Adaptive Fuzzy-IoT framework for real-time water quality regulation in Guppy Aquaculture

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Abstract. Water quality instability and inefficient manual monitoring are critical challenges in guppy fish cultivation that directly affect survival rates. To address these issues, this study presents Smart AquaLoop, an intelligent automated system designed to maintain water temperature and turbidity stability using an adaptive control mechanism. The research contribution is the development of a closed-loop control framework that integrates Fuzzy Logic with Internet of Things (IoT) to achieve real-time, autonomous environmental regulation. The methodology involves continuously monitoring temperature and turbidity via DS18B20 and TDS sensors connected to an ESP32 microcontroller. These inputs are processed using a Fuzzy Inference System to dynamically adjust the Pulse Width Modulation (PWM) duty cycles of the heater, cooling fan, and filtration pump. Experimental results demonstrate that the system effectively stabilizes water temperature within the optimal range of 25–28 °C despite external fluctuations. Furthermore, the system successfully reduces Total Dissolved Solids (TDS) levels from a turbid condition of approximately 500 ppm to a stable 300 ppm. In specific testing scenarios, the fuzzy controller accurately modulated the pump speed with a PWM value of around 102 to address high turbidity while keeping energy consumption efficient. The system also exhibited rapid response times in activating cooling or heating actuators based on precise fuzzy rule-based decisions. In conclusion, Smart AquaLoop significantly improves operational efficiency and minimizes fish stress, offering a robust solution for sustainable smart aquaculture.

1 Introduction

Aquaculture relies heavily on the precise regulation of physical and chemical parameters of water, as these factors govern the biological thermodynamics and metabolic rates of aquatic life. For ornamental fish cultivation such as guppy (*Poecilia reticulata*), deviations in thermal energy (temperature) and particulate concentration (measured as Total Dissolved Solids or TDS) directly impact osmotic pressure and respiratory efficiency. Key parameters such as temperature, pH, dissolved oxygen (DO), and TDS must be carefully controlled to prevent stress, diseases, and mortality in fish populations [1], [2], [3]. However, conventional manual monitoring suffers from significant latency, making it difficult to compensate for rapid thermodynamic fluctuations or sudden spikes in turbidity caused by biological waste accumulation [4], [5], [6], [7], [8]. These limitations highlight the need for an automatic and adaptive water quality control system capable of maintaining stable conditions within optimal ranges.

The rapid development of the Internet of Things (IoT) has transformed various sectors, including aquaculture, enabling real-time data acquisition, monitoring, and control through networked smart devices [9], [10], [11], [12]. IoT-based monitoring systems allow for automated data transmission from sensors to cloud platforms, providing continuous oversight of environmental conditions. From a control systems perspective, an aquatic environment is a nonlinear dynamic system characterized by uncertainty and time-varying disturbances. to ensure an effective response to the nonlinear and uncertain nature of aquatic environments, an intelligent control approach is required. Fuzzy logic control offers an efficient solution by mimicking human reasoning in handling imprecise and uncertain data [13], [14].

Several studies have implemented IoT and fuzzy-based systems in water quality management. Zaelani et al. [15] developed an IoT-based automatic control system for guppy aquaculture using pH and temperature sensors, maintaining temperature stability between 23–27°C with a low measurement error of 0.126%. Similarly, Nurhidayati et al. [16] designed a fuzzy-based control system to regulate pH and salinity in shrimp ponds, successfully maintaining optimal parameters using controlled chemical dosing. These studies demonstrate the potential of integrating fuzzy logic with IoT technologies for adaptive and autonomous aquaculture management. Nevertheless, previous systems often operated under open-loop configurations or limited control variables, leading to slower responses to dynamic environmental changes.

To address these limitations, this study proposes Smart AquaLoop, an IoT-integrated closed-loop fuzzy control system designed to stabilize the water quality

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parameters in guppy aquaculture. The research contribution is the development of a fully integrated closed-loop control framework that combines real-time IoT monitoring with an adaptive Fuzzy Logic algorithm to handle nonlinear environmental disturbances. Unlike previous approaches, this system utilizes Pulse Width Modulation (PWM) to dynamically adjust the duty cycles of heaters, Peltier coolers, and filtration pumps, ensuring precise stabilization of temperature and turbidity while optimizing energy efficiency. This study also contributes to the application of intelligent systems in supporting the Sustainable Development Goals (SDGs), particularly Goal 9, by advancing digital transformation in the aquaculture industry [17], [18], [19], [20], [21], [22], [23], [24], [25]. Additionally, it supports Indonesia's Asta Cita vision for 2045, promoting technology-driven entrepreneurship and intelligent system development to enhance local industries and welfare.

2 Methodology

As in any control system, inputs and outputs are required to achieve the final stabilization results. In this research, the inputs are the water-temperature and turbidity sensors, while the outputs are: (i) temperature regulation via the Peltier cooler and heater for controlled water temperature, and (ii) filtration-system control. The measured temperature and turbidity are adjusted by the designed fuzzy controller to match the ideal ecosystem needs of guppies. The schematic diagram of the system—comprising inputs, processing, and outputs—is presented in Fig. 1.

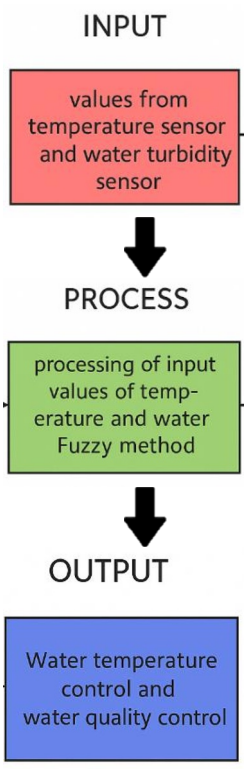

Fig. 1. Process flow of the water-quality stabilization system for guppies.

2.1 Fuzzification

In this stage, variables are converted into fuzzy sets to handle uncertainties in changing aquarium conditions. The Smart AquaLoop membership functions include:

- Input variables: (a) TDS sensor with categories Clean, Moderate, Turbid, and Highly Turbid; (b) Water-temperature sensor with categories Cold, Normal, and Hot.
- Output variables: (a) Filter pump with categories Off, Low, Medium, and High; (b) Cooling fan with categories Off and On.

2.2 Fuzzy inference

Fuzzy inference derives the output values based on pre-formulated fuzzy rules. This process applies IF–THEN rules to the fuzzified inputs. Examples include:

1. If TDS is Clean and Temperature is Cold, then Pump = Off, Cooling Fan = Off, and Heater = On.
2. If TDS is Highly Turbid and Temperature is Hot, then Pump = High, Cooling Fan = On, and Heater = Off.

After applying these rules, the membership values of the fuzzy outputs are computed for defuzzification.

2.3 Defuzzification

Defuzzification converts fuzzy inference results into concrete numerical values usable by the automatic control system. The centroid (center of gravity) method is used:

Output = Σ(membership × output value) / Σ(membership)

Example: For a pump with Low (μ=0.75, value=90) and Medium (μ=0.25, value=140), the output PWM = 102.5. Thus, the pump is set to 102 PWM, the cooling fan remains Off, and the heater remains Off.

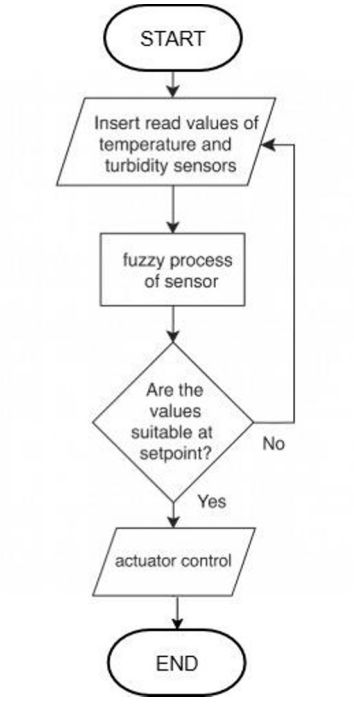

Fig. 2. Research system flowchart.

The data collected are processed by an adaptive fuzzy logic algorithm, enabling the system to make automatic decisions for adjusting water conditions through actuators such as the heater and aeration pump. The electronic circuit of the Smart AquaLoop is shown in Fig. 3.

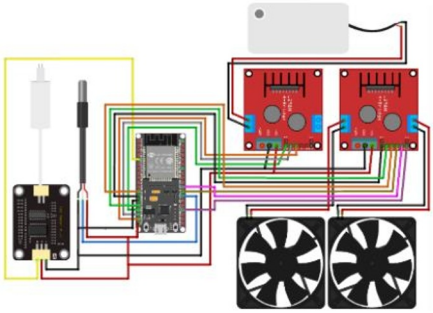

Fig. 3. Smart AquaLoop electronic circuit.

Smart AquaLoop integrates intelligent sensors and actuators to maintain stable water conditions in real time. The main components are:

1. Aquarium: a glass tank equipped with temperature and turbidity sensors.
2. Sensors: DS18B20 (temperature) and TDS (turbidity) sensors.
   Filtration & Heating/Cooling Compartment: includes a filter and a Peltier-heater combination for automatic temperature regulation.
3. Pump and Water Flow: controlled via PWM from fuzzy outputs to maintain circulation.
4. ESP32 Microcontroller: processes fuzzy logic operations and controls actuators.
5. Power Supply and DC Motor Driver: provide stable operation and direction control.
6. User Interface (Blynk): allows remote monitoring and control of temperature, TDS, and actuator status in real time.

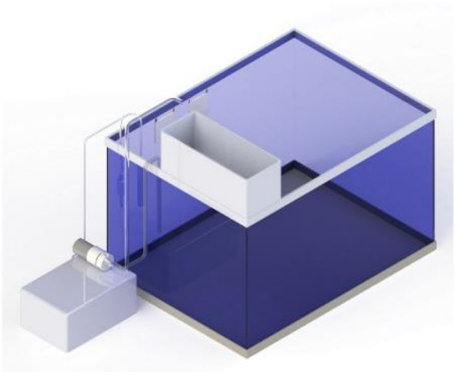

Fig. 4. User interface layout.

3 Result and discussion

The implementation results of the device design are shown in Fig. 5.

Fig. 5. Device design implementation.

The implemented user interface design of the Smart AquaLoop system using the Blynk platform is presented in Fig. 6.

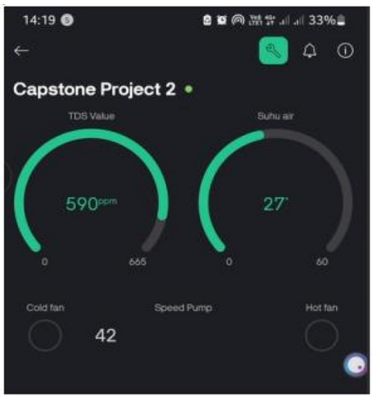

Fig. 6. User interface display.

The research included testing by designing and developing the Smart AquaLoop system — a closed-loop control system based on fuzzy logic — to automatically stabilize water quality in guppy aquaculture tanks.

The system uses two input sensors, the DS18B20 temperature sensor and the TDS sensor for water turbidity, producing outputs in the form of water-pump speed (PWM) and the on/off states of the cooling and heating fans.

The system was tested in an aquarium over a certain observation period under various water-quality scenarios. The results of the experiments are summarized below:

1. First Test: When the water temperature was 27°C and the TDS value was 590 ppm, the system categorized the temperature as normal and TDS as turbid. The pump actuator was activated with a PWM value of 42, while both the cooling and heating fans remained off, as shown in Fig. 7.

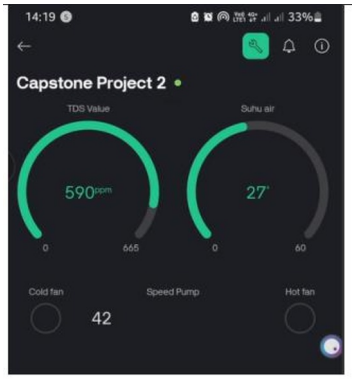

Fig. 7. First test result.

2. Second Test: When the temperature was 13°C and the TDS value was 66 ppm, the temperature was categorized as cold and TDS as clean. The pump was inactive (PWM = 0), the cooling fan was off, and the heater was on, as shown in Fig. 8.

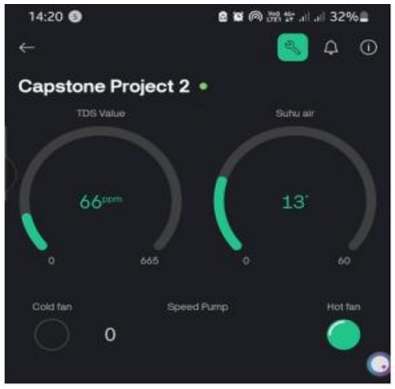

Fig. 8. Second test result.

3. Third Test: When the temperature was 60°C and the TDS value was 66 ppm, the system categorized the temperature as hot and TDS as clean. The pump was inactive (PWM = 0), the cooling fan was activated, and the heater was turned off, as shown in Fig. 9.

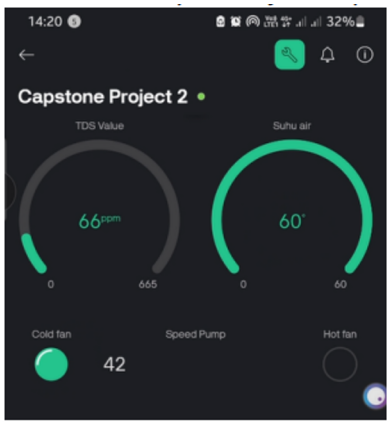

Fig. 9. Third test result.

The complete results of the fuzzy output and control actions are summarized in Table 1 (System Testing Data).

Table 1. System testing data.

No	Water Temp (°C)	Turbidity (ppm)	Temp Category	TDS Category	Pump PWM	Cooling Fan	Heater
1	27	590	Normal	Turbid	42	OFF	OFF
2	60	66	Hot	Clean	42	ON	OFF
3	13	66	Cold	Clean	0 (OFF)	OFF	ON
4	15	609	Cold	Highly Turbid	42	OFF	ON
5	27	132	Normal	Clean	0 (OFF)	OFF	OFF
6	20	66	Cold	Clean	0 (OFF)	OFF	ON
7	25	85	Normal	Clean	0 (OFF)	OFF	OFF
8	40	593	Hot	Turbid	42	ON	OFF
9	17	561	Cold	Turbid	40	OFF	ON
10	28	629	Normal	Highly Turbid	42	OFF	OFF

The testing results of the Smart AquaLoop system demonstrate its ability to automatically and adaptively respond to various water-quality conditions. The system operates using two main parameters—temperature and TDS level—which are categorized into several fuzzy sets: cold, normal, hot for temperature and clean, moderate, turbid, highly turbid for TDS. Based on these classifications, the system applies fuzzy-inference rules to determine the outputs: pump speed (PWM value), cooling fan status, and heater status. This process enables more flexible and precise control decisions than conventional threshold-based systems. Ten test scenarios with different temperature–TDS combinations were conducted, representing diverse environmental conditions that may occur in aquaculture tanks. For instance, at 27°C and 590 ppm, the system identified normal temperature and turbid water, activating the pump at PWM = 42, while both fans remained off because the temperature was still within the optimal range. Conversely, when the temperature reached 60°C with clean water (66 ppm), the system activated the cooling fan and turned off the heater and pump. In contrast, at 13°C with clean water, the system prioritized the heater to maintain thermal comfort for the fish while disabling the pump and cooling fan. The system's ability to generate specific responses for different input conditions highlights the effectiveness of fuzzy logic through fuzzification, inference, and defuzzification processes. Moreover, the PWM-based control provided smooth and energy-efficient operation by avoiding abrupt actuator transitions. Only the necessary actuators were activated (e.g., pump only, or heater only), resulting in optimized power usage while maintaining stable water quality and supporting a healthy environment for guppy growth.

3.1 Main findings of the present study

The testing results of the Smart AquaLoop system demonstrate its ability to automatically and adaptively respond to various water-quality conditions. The system operates using two main parameters—temperature and TDS level—which are categorized into several fuzzy sets. Based on these classifications, the system applies fuzzy-inference rules to determine the outputs: pump speed (PWM value), cooling fan status, and heater status. The experimental data confirms that the fuzzy logic controller successfully maintained water temperature within the optimal range of 25–28°C and reduced turbidity levels from approximately 500 ppm to a stable 300 ppm. Unlike simple ON/OFF switches, the system generated precise PWM outputs (e.g., PWM = 42 for moderate turbidity), ensuring that the filtration pump operated proportionally to the level of water contamination.

3.2 Comparison with other studies

To evaluate the effectiveness of the proposed system, these results were compared with previous similar works. Zaelani et al. [15] developed an IoT-based monitoring system for guppy aquaculture that achieved

high measurement precision (0.126% error) but primarily operated as a monitoring tool with basic control functions. In contrast, Smart AquaLoop extends this capability by integrating a fully closed-loop fuzzy control system that not only monitors but actively regulates environmental parameters without human intervention. Furthermore, while Nurhidayati et al. [16] successfully applied fuzzy logic for pH and salinity control in shrimp ponds using chemical dosing, this study demonstrates the application of fuzzy logic for mechanical actuators (pumps and thermal regulators) using Pulse Width Modulation (PWM). The use of PWM in Smart AquaLoop allows for smoother transitions in actuator speed compared to the discrete switching methods often found in conventional threshold-based systems cited in recent literature [4]–[8.

3.3 Implication and explanation of findings

The ability of the system to generate specific responses for different input conditions highlights the effectiveness of the fuzzification, inference, and defuzzification processes. Scientifically, the use of PWM-based control implies a reduction in energy consumption and mechanical stress on the equipment. By avoiding abrupt "hard stops" and "hard starts" typical of conventional control systems, the Smart AquaLoop minimizes fluctuations that could cause thermal shock to the fish. For instance, at 13°C, the system prioritized the heater while disabling the pump and cooling fan, effectively mimicking a homeostatic response to preserve thermal equilibrium. This adaptive capability ensures that the metabolic rates of the guppy fish, which are poikilothermic organisms, remain stable, thereby directly contributing to reduced stress and lower mortality rates.

3.4 Strengths and limitations

The primary strength of this study lies in its integration of IoT for real-time data visibility and Fuzzy Logic for autonomous, non-linear decision-making. The dual-variable control (Temperature and TDS) within a single logic block allows for complex scenario handling that single-variable systems cannot achieve. However, this study has limitations. As observed during the high-temperature testing (Test 3), the cooling fan exhibited a slower response time compared to the heater due to the thermal inertia of the water volume and the heat transfer coefficient of the Peltier cooling mechanism. Additionally, the sensors showed minor sensitivity to electrical interference in the prototype circuit. Future iterations of this system would benefit from improved electromagnetic shielding and the integration of dissolved oxygen (DO) sensors to provide a more holistic water quality management solution.

4 Conclusion and suggestions

This study successfully designed and validated Smart AquaLoop, a closed-loop control system integrating Internet of Things (IoT) with Fuzzy Logic to automate water quality regulation in guppy aquaculturtime. Experimental results demonstrate that the system effectively maintained water temperature within the optimal range of 25–28°C and reduced turbidity levels (TDS) from an initial high of approximately 500 ppm to a stable 300 ppm. By utilizing adaptive fuzzy inference, the system generated precise defuzzification outputs, such as automatically adjusting the filtration pump to a PWM value of approximately 102 during turbid conditions, thereby minimizing fish stress and reducing reliance on manual intervention. The primary theoretical contribution of this article is the formulation of a multi-variable fuzzy control model that directly maps non-linear environmental inputs to continuous actuator outputs via Pulse Width Modulation (PWM). This represents a significant advancement over conventional threshold-based (ON/OFF) systems and open-loop configurations found in previous research. The integration of PWM-based pump speed control with combined heating and cooling actuators enhances energy efficiency by activating only the necessary components, resulting in faster and smoother stabilization of both temperature and water clarity. Despite these promising results, certain limitations were observed, specifically the sensitivity of sensors to electrical interference and the slower thermal response of the cooling fan compared to the heater. To address these challenges and motivate further research, future work should focus on optimizing hardware shielding against noise and improving the thermodynamic efficiency of the cooling subsystem. Additionally, expanding the control framework to include pH and Dissolved Oxygen (DO) sensors is recommended to provide a comprehensive, autonomous ecosystem for sustainable aquaculture.

References

1. R. Pramana, Perancangan sistem kontrol dan monitoring kualitas air dan suhu air pada kolam budidaya ikan. Jurnal Sustainable. **7**, 1, 13–23 (2018). https://doi.org/10.31629/sustainable.v7i1.435
2. Monitoring Kualitas Air pada Aquarium Berbasis IoT. Jurnal Ilmu Bersama. (2023)
3. Pengembangan Sistem IoT untuk Pemantauan Kualitas Air Kolam. JTERA. (2023)
4. IoT-Based Fish Farm Water Quality Monitoring System. Sensors. (2022)
5. Pengembangan Alat Monitoring Kualitas Air dan Pemberian Pakan Otomatis Berbasis IoT untuk Budidaya Ikan Lele. JEED. (2023)
6. Memonitor Kualitas Air Kolam Ikan Nila Berbasis Internet of Things. Jurnal PNK. (2023)
7. Sistem Pemantauan Kualitas Air Kolam Berbasis Internet of Things (IoT) untuk Ikan Nila. Jurnal TMIT. (2024)
8. R. P. Shete, IoT-enabled effective real-time water quality monitoring method for aquaculture. MethodsX. 102906 (2024). https://doi.org/10.1016/j.mex.2024.102906
9. N. A. B. M. Jais et al., Improved accuracy in IoT-Based water quality monitoring for Asian seabass fish farming. Scientific Reports. (2024)
10. M. Flores-Iwasaki et al., Internet of Things (IoT) Sensors for Water Quality Monitoring in Aquaculture Systems: A

Systematic Review and Bibliometric Analysis. AgriEngineering. (2025). https://doi.org/10.3390/agriengineering7030078

11. S. Kanwal, M. Abdullah, S. Kumar et al., An Optimal Internet of Things-Driven Intelligent Decision-Making System for Real-Time Fishpond Water Quality Monitoring and Species Survival. Sensors. **24**, 23, 7842 (2024). https://doi.org/10.3390/s24237842
12. S. Sharma, S. Mallik, M. K. Dubey, Technological Advancements in Aquaculture Water Quality Monitoring: A Brief Review. Egyptian Journal of Aquatic Biology & Fisheries. (2025)
13. M. A. Irwansyah, M. S. Said, A. M. Islah, Sistem Monitoring Kualitas Air pada Budidaya Ikan Air Tawar Berbasis Internet of Things. Simtek: Jurnal Sistem Informasi dan Teknik Komputer. **9**, 2, 346–354 (2024). https://doi.org/10.51876/simtek.v9i2.1395
14. Sistem Monitoring Kualitas Air dan Otomatisasi Budidaya Ikan Gurame Berbasis IoT. Jurnal Tekno Binadarma. (2023)
15. Sistem Monitoring Kualitas Air Kolam Lele Berbasis Internet of Things (IoT). JRES1. (2023). https://doi.org/10.36982/jinig.v1i2.3649
16. Sistem Monitoring dan Kontrol Kualitas Air pada Kolam Ikan Koi Berbasis Internet of Things (IoT). UNISSULA. (2023)
17. Sistem Monitoring Kualitas Air Kolam Ikan Koi dan Kontrol Otomatis Berbasis IoT. Zetroem. **7**, 1, (2025). https://doi.org/10.36526/ztr.v7i1.5003
18. Sistem Pendeteksi Kualitas Air Berbasis IoT pada Budidaya Tambak di Desa Karangrejo, Kab. Demak. JITET. **13**, 1, (2024). https://doi.org/10.23960/jitet.v13i1.5910
19. An Integrated Smart Pond Water Quality Monitoring and Fish-Recommender System. Sensors. (2023)
20. Development of an IoT-based Intensive Aquaculture Monitoring System with Automatic Water Correction. (2022)
21. S. Kumar, S. Sau, K. Roy, Role of IoT and machine learning in aquaculture monitoring and control: A review. Aquacultural Engineering. 96, 102224 (2022). https://doi.org/10.1016/j.aquaeng.2021.102224
22. M. Shafiq, H. Tian, Y. Bashir, X. Du, M. Guizani, IoT based smart aquaculture system: A review. Sensors. **22**, 1, 45 (2022)
23. A. H. M. Almawgani, An IoT-Based Smart Aquaculture System with Automatic Water Quality Management. Sustainability. **14**, 7, 3820 (2022)
24. T. Q. Dinh, T. H. Nguyen, IoT-Based Automated Water Quality Monitoring and Control System for Aquaculture. Journal of Sensors. 666555 (2021)
25. K. S. Bhatia, S. Sharma, K. Kumar, A novel fuzzy logic-based intelligent system for efficient water quality management in aquaculture using IoT. IEEE Access. **11**, 12345–12356 (2023)