A fuzzy logic-driven system for precise water quality monitoring and management in enhancing aquatic farming

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Abstract

Constraints on natural resources and global warming have made premium seafood a global issue in modern culture. By implementing fish farming IoT technologies, seafood production can increase significantly by optimizing resource consumption and improving fish growth rates. Such objectives require control, measurement, and monitoring of parameters like temperature, pH, water level, and feeding rate, along with fish growth structure. Proper farming of fish is crucial to global food production; hence, suitable water parameters are fundamental for the development and wellbeing of aquatic organisms. This work offers a flexible, efficient method by using a precise water quality monitoring and maintenance system (PWQM&M) for AF pools. This work is distinguished by using fuzzy logic to AF systems aiming at improving the management and boost accuracy to overcome the system rigidity of conventional fuzzy-based control systems. By doing so, superior performance is achieved in terms of autonomy, responsiveness, and speed while facilitating dynamic Water Quality (WQ) with no human input. WQ monitoring adds value to increasing system performance; controlling AF systems with such complexity enables local WQM manipulation on the diverse parameters of AF environments. An operation test of 48 hours at which appropriate particle levels of oxygen and salt are maintained demonstrates the efficacy for the purpose. This demonstrates the system's effectiveness and their performance in real-world scenarios.

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Overview of the Work

AF is among the biggest and most rapidly expanding areas of food manufacturing worldwide and is anticipated to be pivotal in meeting upcoming seafood demands. AF involves cultivating, developing, and collecting diverse fish species in containers and pools within a completely or partially regulated ecosystem to provide aquatic goods throughout the year (Ali *et al.,* 2020). This sector is often recommended for investment because it facilitates continuous seafood production, yielding a 45% higher output than traditional fishing methods (Valenti *et al.,* 2021).

WQ is essential for maximizing production and fostering the growth of wholesome fish. WQ criteria include the pH level, temperature, DO, conductance, and limited chemicals (Oblomurodov *et al.,* 2024). An imbalance in the necessary characteristics of water results in significant water contamination and exhaustion of resources, causing various illnesses in fish and unforeseen expenses, respectively (Hemathilake and Gunathilake, 2022; Branitskiy *et al.,* 2019). Consequently, managing WQ and resource management is essential for harmonizing total operating costs and assessing fish health in aquariums. The most effective management and successful use of resource strategies for AF systems were presented, considering economic characteristics using different optimization methods (Radhakrishnan, Velanganni and Paranthaman, 2024; Wu and Margarita, 2024).

Many of these remedies focus on enhancing aquaculture systems' managerial and financial dimensions by considering the harvesting season, business category, and customer preferences. Nonetheless, these investigations mostly concentrate on establishing a broad economic architecture and do not address the ecological characteristics of fish tanks (Bernardos *et al.,* 2010). Additional research has investigated the effects of many variables, such as fish cost and death rate, to determine the ideal AF feeding strategy (Akhter *et al.,* 2021; Jaiswal and Pradhan, 2023). Consequently, there is an urgent need for improved AF methodologies that promote AF operations by optimizing ecological circumstances (Nakamura and Lindholm, 2025). Moreover, practical optimum control approaches are crucial for addressing several obstacles in implementing real-world AF systems influenced by diverse interior and exterior environmental factors (Nakamura and O'Donnell, 2025). Contemporary AF systems may integrate advanced technologies and techniques, including IoT, deep learning (DL), enhancement, and optimal management theory. Traditional management methods are inadequate owing to the many biological restrictions inherent in the AF ecosystem and its vital elements (Fonseca *et al.,* 2022). Ideal AF management is typically framed as an optimization task to achieve desired development and wholesome fish output, effective resource usage, and ideal surroundings governed by various limitations, including the quality of water, ecological principles, control variables, and user-specified elements (Rastegari *et al.,* 2023; Papadopoulos and Christodoulou, 2024).

Fish farming output and ecological oversight have been much enhanced by FL methods in AF. Authors in (Pillai and Bhatia, 2024) developed a system using FL controllers to monitor and improve fish tank water quality and ecological factors. Real-time management of fish farms made possible by this technology helps to automatically monitor important variables affecting fish growth and productivity. Using IoT-based solutions in aquaculture means large expenses because of the necessary organizational and technical requirements. Small-scale growers will find it less accessible if one uses gauges, controllers, and networking technologies as they complicate matters (Singhal, Yadav and Dwivedi, 2024; Amaliah *et al.,* 2023). Moreover, IoT systems are prone to technological problems that need for constant maintenance and expert advice, hence driving running expenses (Kumar *et al.*, 2020; Bhatia and Bansal, 2024). While producers with limited technological knowledge face difficulties due to the need for technical skills, the accumulation of significant elements raises questions about data security and safety. Employing IoT-based technology to track AF operations triggers issues regarding ecological implications, potential consequences, connectivity, and capacity restrictions. This proposed research intends to improve the efficiency and lifespan of IoT-based PWQM&M for AF by addressing existing limitations and gaps. This ensures that these technologies mitigate possible risks and adverse issues while still providing unambiguous advantages to farmers (Yang *et al.,* 2021).

PWQM & M Using FL and IoT for AF

This work focuses on a particular problem concerning the PWQM&M in AF tanks. The goal is to construct the framework around solving AF problems. Incorporating sophisticated FL methods will no doubt make it easier. Improving architecture AF data systems makes tank management tasks easier and more accurate. The system integrates information from all the sensors which include temperature, pH, DO, ambient atmosphere, and salinity. This data is passed to the AWS Cloud using an IoT network with the Message Queuing Telemetry Transport Protocol (MQTT).

The system ensures continuous Data Stream with uniform Information Dissemination and Membership Schemes. This allows for quick changes, such as turning air intakes and water pumps on, to maintain the appropriate water quality (WQ) levels crucial for sustaining fish and other aquatic organisms. The system as a whole satisfies present day production needs by consistently delivering performance with the ability of real time data transfer. In addition to providing uninterrupted technical maintenance support for tracking WQ and maximizing output from the AF system, the method offers reliable results. Imminent application of the technique has demonstrated remarkable concentrations of DO and saltiness suitable for a 48-hour run time. This tool is useful for AF farmers as it enables them to remotely monitor and adjust the pool water conditions, thereby increasing operating efficiency and production within the sector.

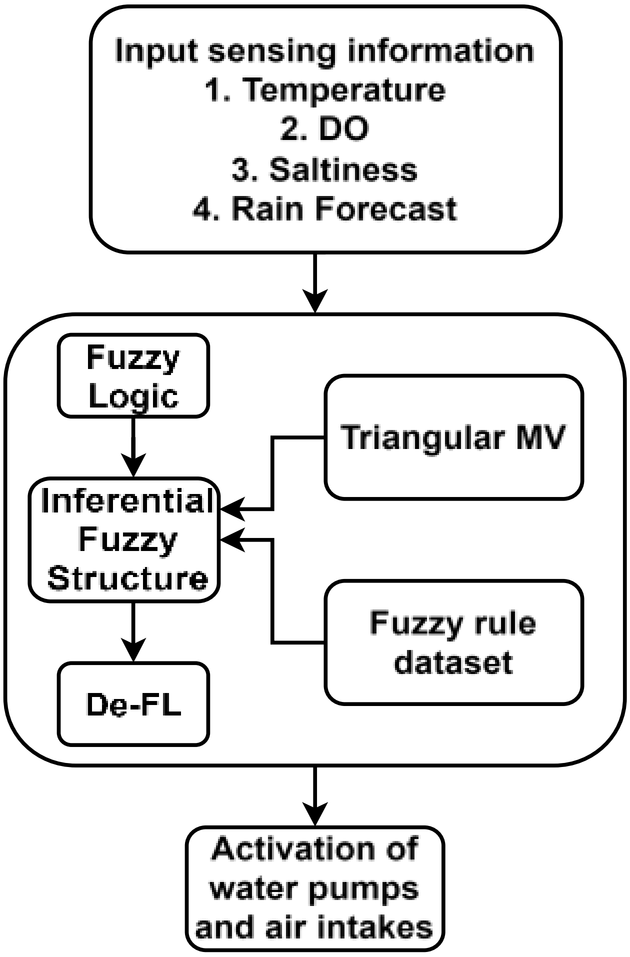

Figure 1: Inferential fuzzy structure.

Computational Modeling

The major emphasis of the FL-based methodology is the objective of making choices. This approach depends on collecting incomplete facts to aid choice-making, where factors like levels of truth and the veracity of assertions are essential. In contrast to conventional sets, FL sets include a wider range of membership assignments. In situations requiring experiential remedies, the membership value (MV) parameter is essential for incorporating FL into the collection. This MV is included in the inferential fuzzy structure, using a mean-weighted method for execution.

This research directs inputs into the FL rule basis structure, producing outputs based on the acquired values. This study includes four principal input variables: temperature (°C), DO (ppm), saltiness (ppt), and rain forecast (RF), as seen in Figure 1. The MV of every input value is crucial in establishing the number of standards, with three MV assigned to every variable, culminating in a total of 25 rules. The simplified FL interpretation for the proposed PWQM&M using FL and IoT is given in Algorithm 1:

Algorithm 1: Simplified Logical Interpretation for PWQM&M using FL and IoT

1. High Temperature & High DO:

- If Saltiness is High and No Rain Forecast (RF = No):

→ Air Intake: OFF, Water Pump: ON.

- If Saltiness is Low and No Rain Forecast:

→ TSS Low:

→ Air Intake: OFF, Water Pump: OFF or ON, depending on condition variations.

2. Low Temperature & Low DO:

- If Saltiness is High and Rain Forecast (RF = Yes):

→ Air Intake: ON, Water Pump: OFF.

- If Saltiness is Low and Rain Forecast:

→ Air Intake: ON, Water Pump: OFF or ON (depending on water salinity or quality).

- If Saltiness is Medium and Rain Forecast:

→ Air Intake: ON, Water Pump: OFF or ON.

3. High Temperature & Medium DO:

- If Saltiness is Very High and No Rain Forecast:

→ Air Intake: ON, Water Pump: ON.

4. High Temperature & High DO & Very High Saltiness:

- If No Rain Forecast:

→ Air Intake: OFF, Water Pump: ON.

5. Low Temperature & Low DO & Very High Saltiness:

- If Rain Forecast:

→ Air Intake: ON, Water Pump: ON.

Low temperature + Low DO always causes Air Intake to be ON for oxygen delivery regardless of saltiness; the Water Pump is ON or OFF depending on salt level and rain. High temperature + high DO generally keeps air intake OFF but water pump ON, particularly in high and very high saltiness circumstances. Even in cases of non-expected rain, medium DO, and very high saltiness support air intake, and the water pump is ON. Generally activating Air Intake ON, Rain Forecast (RF = Yes) focuses on preserving DO under unstable conditions.

Results and Discussion

This section delineates the results of the suggested PWQM&M system using FL and IoT, emphasizing its efficacy in sustaining ideal circumstances for AF for 48 hours.

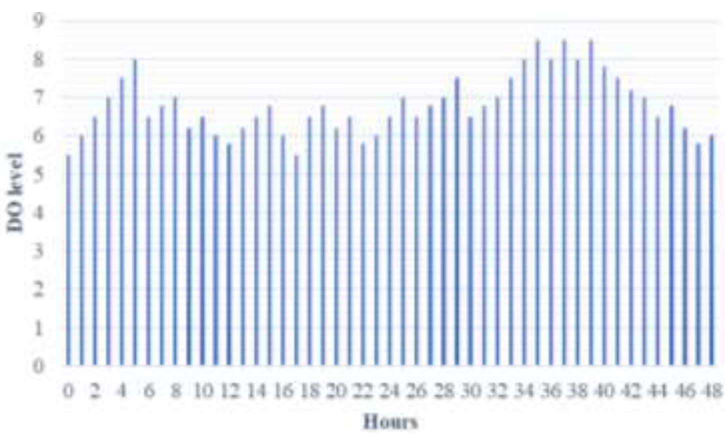

Figure 2: DO (ppm) values observed during the first 48 hours in the PWQM & M system.

The DO values observed during the first 48 hours in Figure 2 demonstrate a steady trend with little variations, indicating efficient aeration and WQ control inside the system. Initially, DO levels consistently increase from roughly 5.5 mg/L to about 8.5 mg/L by the 35th hour, indicating improved oxygenation presumably resulting from favorable environmental and operating circumstances. After this high, a small decrease is seen, with concentrations between 6 and 7 mg/L, indicating an equilibrium between oxygen use by aquatic species and replenishment via aeration systems. The continuous range of dissolved oxygen is essential for the health and development of aquatic species, indicating that the management technique efficiently maintains an appropriate environment for AF operations.

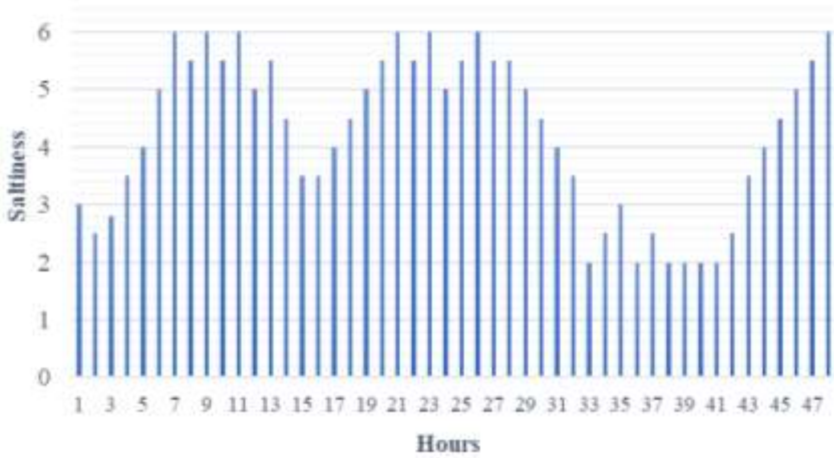

Figure 3: Saltiness (ppt) values observed during the first 48 hours in the PWQM & M system.

Examining saltiness throughout a 48-hour observation period in Figure 3 indicates significant variations in the aquatic ecosystem. During the first ten hours, salinity measurements initially rise steadily from 3.0 ppt to a maximum of 6.0 ppt, indicating likely higher mineral concentration either from evaporation or decreased freshwater intake. Salinity values vary between 5.0 and 6.0 ppt between hours 10 and 30, suggesting a largely constant, albeit slightly changing, salinity phase. After 30 hours, there is a considerable drop in saltiness, ranging from around 2.0 to 2.5 ppt between 33 and 40 hours, most likely related to an intake of freshwater, like precipitation or vigorous pumping activities. Saltiness increases gradually as the 48-hour period ends, peaked at 6.0 ppt by the 48th hour, therefore highlighting the dynamic properties of the aquatic system moulded by both natural and controlled environmental forces.

Conclusion

This study presents an effective and flexible approach by using a precise water quality monitoring and maintenance system (PWQM & M) for AF pools. Unlike current systems, the proposed approach specifically combines IoT technology with fuzzy logic (FL) to increase the accuracy and flexibility of pool management. This guarantees suitable water quality on its own, therefore offering a consistent and efficient option for AF pool control. This study is unusual in that it uses FL to address the challenging properties and variety of AF configurations, therefore allowing sophisticated control options that enhance WQM. A 48-hour operational test revealed the method's effectiveness as it maintained appropriate DO and salinity levels, therefore highlighting its stability and value in practical uses. By means of PWQM&M and fast problem detection, the findings confirm the efficacy of the system and underline its practical advantages, thereby fitting the needs of AF production and greatly improving efficiency.

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