



# Implementation Of Fuzzy Logic in The Dissolved Oxygen and pH Control System to Reduce the Risk of Death of Cyprinus Carpio Fish



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## Abstract

Cultivation of *Cyprinus carpio*, commonly known as the goldfish, in aquariums requires strict monitoring of water quality to maintain the fish's health and ensure its survival. Key parameters such as dissolved oxygen and pH greatly affect the aquatic environment, where imbalances can lead to stress or death. This study aims to design and implement a dissolved oxygen and pH control system using *fuzzy logic* as an alternative to traditional PID-based or rule-based systems commonly used in aquaculture. The proposed system automatically detects water conditions (LOW, NORMAL, HIGH) and activates appropriate control responses. It integrates an SEN0237 dissolved oxygen sensor, an E-201C pH sensor, aerators, dosing pumps, and an Arduino-based microcontroller. Sensor data is processed via fuzzy inference to operate actuators—either to increase oxygen levels or inject buffer solutions for pH normalization. Unlike previous studies that focus on single-parameter control or fixed-response systems, this system offers a dual-parameter adaptive control approach. Experimental validation shows that the system maintains pH at 6–7 and DO at 3–4 mg/L, with sensor accuracy exceeding 95%. Over 10 days, fish survival improved in the controlled aquarium (7/10) compared to the uncontrolled aquarium (5/10). The system demonstrates potential to reduce water quality fluctuations, offering hope for a more stable aquaculture environment. This work contributes to the application of fuzzy logic in small-scale innovative aquaculture systems, highlighting its potential advantages over conventional methods.

**Keywords:** *Cyprinus carpio*; Dissolved oxygen; Fuzzy logic; pH.

## 1. Introduction

### Nomenclature

|      |                                                                |
|------|----------------------------------------------------------------|
| DO   | Dissolved Oxygen                                               |
| e    | error                                                          |
| SP   | set point                                                      |
| MV   | manipulation variable                                          |
| PV   | process variable                                               |
| pH   | measure of acidity                                             |
| mg/L | milligram per liter unit for measuring dissolved oxygen levels |

The cultivation of *Cyprinus carpio* (goldfish) in confined systems, such as aquariums, has gained popularity due to its ornamental value and ease of maintenance. However, goldfish are known to have a relatively weak immune system, making them highly sensitive to fluctuations in water quality [1]-[3]. Waste accumulation from uneaten feed, feces, and inadequate water filtration can lead to suboptimal water conditions, increasing the risk of fish mortality. Therefore, continuous monitoring and control of key water quality parameters, primarily dissolved oxygen (DO) and pH, is essential.

Dissolved oxygen (DO) refers to the concentration of oxygen gas dissolved in water at a specific temperature and pressure. It is a crucial parameter in water quality assessment, as insufficient oxygen disrupts aquatic ecosystems and threatens aquatic life [4], [5]. High DO concentrations are typically found in clean water bodies, while reduced levels indicate pollution or eutrophication. DO can be measured using galvanic probe-based sensors such as the SEN0237, which operates through electrochemical reactions between an anode and cathode.

Similarly, pH is another critical parameter influencing ammonia toxicity and fish health [6]-[10]. Elevated pH levels can increase the concentration of unionized ammonia, which is toxic to fish. Measurement is performed using glass electrode-based pH sensors such as the E-201C, which includes a preamplifier to condition the high-impedance signal for reliable acquisition. A pH range between 6 and 8 is generally ideal for goldfish survival.

In aquaculture systems, control strategies are often implemented to stabilize such variables [11]-[17]. A standard control loop comprises a sensor, an actuator, a controller, and a plant, where a manipulated variable (MV) is adjusted to maintain the process variable (PV) close to the set point (SP). Traditional control approaches, such as Proportional-Integral-Derivative (PID) controllers, have been widely used for linear systems. However, PID lacks adaptability when facing nonlinear behaviors, time delays, or multiple interdependent variables—common in aquaculture environments with fluctuating bio-load and temperature.

Recent studies have introduced adaptive and intelligent control methods, such as Artificial Neural Networks (ANN), Internet of Things (IoT)-based systems, and particularly fuzzy logic controllers (FLC), to enhance robustness and autonomy in water quality management. Fuzzy logic is favored for its ability to handle uncertainty, linguistic rules, and approximate reasoning, making it suitable for systems with imprecise inputs and non-linear characteristics [18]-[20]. The fuzzy logic control (FLC) system comprises three main processes: fuzzification, inference, and defuzzification. In the fuzzification stage, crisp sensor inputs such as pH and DO are converted into fuzzy sets (e.g., LOW, NORMAL, HIGH). The inference mechanism evaluates these inputs using a set of heuristic rules, and the defuzzification stage produces a crisp output to actuate devices such as aerators and dosing pumps.

Previous research on fuzzy logic in aquaculture has often focused on single-parameter regulation (e.g., pH or dissolved oxygen, DO) or been applied in larger, commercial-scale systems. In contrast, this study proposes a compact, low-cost fuzzy logic-based control system for simultaneously regulating pH and DO in a small-scale aquarium setup for goldfish cultivation. The system is not only evaluated in terms of parameter stabilization but also in terms of its practical application in improving fish survival. This study introduces a novel approach by integrating fuzzy logic to simultaneously regulate pH and DO in a dual-loop system within an aquarium-scale setup. The validation of this system via survival outcomes fills a significant gap in literature. It paves the way for innovative aquaculture solutions for home-scale or small-scale ornamental fish farming.

## 2. Proposed System Design and Methodology

### 2.1 System Architecture

The aquarium-based control system developed in this study is a compact and easy-to-implement solution designed to monitor and regulate water quality for *Cyprinus carpio* cultivation. The system, hereinafter referred to as the plant, integrates sensor-based automation with the powerful tool of fuzzy logic. This combination ensures the maintenance of optimal ranges for dissolved oxygen and pH levels. A 3D design was developed using SketchUp to visualize the complete hardware layout, as shown in Figure 1.

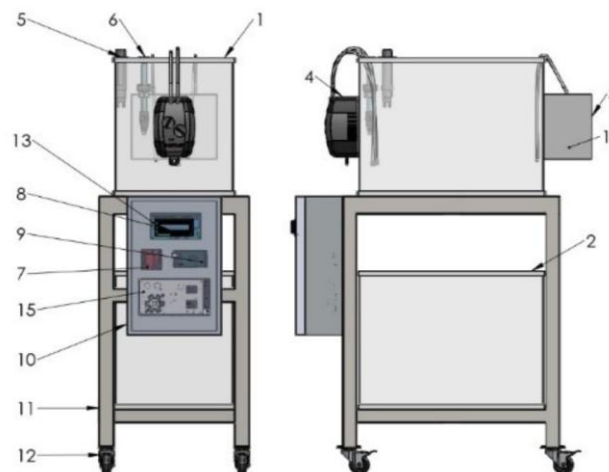


Figure 1. 3D Plant Design

The 3D plant design, with its fifteen main components, is ingeniously integrated into a compact and mobile frame. The system features two aquarium tanks: the primary aquarium tank (1), a transparent acrylic tank measuring  $396 \times 253 \times 282$  mm, equipped with sensors and actuators for water quality control; and the secondary aquarium tank (2), which serves as a control tank without automation for experimental comparison. Both tanks are supported by a steel frame with swivel caster wheels (3), ensuring easy mobility and flexibility in system placement. Inside the primary tank, a dissolved oxygen (DO) sensor (4) of type SEN0237 measures oxygen concentration in mg/L using galvanic probe technology. In contrast, a pH sensor probe (5) of type E-201C monitors the acidity or alkalinity of the water, connected to a signal conditioning preamplifier. To maintain optimal oxygen levels, an aerator (6) is installed to inject air into the water when DO readings drop below the set point. On the right side of the frame, there are two buffer solution storage units: the acid buffer tank (7), which stores acid solution for lowering pH when the water becomes too alkaline, and the base buffer tank (8), which stores alkaline solution for raising pH when it becomes too acidic. Both buffer tanks are connected to dosing pumps (9) that inject precise amounts of acid or base into the aquarium through a tubing system (10) consisting of flexible hoses. The control system is powered by an Arduino Mega 2560 microcontroller (11), which processes real-time sensor data and executes fuzzy logic algorithms to determine the necessary actuator actions. A relay module (12) is used to safely control high-power devices such as the aerator and dosing pumps. The relay module acts as a switch, allowing the microcontroller to control the high-power devices without being directly connected to them, ensuring safety and efficient operation. At the same time, a power supply unit (13) provides regulated DC power to all electronic components. All control electronics are housed within a control panel enclosure (14) mounted on the frame to protect them from environmental exposure. Finally, a well-organized wiring harness (15) connects all sensors, actuators, and the controller, ensuring reliable power delivery and data transmission throughout the system.

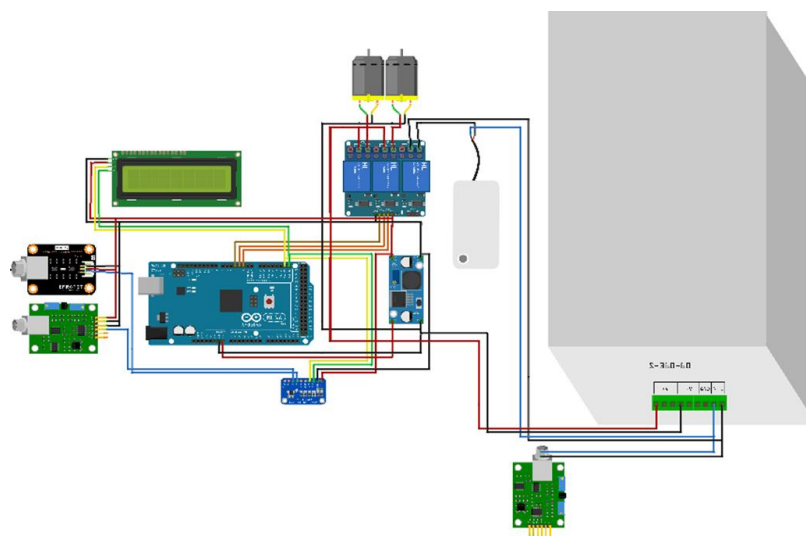


Figure 2. Wiring Diagram of the System

Figure 2 shows the wiring integration of the SEN0237 sensor, pH sensor, aerator, dosing pumps, and microcontroller. The control logic is as follows: when the dissolved oxygen (DO) level is LOW, the aerator is activated until the normal set point is reached; when the pH is LOW (acidic), the base buffer pump is activated; and when the pH is HIGH (alkaline), the acid buffer pump is triggered.

## 2.2 Experiment Setup of Fuzzy Logic Control System

The fuzzy logic control system begins by identifying the key environmental variables: pH and dissolved oxygen (DO). These variables are categorized into linguistic fuzzy sets using triangular membership functions. The selection of membership functions and rule bases was informed by expert knowledge and prior empirical studies on goldfish tolerance levels. Initial parameters were tuned through trial and error during system prototyping, and adjustments were made based on sensor feedback.

Table 1. Input and Output Variables for Fuzzy Control

| Input Variable   | Fuzzy Set                | Output Variable      | Fuzzy Set     |
|------------------|--------------------------|----------------------|---------------|
| pH               | <i>Low, Normal, High</i> | Alkaline Dosing Pump | <i>ON OFF</i> |
| Dissolved Oxygen | <i>Low, Normal, High</i> | Acid Dosing Pump     | <i>ON OFF</i> |
|                  |                          | Aerator              | <i>ON OFF</i> |

The use of fuzzy logic is particularly advantageous in aquaculture applications due to its ability to handle uncertainties and nonlinearities in biological and environmental processes. Traditional PID controllers, while effective in linear systems, are less adaptive to the fluctuating and unpredictable nature of aquatic ecosystems. In contrast, fuzzy logic can make decisions based on approximate reasoning, a feature that instills confidence in its ability to handle uncertainties. This mimics the way humans make decisions, especially when dealing with complex interactions between water quality parameters.

Disturbances in pH and DO levels are corrected automatically by the fuzzy system. Table 1 illustrates the fuzzy inference process, from input detection to actuator activation. In the fuzzification stage, crisp values obtained from the pH and DO sensors are converted into fuzzy values based on the defined membership functions. These fuzzy inputs are then evaluated using a rule base that consists of "IF-THEN" statements. For example, a rule might state: "IF pH is Low AND DO is Normal THEN activate alkaline dosing pump." The inference engine processes these rules in parallel and produces fuzzy outputs, which are then aggregated and defuzzified to produce a crisp actuator control signal.

For example, if the system detects a low pH and normal DO, only the base dosing pump is activated. When DO is LOW, the aerator is turned on. If both parameters are optimal, the system remains idle. These rule-based decisions form the basis for real-time adaptive control.

Table 2 presents the membership function ranges for pH, while Table 3 provides the corresponding ranges for dissolved oxygen (DO), both of which are tailored to the aquarium environment. These triangular membership functions ensure smooth transitions between fuzzy sets, allowing the control system to make gradual adjustments rather than abrupt changes. This gradual response is not just a feature, but a necessity in aquaculture, as sudden fluctuations in chemical parameters can stress or harm the fish. The defined ranges also provide flexibility for fine-tuning, enabling future optimization according to the specific tolerance thresholds of goldfish or other aquatic species. By carefully adjusting the overlap between sets, the system can achieve an optimal balance between responsiveness and stability in maintaining water quality.

Table 2. Membership function ranges of pH

| Membership Function pH               | Input Variable pH               |
|--------------------------------------|---------------------------------|
| Low                                  | [0 3 6]                         |
| Normal                               | [5 7 9]                         |
| High                                 | [8 11 14]                       |
| Membership Function Dissolved Oxygen | Input Variable Dissolved Oxygen |
| Low                                  | [0 2 4]                         |

Table 3. Membership function ranges of Dissolved Oxygen

| Membership Function pH | Input Variable pH |
|------------------------|-------------------|
| Low                    | [0 2 4]           |
| Normal                 | [3 4 5]           |
| High                   | [4 6 8]           |

2.3 Experiment Setup

Figure 4 illustrates the plant frame, which serves as the experimental testbed for data collection. Two aquarium tanks were used to represent different experimental conditions: the upper tank (1), referred to as the primary tank, was

equipped with a fuzzy logic-based control system, while the lower tank (2) served as the control tank with no automation installed. Both tanks are mounted on a steel frame with swivel wheels (3), which are designed to allow easy relocation of the system, ensuring flexibility in the experiment's setup. Inside the primary tank, the dissolved oxygen (DO) sensor (4) of type SEN0237 continuously measures oxygen levels, while the pH sensor probe (5) of type E-201C monitors water acidity or alkalinity. An aerator (6) is installed to inject air into the water when DO readings fall below the desired set point, ensuring oxygen levels remain within optimal ranges.

On the right side of the frame, the acid buffer tank (7) stores acidic solution to lower the pH when the water becomes too alkaline. At the same time, the base buffer tank (8) contains alkaline solution to raise the pH when it becomes too acidic. Both buffer tanks are connected to dosing pumps (9), which play a crucial role in the system by injecting precise amounts of acid or base into the primary tank according to the control commands generated by the fuzzy logic algorithm. Each component in the system is positioned to maximize efficiency, ease of maintenance, and accurate data collection during the experimental period.

The purpose of this experimental setup was to evaluate the system's effectiveness in maintaining water quality parameters and its impact on fish survival. The aquariums, each measuring  $396 \times 253 \times 282$  mm, were placed in an indoor environment with stable lighting. Ambient room conditions were maintained at a temperature range of  $20^{\circ}\text{C}$  to  $25^{\circ}\text{C}$  and relative humidity between 50% and 70%.

Despite the use of only two tanks, the setup was meticulously designed to ensure uniformity and minimize external variation. While this limited scale does not allow for statistical generalization, this preliminary experiment is focused on demonstrating technical feasibility, functional performance, and early survival outcomes to inspire larger future trials.

The sensors were strategically placed inside the tanks to optimize real-time data collection. The E-201C pH sensor and the SEN0237 dissolved oxygen (DO) sensor were submerged in the aquarium water to monitor pH levels and DO continuously. Prior to experimentation, both sensors underwent meticulous calibration using standard buffer solutions (pH) and DO calibration kits, ensuring the accuracy of the data collected.

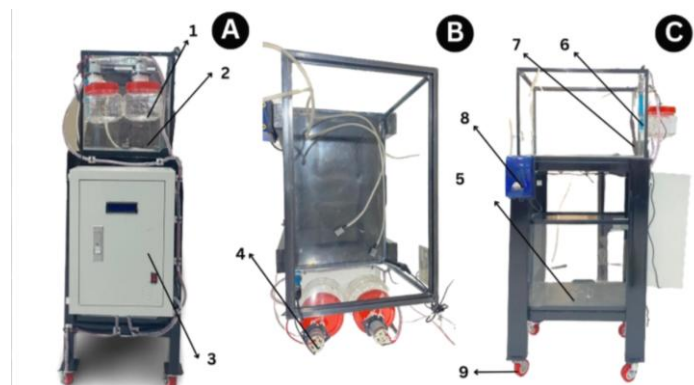


Figure 4. Plant Framework: (a) side view, (b) top view of primary tank, (c) front view

Sensor validation was performed by comparing output voltages to reference measurements, establishing linear regressions for each sensor. Data from both tanks were collected every second for 10 consecutive days using the Arduino Mega microcontroller. Daily fish survival was recorded manually.

To evaluate the system's adaptability, intentional disturbances such as pH shifts (via acid or base buffer injection) and extreme DO changes (using zero-oxygen solutions) were introduced. The system's response to these fluctuations—such as triggering the appropriate dosing pump or aerator—was recorded. This provided intriguing insights into the responsiveness and fault tolerance of the fuzzy logic system. Overall, this experimental procedure was designed to assess the real-time control performance and survivability impact of the fuzzy-based aquarium system under basic but realistic aquaculture conditions.

### 3. Results and Discussion

#### 3.1 System Performance

The fuzzy logic-based aquarium system has consistently demonstrated its ability to maintain stable pH and dissolved oxygen (DO) levels over a 10-day period. Before the application of fuzzy logic, the accuracy of the sensors was rigorously validated against standard reference instruments, ensuring the system's reliability.

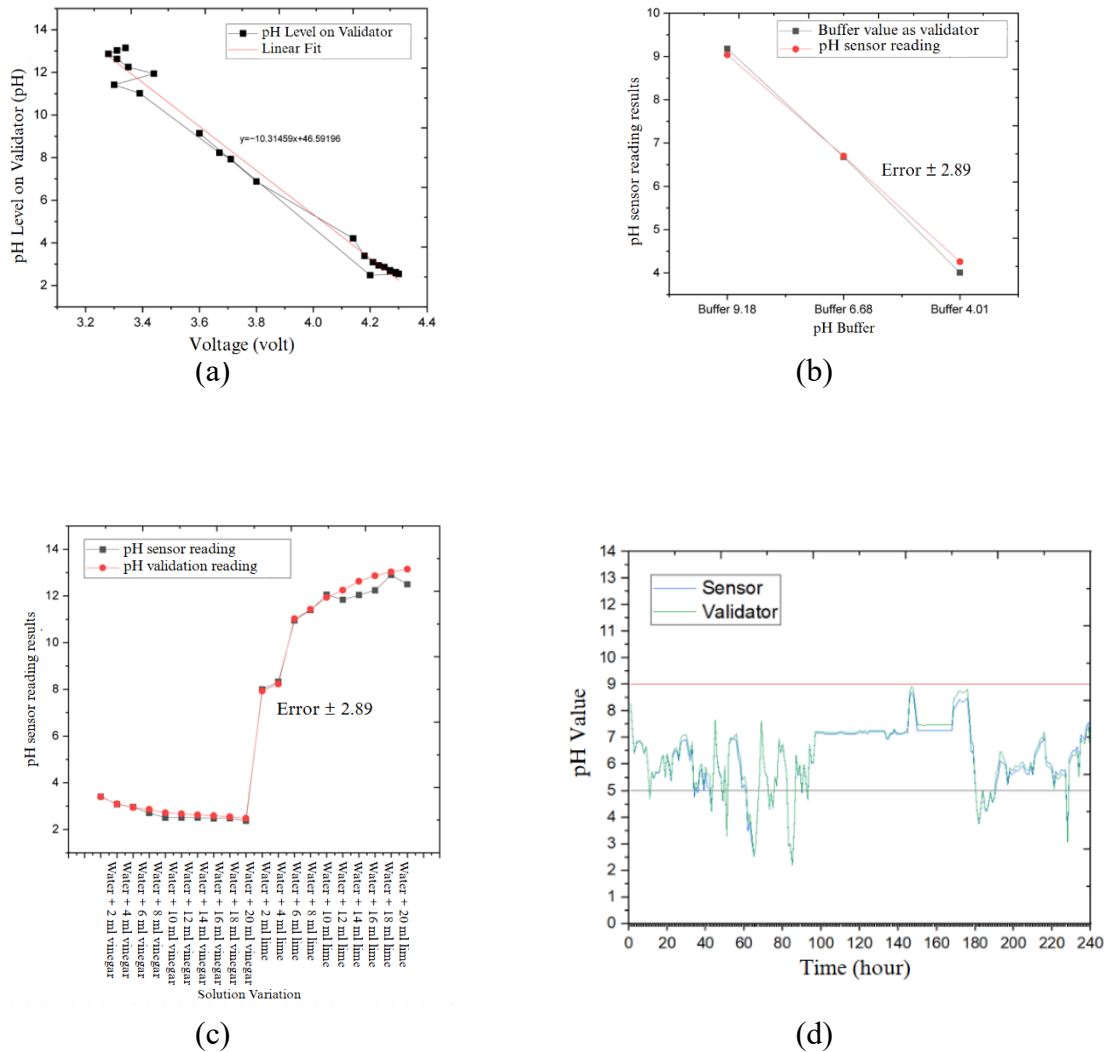


Figure 5. Validation and performance of the pH sensor under various conditions: (a) Calibration using standard solutions to determine linear regression, (b) Validation using commercial pH buffer solutions, (c) Sensor response to different water compositions, (d) Real-time pH regulation using fuzzy logic control in the aquarium

Figure 5(a–c) presents validation of pH measurements under various conditions. The results show a strong linear correlation ( $R^2 > 0.95$ ) with an error margin of  $\pm 2.89$  and an accuracy of 97.06%. Figure 5(d) demonstrates that under fuzzy control, the system was able to maintain pH within the desired range (6–7) despite intentional disturbances. This level of control precision is crucial in aquaculture systems, as pH imbalances can directly impact fish metabolism, oxygen uptake, and immune response. By automatically regulating pH through dosing pumps based on fuzzy inference, the system minimizes human error and ensures consistency in aquatic conditions. The system's rapid recovery of pH values after buffer injection, as indicated by the data log, underscores its ability to handle disturbances effectively.

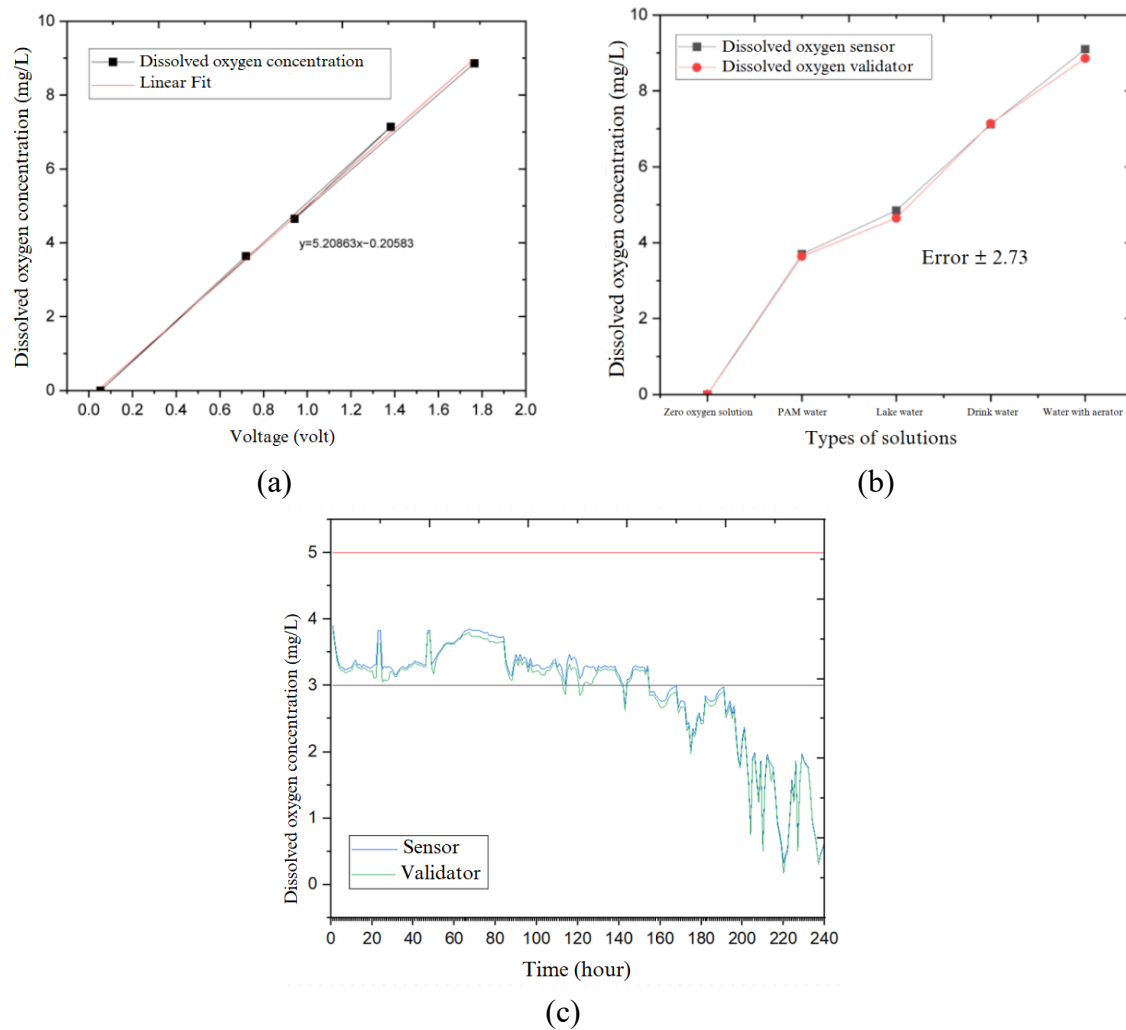


Figure 6. Validation and performance of the dissolved oxygen (DO) sensor under different conditions:

- (a) Calibration using standard DO solutions for linear regression analysis,
- (b) Sensor response to DO variations in prepared test samples
- (c) Real-time DO regulation under fuzzy logic control in the aquarium system

Figures 6(a–b) confirm the accuracy of the DO sensor with a margin of error of  $\pm 2.73$  and 97.23% accuracy. Figure 6(c) illustrates how fuzzy logic effectively maintained DO levels, although a gradual decline was observed on certain days. This decline is likely due to external factors such as turbidity and Total Dissolved Solids (TDS), which were not measured in this system. Water temperature variations may also affect sensor reading and DO solubility. Therefore, integrating sensors for TDS and temperature is recommended for future system iterations. In biological systems, multiple nonlinear factors, including microbial respiration, fish movement, and aeration efficiency, influence dynamics. The fuzzy logic controller's ability to interpret approximate input data and provide proportionate output actions makes it suitable for such complex environments. The declining DO trend in Figure 6(c) further emphasizes the need for a multivariable control strategy in future versions of the system, potentially using multivariable fuzzy control or integration with artificial neural networks.

Under the control of fuzzy logic, the system consistently maintained DO within 3–5 mg/L and pH within 5–9, as evidenced in Figures 5(d) and 6(c). This performance is a clear demonstration of the system's adaptive behavior, as it adjusts actuators in response to real-time input and rule-based inference. Table 4 presents the actuator responses to varying pH conditions. The output from the fuzzy logic rule base matched real actuator performance, validating system consistency.

Table 4. Comparison between fuzzy logic rule base and actual actuator responses for pH regulation.

| <b>Input</b>    | <b>Output (Rule Base)</b> |                             | <b>Output (Real Condition)</b> |                             |
|-----------------|---------------------------|-----------------------------|--------------------------------|-----------------------------|
| <b>PH Value</b> | <b>Acid Dosing Pump</b>   | <b>Alkaline dosing pump</b> | <b>Acid Dosing Pump</b>        | <b>Alkaline dosing pump</b> |
| High (8-14)     | ON                        | OFF                         | ON                             | OFF                         |
| Low (0-6)       | OFF                       | ON                          | OFF                            | ON                          |
| Normal (5-9)    | OFF                       | OFF                         | OFF                            | OFF                         |

Similarly, Table 5 shows aerator response based on DO conditions, with correct durations for each DO range. For example, when the pH level dropped below 5 (indicating an acidic environment), the system correctly activated the base buffer pump to restore pH balance. When compared to conventional systems such as PID controllers, the fuzzy logic system stands out for its flexibility in responding to nonlinear and uncertain conditions.

Table 5. Comparison between fuzzy logic rule base and actual actuator responses for dissolved oxygen regulation.

| <b>Input Dissolved Oxygen Value</b> | <b>Output (Rule Base) Aerator</b> | <b>Time (minute)</b> | <b>Output (Real Condition) Aerator</b> | <b>Time (minute)</b> |
|-------------------------------------|-----------------------------------|----------------------|----------------------------------------|----------------------|
| Low (0-4 mg/L)                      | ON                                | 12                   | ON                                     | 12                   |
| High (4-8 mg/L)                     | OFF                               | 0                    | OFF                                    | 0                    |
| Normal (3-5 mg/L)                   | ON                                | 4                    | ON                                     | 4                    |

As demonstrated in previous studies, fuzzy logic provides robustness in environments with fluctuating parameters, such as DO, pH, and temperature. Unlike basic IoT-based monitoring, this system offers automated control, not just passive data collection. Although no statistical tests were applied due to the limited sample size, future studies will utilize inferential statistics (e.g., ANOVA) on replicated tanks to validate the system's effectiveness.

### 3.2 Fish Survival Analysis

The implementation of the fuzzy logic control system has significantly reduced the mortality of goldfish while maintaining stable environmental conditions. Figure 7 presents a comparison graph of fish survival rates in the aquarium with and without the control system. The goldfish that survived in the aquarium with the control system were 7 out of 10 fish, while the fish that survived in the aquarium without the control system were only five fish.

These results validate the system's ability to create an optimal environment for goldfish development in the aquarium. Importantly, these observations align with recent literature, which has reported increased growth in length in catfish with adaptive control systems, providing further reassurance about the validity and relevance of our research.

Figure 7. presents a comparison of fish survival rates in two different aquarium conditions: one without a control system and one with a fuzzy logic control system. The data shows a clear difference in survival rates, with the control system significantly improving the chances of goldfish survival. This comparison underscores the advanced capabilities of fuzzy logic control systems in optimizing environmental parameters for the survival of goldfish. These findings not only demonstrate the potential of fuzzy control systems to enhance the productivity of aquarium goldfish farming but also inspire further research.

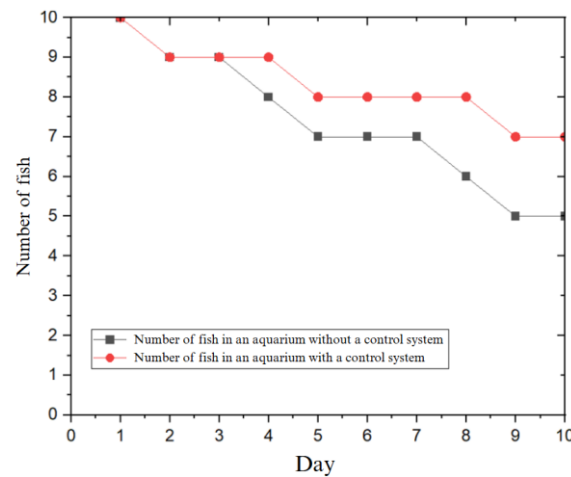


Figure 7. Comparison of fish survival in aquariums with and without fuzzy logic control

The refinement of the control algorithm and exploration of additional variables, such as turbidity, temperature, and TDS levels, as well as the implementation of filtration systems, hold promise for significantly improving the adaptability and overall effectiveness of the system, thereby shaping the future of aquaculture.

#### 4. Conclusions

Our study's findings underscore the significant impact of the developed dissolved oxygen (DO) and pH control systems. This system, which utilizes fuzzy logic to maintain water quality stability in *Cyprinus carpio* aquariums effectively, is a crucial advancement in aquaculture. The system's high sensor accuracy, with 98.04% for pH and 96.92% for DO, and its ability to automatically regulate both parameters to remain within the optimal range under varying conditions, highlight its importance in aquaculture. Furthermore, the application of this control system had a positive impact on fish survival, with 70% (7 out of 10 fish) survival in the aquarium equipped with the system, compared to 50% (5 out of 10 fish) in the aquarium without control, over a 10-day observation period. These results suggest that automated fuzzy control can enhance fish health and reduce mortality risk by maintaining consistent environmental conditions. While the current system is limited to two ecological variables—pH and DO, there is significant potential for future improvements. To further enhance system effectiveness and adaptability, future developments could consider integrating additional parameters such as temperature, turbidity, ammonia, and total dissolved solids (TDS), as well as implementing filtration subsystems. Scaling the study with larger sample sizes and statistical validation is also recommended to support broader application in innovative aquaculture systems.

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