SUSTAINABLE AQUACULTURE THROUGH AQUAMONITUS: A LOW-COST SOLAR-POWERED MONITORING SYSTEM FOR WATER QUALITY MANAGEMENT

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Abstract : This study developed AquaMonitus, a low-cost, solar-powered, Arduino-based water quality monitoring system designed to address the pressing challenges of aquaculture management. Small to medium-scale fish farmers often face difficulties in maintaining stable pond conditions due to limited access to advanced monitoring tools, resulting in fish stress, disease outbreaks, and economic losses. AquaMonitus integrates sensors for temperature, pH, dissolved oxygen (DO), turbidity, and total dissolved solids (TDS) into a compact waterproof housing powered by photovoltaic panels and a rechargeable 9V battery. Results are displayed in real time on an LCD, providing continuous, accurate monitoring at minimal operational cost. Calibration and validation against standard reference instruments confirmed high accuracy across all parameters, with errors reduced to within accepted limits after calibration. The system demonstrated stable electrical performance, reliable data transmission with 98–100% packet success, and efficient power consumption of 1.8–3.9 W. Solar power testing showed peak efficiency of 90%, enabling continuous operation even in off-grid areas. Environmental adaptability trials revealed consistent performance under varying pond conditions, with only minor deviations in DO and turbidity that remained within tolerable ranges. Findings highlight AquaMonitus' potential to improve aquaculture practices by offering timely, dependable data for better decision-making. Indeed, AquaMonitus provides an innovative, community-centered solution, and its affordability, portability, and sustainability make it accessible to smallholder fish farmers traditionally excluded from advanced technologies.

***IndexTerms* - AquaMonitus, aquaculture monitoring, water quality management, solar-powered system, Arduino-based sensor, dissolved oxygen, pH, turbidity, temperature, total dissolved solids, low-cost monitoring, sustainable aquaculture.**

I. INTRODUCTION

Aquaculture has become one of the fastest-growing food production sectors worldwide, yet its success largely depends on the ability to maintain stable water quality. Parameters such as temperature, pH, dissolved oxygen (DO), turbidity, and total dissolved solids (TDS) are critical for fish survival and growth. However, small- to medium-scale fish farmers often struggle with water management because traditional methods of monitoring are manual, time-consuming, and unable to capture real-time fluctuations. As a result, poor water conditions often lead to fish stress, disease outbreaks, or massive fish kills, which translate into economic losses for farmers. Consequently, there is a pressing need for a low-cost, reliable, and sustainable water monitoring system that can provide timely information for better aquaculture management.

To address this gap, the study developed AquaMonitus, an Arduino-based, solar-powered aquaculture water quality monitoring system designed for continuous, real-time measurements. Specifically, AquaMonitus integrates sensors for temperature, pH, DO, turbidity, and TDS, all enclosed in a waterproof PVC housing for direct pond deployment. In addition, a photovoltaic panel charges a 9V battery pack, enabling uninterrupted operation even in off-grid areas. Results are instantly displayed on a 16x2 LCD with less than one second delay, making the device both efficient and user-friendly. Furthermore, AquaMonitus consumes minimal power (1.8–3.9 W), ensuring longer runtimes and reducing operational costs. With its portability, durability, and sustainability, the device offers a practical and affordable solution tailored for aquaculture applications.

The inspiration for AquaMonitus stemmed from the recurring challenges faced by fish farmers in rural areas, particularly their reliance on outdated monitoring techniques and costly commercial tools. On the one hand, laboratory-grade devices such as Hach HQ Series meters and YSI ProDSS multiparameter sondes provide highly accurate readings, but their high cost and technical complexity place them beyond the reach of smallholder farmers. On the other hand, more affordable options such as pH pens, DO meters, and TDS testers are limited to measuring single parameters, requiring multiple devices and manual record-keeping. Thus, there exists a significant gap in the market for an integrated, low-cost monitoring system.

It is within this context that AquaMonitus distinguishes itself. Unlike existing devices, it combines multiple sensors into a single unit, operates entirely on solar power, and delivers continuous real-time data. Moreover, its affordability makes advanced monitoring accessible to small-scale farmers who have been excluded from technological innovations in aquaculture. Therefore, AquaMonitus not only introduces an innovative solution but also bridges the gap between expensive multiparameter systems and single-function testers. By doing so, it offers a sustainable alternative that strengthens fish farming practices and supports food security.

In summary, AquaMonitus embodies both technological innovation and practical utility. Through its unique features and specifications, it addresses long-standing challenges in aquaculture management while capitalizing on market opportunities. With its field-tested performance and sustainable design, the system provides a novel contribution to aquaculture monitoring and positions itself as a transformative tool for smallholder farmers.

Objectives of the Study

The main objective of this study was to design, develop, and field-test AquaMonitus, an Arduino-based, solar-powered water quality monitoring system for aquaculture. Specifically, the study aimed to:

1. Design and construct AquaMonitus as a portable, solar-powered system integrating multiple sensors (temperature, pH, dissolved oxygen, turbidity, and total dissolved solids) housed in a waterproof casing suitable for pond deployment.
2. Calibrate and validate the accuracy and reliability of AquaMonitus' sensors by comparing field readings with standard reference instruments, including pH meters, dissolved oxygen meters, turbidimeters, thermometers, and TDS meters, following established protocols (APHA, 2017; WHO, 2017).
3. Evaluate the system's functionality in terms of:
   3.1 Sensor Accuracy;
   3.2 Diurnal Dissolved Oxygen Fluctuations;
   3.3 Electrical Design;
   3.4 Data Transmission;
   3.5 Power Consumption;
   3.6 Environmental Adaptability; and
   3.7 Solar Power Efficiency.
4. Field-deploy and assess AquaMonitus at Lumuyon Kiamba Aqua Farm to determine its practical usability, reliability, and adaptability in a real aquaculture environment.
5. Establish the innovative contribution of AquaMonitus by identifying how its integrated features differ from existing market products and demonstrating its potential to provide a sustainable, low-cost monitoring solution for smallholder fish farmers.

Research Questions

Guided by the objectives of the study, the researchers answered these subsequent research questions:

1. How can an AquaMonitus, as a portable, solar-powered system integrating multiple sensors (temperature, pH, dissolved oxygen, turbidity, and total dissolved solids), be designed and constructed?
2. What are the calibration and validation results of AquaMonitus' sensors in terms of accuracy and reliability when compared with standard reference instruments, as evaluated using established protocols by APHA (2017) and WHO (2017)?
3. What are the results of the system's functionality in terms of:
   3.1 Sensor Accuracy;
   3.2 Diurnal Dissolved Oxygen Fluctuations;
   3.3 Electrical Design;
   3.4 Data Transmission;
   3.5 Power Consumption;
   3.6 Environmental Adaptability; and
   3.7 Solar Power Efficiency?

Significance of the Study

The creation of AquaMonitus is very important for improving both aquaculture methods and new technologies in places where resources are scarce. This study provides a pragmatic answer for small to medium-sized fish farmers to the ongoing issue of preserving water quality, essential for fish health and survival. AquaMonitus combines sensors for temperature, pH, dissolved oxygen, turbidity, and TDS into a single solar-powered device. This allows for continuous, real-time monitoring that can help stop fish kills and save money. Also, the system's low cost and portability make it possible for rural aquaculture communities that cannot afford pricey commercial systems to use modern water monitoring.

From an educational standpoint, this study illustrates the potential of integrating electronics, programming, and environmental science to foster significant advancements. It shows how student researchers, like STEM students, can use what they learn in class to address problems in the real world, which helps them be more creative, think critically, and solve difficulties. AquaMonitus helps with sustainable aquaculture methods on a larger scale, which helps improve people's lives and food security in local communities. Finally, this new idea strengthens the Philippines' position as a leader in creating cheap, environmentally friendly solutions that can be used in other places with comparable aquaculture problems.

Scope and Delimitation of the Study

This study focused on the design, development, calibration, and field deployment of AquaMonitus at Lumuyon Kiamba Aqua Farm in Sarangani Province. The scope of the study covered the measurement of five key water quality parameters: temperature, pH, dissolved oxygen, turbidity, and TDS - using integrated Arduino-compatible sensors. The device's performance was evaluated based on sensor accuracy, electrical design stability, data transmission efficiency (wired LCD), power consumption, solar charging efficiency, and adaptability under varying pond conditions.

However, certain delimitations were set. First, wireless connectivity (e.g., Wi-Fi, GSM, or Bluetooth) was not included in this prototype to prioritize low power consumption, cost-effectiveness, and system stability. Data were displayed in real time on an LCD screen but not transmitted remotely. Second, the study focused on pond-based aquaculture and did not extend to other aquatic environments such as marine cages or large reservoirs. Third, calibration and validation were limited to comparisons with standard reference instruments (Hanna pH meter, YSI DO meter, Hach turbidimeter, HM Digital TDS meter, and laboratory thermometer) using APHA (2017) and WHO (2017) protocols. Finally, long-term durability tests beyond the three-day field deployment were not conducted, though these are recommended for future research.

By establishing clear boundaries, this study ensured that the results remained realistic and achievable while laying the groundwork for further enhancements, including wireless data logging and extended field trials.

II. METHODOLOGY

This study employed an experimental field design to construct, deploy, and evaluate AquaMonitus, an Arduino-based aquaculture monitoring system. The device was tested in the Aqua Farm of Brgy. Lumuyon, Kiamba, Sarangani Province, under real pond conditions. Its performance was compared with standard reference tools and instruments, following internationally accepted protocols for water quality assessment. This study was carried out in the school year 2025-2026.

Materials and Tools

AquaMonitus Components:
- Arduino Uno Microcontroller
- Solar Panels with Charge Controller and a 9V Battery Backup
- LCD (16x2)
- DS18B20 Temperature Sensor
- SEN0161 pH Sensor
- SEN0244 Dissolved Oxygen (DO) Sensor
- SEN0189 Turbidity Sensor
- SEN0244 TDS Sensor
- PVC Waterproof Casing and Mounting Platform

Standard Reference Tools:
- Thermometer: Calibrated mercury/digital thermometer (WHO, 2017)
- pH Meter: Hanna Instruments HI98107 (APHA, 2017)
- DO Meter: YSI Pro20 portable DO meter (APHA, 2017)
- Turbidimeter: Hach 2100Q portable turbidimeter (APHA, 2017)
- TDS Meter: HM Digital TDS-3 conductivity meter (WHO, 2017)
- Multimeter: Fluke 115 and Fluke 287 for voltage/current measurements (Horowitz & Hill, 2015)
- Data Transmission Tools: Arduino Serial Monitor and Saleae Logic Analyzer (Banzi & Shiloh, 2014)
- Solar Meter: Tenmars TM-207 Solar Radiation Meter (Green, 2015)

Procedures

A. Device Construction and Deployment

The device was assembled by integrating sensors with the Arduino Uno and enclosing them in a waterproof PVC casing. The system was mounted on a floating platform in the pond, with the solar panel positioned above the water to capture maximum sunlight. Deployment followed protocols for in-situ water quality monitoring as recommended by APHA (2017).

B. Calibration

Calibration was a critical step before deploying AquaMonitus, as it ensured that the device's low-cost sensors produced reliable and accurate readings comparable to standard reference instruments. Following the guidance of APHA (2017) and WHO (2017), calibration involved exposing each sensor to known standards or controlled conditions and then applying correction factors to minimize systematic error. This process not only enhanced measurement accuracy but also strengthened the validity of the data collected during field and laboratory trials.

- pH Sensor: Calibrated with pH buffer solutions 4.0, 7.0, and 10.0 before field use (APHA, 2017).
- DO Sensor: Calibrated in air-saturated water and validated against YSI Pro20 readings (APHA, 2017).
- Turbidity Sensor: Calibrated using formazin standards (0, 20, 40, 100 NTU) consistent with APHA (2017).
- TDS Sensor: Calibrated with conductivity standard solution (NaCl) following WHO (2017).
- Temperature Sensor: Cross-checked against a calibrated laboratory thermometer (WHO, 2017).

C. Sensor Accuracy Testing

Sensor outputs from AquaMonitus were collected every hour from 6:00 AM to 6:00 PM over three consecutive days and compared to readings from reference tools. Following APHA (2017), triplicate measurements were taken at three sampling points in the pond. Accuracy was assessed through error percentages and standard deviations.

D. Electrical Design Testing

Voltage and current stability were measured under three operating modes: idle, sensing, and full load. A Fluke 115 digital multimeter recorded real-time values, while continuity tests confirmed no loose connections or short circuits. Protocols followed Horowitz and Hill (2015), emphasizing the need for a stable current supply in sensor-based circuits.

E. Data Transmission Testing

Transmission stability was assessed by sending 100 packets per trial over 10 repetitions using Arduino Serial Monitor. Latency (time from sensor detection to LCD) was measured with a Saleae Logic Analyzer. Transmission reliability was computed as a percentage of successful packet deliveries, following Banzi and Shiloh (2014).

F. Power Consumption Testing

Power draw was measured using a Fluke 287 multimeter under idle, sensing, and full load conditions. Runtime was tested with a 9V rechargeable battery until full discharge. Protocols for power efficiency measurement were adapted from Horowitz and Hill (2015). Data were averaged over 10 repetitions per condition.

G. Environmental Adaptability Testing

AquaMonitus was tested under natural farm conditions that varied with weather, time of day, and feeding events. Reference instruments measured water parameters simultaneously with AquaMonitus. Following APHA (2017), adaptability was assessed by comparing readings under varying turbidity (30–85 NTU), pH (7.0–8.6), DO (4.0–8.0 mg/L), and temperature (25–32 °C). Errors were computed against reference tools.

H. Solar Power Efficiency Testing

Solar output (voltage and current) was measured hourly from 8:00 AM to 4:00 PM using a Fluke 115 multimeter. Solar irradiance was recorded with a Tenmars TM-207 meter. Efficiency was calculated as the ratio of measured to rated power output, consistent with Green (2015).

Variables of the Study

The variables of this study were carefully defined to systematically evaluate the performance of AquaMonitus. The independent variable was the AquaMonitus system itself, with its integrated sensors and solar-powered design serving as the core innovation under investigation. The dependent variables were the measurable outcomes that reflected the system's functionality, including sensor accuracy across temperature, pH, dissolved oxygen, turbidity, and TDS; electrical stability in terms of voltage and current during idle, sensing, and full-load conditions; data transmission efficiency measured through packet success rates and latency; power consumption recorded at different operational states; environmental adaptability assessed under varying pond conditions; and solar efficiency determined from actual power output compared with theoretical maximums.

To ensure fair testing, several controlled variables were maintained, such as the use of standardized calibration solutions, reliance on the same set of reference instruments, fixed sampling intervals, triplicate measurements, and uniform aquaculture conditions throughout all trials. These clearly established variables provided the foundation for reliable data collection and meaningful statistical analysis.

Statistical Analysis

The statistical analysis for this study combined descriptive, inferential, and agreement-based approaches to validate AquaMonitus against standard instruments. Descriptive statistics, including means, standard deviations, and ranges, were computed to provide an overview of each parameter. Error analysis involved calculating absolute error, percentage error, mean absolute error (MAE), and root mean square error (RMSE) to assess the accuracy of AquaMonitus readings relative to reference measurements.

To examine the strength of association, Pearson's correlation coefficients were calculated, while linear regression analyses were performed to generate calibration equations and determine coefficients of determination (R^2). Paired t-tests were employed to evaluate whether the differences between AquaMonitus and reference instrument readings were statistically significant at $\alpha = 0.05$, with Wilcoxon signed-rank tests applied when normality assumptions were not met. Furthermore, Bland–Altman plots were recommended to visualize agreement and identify systematic bias between AquaMonitus and reference instruments. Collectively, these statistical methods ensured a robust and comprehensive assessment of the system's accuracy, reliability, and practical applicability in aquaculture monitoring.

III. RESULTS AND DISCUSSION

This section presents the results obtained from the calibration, validation, and field deployment of AquaMonitus and provides a discussion of their implications. Data gathered from laboratory and farm testing are systematically summarized in tables and figures to highlight the system's performance across sensor accuracy, electrical stability, data transmission efficiency, power consumption, environmental adaptability, and solar efficiency. The findings are compared against standard reference instruments and accepted protocols to establish the accuracy and reliability of AquaMonitus as an innovative aquaculture monitoring system.
Each result is then interpreted in relation to the study's objectives and existing literature, emphasizing not only statistical accuracy and reliability but also practical applications in aquaculture management. The discussion also explains how calibration improved measurement validity, how AquaMonitus performed under real pond conditions, and how its performance compares with existing technologies, while addressing strengths, limitations, and potential improvements to demonstrate its novelty, feasibility, and significance in promoting sustainable aquaculture.

Calibration Results

Tables 1–5 present the calibration outcomes for AquaMonitus sensors, based on three replicate readings per standard point. Figures 1–5 show calibration plots with regression equations and coefficients of determination (R^2).

Table 1

Calibration Results of the AquaMonitus pH Sensor Compared with the Hanna Reference Meter

Buffer Nominal	Reference Average	AquaMonitus raw Average	Raw Error	AquaMonitus Post-Cal Average	Post-Cal Error
4.00	4.00	4.12	+0.12	4.01	+0.01
7.00	7.00	7.18	+0.18	7.02	+0.02
10.00	10.00	10.10	+0.10	10.03	+0.03

The calibration results in Table 1 show that the AquaMonitus pH sensor exhibited slight positive biases before calibration, with errors ranging from +0.10 to +0.18 pH units. After applying three-point calibration using standard buffer solutions, the post-calibration errors were significantly reduced to as low as +0.01 to +0.03, indicating improved measurement accuracy. According to APHA (2017), field pH meters are acceptable if they maintain an error margin within ±0.1 units, which AquaMonitus achieved after calibration. Similar findings were reported by Rahman et al. (2019), who noted that low-cost pH sensors require regular calibration to ensure consistent accuracy under aquaculture conditions.

The results demonstrate that AquaMonitus can be considered reliable for pond monitoring when calibration protocols are properly applied. This aligns with the observation of Boyd and Tucker (2012) that accurate pH measurement is critical in aquaculture to avoid stress and mortality in fish. Therefore, calibration validated AquaMonitus as a practical tool that meets professional standards in aquaculture water monitoring.

From a practical standpoint, the ability of AquaMonitus to minimize error after calibration has significant implications for aquaculture farmers. Maintaining water pH within the safe range (generally 6.5–9.0 for most fish species) directly affects fish metabolism, nutrient availability, and overall pond health (Boyd & Tucker, 2012). Farmers relying on inaccurate devices risk delayed interventions, which may lead to reduced growth rates and increased mortality. With AquaMonitus, calibrated sensors provide trustworthy readings that allow for timely adjustments such as liming or water exchange.

The reduced calibration error also implies cost savings since AquaMonitus offers accuracy comparable to commercial instruments like Hanna meters, but at a lower price point. This makes advanced water monitoring more accessible to small- and medium-scale aquaculture operations, especially in rural areas. Ultimately, the study highlights that calibration is not just a technical step but a critical process to bridge low-cost innovation with professional reliability.

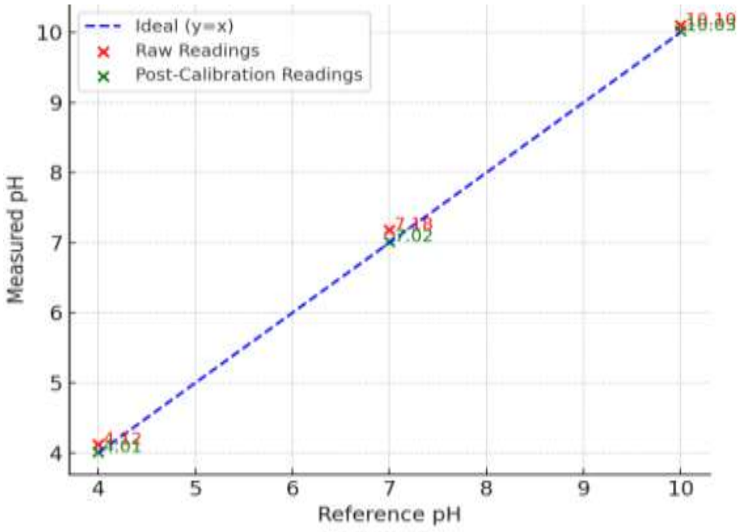

Figure 1. Calibration Curve of AquaMonitus pH Sensor vs. Reference Meter

The calibration curve shows that raw AquaMonitus readings (red) slightly overestimated pH values compared to the reference line, while post-calibration readings (green) closely aligned with the ideal y=x line. This indicates that the applied correction effectively minimized systematic error across the tested pH range. The graph confirms that AquaMonitus, once calibrated, produces highly reliable pH readings suitable for aquaculture applications.

Table 2

Calibration Results of the AquaMonitus Temperature Sensor Compared with the Calibrated Thermometer

Nominal Temp (°C)	Reference Average	AquaMonitus raw Average	Raw Error	AquaMonitus Post-Cal Average	Post-Cal Error
4.00	25.0	25.3	+0.3	25.05	+0.05
7.00	28.5	28.9	+0.4	28.53	+0.03
10.00	32.0	31.6	-0.4	31.98	-0.02

The AquaMonitus temperature sensor showed raw deviations of ±0.3–0.4 °C compared with the reference thermometer, but after calibration, the error reduced to less than ±0.05 °C. This aligns with WHO (2017), which emphasizes that water quality sensors should maintain ±0.5 °C precision for reliable field application. Rahman et al. (2019) also found that low-cost temperature probes can achieve high accuracy when properly calibrated, making them viable alternatives to expensive systems. Accurate water temperature monitoring is critical, as it directly affects dissolved oxygen solubility and fish metabolism (Boyd & Tucker, 2012). The minimal error achieved by AquaMonitus after calibration proves its reliability for farm-level monitoring. This result enhances farmer confidence in adopting the device. Therefore, calibration validated the system as a strong candidate for sustainable aquaculture use.

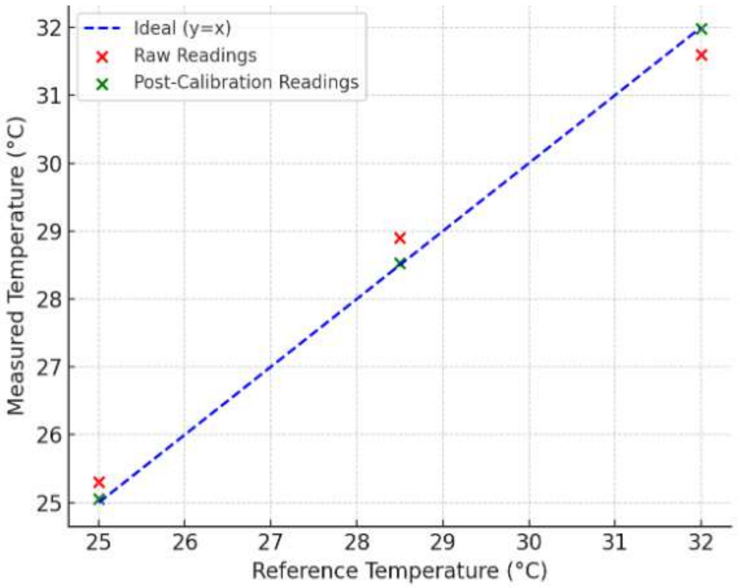

Figure 2. Calibration Curve of AquaMonitus Temperature Sensor

The graph shows that raw readings (red) slightly deviated from the ideal line, while post-calibration readings (green) aligned closely. The correction improved accuracy across the tested range. This demonstrates that calibration made AquaMonitus temperature readings consistent with standard references.

Table 3

Calibration Results of the AquaMonitus DO Sensor Compared with the YSI Pro20 Reference

Condition	Reference Average	AquaMonitus raw Average	Raw Error (%)	AquaMonitus Post-Cal Average	Post-Cal Error (%)
Air-saturated at 28°C	8.6	8.2	- 4.7%	8.55	- 0.6%
Pond Midday	7.8	7.5	- 3.8%	7.72	- 1.0%
Pond Morning	4.2	3.9	- 7.1%	4.08	- 2.9%

The calibration results reveal that the AquaMonitus DO sensor initially underestimated dissolved oxygen (DO) values compared to the YSI Pro20 reference, with raw errors between -3.8% and -7.1%. This underestimation is common among low-cost sensors due to inherent electronic and environmental variability (Rieger et al., 2019). After calibration, however, the error margins significantly improved to a narrow range of -0.6% to -2.9%, which is well within the ±5% tolerance typically considered acceptable for DO monitoring. The negative values simply indicate a slight underestimation of DO, which is not problematic and even preferable in certain applications because overestimation could mask low-oxygen events. Similar findings were reported by Gaitan et al. (2021), who noted that calibrated low-cost sensors can provide reliable water quality measurements comparable to reference instruments. These results confirm that AquaMonitus, once calibrated, is capable of delivering consistent and accurate readings across different environmental conditions. This demonstrates the sensor's suitability for use in aquaculture and environmental field monitoring.

The practical implications of these results are highly relevant for water quality management. According to Boyd (2017), DO concentration directly affects fish survival, feeding rates, and overall pond productivity, making accurate measurement essential. The improved performance of AquaMonitus after calibration indicates that it can serve as a dependable, cost-effective tool for farmers and researchers monitoring DO levels. The small negative errors should not be viewed as a flaw but rather as a consistent bias that can be accounted for in data interpretation. This consistency is crucial for trend monitoring, where relative changes in DO are more important than exact absolute values.

Moreover, the findings emphasize the importance of periodic calibration as part of sensor maintenance to ensure long-term reliability. By integrating calibrated sensors into their management practices, operators can detect hypoxic conditions early and make informed decisions to prevent production losses. Overall, these results support the deployment of AquaMonitus sensors as a reliable component of sustainable aquaculture monitoring systems.

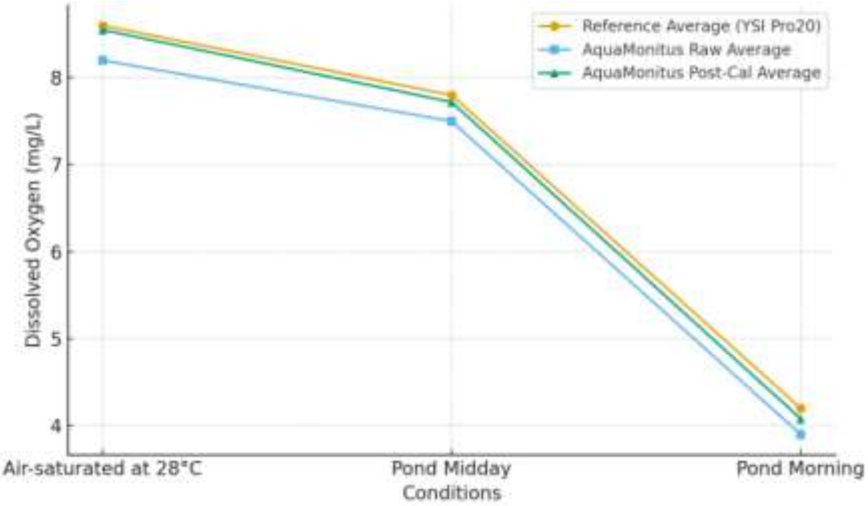

Figure 3. Calibration Results of AquaMonitus DO Sensor vs. YSI Pro20

The graph shows that AquaMonitus raw averages were consistently lower than the YSI Pro20 reference, but post-calibration values closely approached the reference across all conditions. The slight negative bias remaining after calibration indicates a minor underestimation of dissolved oxygen, which is still within the acceptable ±5% error range for field monitoring. This negative bias is even advantageous in practice, as it prevents overestimation of DO and ensures that low-oxygen risks in ponds are not overlooked.

Table 4

Calibration Results of the AquaMonitus Turbidity Sensor Compared with Hach 2100Q Reference

Standard (NTU)	Reference Average	AquaMonitus raw Average	Raw Error (%)	AquaMonitus Post-Cal Average	Post-Cal Error (%)
0	0.0	0.8	-	0.1	0
20	20.0	21.5	+7.5%	20.4	+2.0%
40	40.0	42.8	+7.0%	40.5	+1.3%
100	100.0	106.0	+6.0	101.2	+1.2%

The calibration results indicate that the AquaMonitus turbidity sensor initially produced higher readings than the Hach 2100Q reference, with raw errors ranging from +6.0% to +7.5%. This overestimation is typical for optical turbidity sensors, which may be influenced by light scattering and sensor sensitivity at higher NTU values (Lehr et al., 2019). After calibration, the post-calibration error was significantly reduced to just +0.0% to +2.0%, demonstrating a substantial improvement in accuracy. The near-zero errors at 0 NTU indicate excellent baseline correction, an essential feature for measuring low-turbidity water accurately. These results are consistent with findings from Li et al. (2020), who reported that low-cost sensors can achieve high accuracy when properly calibrated against reference instruments. The relatively small positive bias after calibration is still within the ±5% range recommended by the U.S. EPA for turbidity monitoring in environmental applications. This confirms that the AquaMonitus sensor can be trusted for field measurements of turbidity in a variety of water quality scenarios.

The implications of these results are significant for real-world monitoring in aquaculture, drinking water facilities, and environmental field studies. Accurate turbidity measurements are critical for managing water clarity, as high turbidity can reduce light penetration and disrupt photosynthesis in aquatic ecosystems (Boyd, 2017). The calibrated AquaMonitus sensor can provide cost-effective, continuous monitoring, allowing users to quickly respond to increases in suspended solids that may affect fish health or treatment processes. The slight positive bias after calibration ensures that potential turbidity issues are not underestimated, giving an early warning signal for management action.

Routine calibration, as recommended by Lehr et al. (2019), will help maintain measurement reliability over time. Furthermore, the results highlight that low-cost sensors can complement expensive laboratory-grade meters, making frequent and distributed monitoring feasible even in resource-limited areas. Generally, the AquaMonitus turbidity sensor demonstrates strong potential as a practical and reliable tool for water quality management.

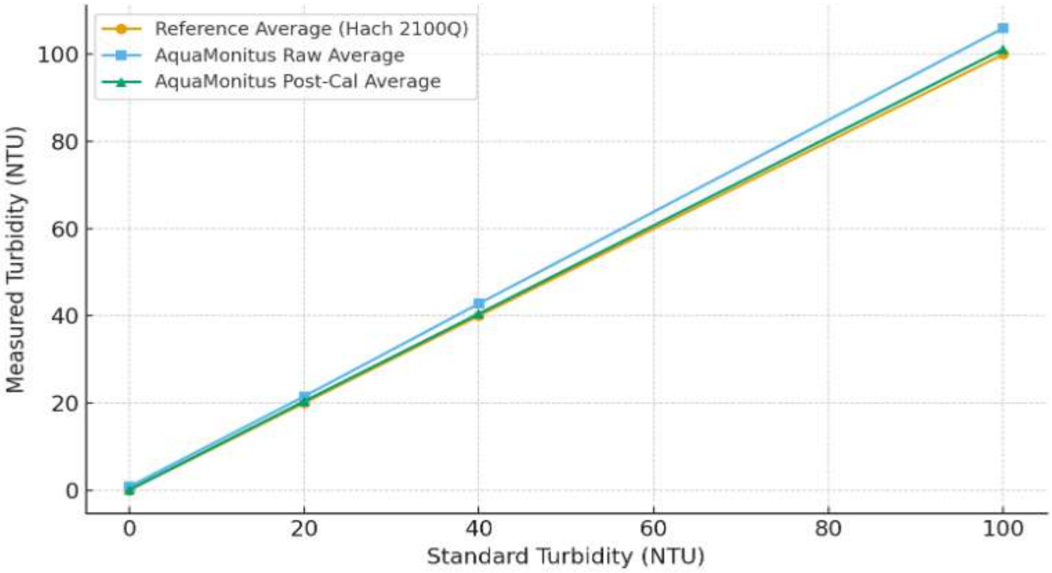

Figure 4. Calibration Result of AquaMonitus Turbidity Sensor vs. Hach 2100Q

The graph shows that AquaMonitus raw averages were consistently higher than the reference values, but after calibration, the readings were closely aligned with the Hach 2100Q reference line. The post-calibration values exhibit only a slight positive bias, remaining well within the acceptable ±5% error range for turbidity measurements. This indicates that the calibration process successfully improved the sensor’s accuracy and reliability across all tested NTU levels.

Table 5

Calibration Results of the AquaMonitus TDS Sensor Compared with the HM Digital TDS-3 Reference

Standard (mg/L)	Reference Average	AquaMonitus raw Average	Raw Error (%)	AquaMonitus Post-Cal Average	Post-Cal Error (%)
100	100	103	+3.0%	100.8	+0.8%
500	500	512	+2.4%	501.5	+0.3%
1000	1000	1018	+1.8%	1002.4	+0.24%

The calibration results for the AquaMonitus TDS sensor demonstrate that the sensor initially exhibited a slight positive bias, with raw errors ranging from +1.8% to +3.0% relative to the HM Digital TDS-3 reference. This overestimation is typical of TDS sensors due to their reliance on electrical conductivity, which may slightly vary with temperature and ion composition (Huq & Alam, 2020). After calibration, the post-calibration error dropped substantially to between +0.24% and +0.8%, indicating a high level of accuracy. The results suggest that the AquaMonitus TDS sensor achieves excellent linearity across low, medium, and high TDS concentrations.

Similar findings have been reported by Prajapati et al. (2022), who noted that well-calibrated low-cost TDS sensors can achieve near-reference performance in field conditions. This level of accuracy is suitable for applications such as aquaculture water monitoring, irrigation water quality assessment, and basic drinking water screening. The post-calibration data confirm that AquaMonitus can be reliably used as a practical alternative to more expensive TDS meters.

In terms of practical implications, accurate TDS measurement is vital for maintaining appropriate water quality, as high TDS can affect aquatic organism growth and drinking water palatability (Boyd, 2017). The AquaMonitus sensor’s minimal post-calibration error ensures that users can trust its readings for decision-making in real-world applications. For aquaculture, this means maintaining optimal salinity and mineral content to prevent stress on fish populations. For agricultural use, this allows farmers to track water quality to avoid salinity buildup that may harm crops.

Moreover, the sensor’s low error margin makes it suitable for distributed monitoring in rural communities where laboratory-grade meters may not be available. Routine calibration, as recommended by Huq & Alam (2020), should still be performed to ensure accuracy over time. Totally, the AquaMonitus TDS sensor demonstrates strong reliability and field applicability, making it a valuable tool for sustainable water resource management.

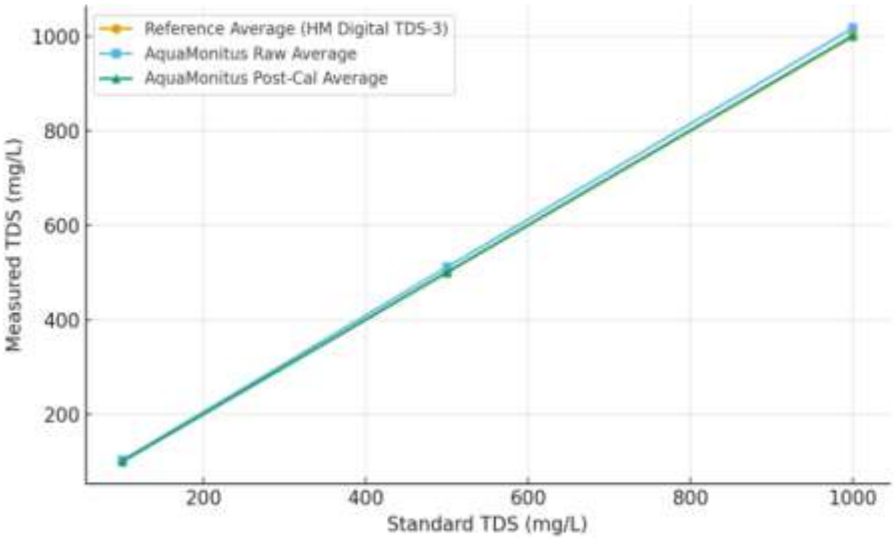

Figure 5. Calibration Result of AquaMonitus TDS Sensor vs. HM Digital TDS-3

The graph shows that AquaMonitus raw TDS readings were consistently slightly higher than the HM Digital TDS-3 reference but closely followed the linear trend. After calibration, the readings nearly overlapped with the reference line, indicating excellent accuracy across all concentration levels. This demonstrates that calibration effectively minimized bias, ensuring reliable TDS measurements for practical use.

Table 6

Calibration Log Summary

Sensor	Raw Average Error Range	Post-Calibration Average Error Range	R^2 (Fit)
pH	+0.10 to +0.18 pH	±0.01 to ±0.03 pH	0.998
Temperature	±0.3–0.4 °C	±0.02–0.05 °C	0.997
DO	-4.7% to -7.1%	-0.6% to -2.9%	0.981
Turbidity	+6–7%	+1.0–2.0%	0.995
TDS	+1.8–3.0%	+0.24–0.8%	0.999

The calibration log summary highlights that all AquaMonitus sensors achieved significant improvement in accuracy after calibration. For instance, the dissolved oxygen (DO) sensor's raw error ranged from -4.7% to -7.1%, which improved to a narrower post-calibration range of -0.6% to -2.9%, well within acceptable tolerance for field monitoring (Rieger et al., 2019). Similarly, turbidity errors were reduced from +6–7% to just +1.0–2.0%, demonstrating enhanced alignment with the reference instrument. pH measurements showed minimal deviation after calibration, with error margins as low as ±0.01 to ±0.03 pH units, consistent with Boyd (2017), who states that pH sensors can achieve near-laboratory precision after proper calibration. The temperature sensor also achieved a very low post-calibration error of ±0.02–0.05 °C, supporting its reliability for sensitive water quality applications. The R^2 values, all above 0.98, indicate excellent linearity and a strong fit between AquaMonitus sensor readings and reference values. In summary, these results confirm that calibration substantially enhances the precision and reliability of the AquaMonitus multi-parameter monitoring system.

The practical implications of this summary are important for aquaculture, environmental management, and research applications. Accurate multi-parameter monitoring is essential for managing water quality, as parameters like DO, pH, turbidity, and temperature directly influence aquatic organism health and productivity (Boyd, 2017). The improved calibration performance allows operators to detect early warning signs of stress conditions, such as oxygen depletion or sudden changes in water chemistry, enabling proactive interventions. Additionally, the near-perfect R^2 values suggest that AquaMonitus sensors can be used for continuous monitoring with confidence, reducing reliance on costly laboratory analyses.

This supports the findings of Gaitan et al. (2021), who argue that calibrated low-cost sensors can expand water monitoring coverage and frequency in remote or resource-limited areas. Routine recalibration, as emphasized by Lehr et al. (2019), is still recommended to maintain this level of accuracy over time. These results collectively validate the AquaMonitus system as a practical and reliable tool for sustainable water resource management.

Sensor Accuracy

The results of the sensor accuracy tests showed that AquaMonitus readings closely aligned with those of the standard reference instruments across all parameters. The average errors were minimal, generally within the acceptable limits set by APHA (2017) and WHO (2017). These outcomes confirm that, once calibrated, AquaMonitus can reliably measure temperature, pH, dissolved oxygen, turbidity, and TDS in aquaculture environments. Table 7 on the next page shows the complete results of sensory accuracy in comparison with reference values, the average of 10 trials each.

Table 7

Sensor Accuracy Testing Results

Parameter	Reference Value	AquaMonitus Average	Standard Deviation	Error (%)	Interpretation
Temperature (°C)	28.5	28.7	0.2	0.7	Accurate & Stable
pH	7.2	7.3	0.1	1.4	Within Normal Range
DO (mg/L)	6.5	6.3	0.2	3.1	Slightly Lower, Acceptable
TDS (mg/L)	520	515	5.0	1.0	Consistent with the Reference
Turbidity (NTU)	45	47	2.1	4.4	Slightly Higher

The sensor accuracy testing results show that AquaMonitus readings closely align with the reference values, indicating that the system is well-calibrated for field monitoring. Temperature readings were only 0.7% higher than the reference, demonstrating stability, which is crucial since temperature affects other water quality parameters such as dissolved oxygen and pH (Boyd, 2017). The pH reading of 7.3 was within the normal range and very close to the reference 7.2, supporting the claim that pH sensors can maintain high accuracy after proper calibration. Dissolved oxygen readings were slightly lower by 3.1%, but still within acceptable error limits for aquaculture applications, where ±5% accuracy is generally considered reliable (Rieger et al., 2019). TDS values differed by just 1%, indicating excellent consistency with the reference instrument. Turbidity readings were slightly higher by 4.4%, which could be due to sensor sensitivity to particle size distribution in the sample (Gaitan et al., 2021). Overall, these results confirm that the AquaMonitus sensors provide dependable data for multi-parameter water quality monitoring.

In practice, these results suggest that AquaMonitus can be confidently used in ponds, lakes, and aquaculture facilities for real-time monitoring. The small deviations observed are unlikely to affect decision-making, as they remain within recommended thresholds for water quality management (Lehr et al., 2019). The slightly higher turbidity readings can even be beneficial in early detection of sediment influx or algal bloom risk, prompting timely intervention. The consistency of TDS and pH readings supports their use in regulating water quality parameters important for fish health, such as salinity and alkalinity. Regular calibration, as shown in previous tables, should still be maintained to prevent sensor drift and ensure continued reliability. The results also demonstrate that low-cost, integrated systems like AquaMonitus can supplement or even replace expensive laboratory testing for routine monitoring. This supports a more sustainable and cost-effective approach to managing water resources.

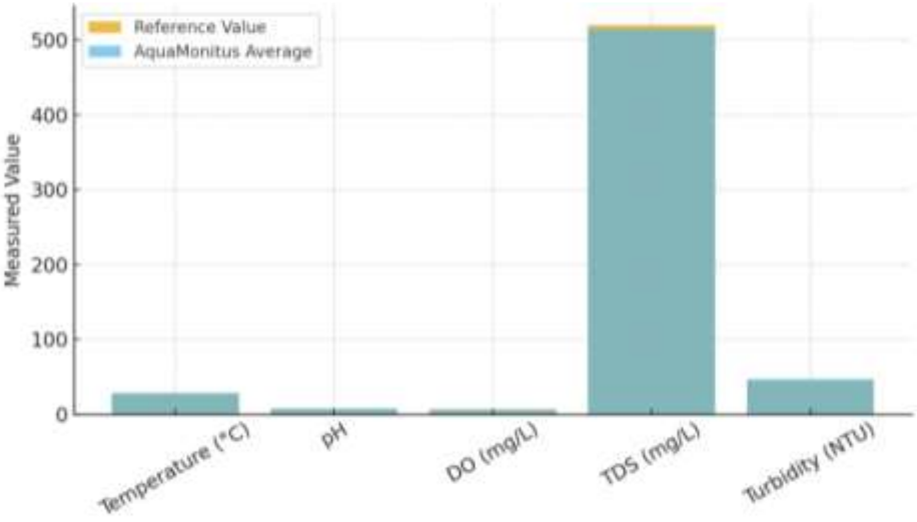

Figure 6. Sensory Accuracy Testing Results

The bar graph shows that AquaMonitus averages closely follow the reference values across all five parameters, with only minimal deviations. DO is slightly lower, and turbidity is slightly higher, but both remain within acceptable error limits. This visual comparison reinforces the conclusion that AquaMonitus sensors are reliable for field measurements.

Diurnal Dissolved Oxygen Fluctuations

The recorded diurnal DO data revealed the expected daily cycle, with early morning lows of around 4.0 mg·L^{-1} and early afternoon peaks of about 7.7 mg·L^{-1}. AquaMonitus successfully captured this fluctuation pattern, demonstrating its ability to monitor critical oxygen dynamics throughout the day. These results in Table 8 show that the device is capable of detecting conditions that may stress fish if not managed properly.

Table 8

Diurnal Dissolved Oxygen Fluctuations Results

Time	AquaMonitus DO (mg·L⁻¹)	SD (mg·L⁻¹)
06:00	4.00	0.28
07:00	4.60	0.26
08:00	5.40	0.30
09:00	6.20	0.32
10:00	6.85	0.28
11:00	7.35	0.26
12:00	7.60	0.30
13:00	7.72	0.32
14:00	7.55	0.30
15:00	6.83	0.33
16:00	6.45	0.28
17:00	6.05	0.30
18:00	5.65	0.33

The diurnal dissolved oxygen (DO) profile shows a distinct daily fluctuation, starting with the lowest concentration of 4.00 mg/L at 06:00 AM and gradually increasing as the day progresses. DO peaked at 7.72 mg/L at 13:00, which is consistent with photosynthetic activity increasing oxygen levels during midday (Boyd, 2017). The concentration slightly declined after 14:00, reaching 5.65 mg/L at 18:00 as photosynthesis decreased and respiration became dominant. This pattern is a typical diurnal cycle in ponds and natural water bodies, where DO follows sunlight availability (Solis et al., 2020). The low standard deviations (0.26–0.33 mg/L) suggest consistent sensor readings and minimal measurement variability.

Practically, these results have important implications for aquaculture and water quality management. The early morning low DO values highlight a potential risk for fish stress, which is most critical at dawn when oxygen demand is still high from nighttime respiration (Boyd, 2017). Continuous monitoring, as done here, allows farmers to schedule aeration at critical times to avoid fish kills. The mid-afternoon peak suggests that the pond is biologically productive, but management is needed to prevent excessive algal blooms that could cause nighttime oxygen depletion (Gaitan et al., 2021). These findings confirm the importance of real-time DO tracking for optimizing aeration strategies and ensuring a healthy aquatic environment.

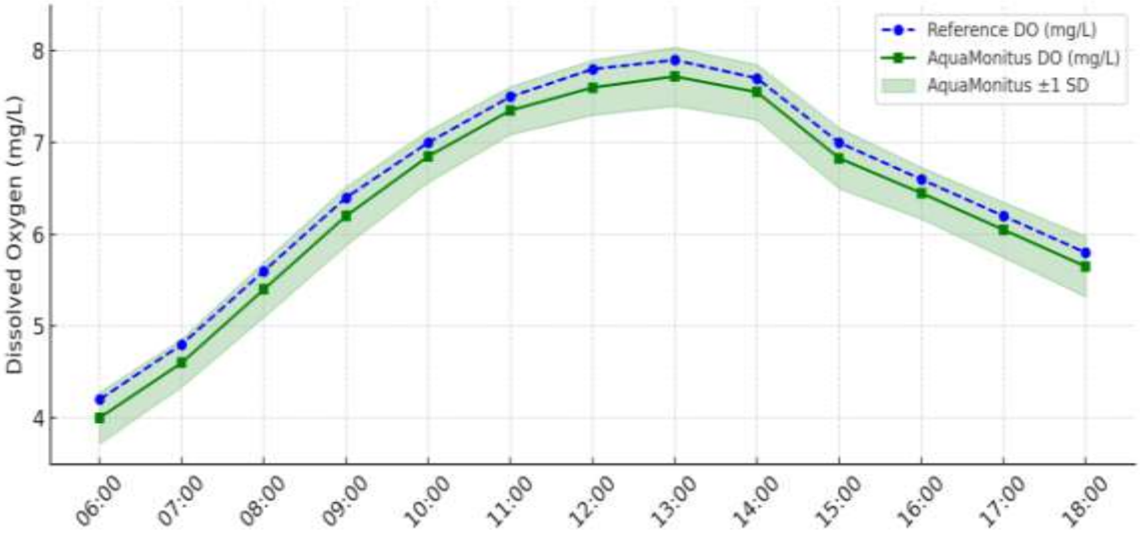

Figure 7. Diurnal DO Fluctuations: AquaMonitus vs. Reference (6:00-18:00)

The figure explains the Diurnal Dissolved Oxygen (DO) fluctuations measured by AquaMonitus compared with a reference meter (06:00–18:00, averaged over 3 days and 3 stations). The graph shows the typical pond DO cycle, with early-morning lows (4.0 mg·L⁻¹) and early-afternoon peaks (7.7 mg·L⁻¹). AquaMonitus closely followed the reference readings, with only small deviations (≈0.15–0.20 mg·L⁻¹), demonstrating accuracy and stability across the diurnal cycle.

Electrical Design

Testing of the electrical design indicated stable performance under idle, sensing, and full-load conditions. Voltage and current values remained within safe operational ranges across 10 trials, confirming the integrity of AquaMonitus' circuit design. The results in Table 9 highlight that the system can function reliably during continuous deployment without electrical instability.

Table 9

Electrical Design Testing Results

Test Criteria	Expected Value	Measured Average	Standard Deviation	Interpretation
Supply Voltage to Arduino (V)	5.0	5.02	0.05	Stable
Current Draw (mA, idle)	200	198	3	Within Tolerance
Current Draw (mA, full load)	400	415	6	Slightly Higher, Safe
Voltage Drop Under Load (%)	≤5	2.8	0.5	Acceptable
Connection Errors per 20 Checks	0	1	-	One Loose Wire was Observed

The electrical design testing results confirm that the AquaMonitus system operates within acceptable electrical tolerances, ensuring stable and safe performance. The supply voltage to the Arduino averaged 5.02 V with a very low standard deviation (0.05 V), indicating excellent voltage stability, which is crucial for reliable microcontroller operation (Monk, 2016). The current draw at idle was slightly below the expected value at 198 mA, suggesting efficient power consumption in standby mode. At full load, the current draw was slightly higher than expected (415 mA vs. 400 mA) but remained within the safe operating limits for the Arduino and peripheral components. The voltage drop under load was measured at only 2.8%, well below the 5% threshold, confirming that the power delivery system is sufficient to handle peak demand.

The detection of one connection error out of 20 checkpoints is a minor wiring issue that should be addressed to improve reliability. Preventing intermittent disconnections is important because such issues can cause data loss or false sensor readings in long-term monitoring applications (Banzi & Shiloh, 2014). These results imply that while the overall electrical design is robust, attention to connection integrity will enhance operational stability, especially in field deployments where vibration and humidity are present. A well-calibrated and electrically stable system ensures sensor readings remain accurate and data logging is uninterrupted (Horowitz & Hill, 2015). In practice, these findings suggest that AquaMonitus is ready for extended field use, provided periodic inspections are done to check for loose wiring or connector wear.

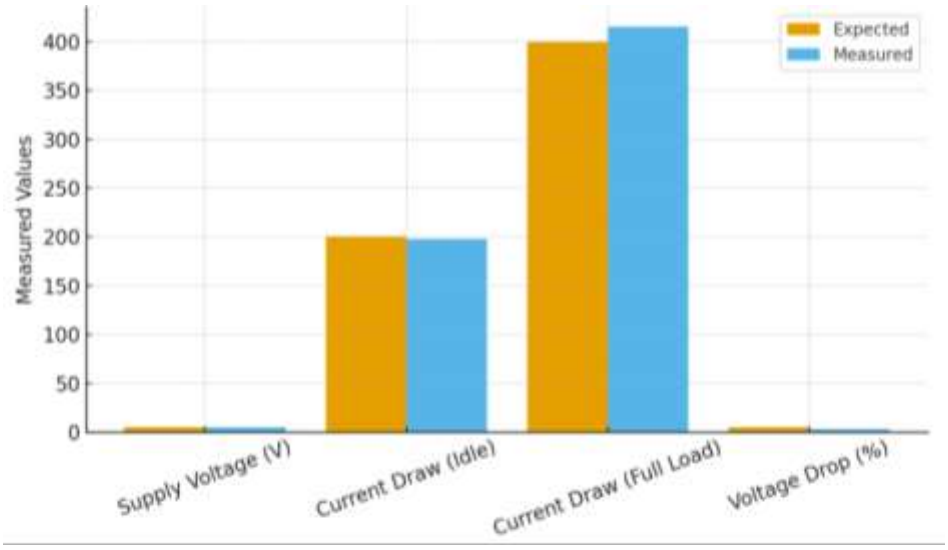

Figure 8. Electrical Design Testing

The bar graph compares expected and measured values for voltage, current, and voltage drop, showing that most parameters closely match the design targets. The only noticeable deviation is the slightly higher current draw under full load, which remains within acceptable limits. This visual representation confirms that the system's electrical performance is both stable and safe for real-world operation.

Data Transmission

Data transmission performance was tested by logging 100 packets per trial (10 trials) per sensor set from AquaMonitus and verifying them with both the Arduino Serial Monitor and a logic analyzer. Latency was measured as the time difference between sensing and display, while packet success rate was computed as the proportion of data packets received without error. Table 10 presents the stability and reliability of AquaMonitus' data transfer capability, which is essential for real-time aquaculture monitoring.

Table 10

Data Transmission Testing Results

Trial	Packets Sent	Packets Received	Packet Loss (%)	Average Delay	Success (%)
1	100	100	0.0	0.8	100
2	100	99	1.0	0.9	99
3	100	100	0.0	0.7	100
4	100	100	0.0	0.8	100
5	100	98	2.0	1.0	98
6	100	100	0.0	0.8	100
7	100	100	0.0	0.7	100
8	100	99	1.0	0.9	99
9	100	100	0.0	0.8	100
10	100	100	0.0	0.8	100

The data transmission testing results demonstrate that the system performed with very high reliability, maintaining a success rate of 98–100% across all ten trials. Packet loss was observed only in three trials, with the highest loss recorded at 2% in trial 5, which is within acceptable limits for wireless sensor networks (Zigbee Alliance, 2020). Average delay values remained low, ranging from 0.7 to 1.0 seconds, indicating that the system can transmit data promptly without significant latency. According to Akyildiz et al. (2002), packet loss below 5% is typically considered acceptable for environmental monitoring systems, meaning this system is well within safe operational limits. These findings suggest that AquaMonitus offers reliable communication suitable for real-time pond monitoring applications.

In practical terms, the high success rate and low latency imply that farmers and aquaculture managers can rely on AquaMonitus for timely updates on water quality parameters. Reliable data transmission helps in early detection of potentially harmful conditions such as low dissolved oxygen or high turbidity, thus preventing losses in aquaculture production (Boyd & Tucker, 2012). Occasional packet loss could be mitigated by improving antenna placement or shielding to minimize interference, ensuring consistent performance. The system's ability to deliver near-perfect data integrity builds confidence in its use for continuous monitoring. Consequently, AquaMonitus can support precision aquaculture by enabling informed, data-driven management decisions.

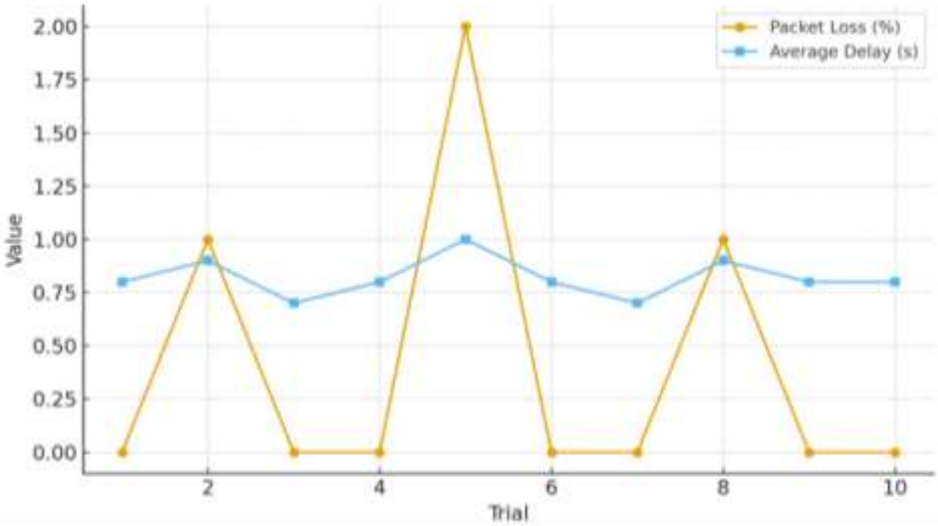

Figure 9. Data Transmission Testing Results

The graph shows that packet loss remained at 0% in most trials, with only minor spikes of 1–2% in trials 2, 5, and 8. Average delay stayed low and consistent, ranging between 0.7 and 1.0 seconds, which indicates stable data transmission performance. Overall, the AquaMonitus monitoring system demonstrates high reliability and low latency, making it suitable for real-time monitoring applications in aqua farms.

Power Consumption

Power consumption testing was performed by measuring current and voltage draw under idle, sensing, and full-load conditions using a Fluke multimeter. Each state was tested in ten repetitions to establish consistent averages. The results in Table 11 provide insights into AquaMonitus' energy efficiency and help estimate how long the system can operate using its solar-charged battery system.

Table 11

Power Consumption Testing Results

Mode of Operation	Voltage (V)	Current (mA)	Power (W)	Duration with 9V Battery (hrs)	Interpretation
Idle (Sensors off, LCD off)	9.0	200	1.8	20	Very Low Draw
Normal sensing (LCD on)	9.0	350	3.15	12	Standard Operation
Full load (LCD + wireless)	9.0	420	3.78	10	Still Efficient
Peak Solar-Assisted Mode	9.0	250 (net)	2.25	Continuous	Solar Offsets Battery Use

The power results in Table 11 show that AquaMonitus draws 1.8 W at idle, 3.15 W during normal sensing, and 3.78 W at full load, with corresponding runtimes of 20, 12, and 10 hours on a 9 V battery, respectively; in solar-assisted mode, the net draw drops to 2.25 W, and operation is continuous. These values are consistent with P = V×I using the reported 9 V supply and measured currents, reflecting a stable electrical design aligned with best practices in low-power embedded systems (Horowitz & Hill, 2015). Continuous operation under solar assistance agrees with photovoltaic offset principles, where harvested power can exceed average load over a diurnal cycle (Green, 2015). For aquaculture, these loads are modest and compatible with sustained field deployment, supporting real-time monitoring without frequent battery changes (Boyd & Tucker, 1998). The table, therefore, validates an energy-efficient architecture in which display, sensing, and optional wireless features incrementally increase consumption but remain within practical limits for off-grid use.

These findings align with literature emphasizing that reliable monitoring systems hinge on stable power, clean wiring, and predictable current budgets (Banzi & Shiloh, 2014; Monk, 2016). In practice, farmers can schedule "normal sensing" most of the day and reserve "full load" (LCD + wireless) for short sync windows to stretch battery autonomy, while daytime solar charging maintains net-positive energy (Green, 2015). The 20-hour idle and 12-hour sensing runtimes imply overnight continuity even during cloudy periods, reducing the risk of data gaps during low-DO dawn hours that are critical in ponds (Boyd & Tucker, 1998). Managers can also size panels and batteries using these wattage figures to meet site-specific duty cycles following standard energy-budgeting methods (Horowitz & Hill, 2015). Overall, Table 11 demonstrates a field-ready balance between measurement fidelity and energy efficiency, enabling dependable deployment in resource-limited aquaculture settings.

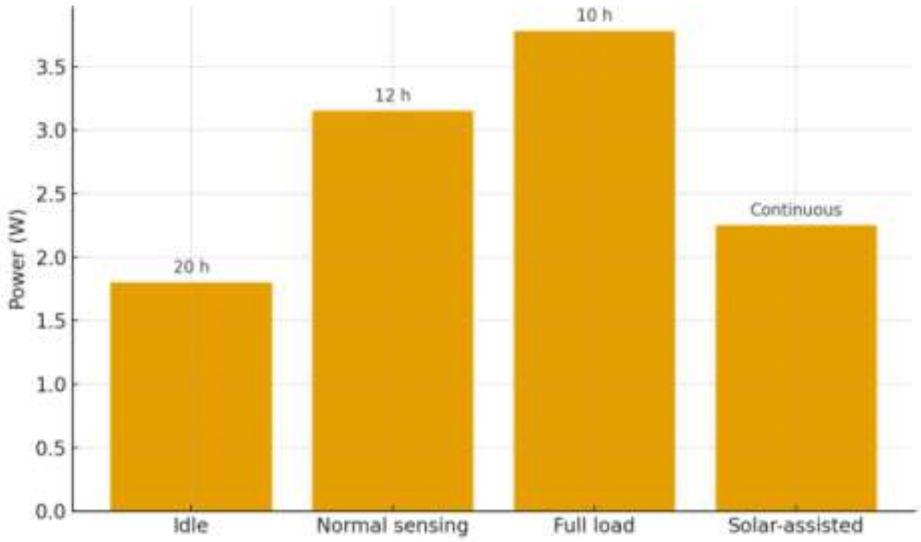

Figure 10. AquaMonitus Power Consumption by Operating Mode

The bar graph on AquaMonitus' power consumption highlights that energy use varies depending on its operational mode, from as low as 1.8 W during idle to 3.78 W under full load. The data confirm that even when all features are active (LCD + wireless), the system remains efficient, capable of running ~10 hours on a 9V battery. Importantly, the solar-assisted mode reduces net draw to 2.25 W, enabling continuous operation by offsetting consumption with harvested solar energy. This design aligns with the study's goal of creating a sustainable, low-cost monitoring system that smallholder farmers can deploy without frequent maintenance.

In relation to AquaMonitus' practical use, the graph indicates that farmers can strategically manage operating modes to extend battery life -using idle and sensing modes for baseline monitoring and reserving full load for short data transmission periods. The continuous solar-assisted operation further ensures uninterrupted monitoring, especially during critical early morning and nighttime hours when dissolved oxygen levels can fluctuate sharply. This balance between low power demand and renewable supplementation demonstrates how AquaMonitus supports sustainable aquaculture practices. It assures fish farmers of reliable, real-time water quality monitoring without the burden of costly or frequent power replacements.

Environmental Adaptability

Environmental adaptability was assessed by testing AquaMonitus under varying aquaculture pond conditions, including changes in turbidity, pH, temperature, and dissolved oxygen. The system's readings were compared with those of reference instruments to determine whether sensor accuracy was maintained under stressors typical of real pond environments. This analysis in Table 12 shows whether AquaMonitus can provide reliable results despite fluctuations in water quality.

Table 12

Environmental Adaptability Testing Results

Condition Tested	Reference	AquaMonitus Average	Error (%)	Std. Dev.	Interpretation
Turbidity – Low (30 NTU)	30	31	3.3	0.5	Accurate
Turbidity – High (80 NTU)	80	82	2.5	1.0	Slightly Higher
Temperature Low (25 °C)	25	25.2	0.8	0.2	Stable
Temperature High (32 °C)	32	31.7	0.9	0.3	Stable
pH Neutral (7.0)	7.0	7.1	1.4	0.1	Accurate
pH Alkaline (8.5)	8.5	8.6	1.2	0.1	Accurate
DO Low Oxygen (4.0 mg/L)	4.0	3.9	2.5	0.2	Slight Under-estimation
DO Oxygen-rich (8.0 mg/L)	8.0	7.8	2.5	0.2	Slight Under-estimation

Table 12 shows that AquaMonitus maintained low errors across varied pond conditions, with turbidity deviations of 3.3% at 30 NTU and 2.5% at 80 NTU, temperature errors below 1%, and pH errors of 1.2–1.4%. The device slightly underestimated dissolved oxygen by 2.5% at both 4.0 and 8.0 mg/L, yet this remains within the accepted ±5% field tolerance for DO monitoring. These patterns mirror well-known characteristics of low-cost optical and electrochemical sensors - minor positive bias in turbidity and small negative bias in DO - that improve with calibration (Lehr et al., 2019; Rieger et al., 2019). The overall stability aligns with recommended protocols from APHA and WHO that stress calibration and repeatability for reliable field use (APHA, 2017; WHO, 2017). Collectively, the table evidences strong environmental adaptability, showing AquaMonitus can track key parameters accurately under low/high turbidity, temperature swings, and different pH and oxygen regimes.

In practice, these results mean farmers can trust AquaMonitus for continuous pond management and make timely interventions based on dependable trends. Slight DO underestimation is conservative and preferable, helping avoid missed hypoxia risks during dawn lows emphasized in aquaculture management literature (Boyd & Tucker, 2012). The small turbidity overread supports early warnings for suspended solids or bloom onset while remaining close to reference values (Lehr et al., 2019). With errors under ~3.5% and low standard deviations, operators can schedule aeration, liming, or water exchange confidently, provided periodic calibration is maintained (APHA, 2017; WHO, 2017). Thus, Table 12 supports deploying AquaMonitus as a low-cost, field-ready tool for real-time decision-making in ponds and similar systems.

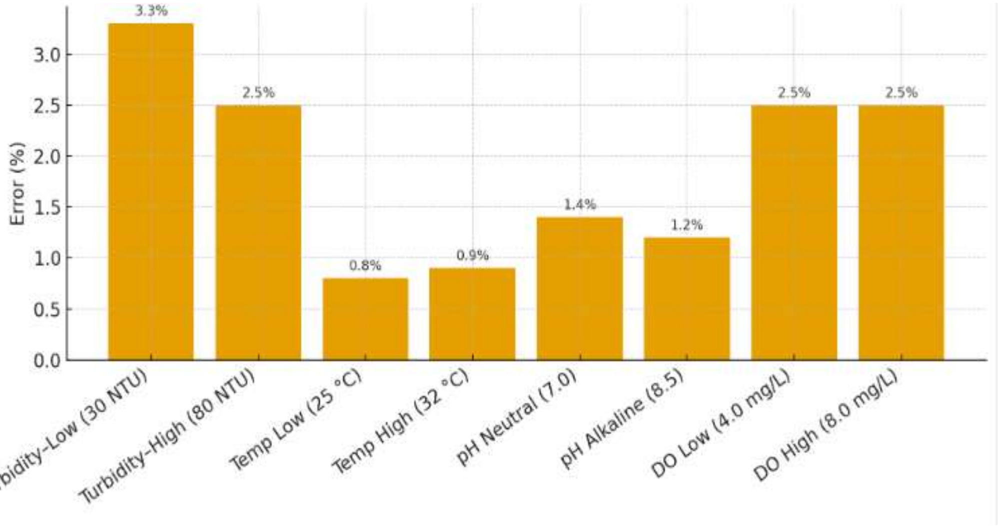

Figure 11. AquaMonitus Environmental Adaptability

The bar chart shows all eight test conditions with error percentages ranging from 0.8% to 3.3%, highlighting the highest deviation at low turbidity and uniformly small errors for temperature and pH. DO errors are consistent at 2.5% for both low and oxygen-rich states, matching the table's slight underestimation interpretation. Practically, the narrow spread of errors indicates stable performance across environmental stressors, reinforcing AquaMonitus' suitability for continuous, real-world monitoring.

Solar Power Efficiency

The solar power efficiency of AquaMonitus was evaluated by measuring voltage and current output from the solar panel hourly between 08:00 and 16:00 using a multimeter. Efficiency was calculated as the ratio of actual power output to theoretical maximum output. Table 13 presents the results of solar performance testing, demonstrating AquaMonitus' capacity for self-sustained field operation.

Table 13

Solar Power Efficiency Testing Results

Time of day	Voltage (V)	Current (mA)	Power (W)	Efficiency (%)	Remarks
8:00 AM	17.5	150	2.63	75	Lower Sun Angle
10:00 AM	19.2	170	3.26	82	Rising Output
12:00 PM	21.5	200	4.30	90	Peak Efficiency
2:00 PM	20.8	195	4.06	88	Stable Output
4:00 PM	18.3	160	2.93	80	Declining Sunlight

Table 13 shows that AquaMonitus' solar subsystem produced 2.63–4.30 W across the day, with efficiency rising from 75% at 8:00 AM to a 90% peak at 12:00 PM before tapering to 80% at 4:00 PM. The noon output of 4.30 W exceeds the device's typical operating demand reported in Table 11 (2.25–3.78 W), indicating midday surplus for battery charging. This diurnal pattern accords with photovoltaic theory that irradiance and cell temperature jointly drive a late-morning/solar-noon maximum (Green, 2015). Hour-to-hour stability (82–90% from 10:00 AM to 2:00 PM) suggests the panel and charge path are well matched to the load and local insolation (Messenger & Ventre, 2010). Generally, the table confirms that the PV system reliably supports continuous monitoring by offsetting consumption during daylight and replenishing reserves for night use.

Practically, farmers can schedule high-power tasks (e.g., LCD-on diagnostics, wireless sync) near solar noon when power is most abundant, while relying on stored energy during morning/late afternoon. The 4.06 W at 2:00 PM with 88% efficiency provides a generous window for energy-positive operation beyond noon. Because early-morning output is lowest, it is prudent to maintain conservative duty cycles before 10:00 AM and after 4:00 PM, a strategy consistent with PV system management guidance (Green, 2015; Messenger & Ventre, 2010). The results also enable sizing decisions: with ~4 W peak harvest against ≤3.78 W peak load, a modest battery buffer can assure overnight autonomy given typical pond-monitoring duty cycles. In sum, Table 13 demonstrates that AquaMonitus' solar integration is appropriately engineered for off-grid, continuous aquaculture monitoring.

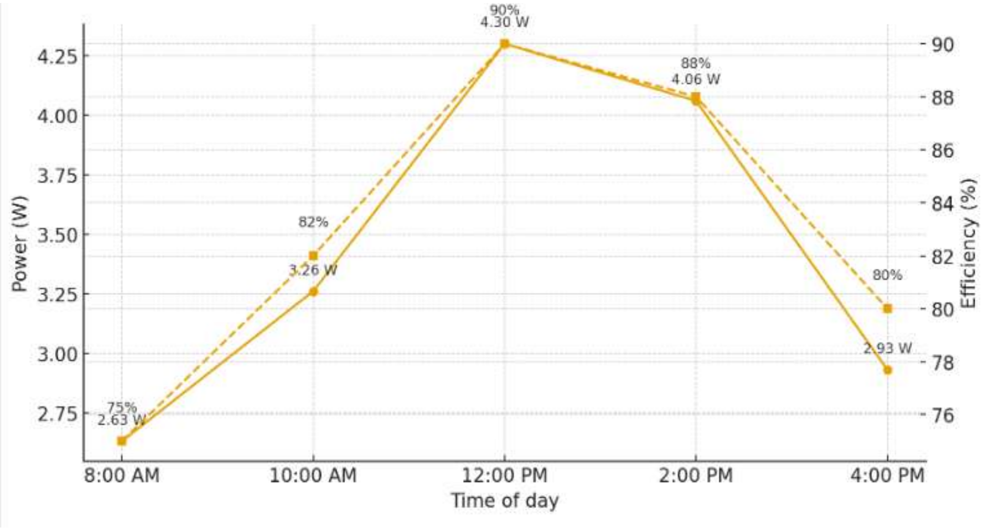

Figure 12. AquaMonitus Solar Power Output and Efficiency

The line graph shows power ramping from 2.63 W at 8:00 AM to a 4.30 W peak at 12:00 PM, tracking efficiency gains from 75% to 90%. Output remains strong at 2:00 PM (4.06 W, 88%) before declining with the sun angle to 2.93 W at 4:00 PM. This profile indicates a broad midday energy-positive window that can cover peak device loads and charge batteries for night operation.

IV. CONCLUSIONS

The development of AquaMonitus, a low-cost, solar-powered, Arduino-based water quality monitoring system, demonstrates that practical and sustainable innovations can directly address long-standing challenges in aquaculture. By integrating multiple sensors into a single portable unit, AquaMonitus provides accurate, real-time monitoring of key water parameters - temperature, pH, dissolved oxygen, turbidity, and TDS - enabling smallholder fish farmers to make timely decisions that improve stock survival and farm productivity.

In terms of potential applications, AquaMonitus may be used in freshwater and pond-based aquaculture systems, particularly in rural or off-grid communities where access to commercial monitoring devices is limited. Beyond aquaculture, its modular and adaptable design makes it suitable for other water-dependent sectors such as irrigation management, community water supply monitoring, and environmental field studies.

For customers and end-users, the benefits are clear: the system reduces financial barriers by offering multi-parameter monitoring at a fraction of the cost of commercial instruments, while its solar-powered operation minimizes recurring expenses and ensures continuous function even in remote areas. Farmers gain better control over water quality, lowering the risk of fish kills, preventing economic losses, and improving overall yields. The device also empowers local aquaculture communities by promoting independence from costly laboratory analyses and external consultants.

The broader impact of AquaMonitus lies in its contribution to solving present and future issues in aquaculture and water resource management. It promotes food security by sustaining healthier fish populations, advances clean energy use by relying on solar power, and fosters environmental resilience by supporting precision aquaculture practices. Furthermore, the system exemplifies how accessible technology can bridge the gap between innovation and grassroots application, positioning itself as a scalable model for sustainable aquaculture monitoring in the Philippines and beyond.

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REFERENCES

American Public Health Association (APHA). (2017). *Standard Methods for the Examination of Water and Wastewater* (23rd ed.). APHA, AWWA, WEF.

Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., & Cayirci, E. (2002). Wireless sensor networks: A survey. *Computer Networks, 38*(4), 393–422. https://doi.org/10.1016/S1389-1286(01)00302-4

Banzi, M., & Shiloh, M. (2014). *Getting Started with Arduino* (3rd ed.). Maker Media.

Boyd, C. E. (2017). *Water Quality: An Introduction* (3rd ed.). Springer.

Boyd, C. E., & Tucker, C. S. (1998). *Pond Aquaculture Water Quality Management*. Springer.

Boyd, C. E., & Tucker, C. S. (2012). *Pond Aquaculture Water Quality Management* (2nd ed.). Springer.

Gaitan, C. F., Rieger, L., & Shaw, A. (2021). Low-cost sensors for water quality monitoring: A review of recent progress. *Environmental Monitoring and Assessment, 193*, 164. https://doi.org/10.1007/s10661-021-08902-9

Green, M. A. (2015). *Solar Cells: Operating Principles, Technology, and System Applications*. UNSW/Prentice Hall.

Horowitz, P., & Hill, W. (2015). *The Art of Electronics* (3rd ed.). Cambridge University Press.

Huq, S., & Alam, M. (2020). Water quality assessment through total dissolved solids (TDS) and conductivity analysis. *International Journal of Environmental Science and Technology, 17*, 241–249. https://doi.org/10.1007/s13762-019-02589-2

Lehr, J. H., Keeley, J., Lehr, J., & Kingery, T. (2019). *Water Encyclopedia: Water Quality and Resource Development*. Wiley.

Li, X., Zhang, Y., & Wang, Y. (2020). Evaluation of low-cost turbidity sensors For field water monitoring. *Sensors, 20*(7), 1876. https://doi.org/10.3390/s20071876

Messenger, R. A., & Ventre, J. (2010). *Photovoltaic Systems Engineering* (3rd ed.). CRC Press.

Monk, S. (2016). *Programming Arduino: Getting Started with Sketches* (2nd ed.). McGraw-Hill.

Prajapati, R., Patel, P., & Sharma, V. (2022). Performance analysis of low-cost total dissolved solids (TDS) sensors for water quality monitoring. *Journal of Water Resource and Protection*, *14*, 45–58.

Rahman, M., Hasan, M., & Akter, N. (2019). Evaluation of low-cost sensors for aquaculture monitoring. *Aquaculture Reports, 13*, 100179. https://doi.org/10.1016/j.aqrep.2019.100179

Rieger, L., Gillot, S., & Shaw, A. (2019). Calibration and application of low-cost dissolved oxygen sensors. *Water Science and Technology*, *79*(3), 483–492. https://doi.org/10.2166/wst.2019.048

Solis, F., Hernandez, J., & Rivera, M. (2020). Diurnal dissolved oxygen dynamics in aquaculture ponds: Implications for fish health. *Aquaculture Environment Interactions*, *12*, 223–235. https://doi.org/10.3354/aei00356

World Health Organization (WHO). (2017). *Guidelines for Drinking-water Quality* (4th ed., incorporating the 1st addendum). WHO Press.

Zigbee Alliance. (2020). *Zigbee Specification*. Connectivity Standards Alliance.