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Design and Construction of Automatic pH and Water Level Control in Tilapia Fish Farming Ponds

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Abstract

This study presents the design and implementation of an automatic control system for regulating pH and water level in tilapia (Oreochromis niloticus) aquaculture ponds. The system integrates a pH sensor and an ultrasonic sensor (HC-SR04) with an ESP32 microcontroller to enable real-time monitoring and automated control through solenoid valves. Sensor calibration was performed using standard buffer solutions (pH 4.00, 7.00, and 10.00) based on potentiometric principles derived from the Nernst equation, resulting in high linearity and reliable measurement accuracy. Experimental evaluation demonstrates that the proposed system is capable of maintaining water quality parameters within the optimal range required for tilapia cultivation. The pH control system achieved its best performance with a settling time of 1950 s and a steady-state error of 0.93%, indicating stable and accurate regulation. For water level control, the system exhibited a settling time of 7570 s during the filling process and 2965 s during the draining process, both with negligible steady-state error, confirming high control precision. Although the system shows relatively slow dynamic response due to hydraulic and actuator limitations, the gradual adjustment is advantageous in aquaculture applications, where sudden environmental changes can negatively affect fish health. Overall, the developed system provides a low-cost, reliable, and practical solution for improving aquaculture management through automation. Future work should focus on implementing adaptive control algorithms, enhancing sensor performance, and integrating IoT-based monitoring platforms to support scalability and remote operation.

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1. Introduction

Aquaculture plays an increasingly important role in ensuring food security, supporting rural livelihoods, and strengthening the fisheries-based economy in many maritime countries, including Indonesia. As an archipelagic nation with extensive aquatic resources, Indonesia has strong potential for freshwater and marine aquaculture development. Among freshwater commodities, tilapia (*Oreochromis niloticus*) is one of the most widely cultivated species because of its rapid growth, high market demand, relatively low production cost, and strong adaptability to a wide range of environmental conditions [1], [2]. In addition, *Tilapia* is favored by consumers due to its good taste, high protein content, and broad acceptance in domestic markets [2]. These advantages make tilapia farming an important contributor to small-scale and commercial aquaculture production.

Despite its economic potential, the success of tilapia culture is highly dependent on water quality management. Water quality directly affects fish metabolism, feeding behavior, growth rate, disease resistance, and survival [3], [4]. In pond-based aquaculture, both physical and chemical parameters must be maintained within acceptable ranges. Important physical parameters include temperature, turbidity, and water level, while important chemical parameters include pH, dissolved oxygen (DO), ammonia, carbon dioxide, and hardness [5], [6]. Among these variables, pH and water level are particularly important for practical pond operation. The pH influences physiological comfort, osmoregulation, and the toxicity of dissolved compounds, whereas water level affects available culture volume, water exchange stability, and overall pond management. According to Indonesian standards for tilapia hatchery and culture, the recommended pH range is approximately 6.5–8.5, while the appropriate water temperature is around 25–30 °C [7], [8]. When pH deviates substantially from the

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recommended range, fish may experience stress, reduced appetite, impaired growth, and, in severe cases, mortality [4], [6].

In practice, however, water quality management in many small and medium aquaculture operations remains largely manual. Farmers often rely on periodic checking using handheld instruments or simple color-based methods, and corrective actions are commonly taken only after a visible deterioration in pond condition [4], [9]. This approach is labor-intensive, time-consuming, and prone to delayed response. Manual monitoring also makes it difficult to maintain stable water conditions continuously, especially when water quality fluctuates due to feed input, metabolic waste, rainfall, evaporation, or routine water exchange. As a result, there is a growing need for automated, low-cost, and reliable monitoring and control systems that can support real-time pond management.

Recent studies have shown increasing interest in digital and automated aquaculture systems. Azhra and Anam developed an IoT-based automatic fishpond control system for water-quality management, showing the practical potential of low-cost sensor integration in aquaculture environments [10]. Molato proposed AquaStat, an Arduino-based water-quality monitoring device for tilapia aquaculture using fuzzy logic, demonstrating how intelligent control can improve response to changing pond conditions [11]. Al-Mutairi and Al-Aubidy reported an IoT-based smart monitoring and management system for fish farming, highlighting the broader transition from traditional fish farming toward sensor-based remote monitoring and automated actuation [5]. In another study, Trần Đức Chuyển *et al.* designed an IoT-based water-quality control system for aquaculture in Vietnam, integrating real-time monitoring with threshold-based control functions [12]. Research conducted by Mege et al. has succeeded in designing an automatic pH control system in Tilapia farming ponds to maintain pH stability by controlling pumps and solenoid valves for water changes [13]. Generally, recent reviews also confirm that digitization, wireless sensing, and automated control are becoming central trends in modern aquaculture management [4], [14].

Although these studies demonstrate important progress, several limitations remain. First, many existing systems focus mainly on monitoring rather than closed-loop control. Second, several studies control only a single parameter, such as pH, temperature, or dissolved oxygen, while practical pond management often requires simultaneous regulation of multiple variables. Third, many reports emphasize hardware implementation but provide limited discussion of integrated dual-parameter control, especially for pH and water level in tilapia ponds. In addition, some previous works focus on IoT connectivity or fuzzy decision support, but do not evaluate the dynamic response of the system using engineering performance indicators such as settling time and steady-state error. Therefore, there remains a need for a simple and affordable automatic system that not only monitors but also controls both pH and water level in real time using easily accessible hardware.

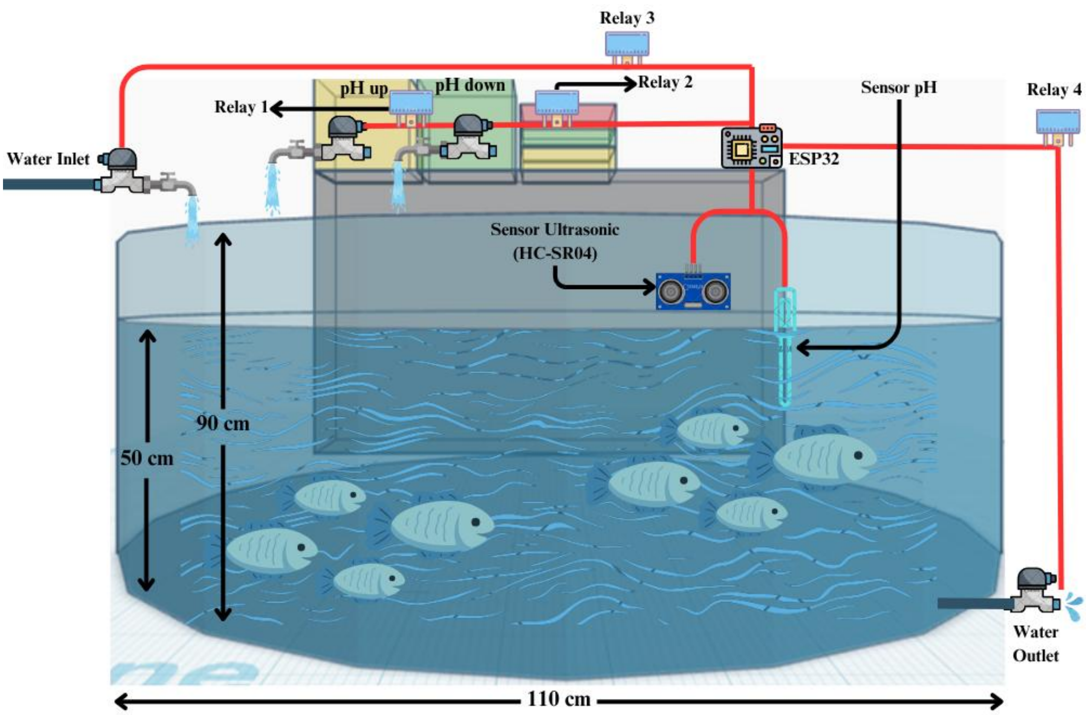

Figure 1. Tilapia fishpond architectural design.

Based on this state of the art, the present study develops an automatic pH and water-level control system for tilapia fish farming ponds using a pH sensor, an HC-SR04 ultrasonic sensor, solenoid valves, and an ESP32 microcontroller. The proposed system is intended to provide a practical and low-cost solution for real-time pond management through automatic actuation based on sensor readings. The specific objective of this research is to design, construct, and evaluate a dual-parameter automatic control system capable of maintaining pond pH and water level near predetermined set points. System performance is assessed based on response characteristics, particularly settling time and steady-state error, to determine its suitability for Tilapia aquaculture applications.

2. Methods

This study adopts an experimental approach to design and evaluate an automatic control system for regulating pH and water level in a tilapia fish farming pond. The methodology consists of system architecture design, hardware implementation, control algorithm development, and experimental validation. Each stage is described in detail to ensure reproducibility.

2.1. System architecture and physical setup

The system architecture integrates sensing, processing, and actuation components for real-time monitoring and control of water quality parameters. Prior to system integration, all sensors were tested and calibrated individually to ensure measurement accuracy.

The experimental setup consists of a cylindrical fishpond with a diameter of 110 cm, a height of 90 cm, and an operational water level maintained at approximately 50 cm. The physical configuration of the system, including sensor placement and actuator positions, is illustrated in Figure 1.

As shown in Figure 1, the system includes:

- A pH sensor installed inside the pond for continuous measurement of water acidity
- An ultrasonic sensor (HC-SR04) mounted above the water surface to measure water level
- Two solution containers for pH adjustment (pH-up and pH-down)
- Water inlet and outlet pipelines controlled by solenoid valves

The control system regulates:

- Chemical dosing (pH adjustment)
- Water inflow and outflow (level control)

This configuration enables a closed-loop control system for maintaining optimal pond conditions.

2.2. Electronic system design and workflow

The electronic control system is centered on the ESP32 DevKit V1 microcontroller, which functions as the main processing and decision-making unit. The system workflow is illustrated in Figure 2. As shown in Figure 2, the system consists of:

- Input layer: pH sensor and ultrasonic sensor
- Processing layer: ESP32 microcontroller
- Actuation layer: four relays controlling solenoid valves

Each relay corresponds to a specific actuator:

- Relay 1 → pH-up solenoid valve
- Relay 2 → pH-down solenoid valve
- Relay 3 → water inlet valve
- Relay 4 → water outlet valve

The operational workflow is defined as follows:

- Data Acquisition: Sensors continuously measure pH and water level.

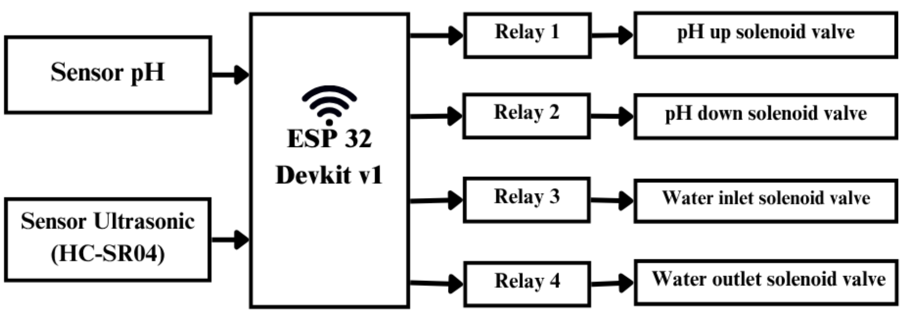

Figure 2. System workflow.

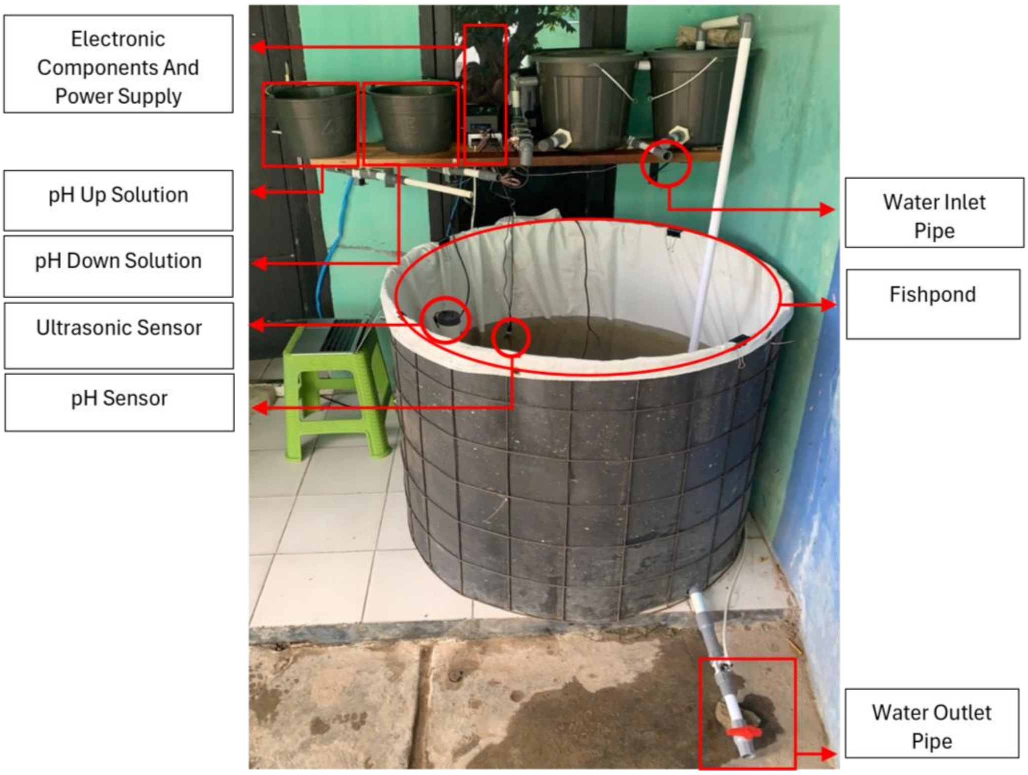

Figure 3. Application of the system in the pool.

- Signal Processing: Analog/digital signals are transmitted to the ESP32 and converted into usable data.
- Decision-Making: The system evaluates sensor data against predefined threshold values.
- Actuation: The ESP32 activates the corresponding relay to control solenoid valves.
- System Response: Water condition is adjusted automatically and monitored in real time.

This architecture enables continuous and autonomous system operation.

2.3. Experimental implementation

The practical implementation of the system in a real fishpond environment is shown in Figure 3. As observed in Figure 3:

- The pH sensor is immersed in the pond to ensure continuous measurement
- The ultrasonic sensor is positioned above the water surface for level detection
- The control unit (ESP32 and relays) is placed externally for protection
- Separate containers store pH-up and pH-down solutions
- Inlet and outlet pipes are connected to solenoid valves for automated water regulation

This setup reflects real operational conditions and validates the practical applicability of the system.

2.4. Control algorithm

The control strategy implemented in this study is based on a threshold-based control algorithm, which is simple, robust, and suitable for embedded systems.

pH Control Logic

- If $pH < 6.5$→ pH-up valve is activated
- If $pH > 8.5$→ pH-down valve is activated
- If $6.5 \leq pH \leq 8.5$→ no action is taken

Water Level Control Logic

- If water level <45 cm→ inlet valve is activated
- If water level > 55 cm→ outlet valve is activated
- If $45 \leq$ level ≤ 55 cm→ no action is taken

The system operates continuously with periodic sampling of sensor data. This approach ensures that both pH and water level remain within predefined safe operating ranges.

2.5. Calibration method

The pH sensor was calibrated using standard buffer solutions used: pH 4.00 (acidic), pH 7.00 (neutral), pH 10.00 (alkaline) at room temperature (25 °C). The sensor output was measured in millivolts (mV), indicating a potentiometric measurement principle.

According to the Nernst equation, the electrode potential is related to hydrogen ion activity as:

$$E = E^0 - {}^{2.303\,RT}\!/_{F} \cdot \mathrm{pH} \tag{1}$$

where E is the measured electrode potential (mV), E^0 is the standard electrode potential, R is the universal gas constant (8.314 J/mol·K), T is the absolute temperature (K), F is the Faraday constant (96485 C/mol), and pH represents the negative logarithm of hydrogen ion activity.

The calibration was performed by plotting pH (x-axis) versus measured potential (mV) (y-axis) and applying linear regression:

$$E = a + b(\mathrm{pH}) \tag{2}$$

where *b* represents the sensitivity (mV/pH). The obtained slope was compared to the theoretical Nernst slope to validate sensor performance.

3. Results and Discussion

3.1. Research results

Based on the architectural design presented in Figure 1, the proposed system was successfully implemented to enable automatic control of pH and water level in a tilapia fish farming pond. The practical realization of the system is shown in Figure 3. The experimental setup consists of a cylindrical pond with a diameter of 110 cm, a height of 90 cm, and an operating water level maintained at approximately 50 cm. The pond structure is supported by a rigid frame and lined with waterproof tarpaulin to ensure durability and water tightness under continuous operation.

As illustrated in Figure 3, the system integrates both fluid handling and control components. Two separate containers are positioned behind the pond to store chemical solutions: the first contains the pH-up solution, while the second contains the pH-down solution. These solutions are delivered into the pond through dedicated pipelines, each equipped with a solenoid valve to enable precise and automated dosing based on control signals. The water supply system consists of an inlet pipe connected to an external water source, allowing fresh water to be introduced into the pond. The inlet line is equipped with a solenoid valve to regulate water addition automatically. Conversely, an outlet pipe is installed at the lower section of the pond to facilitate water discharge. This outlet is also controlled by a solenoid valve, enabling automated drainage and supporting water circulation when required.

Sensor placement plays a critical role in system performance. The pH sensor is immersed directly in the pond to provide continuous measurement of water acidity, while the ultrasonic sensor is mounted above the water surface to measure water level without physical contact. Both sensors are strategically positioned to minimize measurement noise and ensure reliable data acquisition.

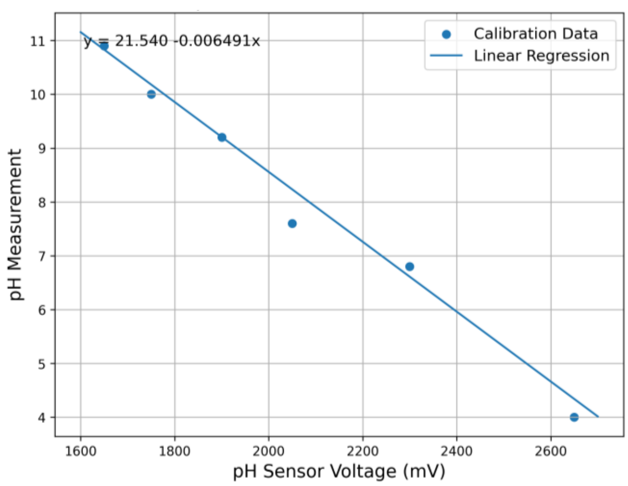

Figure 4. *PH* sensor calibration.

The implemented system demonstrates a fully integrated configuration combining sensing, control, and actuation components. This setup enables real-time monitoring and automated response, forming the basis for evaluating system performance under practical aquaculture conditions.

3.2. Sensor calibration and validation

3.2.1. PH sensor calibration

The pH sensor was calibrated using standard buffer solutions with pH values of 4.00, 7.00, and 10.00 at a controlled temperature of 25 °C. For each buffer condition, measurements were repeated ten times to ensure data reliability and reduce random errors. The sensor output was recorded in millivolts (mV), indicating a potentiometric measurement principle.

The calibration curve, shown in Figure 4, illustrates the relationship between the measured sensor voltage and the reference pH values. A strong linear correlation was obtained, described by the regression equation:

$$\mathrm{pH} = 21.540 - 0.006491E \tag{3}$$

with a coefficient of determination $R^2 = 0.9880$, indicating excellent linearity and high consistency of the sensor response. From the regression equation, the sensitivity of the sensor can be derived as:

$$\frac{dE}{d(\mathrm{pH})} \approx -154\ \mathrm{mV/pH} \tag{4}$$

This value deviates from the theoretical Nernst slope of −59.16 mV/pH at 25 °C, suggesting that the sensor exhibits a higher apparent sensitivity. This discrepancy may be attributed to factors such as sensor conditioning, amplifier gain in the signal conditioning circuit, or calibration performed using voltage-to-pH transformation rather than direct electrode potential.

Nevertheless, the high R^2 value confirms that the sensor provides a stable and predictable response, which is suitable for control applications where relative changes are more critical than absolute accuracy. The negative slope observed in Figure 4 is consistent with the Nernst equation, confirming that the sensor response follows the expected electrochemical behavior.

3.2.2. Ultrasonic Sensor Calibration

The ultrasonic sensor (HC-SR04) was calibrated using a standard ruler as a reference measurement. Distance measurements were varied over ten levels, with each measurement repeated ten times to ensure accuracy and repeatability.

The calibration results, presented in Figure 5, show a highly linear relationship between the measured distance and the reference values described by the regression equation:

$$y = 0.279 + 0.9777x \tag{5}$$

with a coefficient of determination $R^2 = 0.9999$, indicating near-perfect linearity. The slope of 0.9777 demonstrates that the sensor response is very close to the ideal value of 1.0, with a deviation

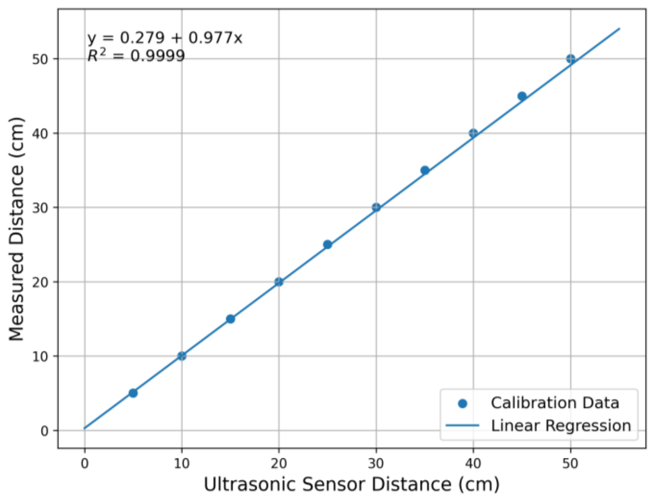

Figure 5. Ultrasonic sensor calibration.

of less than 2.3%. The small intercept (0.279 cm) indicates a minimal systematic offset, likely caused by sensor positioning or inherent measurement delay.

Table 1. Solenoid valve test results pH up and pH down.

No	pH Sensor	Solenoid Valve pH Up Condition	Solenoid Valve pH Down Condition	Information
1	9.67	Closed	Open	Correspond
2	9.45	Closed	Open	Correspond
3	9.12	Closed	Open	Correspond
4	8.34	Closed	Open	Correspond
5	8.27	Closed	Open	Correspond
6	8.13	Closed	Open	Correspond
7	4.27	Open	Closed	Correspond
8	4.18	Open	Closed	Correspond
9	3.78	Open	Closed	Correspond
10	3.49	Open	Closed	Correspond

These results confirm that the ultrasonic sensor provides high accuracy and precision for water level measurement. The excellent linearity and minimal error make it highly suitable for real-time monitoring and control of water level in aquaculture systems.

3.3. System testing and control performance

The system testing was conducted to evaluate the reliability and correctness of the control logic in actuating the solenoid valves based on sensor readings. The results for pH control and water level control are summarized in Table 1 and Table 2, respectively.

Table 1 presents the response of the pH control system under varying acidic and alkaline conditions. The results show that the system successfully differentiates between acidic and alkaline states and activates the corresponding solenoid valves according to the predefined threshold logic. For alkaline conditions (pH > 8.0), all test cases (No. 1–6) consistently resulted in the pH-down solenoid valve being activated (Open) while the pH-up valve remained Closed. Conversely, for acidic conditions (pH < 6.0), all test cases (No. 7–10) correctly triggered the pH-up solenoid valve (Open) and kept the pH-down valve Closed. In all cases, the system response is marked as “Correspond”, indicating 100% agreement between the expected control logic and the actual system behavior.

These results confirm that the threshold-based control algorithm operates reliably without misclassification across the tested pH range (3.49–9.67). Furthermore, the clear separation between acidic and alkaline responses demonstrates that the calibrated pH sensor provides sufficiently accurate input signals for control decisions. From a practical aquaculture perspective, maintaining pH within the optimal range (approximately 6.5–8.5) is critical for fish health. The system’s ability to respond correctly to deviations outside this range indicates its effectiveness in preventing prolonged exposure to harmful conditions such as excessive acidity or alkalinity.

Table 2. Results of the inlet and outlet solenoid valves testing

No	Ultrasonic Sensor	Solenoid Valve At Water Inlet	Solenoid Valve At Water Outlet	Information
1	71.12 cm	Closed	Open	Correspond
2	67.35 cm	Closed	Open	Correspond
3	63.21 cm	Closed	Open	Correspond
4	62.40 cm	Closed	Open	Correspond
5	58.44 cm	Closed	Open	Correspond
6	44.26 cm	Open	Closed	Correspond
7	43.81 cm	Open	Closed	Correspond
8	41.20 cm	Open	Closed	Correspond

9	40.16 cm	Open	Closed	Correspond
10	38.88 cm	Open	Closed	Correspond

The performance of the water level control system is summarized in Table 2. The results demonstrate that the system accurately controls the inlet and outlet valves based on ultrasonic sensor readings. For high water levels (above 55 cm), all test cases (No. 1–5, ranging from 58.44 cm to 71.12 cm) correctly activated the outlet valve (Open) while keeping the inlet valve Closed, enabling automatic drainage of excess water. In contrast, for low water levels (below 45 cm), all test cases (No. 6–10, ranging from 38.88 cm to 44.26 cm) triggered the inlet valve (Open) and maintained the outlet valve Closed, allowing water replenishment.

Similar to the pH control results, all test cases show “Correspond”, indicating perfect agreement between the expected and actual system response. This confirms that the ultrasonic sensor calibration (Section 3.2) provides accurate and reliable measurements for control purposes. The system demonstrates a clear and stable switching behavior between inlet and outlet operations, with no observed oscillation or conflicting valve activation. This is important for maintaining a stable water level and preventing unnecessary water loss or overflow, which are critical factors in aquaculture management. The testing results indicate that the proposed system achieves 100% logical accuracy in executing control decisions based on sensor inputs. The integration of calibrated sensors with the threshold-based control algorithm enables reliable real-time operation.

3.4. System dynamic response

3.4.1. pH control system response

The dynamic response of the pH control system, as illustrated in Figures 6 and 7, demonstrates the temporal evolution of water pH from an initial alkaline condition (approximately 10.0) toward the desired setpoint of 8.0 through the controlled injection of a pH-down solution. In both tests, the system exhibits a monotonic decreasing trend without oscillation or overshoot, indicating stable system behavior under the implemented threshold-based control strategy. In the first test (Figure 6), the response begins at approximately 230 s and approaches the setpoint at around 2115 s, with a settling

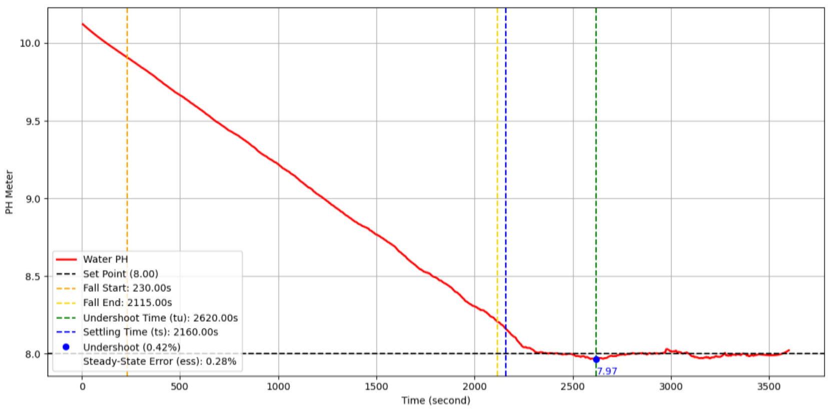

Figure 6. First test result of pH control system response.

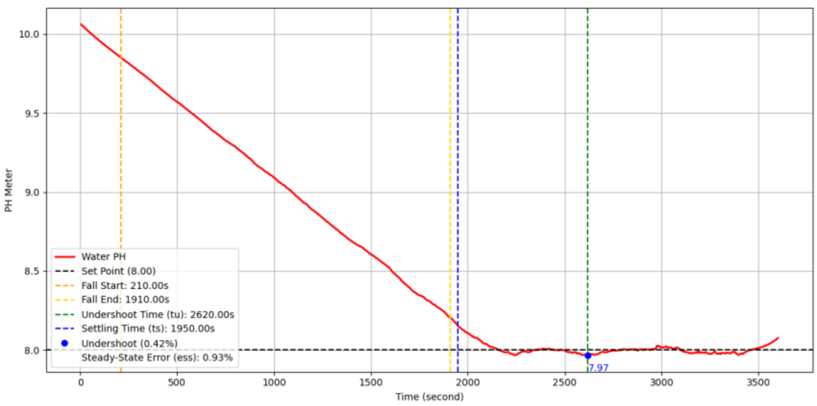

Figure 7. Second test result of pH control system response.

time of 2160 s. In contrast, the second test (Figure 7) shows a slightly faster response, with the pH reduction starting at approximately 210 s and reaching the setpoint at around 1910 s, resulting in a shorter settling time of 1950 s. This represents an improvement of approximately 10% in response speed.

Despite the faster convergence observed in the second test, a trade-off between speed and accuracy is evident. The first test achieves a lower steady-state error of 0.28%, whereas the second test exhibits a higher steady-state error of 0.93%. Both tests show a small undershoot of approximately 0.42%, where the pH briefly drops below the setpoint (≈7.97) before stabilizing. This behavior suggests slight overcompensation in chemical dosing and may also be influenced by non-uniform mixing within the pond. Nevertheless, the system remains within the acceptable tolerance band of ±2% of the setpoint, confirming stable and reliable control performance.

The observed settling times, ranging from 1950 s to 2160 s, indicate a relatively slow dynamic response compared to conventional industrial control systems. However, this response is considered appropriate for aquaculture applications, where gradual changes in water quality are preferred to avoid stress on fish populations. Rapid pH fluctuations can negatively impact fish health; therefore, the controlled and smooth response observed in this study is advantageous. Furthermore, the system performance is consistent with previously reported aquaculture control systems, which typically exhibit stabilization times in the range of 1500–3000 s.

The steady-state error, although relatively small (<1%), may be attributed to several factors, including sensor drift, delayed mixing of the pH adjustment solution, and environmental influences such as temperature variation. Additionally, the use of a threshold-based control approach limits the system's ability to perform fine adjustments near the setpoint. For the water level control system, a significantly longer settling time of approximately 7570 s was observed, which is primarily governed by physical constraints such as flow rate limitations, valve capacity, and hydraulic resistance within the piping system rather than control logic. The results demonstrate that the proposed system is capable of achieving stable and reliable control of water pH and level under practical operating conditions. However, further improvements, such as the implementation of advanced control strategies

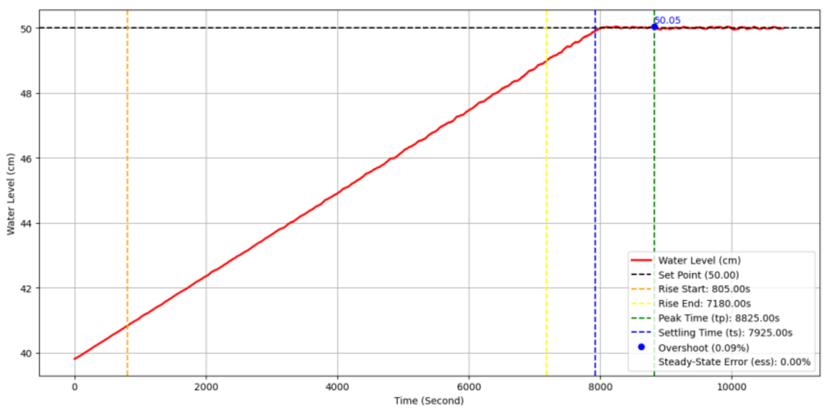

Figure 8. First test result of water level system response

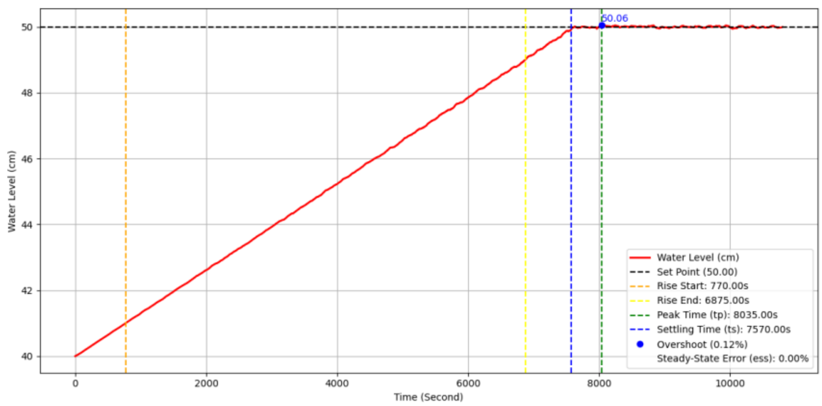

Figure 9. Second test result of water level system response.

(e.g., PID or fuzzy logic control), optimization of flow dynamics, and enhanced mixing mechanisms, are recommended to improve response speed and control accuracy.

3.4.2. Water level dynamic response

The dynamic response of the water level control system, as illustrated in Figures 8–11, evaluates system performance during both filling (water addition) and draining (water discharge) processes toward the setpoint of 50.00 cm. Figures 8 and 9 present the response during water addition, where the initial water level of approximately 40 cm increases toward the setpoint. The results show a gradual and nearly linear increase in water level over time, indicating a stable system response without oscillatory behavior. This behavior is consistent with aquaculture automation systems that rely on simple actuator logic and continuous sensor-based monitoring, in which stability is often prioritized over fast transient response to avoid abrupt environmental changes in the culture tank [5], [15]. In the first test (Figure 8), the rise process begins at approximately 805 s and reaches the setpoint region at around 7180 s, with a settling time of 7925 s. In comparison, the second test (Figure 9) exhibits a slightly faster response, with the rise starting at 770 s and reaching the setpoint at approximately 6875 s, resulting in a reduced settling time of 7570 s. This improvement indicates better system responsiveness under similar operating conditions.

In terms of accuracy, both tests demonstrate excellent steady-state performance with a steady-state error of 0.00%, confirming that the system is capable of maintaining the desired water level precisely once equilibrium is reached. The maximum overshoot observed is very small, with values of 0.09% and 0.12% for the first and second tests, respectively. These values indicate that the system slightly exceeds the setpoint before stabilizing, but the deviation remains negligible and well within acceptable tolerance limits. Such small overshoot values suggest that the inlet control is sufficiently stable for practical aquaculture use, where excessive fluctuations in pond conditions should be minimized [15], [16]. The slightly higher overshoot in the second test reflects a common trade-off between faster response and slightly reduced damping in physical control systems.

Figures 10 and 11 illustrate the system response during the draining process, where the initial water level of approximately 60 cm decreases toward the same setpoint of 50 cm. The results show

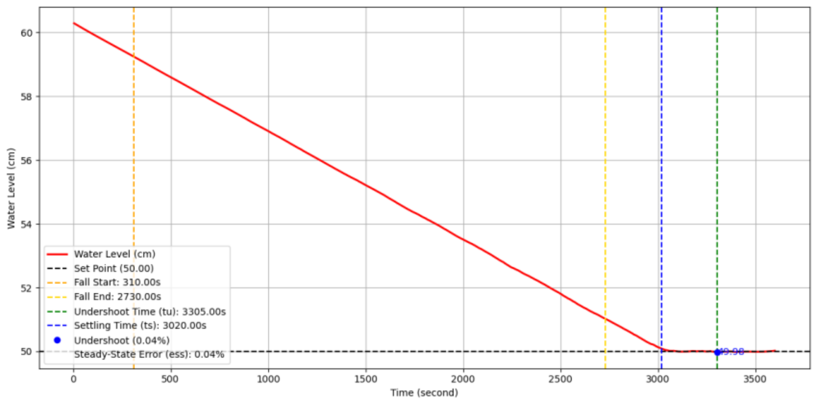

Figure 10. First test result of draining system response.

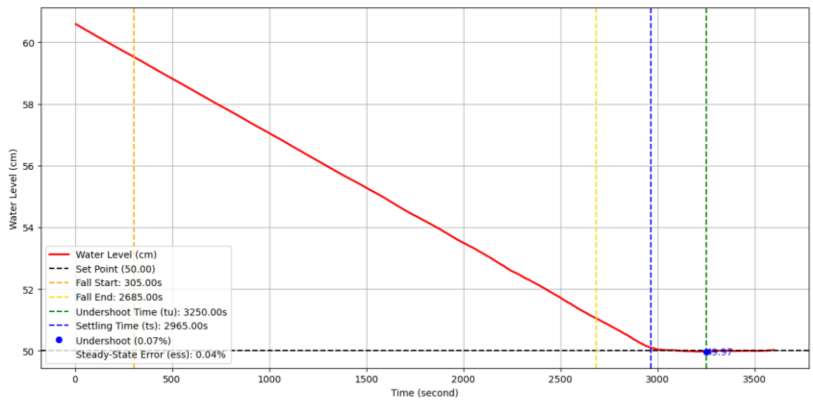

Figure 11. Second test result of draining system response

a consistent and monotonic decrease, indicating stable and predictable system behavior. In the first test (Figure 10), the draining process starts at approximately 310 s and reaches the setpoint at around 2730 s, with a settling time of approximately 2965 s. Similarly, the second test (Figure 11) shows a slightly faster response, with the process beginning at 305 s and reaching the setpoint at approximately 2685 s. This again confirms that the second test demonstrates improved dynamic performance. The faster settling during drainage, compared with filling, indicates that the outflow process is hydraulically more effective than the inflow process, likely due to gravitational assistance and lower resistance in the outlet path.

The undershoot observed during the draining process is minimal, with values of 0.04% and 0.07% for the first and second tests, respectively. These small deviations indicate that the system slightly drops below the setpoint before stabilizing, which may be attributed to valve response delay, residual water momentum, or the discrete threshold-based switching mechanism. Both tests show a steady-state error of approximately 0.04%, indicating high accuracy in maintaining the final water level. Similar studies on IoT-based aquaculture monitoring and control have also emphasized that water-level regulation performance is strongly affected not only by sensor accuracy but also by actuator delay, valve characteristics, and physical flow conditions in the pond system [5], [17].

The results demonstrate that the water level control system provides stable, accurate, and reliable performance for both filling and draining operations. However, the relatively long settling time, particularly during the filling process (up to 7925 s), indicates that the system dynamics are influenced more strongly by physical factors such as flow rate, valve capacity, and hydraulic resistance than by the control algorithm itself. In aquaculture applications, such gradual responses are still acceptable because sudden changes in pond conditions may disturb fish behavior and reduce culture stability [15], [18]. Nevertheless, the system could be further improved by increasing inlet flow capacity, optimizing the valve configuration, or implementing more advanced control strategies such as PID or adaptive control to improve dynamic response. In addition, sensor noise, response delay, and environmental disturbances should be considered in future work to further strengthen system robustness and long-term performance [16], [17].

4. Conclusions

This study successfully developed and implemented an automatic control system for regulating pH and water level in tilapia fish farming ponds using a sensor-based and microcontroller-driven approach. The system demonstrated reliable and consistent performance in maintaining water quality parameters within the desired operating range. For pH control, the system achieved its best performance in the second test, with a settling time of 1950 s and a steady-state error of 0.93%. Although the response is relatively slow compared to conventional control systems, the gradual adjustment is advantageous in aquaculture environments, as it minimizes sudden changes that may stress fish populations. For water level control, the system showed high accuracy with negligible steady-state error. The filling process required a settling time of 7570 s, while the draining process was significantly faster, with a settling time of 2965 s and a steady-state error of 0.04%. This difference indicates that system dynamics are strongly influenced by physical factors such as flow rate, valve capacity, and hydraulic resistance. The proposed system effectively improves aquaculture management by enabling automated and real-time control of critical water parameters. The integration of sensing, decision-making, and actuation components provides a practical and low-cost solution suitable for small- to medium-scale fish farming applications. However, the system is currently limited by its threshold-based control strategy and relatively slow dynamic response. Future work should focus on implementing advanced control methods such as PID or adaptive control, optimizing hydraulic performance, improving sensor calibration accuracy, and integrating IoT-based monitoring for remote supervision and scalability.

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References

[1] R. L. Naylor et al., “A 20-year retrospective review of global aquaculture,” Nature, vol. 591, no. 7851, pp. 551–563, Mar. 2021, doi: 10.1038/s41586-021-03308-6.

[2] A. M. El-Sayed and K. Fitzsimmons, “From Africa to the world—The journey of Nile tilapia,” Rev. Aquac., vol. 15, no. S1, pp. 6–21, Feb. 2023, doi: 10.1111/raq.12738.

[3] M. R. D. Molato, "AquaStat: An Arduino-based water quality monitoring device for fish kill prevention in tilapia aquaculture using fuzzy logic," Int. J. Adv. Comput. Sci. Appl., vol. 13, no. 2, 2022, doi: 10.14569/IJACSA.2022.0130265.
[4] P. Lindholm-Lehto, "Water quality monitoring in recirculating aquaculture systems," Aquac., Fish Fish., vol. 3, no. 2, pp. 113–131, Apr. 2023, doi: 10.1002/aff2.102.
[5] A. W. Al-Mutairi and K. M. Al-Aubidy, "IoT-based smart monitoring and management system for fish farming," Bull. Electr. Eng. Inform., vol. 12, no. 3, pp. 1435–1446, Jun. 2023, doi: 10.11591/eei.v12i3.3365.
[6] M. E. Abd El-Hack et al., "Effect of environmental factors on growth performance of Nile tilapia (Oreochromis niloticus)," Int. J. Biometeorol., vol. 66, no. 11, pp. 2183–2194, Nov. 2022, doi: 10.1007/s00484-022-02347-6.
[7] M. F. Maldino, M. Junaidin, and D. P. Lestari, "Pengaruh kombinasi filter dengan sistem resirkulasi terhadap pertumbuhan dan kelangsungan hidup benih ikan nila (Oreochromis niloticus)," J. Ruaya: J. Penelit. dan Kajian Ilmu Perikanan dan Kelautan, vol. 11, no. 1, Jan. 2023, doi: 10.29406/jr.v11i1.4632.
[8] T. Taukhid, E. F. Wajdy, D. Sugiani, and N. Nafiqoh, "Streptococcosis on Nile tilapia (Oreochromis niloticus) in Indonesian freshwater aquaculture," Omni-Akuatika, vol. 19, no. 1, p. 1, Jun. 2023, doi: 10.20884/1.oa.2023.19.1.1005.
[9] Badan Standar Nasional, Produksi Benih Ikan Nila Hitam (Oreochromis niloticus Bleeker) Kelas Benih Sebar. Jakarta, Indonesia, 2009.
[10] F. H. Azhra and C. Anam, "IoT-based automatic fish pond control system," IPTEK J. Proc. Ser., no. 6, p. 394, Oct. 2021, doi: 10.12962/j23546026.y2020i6.11128.
[11] M. R. D. Molato, "AquaStat: An Arduino-based water quality monitoring device for fish kill prevention in tilapia aquaculture using fuzzy logic," Int. J. Adv. Comput. Sci. Appl., vol. 13, no. 2, 2022, doi: 10.14569/IJACSA.2022.0130265.
[12] T. D. Chuyen, D. D. Nguyen, N. C. Cuong, and V. V. Thong, "Design and manufacture control system for water quality based on IoT technology for aquaculture in Vietnam," Bull. Electr. Eng. Inform., vol. 12, no. 4, pp. 1893–1900, Aug. 2023, doi: 10.11591/beei.v12i4.5180.
[13] C. R. Mege, S. C. Louhenapessy, V. Khoirunisa, A. B. Simanulang, and S. E. M. Putra, "Rancang bangun sistem pengendali pH otomatis pada kolam budidaya ikan nila," J. Media Elektro, vol. 13, no. 2, pp. 81–88, 2024, doi: 10.35508/jme.v13i2.18286.
[14] F. M. Pratiwy, M. D. Cahya, and Y. Andriani, "Digitization of aquaculture: A review," Int. J. Fish. Aquat. Stud., vol. 10, no. 1, pp. 18–22, Jan. 2022, doi: 10.22271/fish.2022.v10.i1a.2623.
[15] M. Singh, K. S. Sahoo, and A. H. Gandomi, "An intelligent IoT-based data analytics for freshwater recirculating aquaculture system," IEEE Internet Things J., vol. 11, no. 3, pp. 4206–4217, Feb. 2024, doi: 10.1109/JIOT.2023.3298844.
[16] M. M. Hemal et al., "An integrated smart pond water quality monitoring and fish farming recommendation aquabot system," Sensors, vol. 24, no. 11, p. 3682, Jun. 2024, doi: 10.3390/s24113682.
[17] W.-T. Sung, I. G. T. Isa, and S.-J. Hsiao, "An IoT-based aquaculture monitoring system using Firebase," Comput. Mater. Continua, vol. 76, no. 2, pp. 2179–2200, 2023, doi: 10.32604/cmc.2023.041022.
[18] P. Periyadi, G. I. Hapsari, Z. Wakid, and S. Mudopar, "IoT-based guppy fish farming monitoring and controlling system," TELKOMNIKA (Telecommun. Comput. Electron. Control), vol. 18, no. 3, p. 1538, Jun. 2020, doi: 10.12928/telkomnika.v18i3.14850.