a user-friendly interface for real-time monitoring (Otwell, 2015; Ramadhani et al., 2022). The system is designed to not only monitor key water parameters but also to automatically regulate pH levels, thereby improving aquaculture productivity and reducing fish mortality risks.

2. Literature Review

2.1. Water Quality and Koi Fish Cultivation

Water quality is a critical factor in koi aquaculture, as fluctuations in pH, TDS, and temperature directly affect fish health and growth. The ideal pH range for koi is 6.5–8.0, TDS should be maintained below 300 ppm, and water temperature between 24–28°C is considered optimal (Kurniawan et al., 2023; Yulianto & Handayani, 2022). Deviation from these ranges often leads to stress, disease susceptibility, and increased mortality. Therefore, continuous monitoring and precise control of water parameters are essential to ensure sustainable koi cultivation.

2.2. Mamdani Fuzzy Logic

Fuzzy logic provides a computational approach to decision-making under uncertain or nonlinear conditions. The Mamdani method, in particular, is widely adopted due to its use of linguistic IF–THEN rules and centroid-based defuzzification, which allow for smooth and adaptive control responses (Mamdani & Assilian, 1975; Zadeh, 1965). In aquaculture, fuzzy logic has been applied to interpret water quality indicators and determine corrective actions, such as adjusting acidity levels (Setiawan et al., 2023). However, many existing implementations remain limited to laboratory-scale experiments and lack integration with real-time web-based monitoring.

2.3. IoT and the ESP32 Microcontroller

The Internet of Things (IoT) enables real-time data acquisition and remote monitoring, making it suitable for aquaculture applications. The ESP32 microcontroller, equipped with built-in Wi-Fi and Bluetooth, offers both data processing and wireless communication capabilities (Chen et al., 2021). When combined with sensors such as the pH 4502C, TDS Meter V1.0, and DS18B20, the ESP32 can support reliable and continuous measurement of critical water quality parameters. Despite its advantages, IoT-based systems often face challenges in visualization and user accessibility, particularly for non-technical users.

2.4. Laravel Framework as a Web Platform

Laravel is a PHP-based framework that supports Model-View-Controller (MVC) architecture, modular development, and robust database management (Otwell, 2015). Compared to other frameworks, Laravel offers greater flexibility for integrating real-time data visualization, storage, and export features, making it a practical choice for monitoring applications (Ramadhani et al., 2022). In the context of aquaculture, Laravel enables the development of an interactive and user-friendly dashboard, which empowers farmers to both observe water conditions in real time and analyze historical trends.

2.5. Research Gap

Although prior studies have applied fuzzy logic and IoT for water quality monitoring, most systems lack a comprehensive integration of intelligent decision-making, real-time control, and user-friendly visualization. This study addresses the gap by combining Mamdani fuzzy logic with an IoT-based system and implementing a Laravel web application to deliver a complete solution for automated koi pond water quality management.

3. Methodology

3.1. Research Type

This study is classified as engineering research that combines system design, implementation, and experimental validation. The research adopts a quantitative experimental approach to evaluate the accuracy of sensors, the effectiveness of the fuzzy logic controller, and the responsiveness of the web-based monitoring interface.

3.2. Research Stages

The research methodology was carried out in five main stages: (1) Literature Review and Problem Identification – reviewing related studies and identifying limitations of existing water quality monitoring systems. (2) System Design – developing both hardware (sensor modules, microcontroller, actuators) and software (fuzzy logic rules, web application). (3) System Implementation – assembling hardware components and coding fuzzy logic algorithms on the ESP32, as well as building the Laravel-based web dashboard. (4) Testing and Validation – calibrating sensors, evaluating the performance of fuzzy control, and assessing real-time synchronization between sensors and the web application. (5) Data Analysis – analyzing test results to determine system accuracy, error rate, and overall reliability.

The general scheme of the research stages is illustrated in Figure 1.

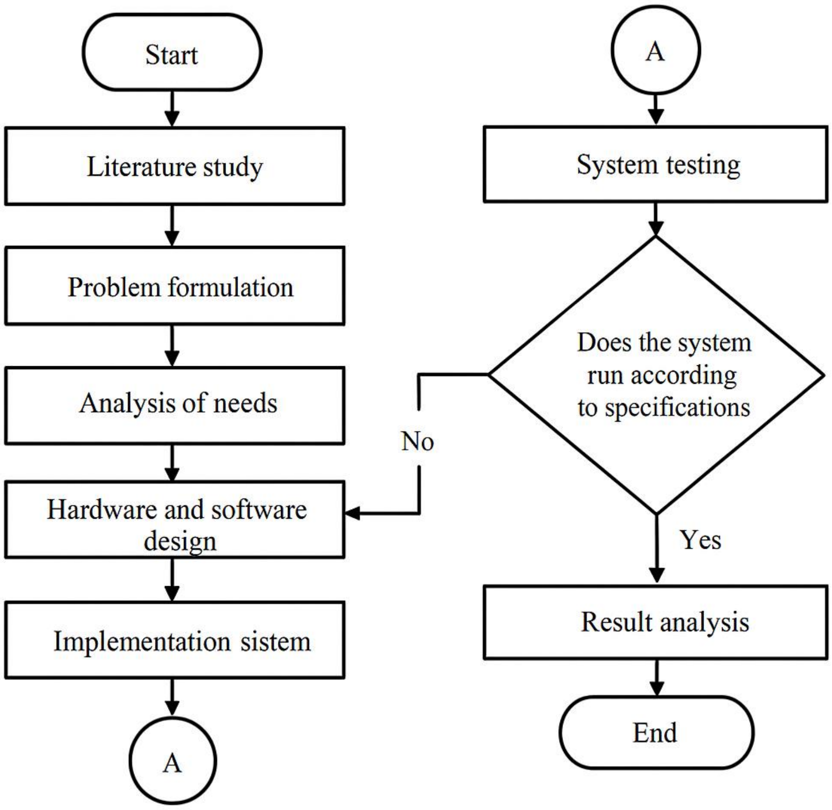

Figure 1: Flowchart of the Research Methodology for the Koi Pond Water Quality Monitoring System

3.3. System Design

3.3.1. Hardware Design

The hardware design aims to develop an automatic control device for water quality based on pH, TDS, and temperature parameters. The main components include: 1) ESP32 as the microcontroller, 2) pH sensor 4502C for detecting water acidity levels, 3) TDS Meter V1.0 for measuring the concentration of dissolved solids, 4) DS18B20 temperature sensor for measuring water temperature, 5) DC mini pump as the actuator for injecting pH up or pH down solutions based on fuzzy logic output, 6) Relay module as the pump control switch

All components are assembled into a single enclosed system using a protective box to enhance equipment durability and safety (Gunawan et al., 2023).

3.3.2. Software and Web Monitoring Design

Sensor data processing and fuzzy logic computation are carried out using the Arduino IDE, after which the data are transmitted via Wi-Fi to a local database. The web interface is developed using the Laravel framework to display real-time water condition information, including a feature for downloading historical data in Excel format.

The application structure follows the Model-View-Controller (MVC) principle, consisting of: 1) Model: manages data from sensors, 2) View: displays data on the web dashboard, 3) Controller: handles decision-making logic and interface interactions. (see: Otwell, 2015; Ramadhani et al., 2022).

3.4. Implementation of Mamdani Fuzzy Logic

The decision-making process in this system applies the Mamdani fuzzy logic method, which is suitable for handling nonlinear and uncertain parameters such as water quality. The system uses two input variables—pH (low, normal, high) and TDS (ideal, moderate, poor)—and two output variables—pH up and pH down solution volume.

3.4.1. Fuzzy Logic Workflow

The membership functions are designed in the form of triangular and trapezoidal shapes, and the inference process is carried out using the Max–Min method. Defuzzification is performed using the Centroid method to determine the final crisp output value (Mamdani & Assilian, 1975; Zadeh, 1965).

The fuzzy logic flow implemented in the system is illustrated in Figure 2.

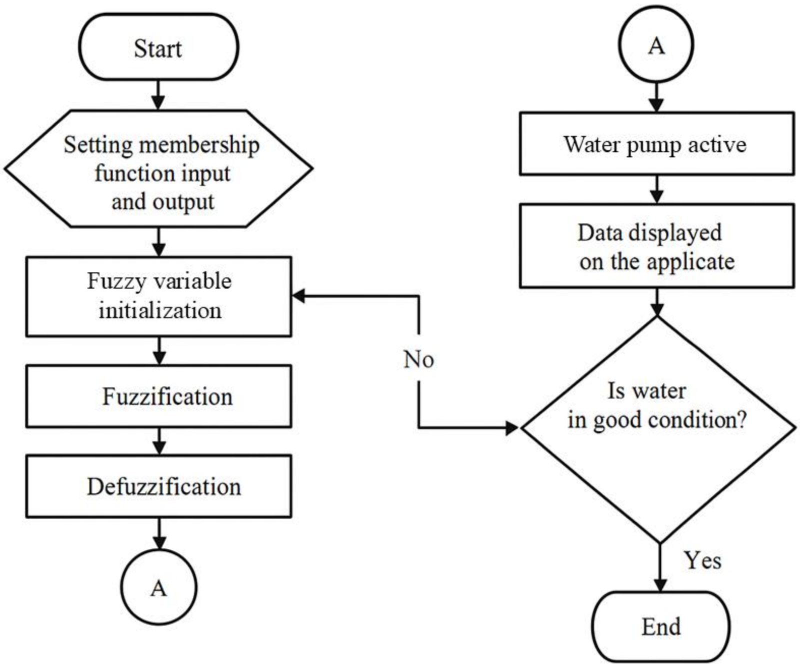

Figure 2: Flowchart of the Mamdani Fuzzy Logic Decision-Making System

3.4.2. Membership Functions

Membership functions were defined using triangular and trapezoidal shapes. For example, the pH input was divided into five categories (very acidic, acidic, normal, alkaline, very alkaline), as shown in Figure 3. The same approach was applied to TDS and control outputs, with ranges adjusted based on aquaculture water quality standards.

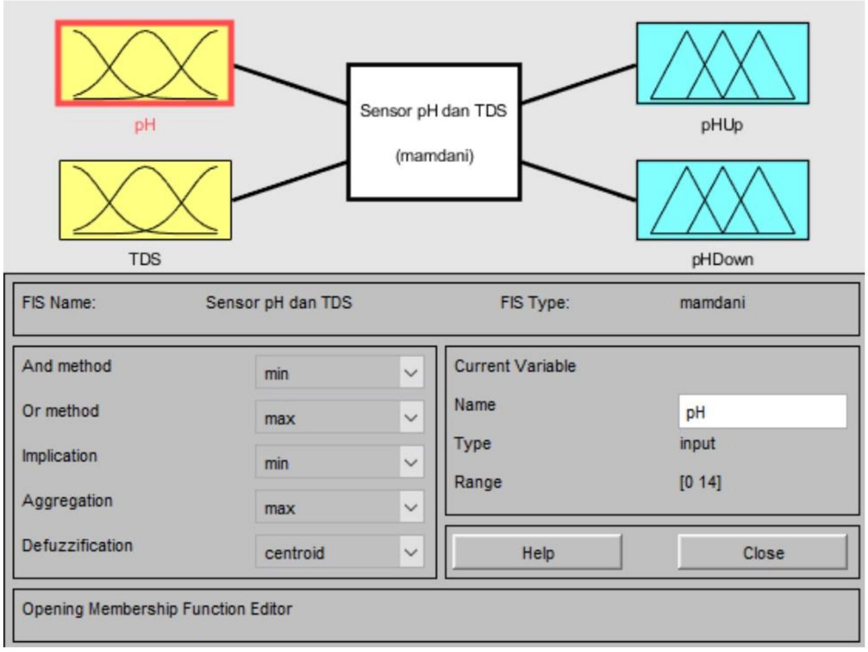

Figure 3: Membership Function for pH Input Variable

Other variables (TDS, pH up, pH down) were structured similarly, but their ranges are summarized in Table 1.

Table 1: Linguistic Terms of Input and Output Variables

Variable	Range (Unit)	Categories
pH	0–14	Very Acidic, Acidic, Normal, Alkaline, Very Alkaline
TDS	0–1000 ppm	Ideal, Moderate, Poor, Very Poor
Output (pH up / pH down, ml)	0–200	Off, Low, Medium, High, Very High

3.4.3. Input–Output Rules

The fuzzy inference process follows the Max–Min method, with rules structured in the form of IF–THEN statements. For example:

1. IF pH is low AND TDS is moderate THEN pH up = medium.
2. IF pH is high AND TDS is ideal THEN pH down = high.
3. IF pH is normal AND TDS is ideal THEN no action.

A representative set of rules is summarized in Table 2.

Table 2: Example of Fuzzy Input–Output Rules

pH Condition	TDS Condition	System Action
Low	Moderate	Pump pH up (medium)
High	Ideal	Pump pH down (high)
Normal	Ideal	No action
High	Poor	Pump pH down (very high)
Low	Poor	Pump pH up (high)

Defuzzification is performed using the Centroid method, producing precise crisp values for pump activation. Testing showed that the fuzzy controller achieved an average error of only 0.93% compared to manual calculations.

3.5. System Testing and Validation

System testing was conducted in three stages: 1) Sensor Calibration: testing the accuracy of pH, TDS, and temperature sensors using reference data. 2) Fuzzy Control Test: observing the system's response in stabilizing water pH through the automatic pump based on input parameters. 3) Web Monitoring Test: observing the accuracy of real-time sensor data displayed on the web interface.

The test results were analyzed quantitatively to evaluate system reliability. The average error of each sensor and the fuzzy control system was recorded, while the performance of the monitoring system was assessed based on the consistency of the data displayed on the web interface.

4. Results and Discussion

4.1. Sensor Performance

Calibration confirmed that all sensors performed accurately. The pH sensor achieved 95.27% accuracy, the TDS sensor 97.95%, and the temperature sensor 98.35% (Table 3).

Table 3: Sensor Calibration Results

Sensor	Accuracy (%)	Error (%)
pH 4502C	95.27	4.73
TDS V1.0	97.95	2.05
DS18B20 Temp	98.35	1.65

These values indicate that the sensor suite is reliable for real-time water quality monitoring.

4.2. Fuzzy Logic Control Performance

The fuzzy system provided outputs consistent with manual and simulation results. An excerpt is shown in Table 4, with an average error of less than 1%.

Table 4: Validation of Fuzzy Logic Controller

Test Type	Expected Output (ml)	System Output (ml)	Error (%)
Manual Calculation	151.4	–	–
Simulation	152.0	–	–
System Implementation	–	149.8	0.93

This proves the effectiveness of Mamdani fuzzy logic in handling fluctuations without overcorrection.

4.3. Web Application Performance

The Laravel-based dashboard successfully displayed real-time data with only a 1–2 second delay. Table 5 shows a sample of monitoring results.

Table 5: Example of Real-Time Monitoring Data

pH	TDS (ppm)	Temp (°C)	Pump Action
6.77	208.8	25.3	None
6.81	216.7	25.3	None
8.40	260.0	25.5	Acid Pump

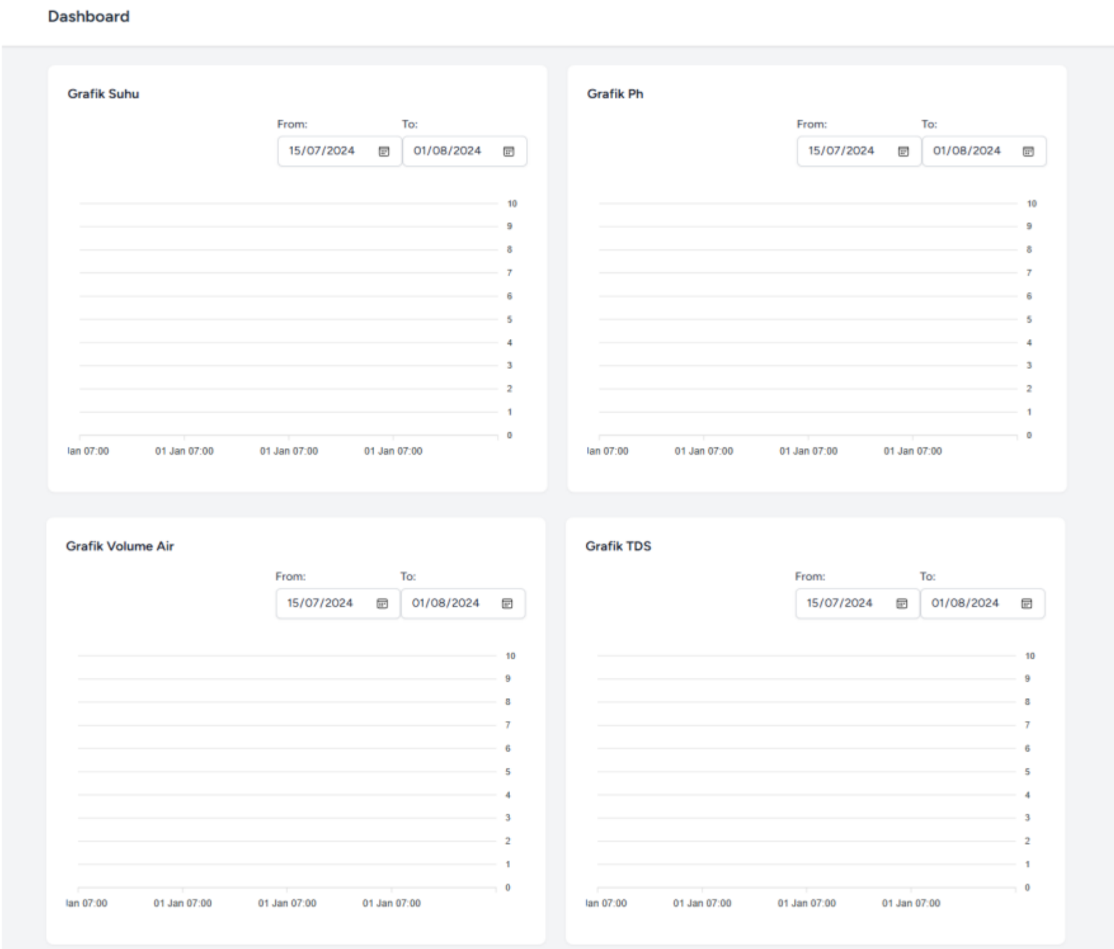

Figure 4: Laravel-Based Web Monitoring Dashboard

4.4. Discussion of Findings

The integration of fuzzy logic, IoT-based monitoring, and a web interface offers three major benefits: (1) Real-time monitoring of water parameters. (2) Automated control, minimizing human error. (3) Data-driven management, enabling farmers to optimize long-term pond maintenance.

Despite its strengths, the system still depends on Wi-Fi and lacks an automatic alert feature. Future work should integrate SMS/email notifications and additional water quality parameters (e.g., dissolved oxygen).

5. Conclusion

This study successfully designed and implemented a web-based water quality control system for koi ponds using the Mamdani fuzzy logic method integrated with the Laravel framework. The system combines pH, TDS, and temperature sensors with an ESP32 microcontroller to enable real-time monitoring and automated control.

Experimental results demonstrated high accuracy, with sensor performance exceeding 95% and the fuzzy logic controller achieving an average error of only 0.93%. The Laravel-based dashboard provided responsive data visualization with minimal delay (1–2 seconds), allowing farmers to observe pond conditions conveniently.

The findings confirm that the system is effective in maintaining optimal water quality, thereby improving aquaculture productivity and reducing the risk of fish mortality. Its main advantages include real-time monitoring, adaptive control, and a user-friendly interface.

Nevertheless, the system still depends on Wi-Fi connectivity and lacks automated alerts for extreme water conditions. Future development should focus on integrating notification features (e.g., SMS or email) and expanding monitoring to additional parameters such as dissolved oxygen or ammonia.

In conclusion, this study contributes to advancing aquaculture management by demonstrating the practical application of fuzzy logic and IoT technology for efficient and reliable koi pond water quality control.

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