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Design of an IoT-Based Monitoring and Control System for Catfish Cultivation Using Sugeno Fuzzy Logic

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Abstract

Water quality is a crucial factor in catfish farming because it directly affects fish growth and survival. However, manual water quality monitoring makes it difficult for farmers to detect changes in conditions quickly and accurately. This study aims to design and implement an Internet of Things (IoT)-based water quality monitoring and control system for ponds using Sugeno fuzzy logic to support efficient and adaptive catfish farming. The system is designed using an ESP32 microcontroller integrated with pH (PH405), temperature (DS18B20), TDS (SEN0244), and water level (HC-SR04) sensors. The system development method uses the Extreme Programming (XP) approach with planning, design, coding, and testing stages. The system displays sensor data in real-time through the Blynk application and a 20x4 I2C LCD, and stores data in the Firebase Realtime Database. Decisions on water drainage and refilling are made automatically based on the evaluation of pH and TDS parameters using Sugeno fuzzy logic. Test results show that the system is capable of automatically and accurately responding to unfavorable water conditions. This system has proven effective in continuously monitoring and controlling pond water quality, providing a practical solution for farmers to reduce the risk of fish mortality due to deteriorating water quality.

***Keywords**: Internet of Things, Catfish Farming, Fuzzy Sugeno, ESP32, Water Quality, Pond Automation*

1. Introduction

The development of Internet of Things (IoT) technology has had a significant impact on various aspects of human life, including the fishing industry. This technology enables physical devices such as sensors and actuators to connect to each other via the internet, allowing them to exchange data and communicate automatically without direct human intervention [1]. In the context of freshwater fish farming, the application of IoT offers a promising solution for enhancing the efficiency of real-time and continuous monitoring of pond water quality.

One of the most commonly farmed freshwater fish species is the catfish. In addition to being easy to raise, this fish has high economic value with steadily increasing market demand. The success of catfish farming heavily depends on water quality, particularly pH, temperature, and total dissolved solids (TDS) parameters, which influence fish metabolism, growth processes, and resilience. Imbalances in these parameters can cause stress in fish, slow growth, and even trigger mass mortality, resulting in economic losses for farmers [2].

In East Sumba Regency, East Nusa Tenggara, the trend in catfish farming shows an increase in production from 778 kg in 2017 to 2.5 tons in 2018. Total production from 2019 to 2022 reached 18 tons, indicating significant potential in this sector [3]. However, in the farming process, monitoring pond water quality using conventional and non-continuous methods remains one of the main challenges faced by farmers in maintaining pond environmental quality. Monitoring with this method also has limitations in terms of time and measurement accuracy, causing rapid changes in water conditions to go undetected promptly, resulting in delayed responses to issues [4].

As a solution, an automated system based on fuzzy logic is used in this study to manage uncertainty in decision-making related to water conditions. Sugeno fuzzy logic is considered effective because it can interpret data from various sensors and provide automatic responses based on linguistic rules [5].

Previous studies have demonstrated the successful application of Internet of Things (IoT) technology in pond water quality monitoring systems. Soambaton et al. [6] developed a tilapia pond monitoring system using ammonia, temperature, water level, and pH sensors. Hidayat et al. [7] designed a pH and temperature monitoring device for catfish ponds based on ESP8266, yielding valid measurement results. Nursobah et al. [8] built a prototype telemetry system for monitoring the temperature and pH of tilapia pond water, which can be monitored through the MyCayenne application. Prasetya et al. [4] designed a web-based system for monitoring the temperature, pH, and water level of gurami ponds, as well as controlling feeding and drainage. Meanwhile, Suhartono et al. [9] implemented an IoT system for automatic temperature control.

Based on the above description, this study aims to design an Internet of Things-based monitoring and control system for catfish ponds that can measure pH, temperature, and TDS parameters in real-time. The system was developed using the Extreme Programming (XP) method, which encourages active collaboration between developers and stakeholders and emphasizes strong communication, flexibility, and responsiveness to changing user needs [10]. The system uses an ESP32 as the main controller, integrated sensors such as PH405 to measure water acidity, HC-SR04 to measure water level, SEN0244 to measure total dissolved solids (TDS), and DS18B20 to measure pond water temperature, as well as a relay actuator to activate the water pump. In addition, the system is supported by the application of Sugeno fuzzy logic as a smart and flexible decision-making mechanism in determining the need for pool water replacement [11].

2. Research Methods

In this study, the Extreme Programming (XP) method was used as a system development approach because it is considered flexible and capable of responding quickly and efficiently to changes in user requirements. The XP method consists of planning, design, coding, and testing as illustrated in figure 1.

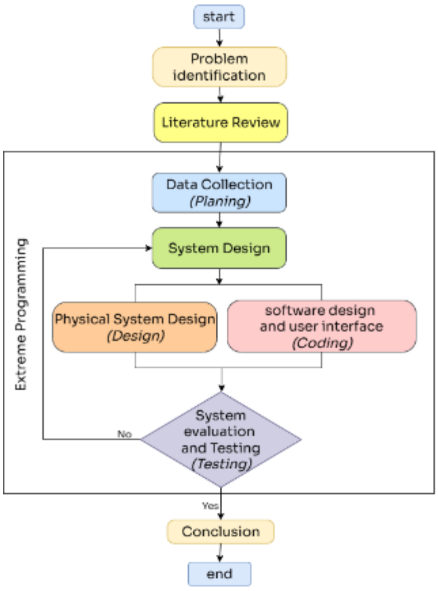


Fig. 1: Steps in the research process

1. Data Collection and Analysis (Planning)

The initial stage of system development began with data collection and analysis through literature studies, field observations, and direct interviews with catfish farmers. Literature studies were conducted to understand the working principles of pH, temperature (DS18B20), and TDS sensors, as well as the implementation of Sugeno fuzzy logic in water quality monitoring systems. Additionally, references related to IoT platforms such as Blynk and Firebase were reviewed to ensure technical compatibility of the system. Field observations were conducted at one of the catfish farming locations in East Sumba Regency to identify the challenges faced by farmers in the water quality monitoring process. From the observations, it was found that most farmers still rely on conventional methods such as observing fish movement and detecting water pond odors, to evaluate water quality. Interviews with farmers were additionally carried out to directly identify system requirements, including preferences for automatic notifications and an autonomous water drainage mechanism in response to declining water quality. The results of this phase were used as the basis for designing an adaptive system tailored to real-world conditions on-site, as well as the foundation for developing fuzzy parameters and selecting the sensors and actuators to be used.

2. System Design and Prototyping (Design)

The system design and prototype development phase aims to map and integrate all hardware and software components used in the pond water quality monitoring and control system. This phase consists of several stages, including fuzzy logic, architecture diagrams, and schematic diagrams.

2.1. System Workflow

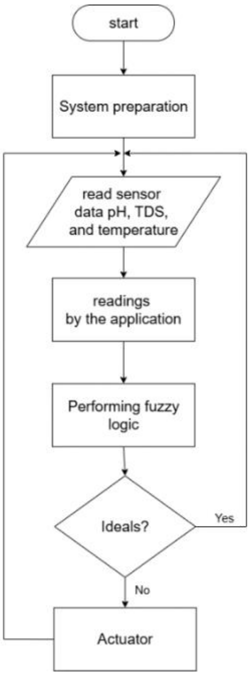


Fig. 2: System Workflow

Figure 2 illustrates the system workflow, which begins with the reading of pH and TDS sensor data as input variables in fuzzy logic. The data obtained from these readings is sent in real time to the Blynk application to be displayed to the user. Next, the system performs fuzzy logic processing to determine whether the water quality of the pool is within ideal limits. If the ideal conditions are met, the actuator (pump) remains off. Conversely, if the conditions are not ideal, the system will automatically activate the pump. After the decision is made, the system will perform a looping process to re-read the pH and TDS values, then process them again using fuzzy logic for continuous monitoring and control.

2.2. Fuzzy Logic Modeling

1. Fuzzy Logic Input

The pH input variable is divided into three linguistic sets, namely Acidic, Neutral, and Alkaline. A pH value < 6.5 is considered Acidic, 6.5–8.5 as Neutral, and > 8.5 as Alkaline. Figure 3 is a representation of the pH membership function.

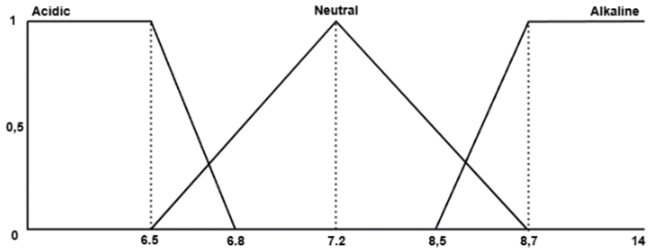


Fig. 3: pH membership function

Meanwhile, the TDS input variable is divided into three linguistic sets, namely Low, Normal, and High. TDS values < 500 are considered low, 500–700 as normal, and > 700 as high. Figure 4 is a representation of the TDS membership function.

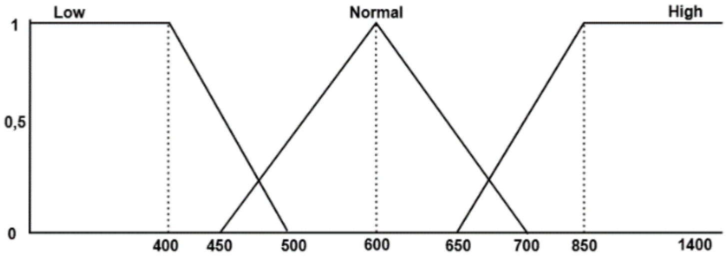


Fig. 3: TDS membership function

2. Fuzzy Logic Output

The membership function output for pump conditions is based on two main system states, namely the pump is off and the pump is on. This determination is based on decision-making logic regarding the pH and TDS parameters that have been fuzzyfied. The output is then discretely categorized into two parts, namely: Pump Off (value 0) and Pump On (value 1), which represent the status of the actuator in the pool water quality control system. The pump output variable can be seen in Figure 5**.**

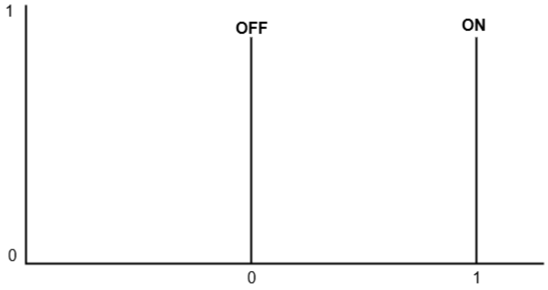


Fig. 5: Pump Output Variable

3. Interference System

Fuzzy logic rules are formulated based on combinations of input variables pH and TDS with output variables representing pump status. These combinations result in a total of nine rules representing all possible input conditions in the decision-making system.

[R1] IF pH = Acidic AND TDS = Low THEN Pump = ON (1)
[R2] IF pH = Acidic AND TDS = Normal THEN Pump = ON (1)
[R3] IF pH = Acidic AND TDS = High THEN Pump = ON (1)
[R4] IF pH = Neutral AND TDS = Low THEN Pump = OFF (0)
[R5] IF pH = Neutral AND TDS = Normal THEN Pump = OFF (0)
[R6] IF pH = Neutral AND TDS = High THEN Pump = ON (1)
[R7] IF pH = Alkaline AND TDS = Low THEN Pump = ON (1)
[R8] IF pH = Alkaline AND TDS = Normal THEN Pump = ON (1)
[R9] IF pH = Alkaline AND TDS = High THEN Pump = ON (1)

4. Defuzzyfication

The defuzzification stage is the final process in Sugeno's fuzzy logic system, which is used to convert the results of fuzzy rule evaluation into numerical (crisp) outputs that can be used by the system as a basis for decision making. In this stage, defuzzification is performed based on the input parameters that have been analyzed using the previously formulated fuzzy rules. Each rule then produces an output in the form of a fixed value (constant) that represents the action on the water pump actuator, namely the off or on condition. The final output value is determined using the following average formula.

$$\mathrm{Z} = \frac{\Sigma \alpha_i \mathrm{Z}_i}{\Sigma \alpha_i}$$

2.3 Diagram Architecture

Figure 6 shows the system architecture diagram, which includes a microcontroller as the control center, sensors as input modules, and actuators in the form of relays to control the water pump as output modules.

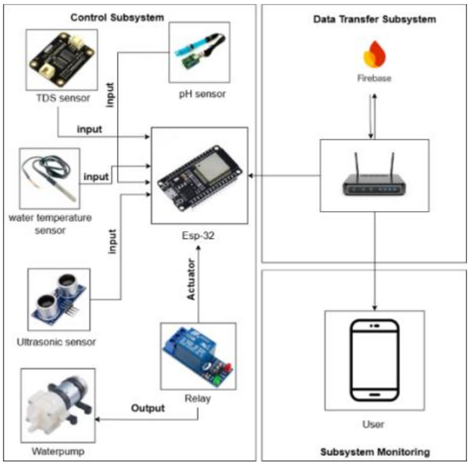


Fig. 6: System Architecture Diagram

The main control unit uses an ESP32 microcontroller with built-in Wi-Fi connectivity to support data communication to the cloud service. The system's input section consists of a pH sensor to measure water acidity, a DS18B20 temperature sensor to read the pool temperature, a TDS sensor to detect dissolved solids, and an HC-SR04 ultrasonic sensor to measure the water surface height. All data from these sensors is processed by the ESP32 and used as the basis for decision-making using Sugeno fuzzy logic.

2.4 Schematic Diagram

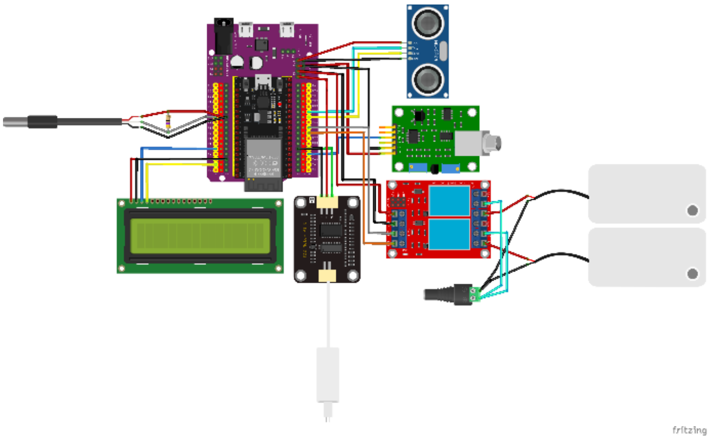


Fig. 7: Schematic Diagram

Figure 7 is a schematic diagram of the prototype system consisting of sensors such as PH-405, SEN0244, HC-SR405, and DS18B20, an ESP32 microcontroller with an expansion board, actuators in the form of a 2-channel relay, a 12V water pump, a 4.7kΩ resistor, a 12V adapter, and jumper cables.

3. System Code Development and Prototyping (Coding)

The design of this system software consists of three main components: a microcontroller program, a Blynk-based mobile application, and a Firebase cloud system. Microcontroller programming is performed using the Arduino IDE with the C++ language, which reads data from the pH sensor, DS18B20 temperature sensor, TDS sensor, and HC-SR04 ultrasonic sensor. The data obtained is then processed using the Sugeno fuzzy logic algorithm to determine the status of automatic water drainage and filling through pump control. The mobile application was developed using the Blynk platform, which enables real-time visualization of sensor data and remote control through a simple and responsive user interface. The data storage system uses Firebase Realtime Database to quickly store and synchronize data between the microcontroller device and the user application.

4. Testing Phase

The testing phase was conducted to ensure that the system operates according to user requirements. Functional testing was performed on the sensors, data transmission, and fuzzy logic. Additionally, simulations were conducted under various water conditions to observe the system's response in automatically activating the pump. Test results were recorded and analyzed to assess the accuracy of sensor readings and the effectiveness of the decision-making system.

3. Result and Discussion

1. Prototype Design Implementation

Following the design phase of the pond water quality monitoring and control system, the subsequent step involved implementing the design through the development of a prototype.

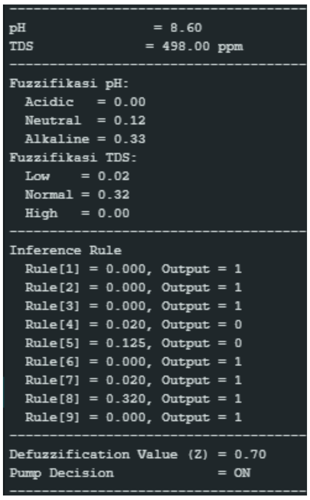
(a) (b) (c)

Fig. 8: Prototype Design

Figure 8 shows the results of the prototype system design. Figure (a) shows the front view, (b) the rear view, and (c) shows the internal components of the monitoring and control system for the catfish pond, which consists of several devices such as an ESP32 equipped with an expansion board as the control system center, an HC-SR04 ultrasonic sensor to detect the water level in the pond, a PH-405 sensor as the pH input for the water, a DS18B20 sensor as the temperature input for the water, and a SEN0244 sensor as the TDS input for the pond water. The device is also equipped with an actuator in the form of a relay that will control the ON/OFF of the water pump to drain the water from the pond and simultaneously refill it.

2. Sugeno Fuzzy Logic Testing

This test aimed to evaluate the performance of Sugeno fuzzy logic in the prototype that had been designed to ensure that its functionality ran according to the design objectives. sensor was tested using two types of liquids, namely a 500 ppm solution and a standard TDS solution of 1,382 ppm. Additionally, the HC-SR04 ultrasonic sensor was tested for reading object distances, while the DS18B20 sensor was tested for reading water temperature.



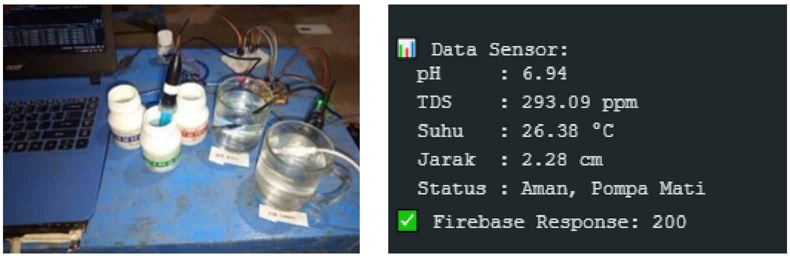
```
------------------------------------------
pH                 = 8.60
TDS               = 498.00 ppm
------------------------------------------
Fuzzifikasi pH:
  Acidic   = 0.00
  Neutral  = 0.12
  Alkaline = 0.33
Fuzzifikasi TDS:
  Low    = 0.02
  Normal = 0.32
  High   = 0.00
------------------------------------------
Inference Rule
  Rule[1] = 0.000, Output = 1
  Rule[2] = 0.000, Output = 1
  Rule[3] = 0.000, Output = 1
  Rule[4] = 0.020, Output = 0
  Rule[5] = 0.125, Output = 0
  Rule[6] = 0.000, Output = 1
  Rule[7] = 0.020, Output = 1
  Rule[8] = 0.320, Output = 1
  Rule[9] = 0.000, Output = 1
------------------------------------------
Defuzzification Value (Z) = 0.70
Pump Decision             = ON
------------------------------------------
```

Fig. 9: Sugeno Fuzzy Logic Testing

Figure 9 shows the results of testing Sugeno fuzzy logic in the prototype that has been designed. When the pH value reaches 8.6 and the TDS value is 498, the results obtained are consistent with the manual calculation simulation described earlier. The pH fuzzification value of the water is in the neutral category at 0.125 and the basic category at 0.33. Meanwhile, the TDS fuzzification value is in the low category at 0.02 and the normal category at 0.32. Based on the inference stage (rule evaluation), the active or fulfilled rules are rules 4, 5, 7, and 8. Furthermore, in the defuzzification stage, an output value of 0.70 is obtained. Since this value is close to 1, it is rounded up to 1, meaning the pump is activated to drain water from the pond.

3. Prototype Component Testing

After the prototype was assembled, each main component was tested to ensure that all parts functioned properly and in accordance with the system design. This testing included the main sensors, control system (ESP32 microcontroller), and actuators (relays and water pumps) in response to changes in water quality in the pond.



```
📊 Data Sensor:
  pH     : 6.94
  TDS    : 293.09 ppm
  Suhu   : 26.38 °C
  Jarak  : 2.28 cm
  Status : Aman, Pompa Mati
✅ Firebase Response: 200
```

(a) (b)

Fig. 10: Sensor Testing

Figure 10 (a) shows the sensor testing process in reading input values, and (b) shows the reading results on the serial monitor. The PH405 pH sensor was tested using standard buffer solutions with pH values of 4.01 (acidic), 6.86 (neutral), and 9.18 (alkaline) to verify the accuracy of the readings. The SEN0244 TDS sensor was tested using two types of liquids, namely standard TDS solution water of 500 ppm and standard TDS solution of 1,382 ppm. Additionally, the HC-SR04 ultrasonic sensor was tested for object distance measurement, while the DS18B20 sensor was tested for water temperature measurement. Table 1 shows the results of the sensor tests that have been conducted.

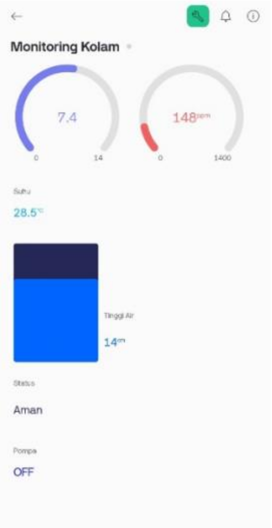
Table 1: Sensor Test Results

Component	Test Result
pH Sensor (PH405)	Successfully read the acid pH value in a 4.01 buffer solution, the neutral pH in a 6.86 buffer solution, and the base pH in a 9.18 buffer solution.
SEN0244 Sensor	Successfully read the TDS value in the TDS solution with a value of 500 ppm and the TDS solution with 1382 ppm.

HC-SR04 Sensor	Successfully reads water levels with an accuracy of ±1 cm, test range 2–15 cm.
Temperature Sensor (DS18B20)	Successfully detected a stable temperature of 27–31°C
Relay & Pump	Successfully responded by activating the pump according to the fuzzy output value.

4. Blynk for System Monitoring

The Blynk application is used as a platform for real-time system monitoring and control via a smartphone device.



Suhu
28.5°C

Tinggi Air
14cm

Status
Aman

Pompa
OFF

Fig. 11: Blynk for System Monitoring

Figure 11 shows the Blynk application dashboard used to monitor pond water quality. In this view, users can directly see the pH, TDS, temperature, and water level values in real time. The system status is displayed with the message “Status Aman” (Safe) and “Pompa OFF” (pump OFF) indicating that based on the results of the Sugeno fuzzy logic evaluation, the current water quality is in the acceptable category, so no draining or refilling of water is required.

5. Complete Device Testing

Complete prototype testing was conducted using a simulation pond to represent controlled conditions in a catfish pond.

Fig. 12: Comprehensive Testing

Figure 12 shows the testing conducted in the simulation pond, which aimed to evaluate the prototype's performance in responding automatically to changes in water quality parameters using Sugeno fuzzy logic, as well as to ensure the reliability of all components under actual operating conditions.

Table 2: Overall Test Results

Treatment	LCD display and blynk	Waterpump Process	LCD and Blynk dsiplay after the process
Given water with vinegar mixture	pH: 2,6 TDS: 293 Temperature: 27°C Status: Unsafe	Under predefined conditions, the draining pump is automatically activated to discharge water from the system. Once the water level reaches the specified threshold, the pump is deactivated. Subsequently, the refilling pump is triggered to replenish the water, and it remains active until the water level attains the predefined upper limit, at which point the pump is automatically deactivated. This automated sequence ensures precise control of water levels without requiring manual intervention.	pH: 7.4 TDS: 280 Temperature 27°C Status: Replaced
Given water mixed with baking soda	pH: 9,8 TDS: 480 Temperature: 27°C Status: Unsafe	Under predefined conditions, the draining pump is automatically activated to discharge water from the system. Once the water level reaches the specified threshold, the pump is deactivated. Subsequently, the refilling pump is triggered to replenish the water, and it remains active until the water level attains the predefined upper limit, at which point the pump is automatically deactivated. This automated sequence ensures precise control of water levels without requiring manual intervention.	pH: 7,6 TDS: 338 Temperature: 24°C Status: Replaced
Given water mixed with kitchen salt	pH: 8,3 TDS: 873 Temperature: 29°C Status: Unsafe	Under predefined conditions, the draining pump is automatically activated to discharge water from the system. Once the water level reaches the specified threshold, the pump is deactivated. Subsequently, the refilling pump is triggered to replenish the water, and it remains active until the water level attains the predefined upper limit, at which point the pump is automatically deactivated. This automated sequence ensures precise control of water levels without requiring manual intervention.	pH: 7,7 TDS: 336 Temperature: 26°C Status: Replaced
Given hot water	pH: 7,8 TDS: 336 Temperature: 32°C Status: Safe	Both pumps are off	*Not processed because temperature parameters are only used as system monitoring data.

Table 2 shows the results of the overall prototype testing conducted in the simulation pond to evaluate the prototype's automatic response to changes in water quality. When the water was mixed with vinegar solution and the pH value dropped to 2.6, the system detected unsafe conditions and automatically activated the drain pump, then continued the clean water filling process after the water level reached the lower limit. Upon completion of the process, the system re-scanned the water parameters and presented the updated status, confirming that the water had been successfully replaced. A similar treatment was performed by adding baking soda until the pH reached 9.8 and table salt until the TDS increased to 873 ppm. In both conditions, the system responded according to fuzzy logic and performed the draining and water filling processes. Afterward, the sensor re-scanned the parameters and updated the status on the Blynk dashboard and LCD. In the case of hot water treatment, although the temperature rises to 31°C, the system did not take action because temperature was only used as a monitoring parameter. The test results show that the prototype can detect unsafe conditions and automatically replace the water, then update the sensor readings independently without requiring manual intervention.

4. Conclusion And Suggestions

The prototype system for monitoring and controlling the water quality of catfish ponds based on IoT with Sugeno fuzzy logic has been successfully implemented using an ESP32 microcontroller and various sensors (pH, TDS, temperature, and water level). The system is able to monitor water conditions in real time, present data through both the Blynk platform and a local LCD display, and autonomously regulate the water pump when pH and TDS levels surpass predefined threshold values. The system has demonstrated responsiveness and efficiency in autonomously maintaining the quality of pond water.

Although the system has been successfully implemented, certain limitations remain that should be addressed in future development. Specifically, those related to the restricted number of input parameters within the fuzzy logic framework. It is therefore recommended that future iterations incorporate additional parameters, such as temperature, ammonia concentration, and water flow rate, alongside features like automatic temperature regulation and multi-platform notifications, to enhance the system's accuracy, adaptability, and user-friendliness.

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