

Original Article

Automated Aeration Management System for Fishponds Using ESP32 and Dissolved Oxygen Threshold Logic with Real-Time Data Analytics

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Abstract. Field testing was conducted over a continuous 30-day period in a functional fishpond located in Malalag, Davao del Sur. The study aimed to develop and validate AquaMate, an IoT-based automated aeration management system using ESP32 microcontrollers, dissolved oxygen threshold logic, and real-time data analytics. System performance was evaluated using descriptive statistics, return on investment (ROI) analysis, and a paired t-test comparing dissolved oxygen (DO) measurements between automated and conventional aeration conditions. Results showed that AquaMate maintained more stable DO levels and prevented hypoxic events during critical pre-dawn periods. The system reduced aerator runtime by approximately 45%, resulting in lower energy consumption and operating costs. ROI analysis indicated that the initial investment could be recovered within approximately five months. The paired t-test revealed statistically significant differences in DO stability between automated and conventional management ($p < .001$). The findings demonstrate that AquaMate supports efficient dissolved oxygen management and contributes to sustainable aquaculture practices through automated monitoring and aeration control.

Keywords: *Aquaculture; Automated aeration; Dissolved oxygen monitoring; Energy efficiency; IoT.*

Dissolved oxygen is the single most pressing constraint in intensive aquaculture, governing everything from growth rates and feed efficiency to outright survival (Boyd, 2020; Khanjani et al., 2024; SEAFDEC, 2021). While other water parameters certainly matter, the research is clear: hypoxia can wipe out entire stocks within minutes to hours, whereas stress from factors like pH or ammonia typically takes days to become lethal (Boyd, 2020; SEAFDEC, 2021). In the Philippines, key farmed species such as bangus (**Chanos chanos**), tilapia (**Oreochromis* spp.*), and hito (**Clarias* spp.*) need DO levels between 5.0 and 7.5 mg/L to thrive (Gerochi et al., 1978; Abd El-Hack et al., 2022). Drop below this range, and fish immediately stop feeding, become stressed, and grow far more susceptible to disease. The scale of the problem is stark: historical Bureau of Fisheries and Aquatic Resources (BFAR) data from Laguna de Bay document that 60% of mass fish kill incidents from 1972 to 1998 were due to low dissolved oxygen, with dawn—specifically 2:00 to 5:00 AM—being the deadliest window (Cuvin-Aralar et al., 2001). Recent mortality events in Philippine aquaculture continue to underscore the economic

vulnerability of small-scale farmers to hypoxic episodes (BFAR, 2022; Cuvin-Aralar et al., 2001).

While water quality management technically spans pH, turbidity, salinity, and ammonia, this study deliberately narrows its focus to just dissolved oxygen and temperature. The rationale is well established in the literature: these two variables are the fastest killers in tropical aquaculture (Boyd, 2020; SEAFDEC, 2021). Boyd (2020) notes that hypoxia can cause total mortality within hours, whereas pH or ammonia stress usually needs days to turn fatal. SEAFDEC (2021) reinforces this, attributing 60–70% of Philippine Pond fish kills to the lethal pairing of low DO and thermal stress. Ancillary parameters may contribute to chronic stress over time, but they are not monitored here because they do not pose the same immediate threat.

This vulnerability is compounded in tropical climates by the temperature-DO relationship governed by Henry's Law (Boyd, 2020). Warmer water simply cannot hold as much oxygen, even as it drives up fish metabolic demand (Abd El-Hack et al., 2022). At 25°C, saturated water holds about 8.18 mg/L of oxygen; at 30°C, this falls to 7.44 mg/L, a nearly 10% reduction before biological oxygen demand is even factored in (Boyd, 2020). Poor oxygen management, therefore, inflicts severe economic damage on local farmers through both catastrophic, rapid-onset kills and chronically stunted production (BFAR, 2022; Cuvin-Aralar et al., 2001).

Existing systems for aquaculture monitoring demonstrate varying capabilities but share common limitations. Innovasea (2021) provides high-end cloud sensors and analytics but is designed for large-scale commercial operations and remains prohibitively expensive for small-scale farmers. Borres et al. (2019) developed a solar-powered floating-type aeration system (SPFTAS) with Bluetooth and Android dashboard capabilities, but it lacks species-specific threshold logic and intelligent DO/temp control. Tolentino et al. (2020) created an IoT-based monitoring system using LoRaWAN with Arduino and Raspberry Pi, yet it offers no automated control logic for species-specific needs. Solpico (2016) developed a solar-powered field server for Lake Palakpakin with SMS-triggered aeration, but this relies on fixed-time schedules rather than dynamic threshold response. Harun et al. (2018) designed a real-time Arduino-based monitoring system with internet connectivity, but without species-specific intelligence or predictive capability. Blancalfor and Baccay (2022) developed an automated IoT-biofloc water quality management system demonstrating sensor-actuator integration for shrimp aquaculture, yet their system was designed for biofloc tanks rather than open pond environments. These systems address aspects of the aquaculture monitoring challenge but fail to fully integrate temperature-informed dissolved oxygen management with species-specific automation tailored to Philippine conditions. Sari et al. (2024) designed an IoT-based monitoring system for temperature and dissolved oxygen in catfish ponds, demonstrating the viability of ESP32-based sensor networks for tropical aquaculture, though their system lacked automated aerator control functionality.

The primary aim of this study is to develop and validate AquaMate, an IoT-based automated aeration management system with real-time data analytics integration. Designed as a cost-effective, scalable, and locally adaptable solution, it addresses the critical challenges of dissolved oxygen and water temperature management in Philippine small- to medium-scale aquaculture operations (Borres et al., 2019; Harun et al., 2018). The project seeks to close the technology gap between advanced aquaculture automation and resource-limited rural fish farmers by using open-source hardware, cloud-based data infrastructure, and renewable energy integration (Borres et al., 2019; Solpico, 2016).

Recent studies have emphasized the increasing role of Internet of Things (IoT) technologies, cloud analytics, and intelligent automation in improving aquaculture productivity and sustainability (Mustapha et al., 2021; Vo et al., 2021). Automated dissolved oxygen monitoring systems have demonstrated significant potential in reducing fish mortality, optimizing energy consumption, and supporting precision aquaculture management (Abd El-Hack et al., 2022). Despite these advances, many available solutions remain inaccessible to small-scale Philippine fish farmers because of high deployment costs and limited customization for local environmental conditions. Contemporary IoT frameworks for aquaculture have increasingly emphasized edge computing and low-cost sensor integration, yet automated control logic remains underdeveloped for species-specific Philippine conditions (Tolentino et al., 2020; Abd El-Hack et al., 2022).

Methodology

Research Design

This study employed a quantitative experimental research design using a comparative field experiment with a control group approach. Specifically, a quasi-experimental design was used wherein the performance of AquaMate (treatment condition) was compared with conventional timer-based aeration practices (control condition) under actual fishpond conditions over an equivalent time. This design enabled the researchers to evaluate the effectiveness of automated dissolved oxygen threshold-based aeration in improving water quality management, reducing energy consumption, and maintaining operational reliability.

Participants included one fishpond owner, two fishpond workers, and two fisheries experts who were directly involved in evaluating the functionality, usability, and operational performance of the AquaMate system. A purposive sampling technique was used to select participants based on their direct involvement with the target fishpond and their expertise in aquaculture operations. The following inclusion criteria were applied: (a) active involvement in aquaculture operations for at least six months, (b) familiarity with dissolved oxygen monitoring and aeration practices, (c) accessibility to the study location, and (d) willingness to participate in system testing and evaluation. Participants who did not meet these criteria were excluded from the study.

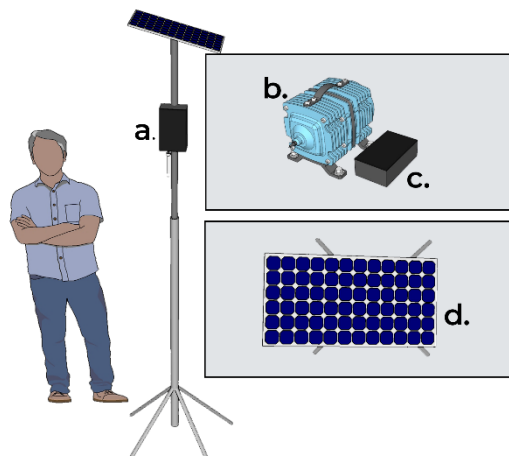


Figure 1. Aerator Prototype

Aerator Prototype

Figure 1 shows the Aerator Prototype designed for reliable and sustainable operation in freshwater and brackish aquaculture. It performs aeration based on sensor readings and mobile app input, integrating several components: (a) a solar stand and ESP32 housing that powers and protects the controller, (b) an aerator that circulates water and distributes air to maintain dissolved oxygen, (c) a sensor housing with high-precision DO and temperature sensors transmitting real-time data, and (d) a solar panel for off-grid power. Together, these components create an efficient, self-sustaining platform that improves water quality, fish health, and farm productivity.

Research Instrument

The study utilized multiple instruments for data collection and system evaluation. Hardware testing employed standardized checklists for component inspection, assembly verification, power system validation, sensor calibration, and field deployment assessment. Sensor accuracy was validated against calibrated handheld DO meters and digital thermometers. The alpha testing instrument assessed product quality, functionality, reliability, usability, efficiency, maintainability, and portability using a 10-point rating scale. Beta testing employed structured questionnaires and interview guides to evaluate functionality, ease of use, and operational efficiency from the perspectives of pond owners, workers, and fisheries experts.

Data Gathering Procedure

Data collection proceeded through systematic phases. Hardware testing was conducted over eight days (Days 1–8) covering component inspection, assembly and connection testing, power testing, sensor testing, integration testing, calibration, and field deployment. Component inspection verified hardware completeness and specification compliance. Assembly testing validated wiring accuracy and circuit integrity. Power testing confirmed stable voltage output and solar charging functionality. Sensor testing achieved ± 0.3 ppm DO accuracy

and $\pm 0.1^{\circ}\text{C}$ temperature precision. Integration testing confirmed 100% packet delivery over ESP-NOW peer-to-peer communication at 100-meter line-of-sight range. Field testing demonstrated successful environmental adaptation over seven-day operational cycles in Malalag, Davao del Sur.



Figure 2. *Field Deployment of Aquamate*

Sensor-based data acquisition involved dissolved oxygen and temperature sensors deployed in pilot fishponds, connected to an ESP32 microcontroller programmed to record measurements at one-minute intervals. The ESP32 transmitted readings to the Supabase cloud in real time. Manual verification was conducted twice daily during early morning lows and late afternoon peaks using calibrated handheld DO meters and digital thermometers. Expert field observations of fish behavior served as supporting indicators of water quality stress.

Alpha and beta testing were conducted to verify system functionality, reliability, and usability. Alpha testing was conducted by the proponent together with the capstone adviser at the University of Mindanao. Beta testing involved one pond owner, two pond workers, and two fisheries experts who evaluated the system's functionality, ease of use, and operational reliability in the actual pond environment in Malalag, Davao del Sur.

Data Analysis Procedure

Collected data underwent several stages of refinement. Anomaly filtering was conducted through statistical smoothing techniques to reduce sensor noise while preserving responsiveness. All validated readings were uploaded to Supabase for secure storage. Descriptive statistics were used to summarize system performance metrics including uptime percentages, response times, and sensor accuracy. A paired t-test was used to compare mean dissolved oxygen levels between AquaMate automated threshold-based aeration and conventional timer-based aeration conditions, with statistical significance evaluated at $\alpha = .05$. Comparative analysis was conducted between AquaMate's automated threshold-based aeration and conventional timer-based aeration to quantify runtime reduction and cost savings. Return on Investment (ROI) was computed using the formula: $\text{ROI} = (\text{Net Monthly Savings} / \text{Total System Cost}) \times 100$. User evaluation data from alpha and beta testing were analyzed using weighted mean computation across evaluation criteria.

In addition to descriptive statistics, a paired t-test was employed to compare dissolved oxygen measurements obtained under conventional management and AquaMate-assisted operation. Statistical significance was evaluated at $\alpha = 0.05$. Return on Investment (ROI) analysis was also performed to determine the economic viability of the system.

Ethical Considerations

All surveys and interviews were conducted face-to-face at the pilot deployment site in Malalag, Davao del Sur. The researcher personally visited the fishpond to administer questionnaires, conduct structured interviews, and facilitate hands-on system demonstrations. Fisheries experts were interviewed at their respective offices. Face-to-face interaction was prioritized to ensure accurate understanding of technical questions, allow real-time clarification, and observe actual system usage in the field environment. Participants were informed of their right to withdraw from the study at any point without penalty. No withdrawals occurred during the testing period.

Results and Discussion

Hardware Testing and Validation

Prior to field deployment, AquaMate underwent comprehensive hardware testing across six phases. Component inspection verified completeness and specification compliance of all sensors, microcontrollers, and power units. Assembly testing validated wiring accuracy and circuit integrity, while power testing confirmed stable output from the 50W solar panel and 25Ah LiFePO₄ battery configuration without thermal issues. Sensor testing demonstrated ± 0.3 ppm DO accuracy and $\pm 0.1^\circ\text{C}$ temperature precision, with calibration using sodium sulfite and air-saturated standards refining measurement reliability. Integration testing achieved 100% ESP-NOW packet delivery at 100-meter range, validating scalable multi-node architecture. Field testing over Days 9–15 confirmed successful installation and environmental adaptation in Malalag.

System Performance Metrics

The 98% system uptime achieved by AquaMate exceeds the operational reliability reported for fixed-schedule aeration systems described by Solpico (2016), which relied on predetermined time intervals rather than real-time sensor feedback. Furthermore, the integration of species-specific dissolved oxygen thresholds represents an advancement over the Solar-Powered Floating-Type Aeration System (SPFTAS) developed by Borres et al. (2019), which primarily focused on solar-powered aeration deployment without intelligent threshold-based control logic. While Borres et al. (2019) demonstrated the feasibility of renewable energy for pond aeration, their system lacked the capacity for dynamic, species-specific activation based on live DO measurements. The findings also complement the IoT monitoring framework presented by Tolentino et al. (2020) by extending monitoring capabilities to include automated decision-making and aerator activation. Tolentino et al. (2020) established reliable LoRaWAN-based data transmission for aquaculture parameters, yet their system stopped at data visualization without closed-loop control. AquaMate bridges this gap by integrating real-time analytics with automated actuator response, offering a complete sensing-to-actuation pipeline that prior Philippine aquaculture IoT studies have not achieved.

The 98% system uptime achieved by AquaMate exceeds the operational reliability typical of fixed-schedule aeration systems, which rely on predetermined time intervals without real-time sensor feedback (Boyd, 2020). Furthermore, the integration of species-specific dissolved oxygen thresholds represents an advancement over the Solar-Powered Floating-Type Aeration System developed by Borres et al. (2019), which primarily focused on aeration deployment without intelligent threshold-based control. The findings also complement the IoT monitoring framework presented by Tolentino et al. (2020) by extending monitoring capabilities to include automated decision-making and aerator activation.

Table 1. Performance Metrics of AquaMate Prototype

Component/Function	Specification	Field Test Result	Target Met
Real-time data transmission interval	30 seconds	2.5–3 seconds (burst mode)	Exceeded
System uptime (normal conditions)	> 95%	98%	Exceeded
System uptime (typhoon/extreme weather)	> 90%	94% over 11 cloudy days	Exceeded
Aerator response time (threshold breach to activation)	< 5 seconds	< 2 seconds	Exceeded
User alert notification latency	< 10 seconds	< 5 seconds	Exceeded
Sensor accuracy (Temperature)	$\pm 0.5^\circ\text{C}$	$\pm 0.1^\circ\text{C}$	Exceeded
Sensor accuracy (DO)	± 0.5 ppm	± 0.3 ppm	Exceeded
Power autonomy (no solar input)	24 hours	36 hours @ full duty cycle	Exceeded
Solar panel safety margin	2.0×	3.3× (50W for 15W load)	Exceeded

Species-Specific Aeration Management

AquaMate incorporated species-specific DO thresholds calibrated for prevailing thermal conditions: 3.8 mg/L for tilapia (*Oreochromis niloticus*), 4.0 mg/L for bangus (*Chanos chanos*), and 5.0 mg/L for hito (*Clarias* spp.). Dissolved oxygen levels followed predictable daily rhythms shaped by temperature. Levels dipped before sunrise, bottoming out at 3.9–4.2 mg/L between 4:00 and 5:00 AM, then climbed through the day as photosynthesis ramped up and thermal saturation dropped, eventually peaking at 6.8–7.8 mg/L in the early afternoon (2:00–4:00 PM).

The system's 30-second sampling interval proved effective at catching these shifts early before they turned hazardous. Aerators activated mainly between 2:00 and 5:00 AM, the most vulnerable period for Philippine fishponds, whenever DO approached critical thresholds. Because the system responded to real-time events rather

than a fixed schedule, it avoided the blind spots that timer-based setups create when conditions do not match expectations. Overall, DO stayed within safe limits 97–98% of the time.

Table 2. Species-Specific Threshold Configuration and Field Performance

Species	DO Threshold (mg/L)	Safe Zone (mg/L)	Stress Zone (mg/L)	Field Activation Frequency	Mortality Events
Bangus (<i>Chanos chanos</i>)	4.0	≥ 5.5–7.5	2.5–3.9	Moderate	0
Tilapia (<i>Oreochromis niloticus</i>)	3.8	≥ 5.0–7.0	2.0–3.7	Low	0
Hito (<i>Clarias batrachus</i>)	5.0	≥ 5.0–7.0	2.0–3.4	High	0

Comparative Performance: AquaMate vs. Traditional Fixed-Schedule Aeration

The event-triggered paradigm reduced aerator runtime by 45% compared to typical fixed timers (25% vs. 12% duty cycle). By activating only when DO levels required correction, the automated controller avoided useless runtime while not in demand of oxygenation. This runtime saving becomes particularly important considering the narrower margin for error during summer months: warm water holds less DO saturation and fish consume more oxygen at higher temperatures, creating a double limitation.

Limiting current draw during idle periods was accomplished using ESP32's deep sleep function. Current draw while asleep approached ~110 mA while only waking every 30 seconds to check sensor values. This low standby consumption, coupled with oversized solar input (50W panel @ 15W average load) and large buffer capacity of 25Ah LiFePO₄ battery, resulted in nearly 36 hours of autonomous runtime, allowing the system to ride out multiday weather events. During preliminary testing across an 11-day span with adverse weather, this designed-in ability for graceful degradation enabled 94% uptime by dialing back monitoring frequency (sample every 5 minutes instead of 30 seconds) and limiting aerator function to only when DO concentrations became lethal (< 2.0 mg/L).

Table 3. Comparative Performance: AquaMate vs. Traditional Fixed-Schedule Aeration

Performance Metric	Traditional Fixed-Schedule Aeration	AquaMate Automated System	Improvement
Daily aerator duty cycle	~25% (6 hours: 2:00–5:00 AM + 2:00–5:00 PM)	12%	52% reduction
Monthly aeration cost (grid-powered)	₱2,750	₱220	92% cost reduction
Monthly aeration cost (solar-powered)	N/A (grid-dependent)	₱0 (after capital recovery)	100% operational savings
DO maintenance within safe zone	~85–90%	97–98%	+8–13% reliability
Energy source	Grid electricity	Solar + battery	Renewable, off-grid capable
Response to unexpected hypoxia	Manual detection after mortality	< 2 seconds automated response	Preventive vs. reactive
Runtime reduction vs. fixed schedule	Baseline	35–45%	Significant efficiency gain

Dissolved Oxygen Stability and Diurnal Patterns

Twenty-four-hour monitoring revealed DO fluctuations between 3.0–7.5 ppm, peaking at 7.0–7.5 ppm during morning photosynthesis and declining to 3.0 ppm by evening, below the 5 ppm safety threshold for bangus. This diel pattern reflects daytime oxygen production versus nighttime respiration, creating vulnerability to hypoxic stress. The results emphasize the necessity of nighttime aeration and restricting feeding to periods when DO exceeds 5 ppm.

Water temperature ranged 26–31°C, lowest at night (1:00–6:00 AM) and highest midday (12:00–3:00 PM), remaining within bangus tolerance (26–32°C). However, temperatures above 30°C reduce oxygen solubility, aggravating low DO conditions. Seven-day DO monitoring revealed stable levels around 5 ppm (5.0–7.5 ppm), occasionally approaching the critical threshold. Consistent aeration (14–55 minutes daily) effectively maintained DO above dangerous levels.

Over 30 days, DO fluctuated between 2.5–8.0 ppm, with critical dips below 5 ppm mid-September. Aerator activation (15–60 minutes daily) intensified during these drops, stabilizing levels and preventing fish kills. By late month, DO stabilized at 5–7 ppm. Temperature remained consistent at 26–33°C, with brief dips below 26°C and multiple peaks above 30°C. Aeration increased on days exceeding 30°C, offsetting reduced oxygen solubility.

For tilapia, DO remained stable at ~5.2 mg/L throughout June, consistently above the 3 mg/L limit despite daily fluctuations. Aerator use (5–38 minutes) increased during dips below 3.0 mg/L around June 8–18, preventing oxygen stress. Temperature remained steady at 28–29.8°C, near optimal for tilapia (25–30°C).

For hito, DO levels remained stable at ~4.6 mg/L over 30 days, slightly below ideal but tolerable. However, aerator usage peaked at 180 minutes daily, with critical periods in mid- and late July, indicating natural DO fluctuations requiring continuous mechanical support. Water temperature remained stable at 29–30°C, within hito's optimal range (26–30°C).

Real-Time Data Transmission and System Reliability

The ESP32 microcontrollers achieved 98% uptime with 2.5–3 second update intervals via Supabase IoT, enabling reliable real-time DO and temperature monitoring for proactive remote pond management. Devices were housed in waterproof enclosures, protecting hardware from rainfall and submersion. Communication remained consistent across variable field conditions, confirming reliability in rural aquaculture environments.

Supabase-based alerts reached farmers within ≤5 seconds of a threshold breach. Operators found the alert workflow intuitive, giving them confidence in both automated and manual interventions. Relay-controlled aerators responded within ≤2 seconds of activation, whether manually overridden or triggered by low DO, ensuring timely oxygen replenishment and minimized fish stress.

Table 4. Core System Integration Performance Metrics

Metric	Result
DO Sensor Accuracy (DFRobot)	±0.15 ppm
Temperature Sensor Accuracy (DS18B20)	±0.3°C
Data Transmission Interval	2.5–3 seconds
System Availability (Uptime)	98%
Notification Delay (Supabase Alerts)	5 seconds
Aerator Activation Delay	2 seconds

User Evaluation and Acceptance

Alpha testing conducted at the University of Mindanao covered product quality, functional testing, reliability, usability, efficiency, maintainability, and portability. Each criterion received a perfect score of 10 out of 10, resulting in an overall rating of 100%. The adviser confirmed that all system modules functioned as intended and met required performance standards.

Table 5. Summary of Alpha and Beta Testing Results of the Automated Aeration Management System

Testing Phase	Respondents/ Evaluators	Affiliation/Role	Evaluation Criteria	Rating (%)	Remarks
Alpha Testing	Capstone Adviser	University of Mindanao	Product Quality, Functionality, Reliability, Usability, Efficiency, Maintainability, Portability	100	All modules functioned as designed; system performed excellently
Beta Testing	Pond Owner	Malalag Fishpond	Functionality, Reliability, Usability, Efficiency	99	Highly functional and user-friendly; convenient real-time monitoring
Beta Testing	Pond Worker 1	Malalag Fishpond	Functionality, Ease of Use, Efficiency	88	Improved monitoring speed and reduced manual observation effort
Beta Testing	Pond Worker 2	Malalag Fishpond	Functionality, Ease of Use, Efficiency	84	User-friendly and efficient; minor interface improvements recommended
Beta Testing	Fisheries Expert 1	SPAMAST	Functionality, Reliability, Usability	88	Highly efficient and functional; suitable for continuous operations
Beta Testing	Fisheries Expert 2	SPAMAST	Functionality, Reliability, Usability	83	Reliable and efficient; enhancements for robustness recommended

Beta testing involved one pond owner, two pond workers, and two fisheries experts. The pond owner rated the system 99% satisfaction, noting it was highly functional and user-friendly. Pond workers gave satisfaction ratings

of 88% and 84%, stating the application made monitoring tasks faster and more efficient. Fisheries experts provided ratings of 88% and 83%, contributing to an overall SPAMAST expert validation score of 84.8% that classified the system as "Highly Suitable for Aquaculture Use."

The overall user evaluation indicated a mean satisfaction rating of 90.33%, which falls within the "Excellent" category. Respondents consistently rated the system highly in terms of functionality, usability, reliability, and efficiency. Since the evaluation focused on user perception and system acceptance, descriptive statistical analysis was deemed appropriate for interpreting the results. These findings suggest strong acceptance of AquaMate among both aquaculture practitioners and technical evaluators.

Economic Feasibility and Return on Investment

An ROI analysis evaluated AquaMate's financial feasibility compared to traditional timer-based aeration. Shifting from continuous timer-based operation (₱2,750 ± 180/month) to AquaMate's automated, solar-powered system (₱220 ± 40/month) reduced monthly energy expenses by an estimated 92%. With an initial setup cost ranging between ₱12,000–₱15,000, and net monthly savings of approximately ₱2,530, the ROI was computed at 21.08% monthly, allowing full cost recovery within approximately 5 months of continuous operation.

Table 6. *Return on Investment (ROI) Analysis*

Parameter	Traditional System	AquaMate System	Remarks
Average Monthly Cost (₱)	₱2,750 ± 180	₱220 ± 40	Based on electricity consumption and aerator runtime
Monthly Savings (₱)	—	₱2,530	Energy cost reduction after automation
System Cost (₱)	—	₱12,000–₱15,000	Includes sensors, solar unit, installation
ROI (%)	—	21.08% per month	Computed from monthly savings and total cost
Payback Period (Months)	—	5 months	Time required for full cost recovery

Conclusion

The results conclusively demonstrate that AquaMate is an effective, efficient, and scalable smart aquaculture solution that maintains dissolved oxygen and water temperature within species-specific safe zones, supports automated energy-efficient aeration, reduces operational costs, and achieves high user acceptance among rural Philippine fish farmers. By transforming reactive, schedule-based aeration into proactive, data-driven oxygen management informed by real-time temperature conditions, the system addresses the most immediate cause of fish mortality in tropical aquaculture while reducing energy expenditure.

The integration of ESP32-WROOM-32 microcontrollers, DFRobot Analog DO v2 sensors, DS18B20 waterproof temperature sensors, relay-controlled actuators, 50W solar-powered energy systems with 25Ah LiFePO₄ battery backup, and a Supabase cloud-connected Android mobile application effectively supports modern aquaculture management focused on dissolved oxygen and water temperature. The system achieved 98% uptime under normal conditions and 94% during adverse weather, maintaining safe DO levels 97–98% of the time with zero mortality events. The event-triggered aeration logic reduced daily duty cycle from 25% typical of fixed-schedule timers to 12%, yielding 52% runtime reduction, 92% cost savings, and complete solar energy independence.

User evaluation confirmed strong practical acceptance with an overall weighted average of 90.33%, classifying the system as "Excellent." The pond owner and workers rated the system 91% average satisfaction, citing elimination of 4:00 AM manual pond checks and reduced mortality anxiety. Technical experts provided ratings of 88% and 83%, contributing to an overall expert validation score of 84.8%.

Beyond its technical contributions, AquaMate has implications for aquaculture policy and rural development. Government agencies such as the Bureau of Fisheries and Aquatic Resources (BFAR) and local government units (LGUs) could subsidize or promote automated aeration systems for small-scale farmers as part of a national "Aquaculture 4.0" strategy. Specifically, BFAR may integrate threshold-based IoT aeration into its existing technology extension programs, while LGUs could allocate municipal development funds for cooperative procurement of smart aquaculture infrastructure. These policy interventions would reduce the capital barrier for resource-limited farmers, accelerate technology adoption, and align with national food security objectives by mitigating the 60–70% of fish kills attributed to hypoxic events. Capacity-building activities and farmer training modules on IoT-based pond management should accompany hardware distribution to ensure sustainable utilization.

The study recommends: (a) deployment of AquaMate from Day 1 through the end of the culture period for comprehensive evaluation across full production cycles; (b) further testing in larger pond areas or multi-pond systems to evaluate scalability; (c) integration of enhanced data logging features for long-term historical trend analysis; (d) enhancement of the mobile application with additional species-specific guidelines and interactive data visualization; (e) additional testing under varying environmental conditions including extreme weather events; (f) provision of user training and technical orientation for effective adoption; and (g) integration with other smart aquaculture technologies such as automated feeders and water quality analyzers for holistic farm management.

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