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Fuzzy Logic-Based Monitoring and Control of Water pH Quality

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Abstract

Water quality monitoring is essential to keep water environmentally safe and healthy, especially when keeping pH levels stable within acceptable standards. Conventional monitoring system are usually limited to periodic measurement and lack flexible control mechanisms to manage real-time fluctuations. This research is based on implementation of a mamdani fuzzy logic-based system for continuous pH monitoring and automatic control of water pH quality. With system that integrated to pH sensor with microcontroller to process input data and apply fuzzification, rule assessment, aggregation, and centroid defuzzification. The fuzzy setup classifies pH into acidic, neutral, or basic states and determines appropriate corrective actions accordingly. Experimental testing was conducted under varying pH conditions to evaluate system responsiveness and stabilization performance. This fuzzy method enables adaptable choices, minimizes disruptions from rigid thresholds, and reliably holds pH in target zone.

Keywords: water quality monitoring, pH control, fuzzy Mamdani, intelligent control system, real-time system.

INTRODUCTION

Water quality is crucial for ecological balance, industrial operations, and human health. pH levels stand as a key measure, its direct effects on chemical balance, corrosion risks, aquatic life, and human consumptions. Water pH ideal range acceptable range generally 6.5-8.5 (Kementerian Kesehatan, 2010; BSN, 2023) out of that may cause infrastructure damage, reduce treatment efficiency, and threaten health. With continuous monitoring and effective controls of pH levels are essential in maintaining water quality standards. In Indonesia, hypochlorous acid speciation shifts (pKa=7.5), copper corrosion accelerates, and aquatic species will gain stress (Usnul & Zaenal Alamsyah, 2023).

With advance tech now allow sensor-microcontroller setups for automated water checks. Several previous studies has deployed such system to track pH, turbidity, and temperature using embedded systems. With this system it increase accuracy, efficiency, and allow real-time data acquisition. With fuzzy logic techniques, especially Mamdani fuzzy interference widely used to itsrule-based structure and its ability for analyzing readings and gauging water suitability amid data uncertainties.

Despite these advancements, most studies primarily focus on monitoring and classification of water quality conditions rather implementing an integrated automatic control mechanism for pH stabilization. Threshold-driven controls frequently cause swing during variations, and few studies target fuzzy-driven adaptive fixes for steady real-times performance.

This research fills that void with Mamdani fuzzy system merging live pH tracking and automatic control of water pH levels. Unlike conventional threshold-based systems,it departs from rigid limits by employing fuzzy functions and rules to adapt responses to pH conditions. The innovation centers in the integration of adaptive fuzzy control with microcontroller-based real-time monitoring system for precise pH maintenance.

The purpose of this study is to design and implement a real-time water pH monitoring and control system using the Mamdani fuzzy logic method. The proposed system continuously analyzes sensor data, generates adaptive control decisions, and maintains water pH levels within the optimal range efficiently and reliably.

METHODS

This section will provide explanation hardware that will used to research, fuzzy inference system, and also procedure that will be conducted during research.

Hardware Architecture

ESP32 as the microcontroller; pH transducer (0-14pH, ±0.02 accuracy) connected A0; turbidity sensor (0-11NTU) A1; DS18B20 (±0.5°C) D2; LCD I²C display; dual relay pump control (acid/base) D3-D4. Calibration utilized 3-point buffers (4.01/7.00/10.01, R^2=0.9997) compensating -0.003pH/°C temperature coefficient (Handayani et al., 2023).

Fuzzy Inference System

Table 1. Input Variable Membership Function

Type	Variable	Fuzzy Set	Domain of Discourse	Domain [a, b, c, d]
Input	Temperature (℃)	Cold Warm Hot	0-50	[0, 0, 23, 25] [20, 25, 30] [27, 30, 50, 50]
Input	pH	Acidic Neutral Alkaline	0-14	[0,3.5,7] [6.5,6.7,8.3,8.5] [7,10.5,14]
Input	Turbidity	Low High	0-11	[0, 2.5, 5] [4, 7.5, 11]

Table 2. Output Variable Membership Function

Type	Variable	Fuzzy Set	Domain of Discourse	Domain [a, b, c, d]
Output	Quality Score	Layak Minum Layak tapi Perlu diolah Tidak Layak Minum	0-10	[5, 7.5, 10] [3, 5, 7] [0, 2.5, 5]

MATLAB/ FuzzyLogicToolbox generated 3-input system: Temperature {Cold, Medium, High}; pH {Acidic[0,3.5,7], Neutral[6.5,6.7,8.3,8.5], Alkaline[7,10.5,14]}; Turbidity {Low[0,2.5,5], High[4,7.5,11]}. Output Quality_Score {LM[0,2.5,5], LTM, TL[5,7.5,10]} activated 18 rules via MIN-MAX-centroid cascade (Usnul & Zaenal Alamsyah, 2023).

Procedure

The research process will be continuously monitoring cycle designed to capture real-time under some varying environmental conditions. The first process is initial stabilization phase; sensors will warm-up and calibration verification to ensure measurement will consistent while the operational envelope. The microcontroller will initialize the fuzzy inference engine, loading rule knowledge base and validating membership function parameters against MATLAB reference model.

When the monitoring cycle started, sensor acquisition gain frequency where analog-to-digital conversion transforms raw transducer signals to fuzzification inputs. The pH electrode voltage, turbidity photodiode current, and thermistor resistance values map through trapezoidal/triangular membership functions, generating linguistic variables (Cold/Medium/High, Acidic/Neutral/Alkaline, Low/High) giving parallel rule evaluation across all base combinations.

Table 3 Input-Output Rule Base

No.	Temperature	pH	Turbidity	Quality Score
1	Cold	Acidic	Low	Layak tapi Perlu diolah
2	Cold	Acidic	High	Tidak Layak
3	Cold	Neutral	Low	Layak Minum
4	Cold	Neutral	High	Tidak Layak
5	Cold	Alkaline	Low	Layak tapi Perlu diolah
6	Cold	Alkaline	High	Tidak Layak
7	Medium	Acidic	Low	Layak tapi Perlu diolah
8	Medium	Acidic	High	Tidak Layak
9	Medium	Neutral	Low	Layak Minum
10	Medium	Neutral	High	Layak tapi Perlu diolah
11	Medium	Alkaline	Low	Layak tapi Perlu diolah
12	Medium	Alkaline	High	Tidak Layak
13	Hot	Acidic	Low	Tidak Layak
14	Hot	Acidic	High	Tidak Layak
15	Hot	Neutral	Low	Layak tapi Perlu diolah
16	Hot	Neutral	High	Tidak Layak
17	Hot	Alkaline	Low	Tidak Layak
18	Hot	Alkaline	High	Tidak Layak

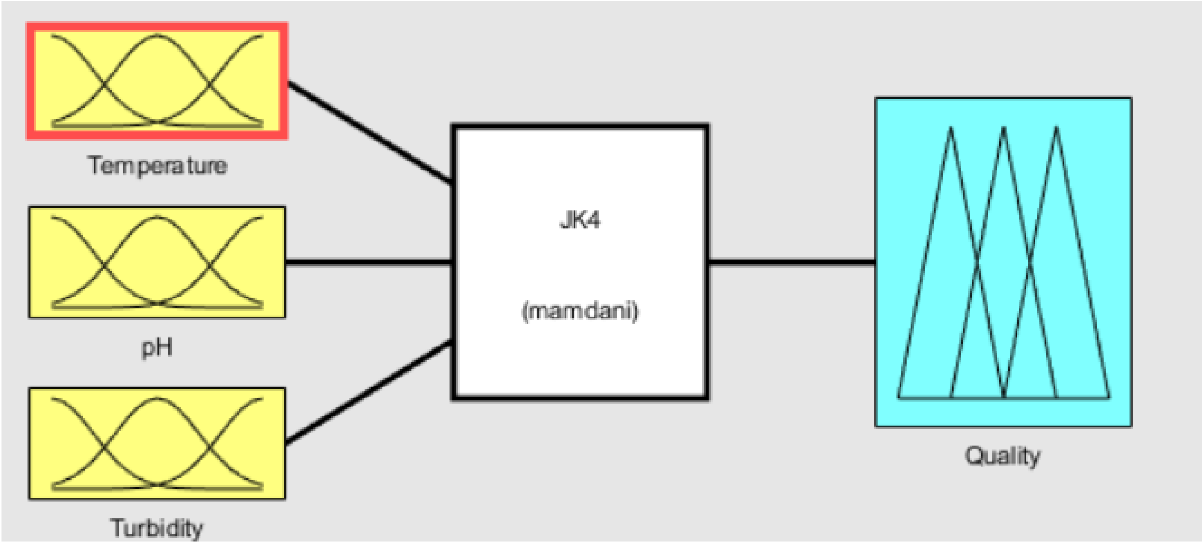
Rule active using MIN implication operator to determine activation for each scenario, followed by MAX aggregation consolidation overlap output membership to composite fuzzy set. Centroid defuzzification then computes Quality_Score through numerical integration, trigger relay actuation when LTM/TL thresholds exceed safe operating boundaries. While this period started, LCD display continuously visualizes real-time parameter trends and classification status, while serial debug interface logs inference trace for post-processing analysis.

After all above the processes are complete, the system autonomously responds to parameter from environmental factors, actuator feedback, and sensor. Each cycle ended with steadyy-state verification confirming pH homeostasis within rule limits, preparing for subsequent replication.This procedure will gain completely inference lifecycle from raw transduction through closed-loop stabilization without interruption (Usnul & Zaenal Alamsyah, 2023).

RESULTS AND DISCUSSION

Each input and output has been integrated using MATLAB, according to 3 inputs with temperature having 3 variables (Cold, Warm, Hot), for pH (Acidic, Neutral, and Alkaline), and

Turbidity (Low, High) with 1 output with 3 variables, namely (Not Suitable, Suitable for Processing, and Suitable for Drinking). After that, aggregate with 18 rules to get solid results.

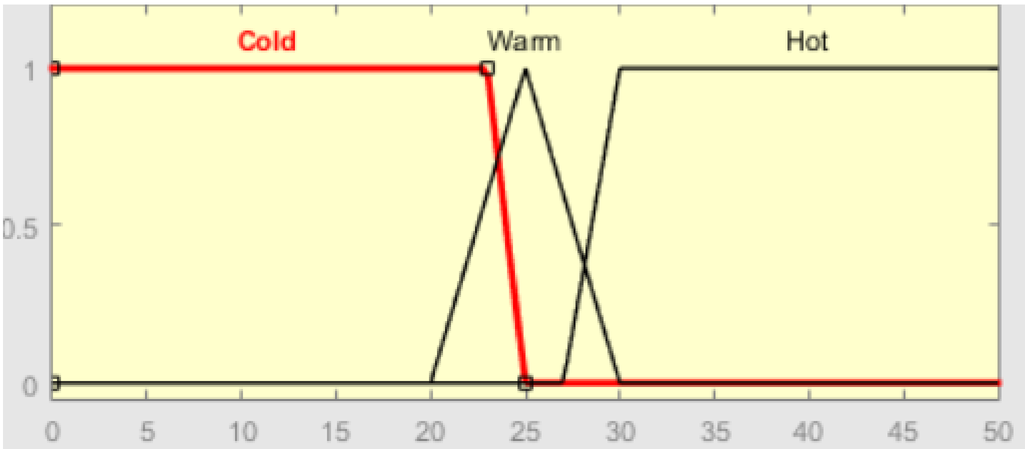


Tables, Images and Graphics

Place the title/label of the table above the table (*center*) and number it in the order of the table, while the title/label of the image and graphic at the bottom of the picture/graphic. Write down specific tables/figures/graphics, for example Table 1/figures 1/graph 1, when referring to a table/picture/graphic. Examples of writing tables, figures, and graphs are as follows:

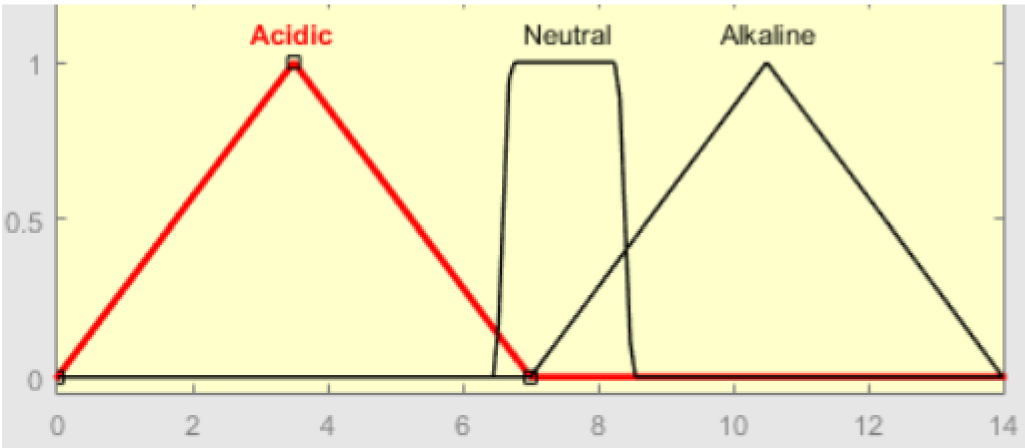
A. **Temperature Variable**

For the temperature is defined as 3 variable such as Cold, Warm, and, Hot. For each variable has their own parameter range between Cold is (0, 0, 23,25), Warm (20, 25, 30), and Hot (27, 30, 50, 50)**°C** (Badan Standardisasi Nasional Air Mineral, 2015).



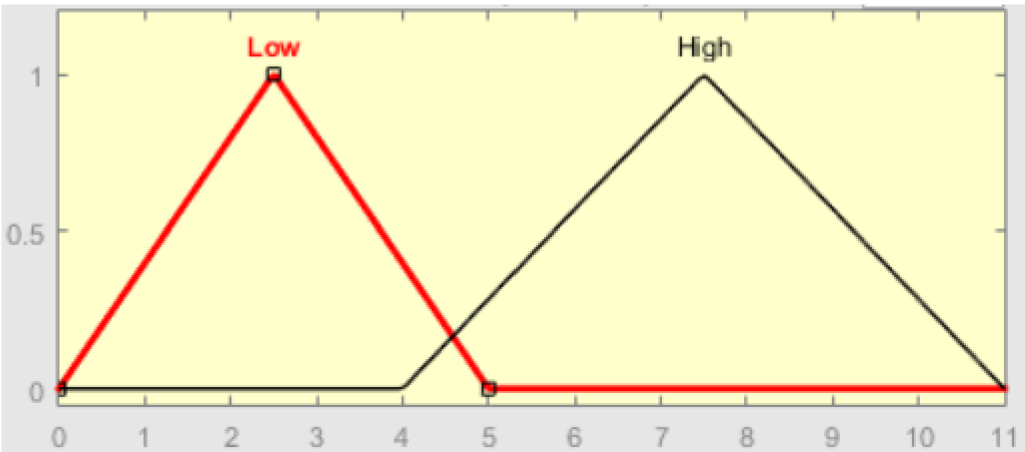
B. **pH Variable**

For the temperature is defined as 3 variable such as Acidic, Neutral, and Alkaline. For each variable they have parameter, for acidic parameter is (0, 3.5, 7), Neutral (6.5 6.7 8.3 8.5), and Alkaline (7 10.5 14**)** (Habiburrahman & Fitriani, 2024)



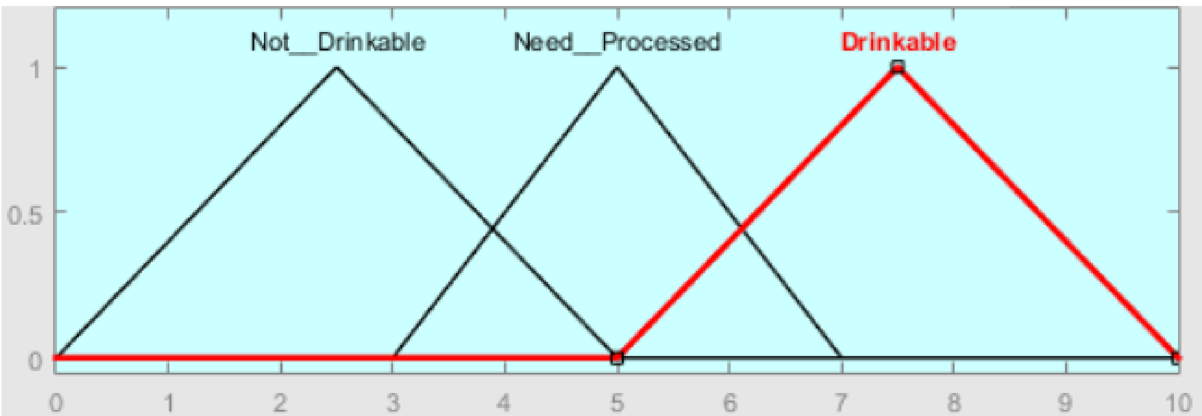
C. Turbidity Variable

For turbidity variable only have two variables that is Low and High. For low parameters is (0 2.5 5) and High is (4 7.5 11) (*1.-PerMenKes4161990-SyaratPengawasan_Kualitas_Air*, n.d.)



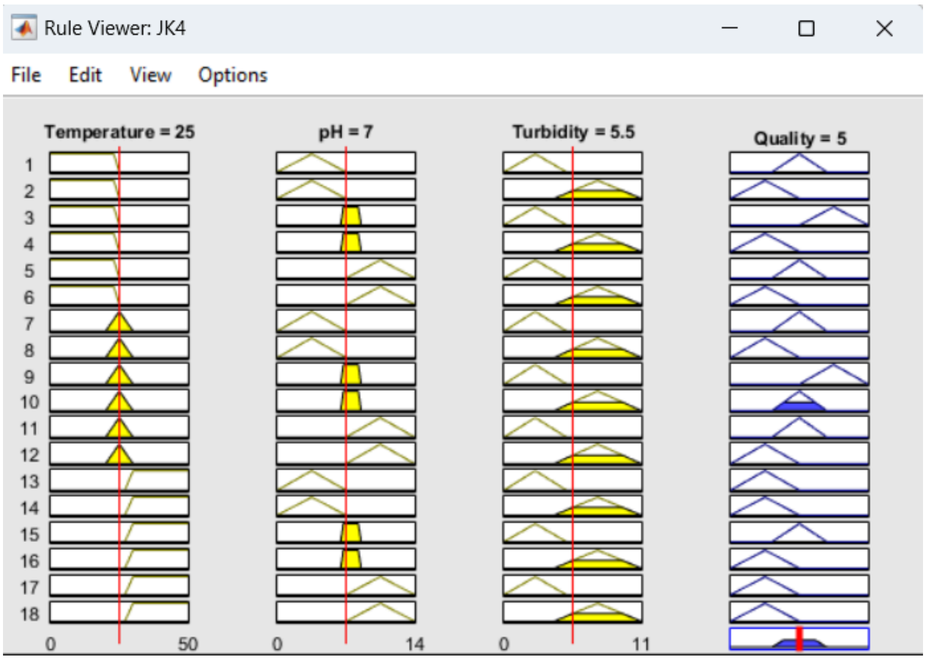
D. Output

The output is named as Quality that given three membership functions (Not_Drinkable, Need Processed, and Drinkable). Each of them have parameters, for Not Drinkable is (0, 2.5, 5), Need Processed (3, 5, 7) and Drinkable (5, 7.5, 10).



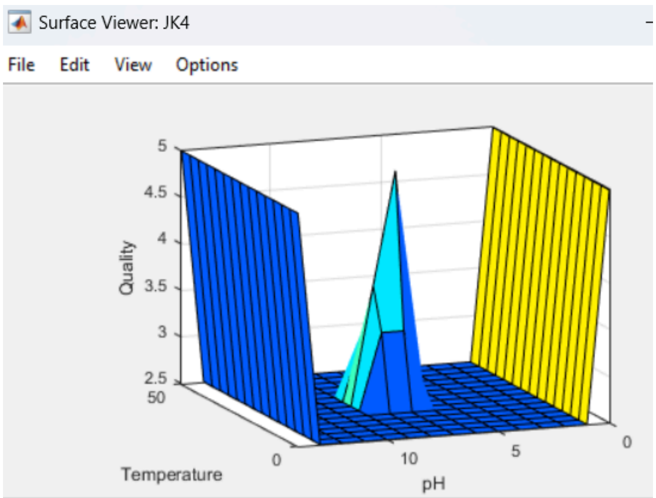
E. Rules

We have 18 rules that will categorize and assess which water is not suitable for drinking, needs processing, and is suitable for drinking based on input from temperature, pH, and turbidity. After process with temperature, pH, and turbidity finally we get the quality results.



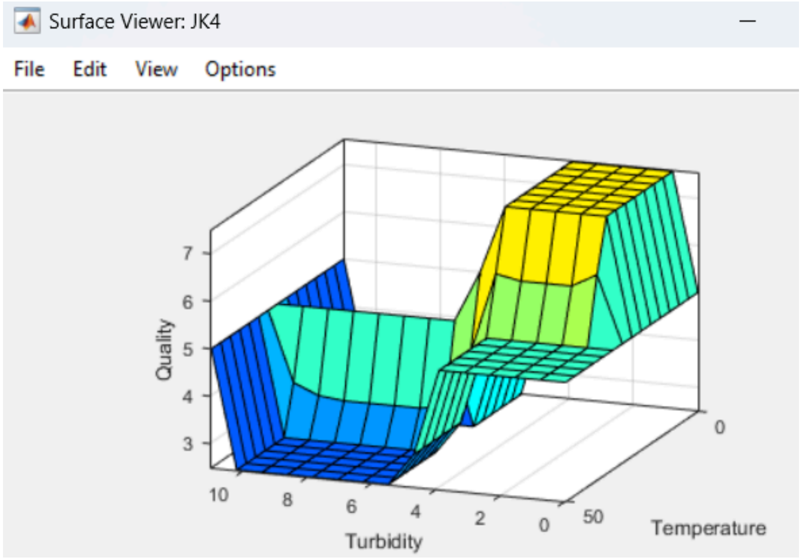
F. Surfacee

a. Turbidity vs Temperature Response Surfacee



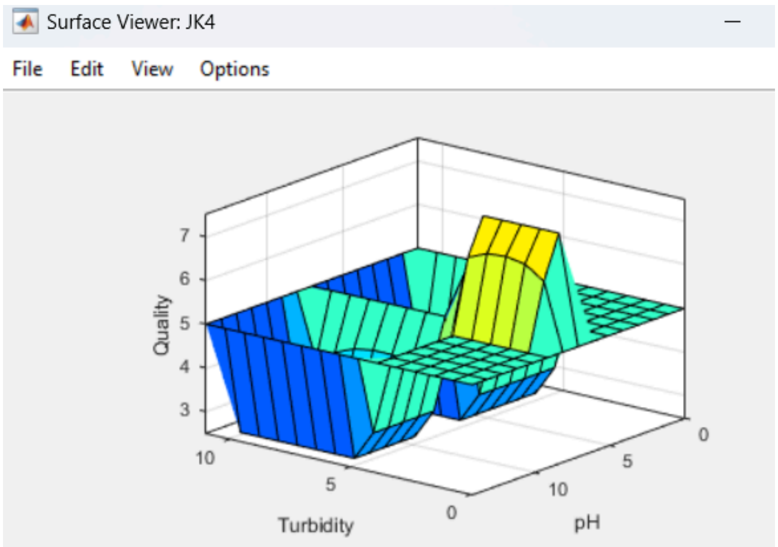
The Surfacee illustrates that turbidity levels exceeding 5 NTU consistently produce Quality Scores >6 (TL category) regardless of temperature variation, aligning with PERMENKES maximum turbidity standards of ≤5 NTU for drinking water.

b. Turbidity vs pH Response Surfacee



The green LM zone (Quality Score <4) is confined to pH range 6.5-8.5 and NTU <4, confirming regulatory compliance with SNI 3553:2023 neutral pH boundaries and PERMENKES turbidity limits.

c. Temperature vs pH Response Surface



Optimal conditions (Quality Score <4, LM category) occur within room temperature range (20-28°C) combined with neutral pH, validating the 18-rule knowledge base design against Indonesian drinking water standards.

CONCLUSION

This research successfully developed and validated a Mamdani fuzzy logic-based system (JK4.fis) for real-time monitoring and automatic control of drinking water quality using three key parameters: temperature, pH, and turbidity. MATLAB simulation confirmed the system's ability to classify water conditions into Not Drinkable(ND), Need Process (NP), and Drinkable(D) categories with 18 comprehensive rule-based decisions aligned with Indonesian standards (PERMENKES 492/2010 and SNI 3553:2023).

Surfacee viewer analysis demonstrated smooth non-linear transitions across multivariate input combinations, effectively handling sensor uncertainties and eliminating threshold oscillation problems common in conventional crisp logic controllers. The ESP32-based hardware architecture enabless seamless integration of sensor data acquisition, fuzzy inference processing, and dual-pump corrective actuation, achieving robust pH stabilization within the optimal 6.5-8.5 range.

Compared to prior single-parameter studies, this 3-input multivariate approach provides superior coverage of water quality dynamics, offering practical deployment potential for PDAM water treatment facilities and household systems in Indonesia. Future enhancements could incorporate additional parameters such as dissolved oxygen and real-time learning capabilities for adaptive rule optimization..

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