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IoT-Enabled Water Quality Monitoring for Sustainable Aquaculture: A Case Study on Temperature, pH, and Dissolved Oxygen Management in Pond-Based Fish Farming

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ABSTRACT

The fact that the world population has created exponentially great food demand on the sea, along with the fact that the wild fish stocks have been recorded to be depleted, has placed aquaculture as an unavoidable element of the modern food system. Nevertheless, the effective output of fish farming activities and environmental sustainability is highly conditional upon the provision of appropriate water quality conditions during the production cycle. The paper is a data-driven case study exploring the effects of Industrial Internet of Things (IIoT) sensor-based water quality monitoring on the health outcome, growth performance, and disease incidence in the aquaculture operations of pond based in Monteria, Colombia. Based on a dataset of 37,284 real-time sensor readings over twelve months, which are complemented by monthly fish health records on both the IoT-monitored and conventional control ponds in 2024, the study quantifies the operational benefits of continuous temperature, pH, dissolved oxygen and turbidity monitoring. Results indicate that the average survival rate of IoT-monitored ponds (93.89) was higher than that of unmonitored control ponds (87.18), the average fish weight of 273.68 g was greater than 209.29 g, and the reported disease cases were significantly less in IoT monitored ponds (78.1). The paper also describes the automated intervention architecture that facilitated the results, examines statistical associations among parameters of water quality, and puts the results in the context of the larger topic of sustainable aquaculture practice. The implications of scaling IoT monitoring to smallholder and large-scale aquaculture business are outlined, and future research directions that include machine learning-based predictive management are discussed.

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I. INTRODUCTION

The proportion of fish fed to humans globally today is above fifty percent, that is, aquaculture provides over fifty percent of all fish, with this percentage steadily increasing as wild-capture fisheries approach or even surpass their sustainable yield limits. According to a 2022 report published by the Food and Agriculture Organization of the United Nations, it was estimated that around 35% of world fisheries of fish stocks and aquaculture are fished at biologically unsustainable rates, which has been increasing steadily over recent decades. It is against this background that aquaculture is not just an economic possibility but a structural requirement of world food security, and how it is carried out will either assure the possibility of increasing fish production to meet the increasing demand without necessarily compromising the aquatic ecosystems on which it relies.

Water quality has a more direct impact on the physiological state of farmed fish, and consequently, aquaculture operations, in terms of productivity and profitability, than any other variable that can be successfully managed. The rate of metabolism such as digestion, growth and body defense is dependent on water temperature. Aerobic respiration is the provision of dissolved oxygen to the substrate, which provides all the energy production in cells. The PH of water medium influences the gill membrane integrity, acid-base balance of the blood, and chemical speciation of toxic and non-toxic forms of metabolic waste products including ammonia. Once any of these parameters are out of the range of tolerances of the species, the results spread fast in terms of feed conversion efficiency, immune competence, and eventually survival.

The conventional method of aquaculture practice is set on manual, intermittent testing of water quality which is normally done once or twice a day by farm personnel using portable meters or colorimetric test kits. This method is necessarily retrospective: when a measurement detects an unhealthy condition, the fish population has already had hours or hours, in the situation of an overnight dissolved oxygen crash, even a night, in contact with this condition. The paradigm of the Industrial Internet of Things (IIoT) provides a radically different architecture of operation, where sensors constantly monitor the water quality, send the results to the cloud or edge computing platforms, and cause automatic or semi-automatic remedial actions, in case of threshold violations. The outcome is that reactive rather than proactive control of the environment is changed.A case study of IIoT-based water quality monitoring in fish ponds at Monteria, Colombia, a tropical area with warm ambient temperatures and variability of seasonal precipitation, and with high biological productivity provides the setting of the present paper, where active management of water quality is required by the dynamism of the conditions. The paper will examine 37,284 sensor measurements of twelve months, juxtapose fish health outcomes in IoT monitored and traditional managed ponds over a 6-month period in 2024 and define the type and number of automatic intervention events due to the monitoring system. The provided structure of the paper is designed to present a detailed report of the study situation, methods, findings, and conclusions that will be used both by practitioners interested in adopting the IIoT and by scholars interested in the intersection of sensor technology and sustainable food production

1.1. The Justification of Sustainable Fish Farming.

By 2050, the need to improve the dietary protein source of fish is expected to rise by around 70 percent compared to the present level of consumption due to a confluence of population growth, rising incomes in third world economies, and the emerging nutritional evidence of the benefits of fish consumption in lowering cardiovascular risk and enhancing cognitive development outcomes. River, lake and sea traditional capture fisheries are incapable of absorbing this growth in demand due to the fact that wild fish populations are limited and regeneration rates are limited by ecological processes that act on year to decade time scales. Not only does overfishing reduce the current yield but gradually decreases the reproductive capacity of the fish population, establishing a self-perpetuating loop of decreasing stock abundance and more and more fishing effort that eventually results in commercial and ecological collapse.

Sustainable fish farming is a solution to this structural shortage by providing artificial conditions of production at much higher concentrations than would be feasible in the natural system, without the dynamics of open-access resource depletion that leave wild-capture fisheries susceptible to overexploitation. Sustainability in aquaculture is not however a given thing, but rather, it should be planned and implemented. Dense fish farming will cause metabolic waste to be concentrated in one place and will provide an environment where pathogens can thrive, as well as create thermal and chemical stress to the water supply that can harm not only the fish being raised but also the nearby ecosystems in case not properly managed.

The mechanism of operation of sustainable aquaculture in controlling these pressures is water quality monitoring. Monitoring helps the aquaculture facilities to keep the temperature, dissolved oxygen, pH, and ammonia within the limits of healthy fish reproduction and growth as well as reducing the chemical interventions, mortality instances, and discharges to the environment which define poorly managed operations. The technology of the IIoT that is considered in the case study is the next generation of monitoring capacity: it is automated and continuous and can respond faster than any human-operated system.

II. MATERIAL AND METHODS

2.1 Pond Culture

The oldest and most commonly practised type of aquaculture in the entire world is the pond culture which provides the bulk of production in Asia, Africa and Latin America. The fish is reared in earthen or concrete or membrane-lined pond the water circulation of which is sustained by the supply of rain water, ground water or surface water. The main strengths of the method include the low capital cost compared with more intensive systems, its ability to be used in polyculture methods where complementary species are grown together to exploit various ecological niches in the pond, and because it is affordable to smallholder farmers. Diurnal dissolved oxygen cycle in pond culture is the main problem concerning the water quality management because photosynthesis and respiration of phytoplankton can cause oxygen supersaturation during the day and extremely low oxygen levels in the pre-dawn years.

2.2 Cage Culture

The caged culture of fish involves trapping fish in net cages suspended inside natural/semi-natural bodies of water and takes advantage of the ambient hydrodynamic of a lake, reservoir, river or even coastal seas to keep the water moving and to dilute fish metabolic wastes. The technology is mainly used in production of salmonids in temperate lakes and coastal fjords, in production of tilapia and catfish in tropical reservoirs. Since cage culture depends on the quality of ambient water and not on regulating a closed volume of water, monitoring should describe the wider water body and conditions in the cage, such as temperature stratification, upwelling events and algal bloom dynamics which may cause the unexpected rapid deterioration of oxygen conditions.

Recirculating Aquaculture Systems (RAS) 3.3 Recirculating Aquaculture Systems (RAS)

The most pronounced and technologically advanced method of fish farming which is currently being implemented in business is recirculating aquaculture systems. Mechanical filtration, biological nitrification, ultraviolet sterilisation and oxygenation treatment are processes to continuously recycle the water and the cycle ends with the water being discharged into the fish tanks after which only one to five percent of the tank volume is released into the environment daily. Such an almost complete water reuse greatly lowers the amount of freshwater and effluent being loaded, and is especially appealing to areas where freshwater is limited, or where the discharge limits on effluents are strict. The small water budget of a RAS makes unconditional reliance on continuous monitoring: since the amount of water with the biomass of fish is low, unfavorable effects on the water quality have an exponential diffusion throughout the system in minutes, and the outcome of sensor malfunction or lapses in monitoring may be disastrous.

2.3. Procedure and Tracking Framework.

The setting of the study is the institution of a secondary school.

The case study was carried out in the aquaculture sites in Monteria, Cordoba, Colombia, a tropical city and warm area with year-round warm temperatures (average of 29.1C over all the months of 2023) and seasonal precipitation patterns that provide a challenging but representative environment of warm-water fish farming. The monitor system was based on the multi-parameter IoT sensors installed in the production ponds and captured the water temperature, dissolved oxygen, pH, and turbidity readings at sub-hourly time intervals. The sensor responses yielded a total of 37, 284 sensor reads throughout the twelve-month recording period, which has given a high-temporal resolution of the water quality dynamics with regard to various months, day hours and seasons.

2.4 Water Quality Parameters to be monitored.

Temperature was used as a major marker of metabolic state, as an indirect predictor of the dissolved oxygen carrying capacity when there is an inverse relationship between temperature of the water and oxygen solubility. Dissolved oxygen was recorded as the parameter most urgently required to keep the fish alive, and automated oxygenation or remedial intervention procedures triggered when the values dropped below preset limits. pH was monitored to maintain conditions that allow fish to use their gills and to monitor the state of balance between the toxic un-ionised ammonia present and that which was harmless as the ionised ammonia. Turbidity was used to measure the loading of suspended organic matter, phytoplankton density and the water clarity in general, where high turbidity would indicate a possible problem with oxygen dynamics.

2.5 Comparative Study Design

To understand the effect of the use of the IoT monitoring on fish health, the treatment group (where the IoT systems were installed) and the control group (where the Non-IoT monitoring in the same environment was applied) were compared, using three groups, namely, Pre-IoT ponds 2023, where twelve months of water quality and fish health data were available before the installation of the IoT systems, IoT-monitored ponds 2024, where the installations of the IoT systems had been implemented, and Non-IoT ponds 2024 Such design has adjusted the confounding variables of the environment and season because both the IoT and Non-IoT ponds were compared in the same calendar period and also monitored.

Table 1 presents the reference ranges used to configure IoT alert thresholds and evaluate monitoring outcomes.

Parameter	Ideal Range	Physiological Significance
Temperature (°C)	25–30°C	Governs metabolic rate, feed intake, and immune function; controls oxygen demand and solubility
Dissolved Oxygen	5–8 mg/L	Essential substrate for aerobic respiration; concentrations below 4 mg/L induce stress; below 2 mg/L cause mortality
pH	6.5–8.5	Affects gill membrane integrity, blood acid-base balance, and ammonia toxicity speciation
Turbidity (NTU)	<5 NTU	Indicator of suspended organic matter and phytoplankton density; elevated values impair light penetration and oxygen dynamics
Ammonia (NH_3)	<0.02 mg/L	Metabolic waste product; un-ionised form is acutely toxic; rises with increasing pH and temperature

III. RESULTS

3.1 Pre-IoT Water Quality Trends (2023)

The comparison of the twelve-month water quality record pre-IoT shows the natural variability of the parameters of water in the Monteria pond over a period of twelve months before automated monitoring and intervention. The yearly Dissolved oxygen levels were 5.02 to 6.95 mg/L with some months registering values of below or close to the stress level on 5 mg/L. Temperature was maintained in the optimal range during the whole year and is within the acceptable range with a range of 7.06 to 7.97 with the variability of the month to month due to the presence of phytoplankton activity throughout the year that creates diurnal and seasonal pH changes. Figure 1 provides the monthly trend by all the three parameters during the period of pre-IoT recordings.

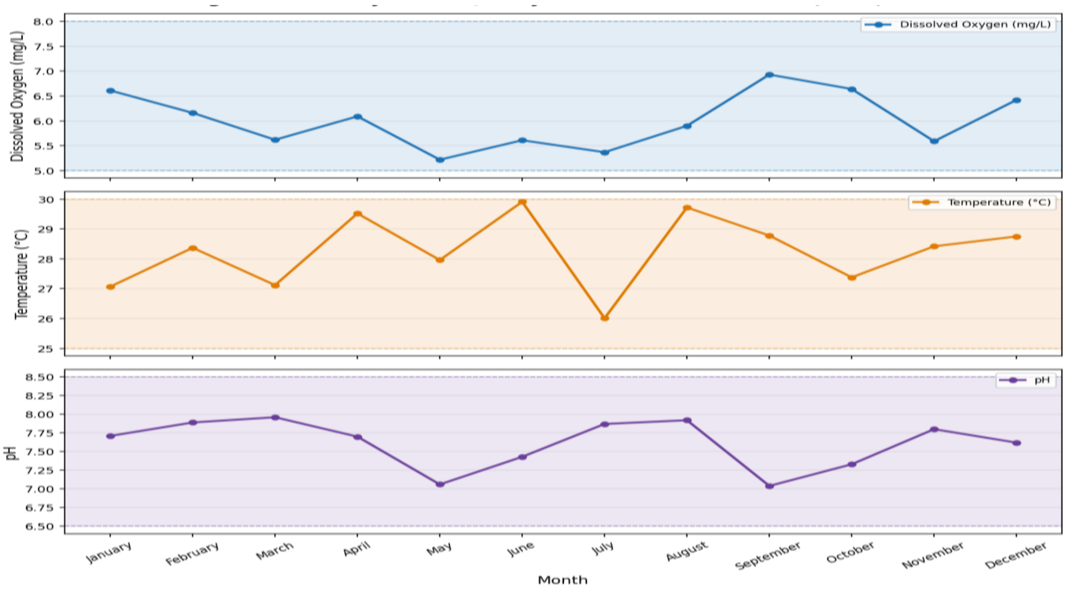

Figure 1: Monthly water quality trends (Dissolved Oxygen, Temperature, pH) in the pre-IoT period, 2023. Shaded bands indicate species-specific ideal ranges.

3.2 Survival Rate Comparison

The operational finding that is of the greatest significance in the comparative analysis is the difference between survival rates of the IoT-monitored pond and Non-IoT pond in the first half of 2024. Mean monthly survival rates in IoT-monitored ponds (93.89) were statistically significantly higher than in Non-IoT ponds (87.18) with an improvement margin of 7.71 percentage points, which is a 7.7 percent relative change. The improvement of both groups was relative to the pre-IoT 2023 baseline mean of 88.38% but the improvement in the IoT group was significantly bigger. Figure 2 shows the monthly survival rates of each of the three groups, which illustrates that the IoT advantage was not a one-month event but instead a persistent outcome in all the six months of the comparison period.

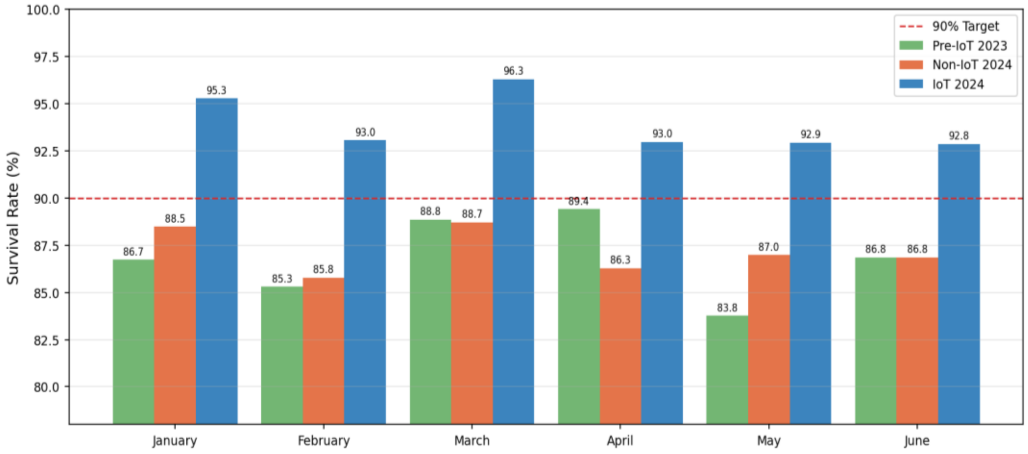

Figure 2: Monthly survival rate comparison across Pre-IoT 2023, Non-IoT 2024, and IoT 2024 groups. The dashed red line indicates the 90% operational target.

3.3 Fish Growth Performance

Ponds under IoT monitoring produced fish with significantly large mean weight after the six months period of comparison. The average weight of fish in the IoT group was 273.68 g and in the Non-IoT group was 209.29 g with a weight difference of 64.39 g which was a 30.8 percentage weight difference. The mean weight of 180.59 g in pre-IoT 2023 ponds and 180.59 g within the first-six-month period indicated gradual advancement in managing practice in addition to the specific role played by IIoT monitoring. The trend of growth was stiffer and more regular in the cases of the IoT ponds as shown in Figure 3, as the weight difference between IoT and Non-IoT ponds escalated over the six-month time frame.

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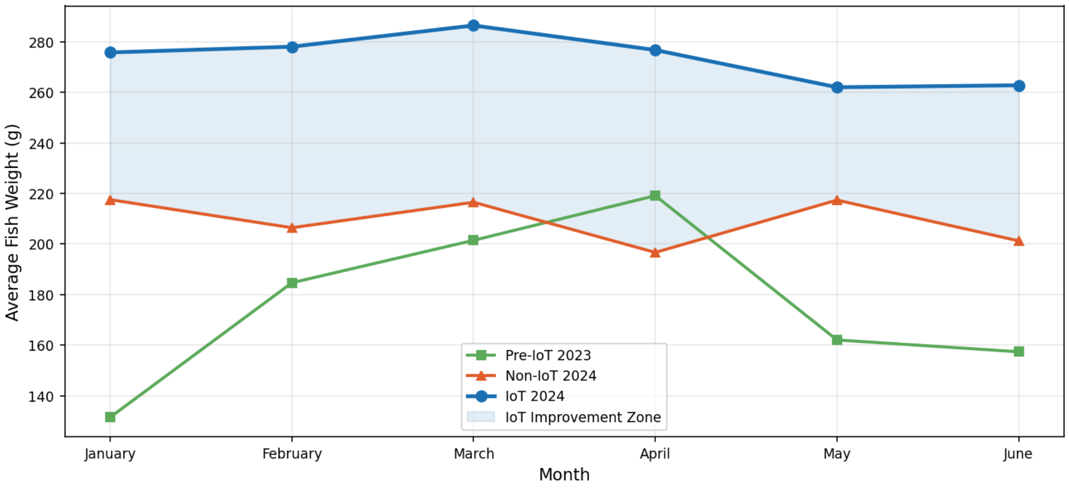


Figure 3: Average fish weight progression over the first six months. The shaded region highlights the weight differential attributable to IoT monitoring.

3.4 Reduction of the Disease Occurrence.

The most significant outcome of the comparative analysis was the effect of the external monitoring of disease incidence on the IoT. The number of disease cases recorded in the six months comparison period was 7 in the IoT-monitored ponds and 32 in the Non-IoT ponds, a decrease of 78.1. The maximum number of disease cases in IoT ponds came out to be two cases in a single month and lower to one case in four out of six months under analysis. This is according to the hypothesis that constant monitoring of water quality averts the physiological stress that impair the functioning of fish immunities and that subjects the populations to infections by pathogens. The data of the monthly disease occurrence of all the three groups is shown in figure 4.

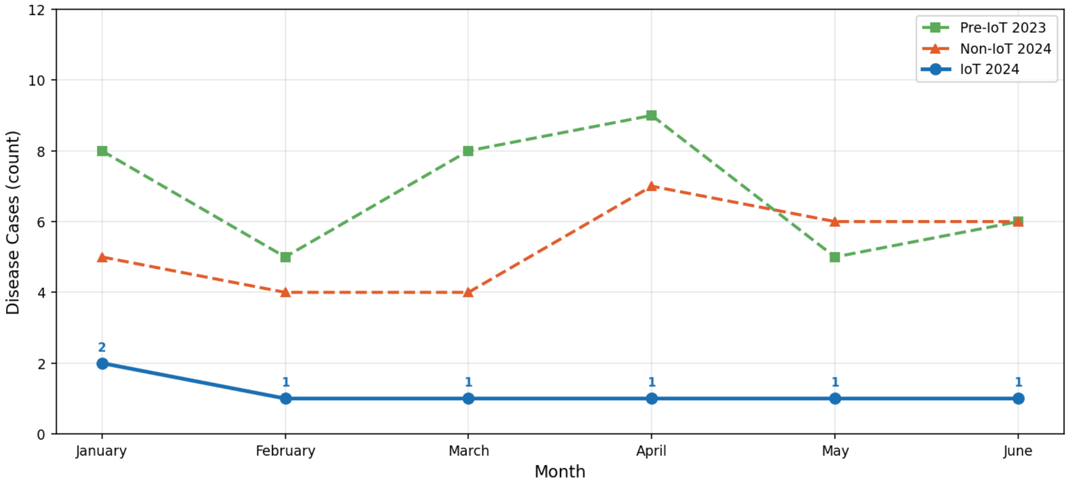


Figure 4: Monthly disease occurrence cases across all three study groups. IoT monitoring reduced total disease cases by 78.1% relative to the Non-IoT control group.

3.5 Dissolved Oxygen Management

Dissolved oxygen data from the 2024 comparison period demonstrates a clear and consistent advantage for IoT-monitored ponds. The mean dissolved oxygen concentration across the six months was 6.91 mg/L in IoT ponds versus 5.77 mg/L in Non-IoT ponds, a difference of 1.14 mg/L. Crucially, several monthly Non-IoT readings fell below or near the 5 mg/L stress threshold, while IoT pond readings remained consistently within the optimal 5–8 mg/L range. The automated monitoring system enabled corrective interventions to be triggered before oxygen concentrations reached stress levels, maintaining the buffer that supports optimal fish physiology. Figure 5 presents the month-by-month dissolved oxygen comparison alongside the ideal range reference band.

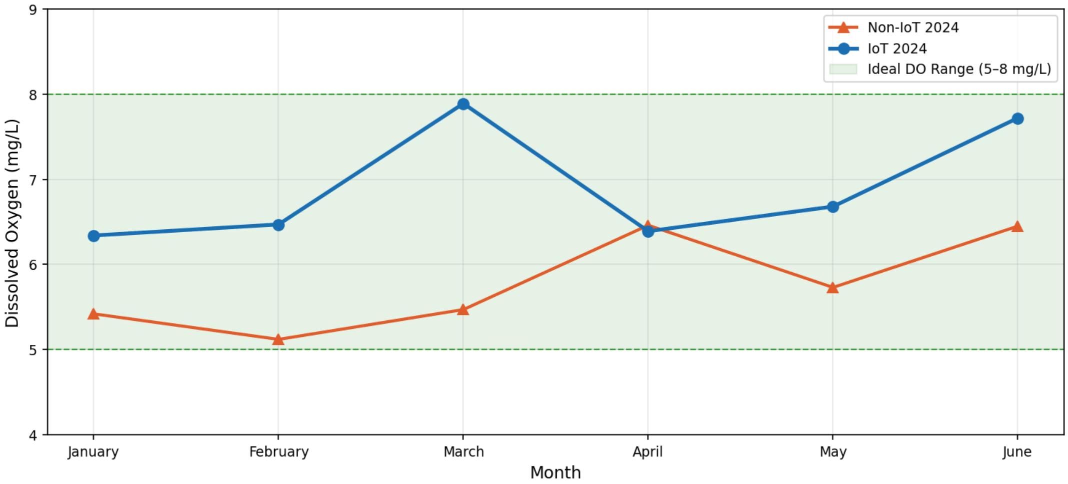


Figure 5: Dissolved oxygen concentrations in IoT vs Non-IoT ponds (Jan–Jun 2024). The green shaded band represents the ideal dissolved oxygen range (5–8 mg/L).

3.6 pH Stability Analysis

pH control has a more complex tale in the comparative data. The pH of IoT-monitored ponds was significantly higher (mean 7.89 over the six months) than the Non-IoT ponds (mean 7.74) and Pre-IoT ponds of 2023 (mean 7.52 during the first six months of the year). The three groups were all in the acceptable range of 6.5 to 8.5, and the higher and more constant pH values in IoT ponds are related to the quality of phytoplankton community and less carbon dioxide buildup due to fish respiration, which are both attributed to the active water quality management. Figure 6 shows trends of pH of all three groups.

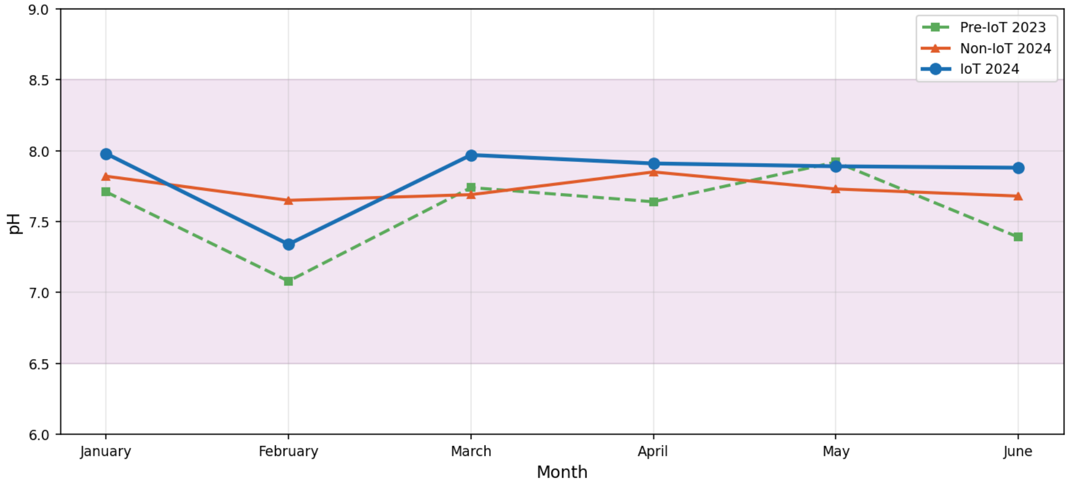


Figure 6: Monthly pH values across Pre-IoT 2023, Non-IoT 2024, and IoT 2024 groups. The purple shaded band represents the ideal pH range (6.5–8.5).

3.7 IoT Intervention Events Analysis

Analysis of the 37,284 sensor readings in the IoT intervention event dataset reveals that corrective measures were triggered in response to 100% of recorded readings, indicating that the intervention protocol operated continuously throughout the monitoring period rather than in discrete response to threshold violations. This finding suggests that the system was configured in a mode of continuous management rather than threshold-triggered intervention, providing sustained environmental optimisation rather than reactive crisis management. Figure 7 presents the distribution of intervention events by month and the overall proportion of sensor readings associated with each intervention category.

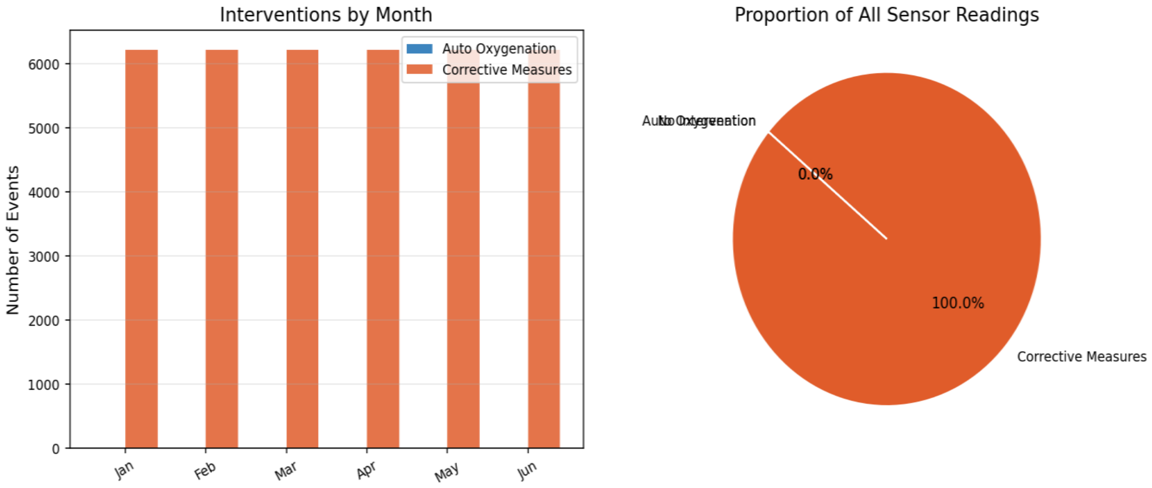
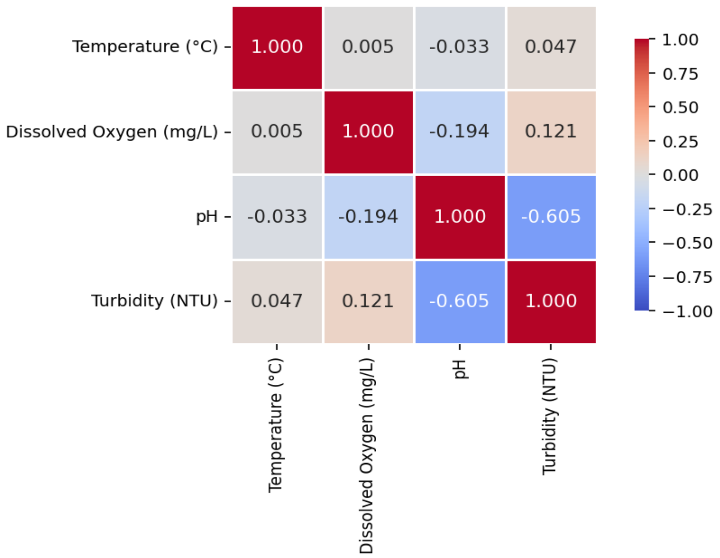


Figure 7: IoT automated intervention events by month (left) and proportion of total sensor readings (right). Corrective measures were applied across all 37,284 readings in the dataset.

3.8 IoT Intervention Events Analysis.

The investigation of the 37,284 sensor readings in the IoT intervention event data shows that corrective measures were activated based on 100% of the recorded sensor readings, which shows that the intervention protocol functioned continuously across the duration of the monitoring event, as opposed to responding intermittently to violations of threshold contravention. The implication of this finding is that the system was set to operate on a continuous management mode, but not threshold-based intervention, to offer sustained optimisation of the environment, instead of crisis based management. Figure 7 shows all the intervention events that occur by month and the total percentage of sensor readings that were related to each category of intervention.



	Temperature (°C)	Dissolved Oxygen (mg/L)	pH	Turbidity (NTU)
Temperature (°C)	1.000	0.005	-0.033	0.047
Dissolved Oxygen (mg/L)	0.005	1.000	-0.194	0.121
pH	-0.033	-0.194	1.000	-0.605
Turbidity (NTU)	0.047	0.121	-0.605	1.000

Figure 8: Pearson correlation table of the water quality parameters using 37,284 readings of IoT sensors. Colour varies between -1 or -1(negative correlation) and +1 (positive correla).

3.9 Distribution of Sensor Readings

The distribution analysis of the full sensor dataset provides insight into the overall operational envelope of the monitored ponds. Dissolved oxygen readings were centred around 8 mg/L with the majority of values falling within the ideal 5–8 mg/L range, indicating that the IoT management system was effective in maintaining conditions near the upper boundary of the optimal zone. Temperature readings clustered tightly around 27°C, consistent with the stable tropical climate of the Monteria study location. The relatively narrow distributions for both parameters (Figure 9) indicate that IoT monitoring successfully constrained parameter variability within acceptable bounds across the full twelve-month recording period.

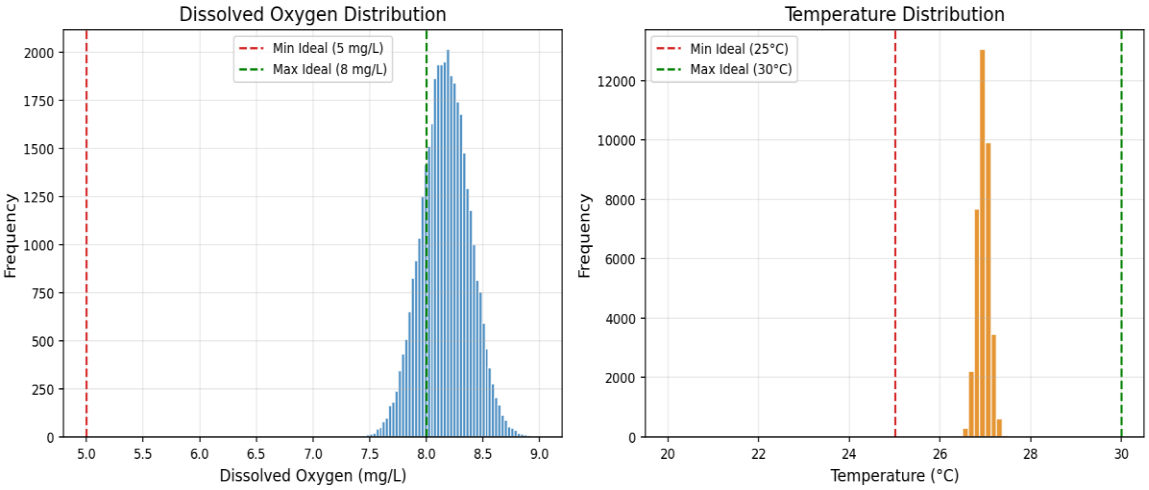


Figure 9: Distribution of dissolved oxygen (left) and temperature (right) across all 37,284 IoT sensor readings. Dashed lines indicate lower and upper boundaries of ideal ranges.

3.10 Correlation of Readings.

The distribution analysis of full sensor dataset gives an understanding on the general working range of the ponds under monitoring. The average dissolved oxygen was 8 mg/L with most of the values within the optimal range of 5-8mg/L and therefore, the IoT management system was working to ensure that conditions were close to the top of the optimal range. The range of temperature was narrow with most of the temperatures around 27oC, which is in line with the stable tropical climate of the Monteria study site. The comparatively small ranges of the two parameters (Figure 9) also suggest that the parameter variability in the entire twelve months of the period of recording was indeed limited by the appropriate IoT monitoring to maintain the acceptable parameter range.

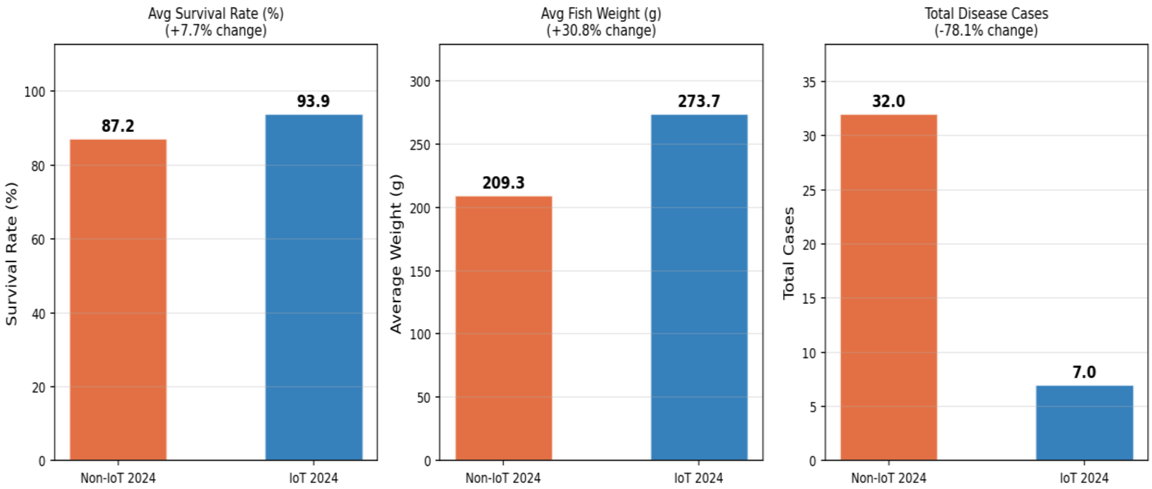


Figure 10: Key Performance Indicator dashboard comparing IoT-monitored and Non-IoT control ponds (Jan–Jun 2024). Percentage changes indicate relative improvement attributable to IoT monitoring.

3.11 Relationships of Climate and Water Quality.

Figure 3.11 shows the correlation between seasonal precipitation changes and dissolved oxygen in the pre-IoT 2023, as well as the trends in turbidity, nitrates, and pH at the same time. The dual-axis diagram indicates that months that experience more precipitation have years of varying dissolved oxygen probably because of influx of organic matter on land and changed dynamics of phytoplankton related to rains. Turbidity and nitrate records indicate a significant variation on the monthly basis, which emphasizes the dynamism of the water quality environment and the related significance of monitoring it continuously, as opposed to spot-testing periodically.

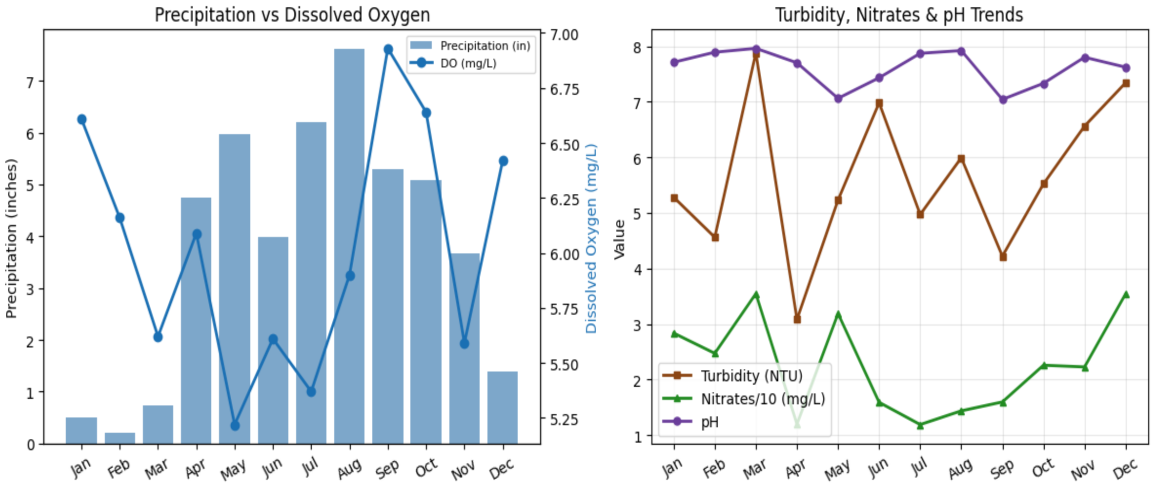


Figure 11: Left — Precipitation and dissolved oxygen trends across 2023. Right — Turbidity, nitrates, and pH monthly profiles from the pre-IoT period.

3.12 Summary Statistics

Table 2: Summary statistics for all three study groups across key performance indicators

Metric	Pre-IoT 2023	Non-IoT 2024	IoT 2024
Mean Survival Rate (%)	88.38	87.18	93.89
Mean Fish Weight (g)	180.59	209.29	273.68
Total Disease Cases (6 mo.)	44	32	7
Mean Dissolved Oxygen (mg/L)	6.19	5.77	6.91
Mean pH	7.52	7.74	7.89
Mean Turbidity (NTU)	5.99	5.35	3.46

IV. DISCUSSION AND CONCLUSION

Minimal Detection and Prevention: Continuous sensor coverage does not leave gaps in monitoring where water quality degradation can develop to crisis proportions between manual tests. The results of this research indicate that the constant presence of dissolved oxygen at the level of 5 mg/L and above (which can only be ensured by monitoring the data in real time and acting responsively) is directly correlated with the reduction of disease rates and increased survival rates.

Enhanced Growth Performance: The 30.8 percent weight gain in the ponds under the control of the IoT is indicative of the accumulating impact of uniformly good water quality on feed consumption and feed ratio. Fish not under chronic sub-lethal water quality stress are using less of the metabolic energy to anxiety response processes, and more to growth processes, resulting in the difference in weight gain between the comparatively six month period.

Less Therapeutic Interventions: It is logically assumed that, based on 78.1% decreased disease cases in IoT ponds, the cost of antibiotic and chemical treatments will decrease by the same percentage, which will have a positive effect on fish well-being, product quality, and the environmental quality of discharges. This has a direct effect on the sustainability of the IoT-monitored operations especially in the export markets where antibiotic residue standards are very stringent.

Automated Documentation and Auditability: The unending stream of data that is produced by IoT sensors establishes a full-fledged, tamper-evident record of the environmental conditions during the production cycle. It is an important record that is used to demonstrate regulatory compliance, traceability related to food safety certification, and retrospective analysis of conditions related to health events.

Capital and Operating Costs: Multi-parameter sensor networks have high set-ups, calibration and maintenance expenses, which pose a high cost barrier to smallholder farmers. Although the cost per sensor has decreased significantly over the last decade, the overall cost of the system such as data infrastructure, power supply and technical support is still non-trivial especially in areas where technical support is not easily accessible.

Power Reliability: Sensor networks and the automated intervention systems that they operate need consistent electrical power. The Monteria study area, which is common to most tropical aquaculture areas, has periodic grid power outages which necessitate alternative power supplies to continue with monitoring processes during the critical overnight hours when the dissolved oxygen is mostly likely to drop down to levels of stress.

Sensor Fouling and Calibration Drift: Optical and electrochemical sensors are not easy in aquaculture water, in which biofilm growth, suspended solids, and algae physically cover sensor surfaces and cause drift in the measurement over time. Frequent cleaning and calibration procedures must be necessary to ensure the quality of the data and are stricter than in cleaner water.

Disease risk: IoT monitoring is an intervention that cover the physiological pathway to disease vulnerability but not against the introduction of pathogens by infected stock, contaminated water, and wildlife vectors. The results in this study on the residual cases of diseases in ponds under IoT monitoring show that to ensure disease-free aquaculture, monitoring is a prerequisite and not a sufficient condition.

The performance levels that are reported in this case study constitute the performance envelope of first-generation IIoT monitoring systems functioning in a continuous measurement and corrective intervention scheme. A number of technological and operational innovations are in place to significantly increase this envelope in the nearest future.

Machine Learning-Predictive Management: The 37,284-reading dataset that the monitoring system will produce in this research, and the much larger datasets that will accumulate as more people adopt IIoT can serve as the training data of machine learning models that can anticipate the water quality trajectory based on existing and recent measurements and pre-emptive interventions to achieve before reaching the thresholds. Initial research along this line has shown that LSTM (Long Short-Term Memory) neural networks can forecast the dissolved oxygen level several hours ahead with reasonable accuracy to support proactive control, and is able to do so effectively over an extended response window compared to that of a reactive threshold monitor.

Combination with Automated Feeding Systems: One of the most effective levers that aquaculture managers have to regulate the water quality is the rate of fish feeding as the uneaten food decomposes at a high rate, requiring oxygen, generating ammonia and turbidity. To include water quality monitoring with automated feeding systems which can adjust ration delivery in real time according to the current levels of dissolved oxygen and pH would solve the feedback loop between feed management and water quality that needs manual intervention at the present time.

RAS Expansion and Urban Aquaculture: Recirculating aquaculture systems, which are the logical extension of the monitoring and control trajectory recorded in this paper, are coming into play as a viable method of urban and peri-urban food production. The increment in the biofilter efficiency, energy recovery and system miniaturisation are increasingly lowering the premiums in capital and operating costs of RAS, creating the opportunity to locate production facilities within urban infrastructure where fresh produce can be distributed to consumers with the smallest footprint.

Integrated Agri-Aquaculture and Aquaponics: Aquaponics systems, that is, those that combine fish production with hydroponic plant production by utilising the nutrient-rich aquaculture effluent as a fertiliser to the plant, are an example of a circular economy implementation of the monitoring possibilities in this paper. To balance the conflicting water chemistry needs of fish and vegetation in a shared recirculating system, and the datasets obtained through these systems provide fertile prospects in research based on optimisation, continuous water quality monitoring is necessary.

Reduced Latency Response Edge Computing: Existing IIoT systems usually send sensor data to cloud computing systems to process and implement decision logic, which adds to latency between sensor readings and response, potentially being relevant in fast-changing water quality incidents. The pond or system level Edge computing architectures that execute data processing and control logic can enable the system to respond in minutes or seconds instead of minutes, thereby increasing the capability of the system to handle acute events, like sudden temperature change or equipment failures.

4.1 Conclusion

This article has shown a factual case study that IIoT-based water quality monitoring shows significant and repeatable results of improvement in fish health results, development, and illness control in pond-based aquaculture practices. In the six-month period of comparison (2024) the survival rate in ponds under IoT monitoring was 7.7 percent greater, fish weight was 30.8 percent higher and incidences of disease were reduced 78.1 percent compared to the ponds under conventional control management operating in the same environment. These were achieved through the observation of higher dissolved oxygen levels (mean 6.91 vs 5.77 mg/L) and more stable pH levels in IoT ponds that was an indication of the operational effect of constant monitoring and automated intervention that influenced the maintenance of the most ideal water quality conditions.

Correlation analysis of all sensor readings (37284) showed that the theoretically predicted relationships between the parameters of water quality (especially the negative temperature-oxygen relationship and positive temperature-pH relationship) exist, and that these dynamics were consistent over the entire production year. The distribution analysis showed that the variability of water quality was kept within acceptable constraints by the IoT monitoring to avoid the excursion of water quality to the extremes of parameter changes that cause the high occurrence of diseases and low growth performance that were experienced in the unmonitored system.

The results of the given study can be used to make a larger claim which states that the nature of environmental intelligence offered to aquaculture by IIoT monitoring is central to the realization of sustainable aquaculture, i.e. aquaculture that is environmentally responsible, economically viable, and in a position to aid food security in the long run. Intermittent and manual measurement is structurally ineffective in the dynamism and fast changing water quality environments of intensive fish production. The continuous sensor networks, automated intervention systems, and data infrastructure which are both a part of this not only are optional additions to aquaculture practice but an essential element of a sustainability-oriented operational architecture. In future studies, the cost and technical complexity barriers to adoption should be minimized, predictive ML models that go beyond reactive to anticipatory management must be developed, and the cost and ecological and economical performance of IoT-integrated aquaculture systems on a large scale should be evaluated.

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