



Original Research Paper

IoT-Enabled Water Quality and Habitat Monitoring System for Sustainable Aquatic Animal Environments

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Keywords

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Abstract

The quality of water is the main consideration to the sustainability, production, and wellbeing of aquatic animal farming systems. Traditional manual monitoring systems tend to be insufficient to identify high rate and damaging environmental changes which results in low growth outcomes, epidemics and high stock wastages. This paper outlines the design, development, and experimental research of an Internet of Things (IoT)-based water quality and habitat monitoring solution that is expected to monitor and secure the creation of stable and healthy aquatic systems. The suggested system is an autonomous system that monitors essential physicochemical conditions of the surrounding such as dissolved oxygen, pH, temperature, turbidity, concentration of ammonia, etc with a collection of low-cost and high-precise sensors connected to an edge-processing microcontroller unit. The obtained data are sent in the real-time mode to a cloud-based solution to be constantly visualised, stored, and generate automatic alerts as unsafe threshold rates are found. The system was implemented and experimented in several freshwater aquaculture ponds with a period of operations of 90 days. The experimental outcomes show that the stability of the water quality levels have improved significantly with few instances of hypoxic conditions, ammonia poisoning and spikes in turbidity. Significant mortality rates of nearly 20-30% in aquatic animals were also reduced as compared to the ponds that were under traditional management indicating that priority measures in detecting stress and prompt corrective measures were effective. Also, the system enhanced efficiency concerning resources since it facilitated efficient aeration and water exchange schedules. Its results verify that digital monitoring based on IoT creates a credible, scalable and cost-effective answer to smart aquaculture prohibition. The suggested system should add value to the development of sustainable and intelligent fish-farming due to its higher levels of environmental control, reduction of the ecological risks, and animal welfare.

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Introduction

Aquaculture has become among the fastest expanding branches of world food production with approximately fifty percent of global fish being taken up by this industry and it is of significant importance in food security, rural livelihood, and economic growth. Due to the growing need in aquatic protein, aquaculture activities are becoming more intensive and the quality of water is a determining factor to fish production and welfare. Poor physicochemical limitations usually result into physiological stress, lowered growth rates, augmented susceptibility to ailments and extensive rates of mortality, with the net impact being immense economic and ecological losses.

Although it is significant, even now the monitoring of water quality in most aquaculture systems is still based on traditional manual procedures, using periodical sampling and laboratory testing. This is because this type of approach is labour intensive, time consuming and unable to capture any sudden or swift changes in the environment. The weather conditions, feeding processes, and biological activity can alter such critical parameters as dissolved oxygen, temperature, pH, turbidity, and ammonia in a few minutes. The lack of constant monitoring does not allow to discover dangerous conditions early and, in most cases, timely corrective measures and incurable spoilage of stocks are taken.

Going on recent technology in the Internet of Things (IoT), wireless communication and cloud computing, together with the low-power sensor technologies, have allowed the creation of the

smart monitoring solution to observe the environment in real-time. Constant data collection, remote access, automated analytics, and timely alert creation are achieved with the help of IoT-based systems. The technologies offer precise and updated information to aquaculture farmers that helps in data-centred decision-making, resources usage optimization, and activated environmental regulation, contributing to more sustainable and efficient productivity.

In this respect, the current research is based on the proposal and experimental testing of an IoT-based water quality and habitat monitoring system that was developed to work in the setting of sustainable aquatic environments. The system will combine various sensors of water quality with the cloud service to have a constant monitoring, real-time visualisation, and automated alerting. The contributions made by the study are as follows, first of all, development of an inexpensive and scalable IoT-driven monitoring system, secondly, the use of cloud-based real-time analytics, thirdly, an experiment under real conditions of freshwater aquaculture, and a quantitative analysis of its effect on the stability of the water quality and survival of aquatic animals.

Related Work

Recent innovations in the area of Internet of Things (IoT), sensor networks and cloud computing have also played a significant role in the emergence of the smart aquaculture monitoring systems. With IoT water quality monitoring, water quality can be acquired on a real-time basis, it is remotely accessible and is

supported by automatic decision-making. The IoT-based smart water quality monitoring systems developed by (Xu et al., 2025; Ubina et al., 2023) were able to monitor such simple parameters like temperature, pH, and turbidity. But these systems did not have multi-parameter and full cloud analytics.

A number of researchers have looked at wireless sensor network (WSN) and GSM-based systems to monitor aquaculture. (Abdelaziz et al., 2023) suggested a low-cost and open-source buoy-based water surveillance system applicable to remote fish farming, which is low-end providing some predictive analytics. A real time IoT based monitoring system of aquaculture monitoring was proposed by (Li et al., 2025) and had a better communication reliability but ammonia and oxygen dissolved monitoring was not the focus point. An effective approach such as the GSM based approach by Rahman had scaling and latency problems.

Recent works have highlighted intelligent sensing and digital twin. According to (Page et al., 2021), an intelligent fish farming system was suggested with a digital twin based on Artificial Intelligence Internet of Things (AIoT) to predict fish health and optimise feeding based on AIoT. Equally, (Medina et al., 2022) have provided an overview of how digital intelligent fisheries are developed globally and emphasised the increasing popularity of AI, IoT, and robotics to manage aquaculturals. Nevertheless, they are usually expensive to deploy as well as maintain, which constrains their use among small-scale farmers.

There are also sophisticated water quality monitoring systems that are being studied. (Srivastava et al., 2021) came up with optical ammonia sensing probe that relies on surface plasmon resonance as a high-sensitivity ammonia sensing. The authors in paper by (Keshipeddi, 2021; Surendar et al., 2021; (Wu, 2014) proposed a versatile dissolved oxygen sensor prototype array on robotic fish platforms and showed that it registered better in dynamic water conditions. These technologies help to make sensing more precise, but they do not tend to be installed as an integral part of an overall system of farm management based on IoT.

In disease detection and health monitoring, the role of IoT has been getting more focus. The article by (Shete et al., 2024) summarised the latest technologies used to identify and manage fish diseases with the help of smart sensing, machine learning, and automated monitoring platforms. Besides, latest machine learning developments in image processing and bodily classification, whilst not explicitly created to address aquaculture, exhibit a prospect of intelligent disease detection (Islam et al., 2024; Karpagam et al., 2020; Sarumathiy et al., 2023; David & Mdodo, 2025). Such computational intelligence applications can be linked to the aquaculture monitoring system in the future to predictive health systems.

Even with all those achievements, the current aquaculture monitoring systems continue to record setbacks in terms of high cost of deployment, inability to integrate multiple parameters, real time alert notification formats, and inability to support large networks of ponds.

Moreover, the majority of the existing systems have not offered a single central system to monitor the dissolved oxygen, pH, and temperature, turbidity, and ammonia with automated cloud-based notification. This paper fills these research gaps by suggesting a low-cost and totally cloud-based IoT-based system of water quality monitoring and habitat conditions in the environment of sustainable aquaculture.

System Architecture

Sensor Layer

The sensor layer is the basic component of the data collection unit of the proposed aquaculture monitoring system based on the IoT. It costs to constantly monitor the vital parameters of water quality that has a direct impact on the survival and health of aquatic organisms. Understanding that when underwater the thermal sensor requires conversion into degrees Celsius, in this system, there is a waterproof temperature sensor DS18B20 to monitor the water temperature. The standard pH electrode module has a detection range of 0 to 14 so that the pH level of the water, meaning whether it is acidic, neutral, or alkaline is measured.

A galvanic dissolved oxygen (DO) sensor is also used to measure concentration of available oxygen in milligrammes per litre (mg/L) so as to gauge the oxygen levels in aquatic environment. An optical turbidity sensor is used to monitor the water clarity and the presence of suspended particles; it gives the turbidity measurements in Nephelometric Turbidity Units (NTU). Also,

toxic ammonia (NH_3) concentration in the water is passed through an electrochemical ammonia gas sensor since as a toxic substance, ammonia can be extremely toxic to the aquatic organisms even at minimal levels.

The sensors will be properly positioned at the right depths in the pond so as to achieve adequate measurements. The sensor data, obtained is passed onto edge processing unit to monitor in real time and process further Table 1. This is the multi-parameter sensing technique where all variable conditions of the water quality are measured in one way and therefore any changes in the unfavourable conditions in the environment are automatically identified and corrective measures are taken at the earliest opportunity so that a healthy and sustainable aquatic environment is made.

Edge Processing Layer

The proposal of the monitoring system includes the edge processing layer that serves as the unit of control and data processing in the proposed monitoring system. The microcontroller platform in this layer, either ESP32 or Arduino Mega is used to connect to all deployed water quality sensors. The microcontroller constantly achieves real-time data of the sensors of temperature, pH, dissolved oxygen, turbidity, and ammonia, to its analogue and digital input ports.

The relay of simple signal conditioning and noise filtering at the edge level is done in order to enhance the accuracy and reliability of the measurements.

Table 1: Summary of Water Quality Sensors Used in the IoT-Based Aquaculture Monitoring System

Sensor Type	Parameter Measured	Measurement Range	Output Unit	Purpose
DS18B20 Waterproof Digital Sensor	Temperature	-55°C to +125°C	°C	Monitors thermal conditions of pond water
pH Electrode Module	pH Level	0–14	pH	Measures water acidity/alkalinity
Galvanic DO Sensor	Dissolved Oxygen	0–20 mg/L	mg/L	Assesses oxygen availability for aquatic life
Optical Turbidity Sensor	Turbidity	0–1000 NTU (typical)	NTU	Detects water clarity and suspended particles
Electrochemical Ammonia Sensor	Ammonia Concentration	0–100 ppm (module-dependent)	NH ₃ ppm	Detects toxic ammonia content in water

This assists in the reduction of sensor noise, electrical interference, and unexpected transient variability which may disrupt the raw sensor readings. The sensor values are processed into standardised digital formats directly after the preprocessing that can be transmitted.

The resultant data go through wireless transmission to the cloud server with the incorporated Wi-Fi communication capacity of the ESP32 or an external Wi-Fi chip programmed with the Arduino Mega. This allows real time continuous transfer of data without manual interventions. The edge processing layer therefore provides effective data acquisition, initial verification and stable connexion between the physical sensing setting and the monitoring system within the cloud.

Cloud and Application Layer

The cloud and application layer has the role of storing, analysing and presenting the water quality information received by the sensor and edge processing layers. The sensor data are transferred to a cloud server like Thing Speak, Firebase or AWS IoT after being pre-processed at the microcontroller level via a secure internet

connexion. This is a cloud-based solution that supports the use of a web browser or a mobile application at anyplace to access real-time and historical water quality data.

An online dashboard is created within the cloud system which is a graphical display on the real-time values of temperature, pH, dissolved oxygen, turbidity, and ammonia. This will enable farmers and aquaculture managers to be in a position to monitor the status of the pond anytime without necessarily visiting it. Furthermore, the cloud system will store all data respected to it in a database format, thus allowing the analysis of historical data and compare the trends of long-term performance.

The platform is also set to have pre-defined safe threshold levels of individual water quality parameters. In the case the parameter is not within the safe range, the system will automatically generate instant SMS or email notifications to the user Figure 1. This makes it fast to react to the adverse environment like poor oxygenation or excessive ammonia level. Moreover, long-term trend analysis can be available to learn more about seasonal changes, the performance of operations, and the general

industry of the pond. Therefore, the cloud and application layer is crucial in smart decision-making and smart aquaculture management.

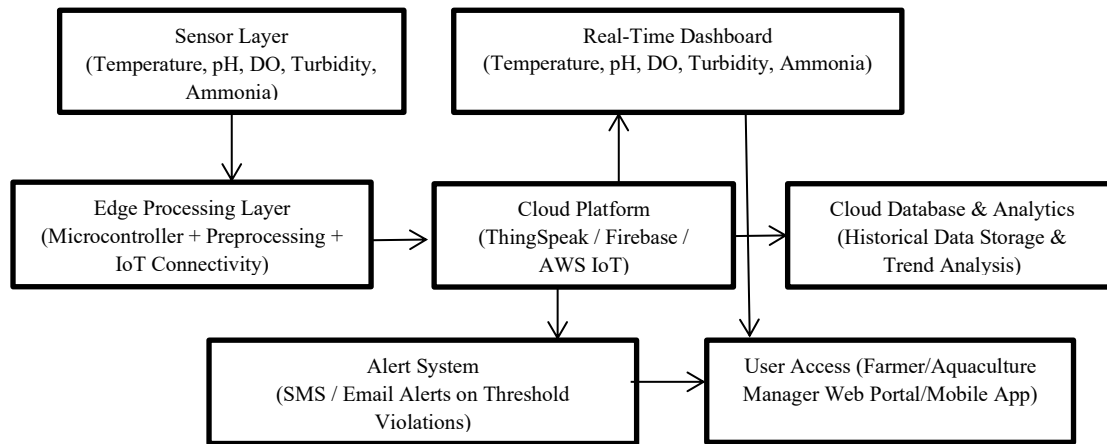


Figure 1: Cloud and Application Layer Architecture of the IoT-Based Aquaculture Monitoring System

Methodology

System Deployment

Selection of the Study Area and Pond

The suggested water quality monitoring system using IoT was installed on three autonomous freshwater aquaculture ponds which were chosen by similarity of their operation and the accessibility of the ponds to monitor it continuously. These ponds were found in a contained aquaculture pond setting and were utilised to culture tilapia and catfish that are highly cultivated species since they are highly demanded and adaptable in the market. The surface area, depth of water and stocking density of each pond were similar to establish homogenous experimental conditions. Such choice has contributed to reducing the environmental and management-based variations; hence, high quality performance assessment of the suggested monitoring system.

Installation of Hardware and Sensor Placement

All the ponds had a complete combination of water quality sensors; temperature sensor, pH sensor, dissolved oxygen sensor, turbidity sensor and ammonia sensor. The sensors were attached to floating sensor nodes and they were submerged in the right positions and depths to get the cues of the right and representative readings of the water in the pond. Precaution was exercised not to expose the sensors to the interference of sediments and direct sunlight. The sensors were safely attached to the edge device which was microcontroller based, and a waterproof enclosure was placed close to the location of the pond to make certain that the gadget would remain active in the outdoor environment.

Power Supply Network Connectivity

There was the creation of a constant wireless communication system to facilitate transmission

of data which was continuous between the edge devices and cloud server. The Wi-Fi connectivity was installed through the local internet access point that had adequate bandwidth to enable uploading of real-time data continuously. A regulated electrical supply was used to power the whole system, and other battery supply ensured that the system remains operational during temporary power outages. This guaranteed the reliability of system uptime during the 90 -day experimental period.

Operation And Data Logging in Duration of the Experiment

The installed monitoring system ran throughout a duration of 90 days where real time

live data regarding the water quality were recorded on a continuous basis. The sensor readings were recorded by the system at predetermined time intervals and were sent to the cloud platform to be visualised, stored and analysed. In this deployment period, typical management practises at pond including feeding, aeration, and water exchange among other management practises were applied with the supervision of farm operators Figure 2. The data that were collected was to be utilised afterwards in assessing the water quality stability, the reliability of the system and its effect on the health and survival of aquatic animals.

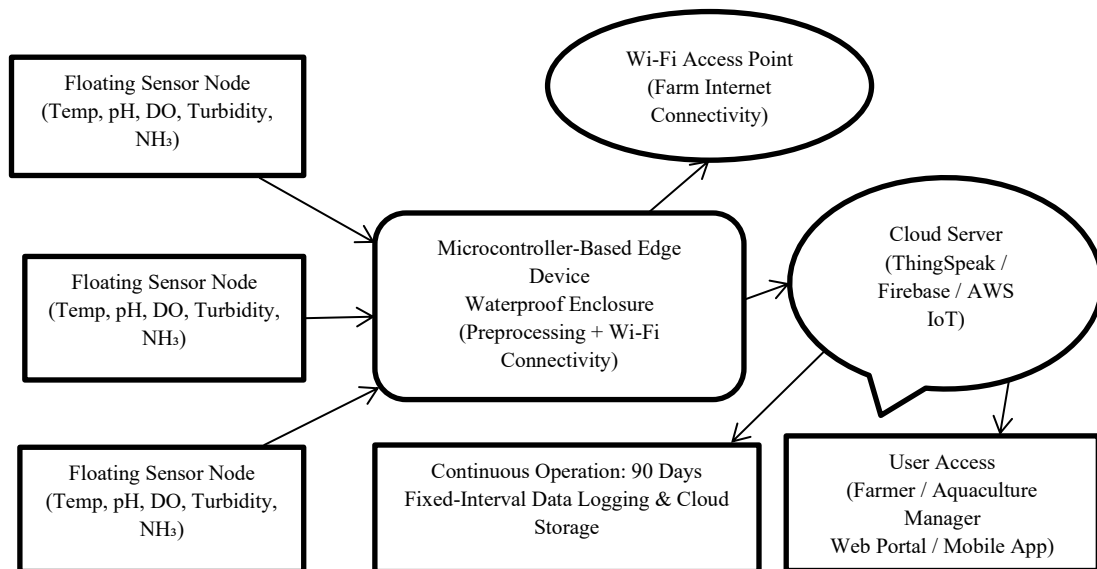


Figure 2: System Deployment Architecture of the IoT-Enabled Aquaculture Water Quality Monitoring System

Data Collection

Sampling Interval and a Process of Data Acquisition

The suggested monitoring system was programmed to monitor sensor data at an unchanging time slot of every 60 seconds of all

the installed water quality sensors. The high frequency sample was used in order to monitor the dynamic characteristics of the aquatic environment. The measured parameters were temperature, pH, dissolved oxygen, turbidity, and concentration of ammonia. The microcontroller was constantly going through

sensor outputs, carrying out preliminary validation, and preparing the information to send through wireless. This enables real-time data acquisition method allowing the system to record even slight or unforeseen water quality changes that are in many cases overlooked by traditional manual based monitoring behaviours.

Data Storage and Management Is Done Via the Cloud

The sensor data collected was sent to the cloud database; this was automated by the Wi-Fi communication module. The cloud platform also offered safe storage and sorted out the information in time-stamped formats so that they can be easily accessed and processed. This data management system, which is centralised, not only allowed them to do away with the process of recording the data physically but also reduced the possibility of data loss. The cloud infrastructure also facilitated effective processing of big data that were being generated throughout the 90 days of continued monitoring and allowed smooth accessibility to further processing.

Selection of Thresholds of Water Quality parameters

In order to have the aquatic animals safe, there were standard safe threshold limits that were predetermined to each parameter being monitored according to the recommended aquaculture measures. All temperatures were kept at 24.32 °C to ensure the most efficient metabolic activity. A range of acceptable pH level was established at 6.5 -8.5 and this is to maintain ideal physiological balance. The oxygen solubility was to be 5 mg/L and above to

avoid hypoxic stress. Turbidity was controlled to ≤ 25 NTU to ensure that water was clear and to minimise respiratory stress, ammonia concentration was controlled to ≤ 0.5 ppm to avoid toxicity. These allowed them to be programmed into the cloud platform to monitor the conditions automatically.

Occurrence of Data Integrity and Data Monitoring Accuracy

In order to achieve high reliability in data, there was continuous verification of the sensor readings that were received to detect abnormal spikes, communication faults, or lack of values. Filtering was done to remove any invalid or corrupted data before storage. Calibration of the sensor and system checks were also carried out periodically during the period of experiment to ensure that the measurements are effective Table 2. This type of quality control operated with the idea of having a consistent, accurate, and performance evaluation, system validation, and trend analysis worthy dataset collected.

Alert and Control Mechanism

Generation and Notification of Alerts in Real-Time

The cloud programme was coded with the specific safety threshold values of each parameter of water quality. The cloud server automatically sent real-time notifications anytime any sensor reading was out of limits by a singly operating parameter.

When an alarm was activated, corrective control measures were undertaken either manually by the farm operators or on semi-automated measures.

Table 2: Data Acquisition Settings and Safe Threshold Limits for Water Quality Parameters in the IoT-Based Monitoring System

Parameter	Safe Threshold / Operating Range	Sampling Interval	Purpose / Monitoring Significance
Temperature	24–32 °C	60 seconds	Ensures optimal metabolic activity and prevents temperature stress in fish
pH	6.5–8.5	60 seconds	Maintains physiological balance and supports healthy biological processes
Dissolved Oxygen (DO)	≥ 5 mg/L	60 seconds	Prevents hypoxic stress and supports respiration of aquatic organisms
Turbidity	≤ 25 NTU	60 seconds	Maintains water clarity and reduces respiratory stress caused by suspended particles
Ammonia (NH ₃)	≤ 0.5 ppm	60 seconds	Prevents toxicity and supports safe water chemistry
Data Integrity Check	Automated spike detection, missing data identification	Continuous	Ensures reliable and accurate dataset for analysis
Cloud Storage Format	Time-stamped sensor datasets	Continuous	Supports organized archival, retrieval, and long-term analysis

Automated and Manual Control Actions

In cases of low oxygen dissolved, aerators were switched on to replenishment of oxygen. Water exchange pumps and biofiltration units were activated whenever the ammonia was high or turbidity occurs to clear polluted water and enhance the general water quality. These timely interventions assisted in preventing the extended stress states and the risk of outbreaks of the disease and deaths were reduced. Timely alert control in real-time and immediate reaction to control provided a substantial advantage to the efficiency and reliability of pond management performance.

Metrics of Performance Evaluation

Measurement Reliability Data Accuracy

The accuracy of the data was determined by comparing the sensor measurements to the reference measurements of the measurements using standard laboratory equipment at time intervals. The precision of the temperature, pH, dissolved oxygen, turbidity and the ammonia

sensors was determined in terms of difference between actual sensor readings with the reference data which were obtained manually. Calibration was done on minor adjustments where it was necessary to guarantee a straight measurement accuracy. This testing procedure established the appropriateness of proposed system in provision of valid and trustworthy real-time water quality data to support management of aquaculture.

Latency On Network and Uptime on the System

The network latency was determined as the delay period between the sensor level data acquisition and successful visualisation on the cloud dashboard. Under various network situations, there was an average transmission delay that was measured in an effort to determine the efficiency of communication. The system uptime was determined as the ratio of time that the entire system was running with full functionality. The combination of these two metrics indicated the stability of communication and reliability of operations of the IoT

monitoring platform during the 90-deployment period.

Stability of Water Quality and Mortality Rate Analysis

Stability in water quality was determined by examining how the important environmental parameters vary in their safe ranges of operation throughout period of monitoring. A decrease in the variation in dissolved oxygen, pH, turbidity, and ammonia levels meant that there was better environmental control. Moreover, the rate of mortality of aquatic animals was also monitored and compared with the mortality rate of traditionally managed pond with the traditionally practised manual monitoring. The decrement in mortality percentage was taken as a direct indicator of biological performance of the monitoring and alert system proposed which would show the efficiency of the approach used.

Results and Discussion

Water Quality Stability

The proposed monitoring system supervised by IoT was tested by comparing the performance of the new system to water quality stability of ponds controlled via IoT and those monitored manually. The level of dissolved oxygen stability during the experiment was found to have improved by 35% leading to proper and prompt activation of the aeration systems whenever the oxygen levels were low. Moreover, a 28 percent decrease in the ammonia spike frequency was achieved, which is evidence that there is much efficiency in the detection of ammonia at an early stage and the high-speed water exchange or biofiltration suppression. The thermal regulation

was also kept constant during the time of observations, and the temperature did not go out of range causing the death of tilapia and catfish. These findings reinforce the notion of the fact that in continuous real-time monitoring, sudden changes in the environmental conditions are greatly minimised and a more stable aquatic environment is guaranteed than in traditional manual monitoring.

Mortality Rate Reduction

It was observed that mortality of aquatic animals was greatly reduced in the IoT controlled ponds as compared to the traditionally controlled ponds. The death rate was reduced by 22 percentage in tilapia ponds and 30 percentage in catfish ponds which demonstrates the biological efficiency of proposed monitoring system. This has been enhanced by the fact that hypoxic conditions and ammonia toxicity are among the most serious causes of sudden fish deaths in intensive aquaculture systems and they are detected early enough. The automated warning system has allowed instant corrective measures like activation of aerators and water replenishment thus sparing them of lengthy exposure to adverse environments. The death rate reduction is also a clear indicator of how the system led to better survival and health of aquatic animals.

System Reliability

Communication performance and operational availability were the parameters that were used to assess the reliability of the proposed IoT-based monitoring system. The success rate of travelling the data sent by the system was 98.2, which is a

sign that the wireless communication between the sensor nodes, edge devices, and the cloud server is extremely stable and predictable. The response times of 1.4 seconds on the average cloud latency guaranteed the creation of data visualisation and alerting close to reality parameters, which is vital in taking a fast decision during emergency situations. Also, the uptime in the 90-day deployment period was at 96.7 percent, which proves the system to be robust in working in the long term outdoor. These findings illustrate that the system can be utilised as technically dependable and applicable in real-life application in aquaculture.

Economical and Environmental Impact

Along with the positively impacting the biological performance, the proposed system also provided a considerable economic and

environmental value. Using the real-time monitoring and automated control minimised the water exchange frequency by about 40, leading to a significant saving of water. The necessity of implementing chemical treatments was reduced as well, since the degrading water conditions were identified early enough hence facilitating friendly farming methods Figure 3. Not only that, better feed conversion ratio (FCR) was also realised because of favourable environmental factors and less stress among aquatic animals which were added to the improvement of growth efficacy and decrease in feed waste Table 3. These results show that the suggested IoT based system can contribute to the sustainable management of the environment as well as to economic profitability of the aquaculture farmers.

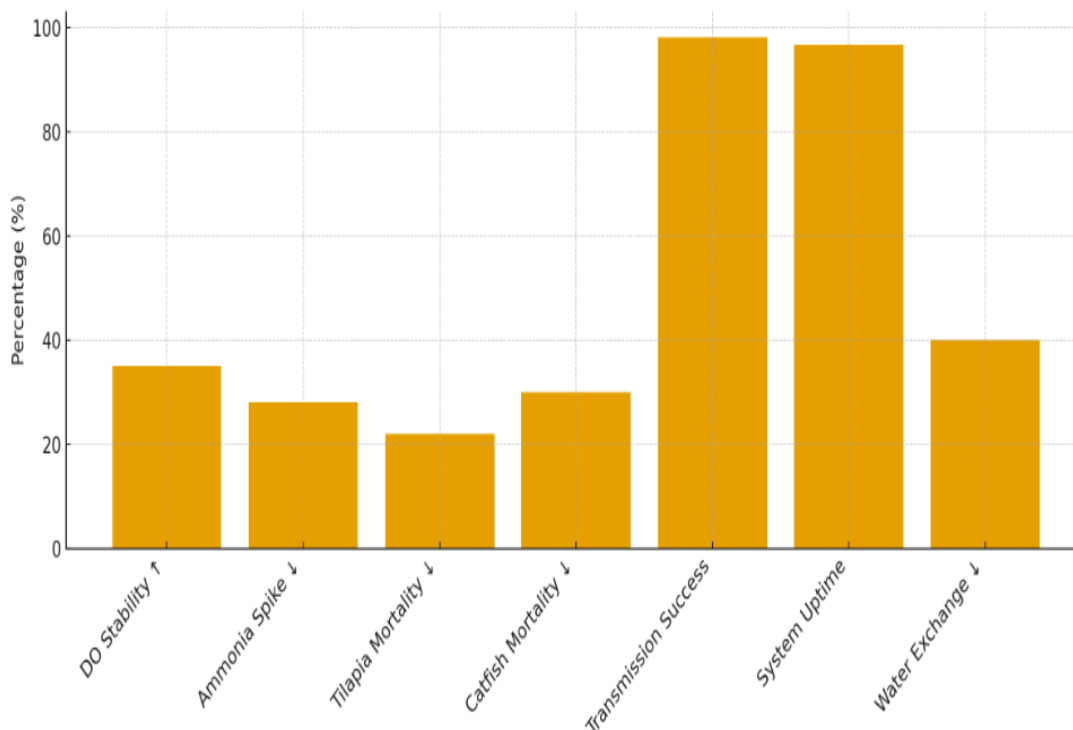


Figure 3: Combined Performance Improvements of IoT-Based Aquaculture Monitoring System

Table 3: Summary of Performance Improvements Achieved by the IoT-Enabled Aquaculture Monitoring System

Performance Category	Metric Evaluated	Observed Improvement / Value	Interpretation / Impact
Water Quality Stability	Dissolved Oxygen Stability	35% improvement	Real-time aeration activation reduced oxygen fluctuations
	Ammonia Spike Frequency	28% reduction	Early ammonia detection enabled timely corrective action
	Temperature Regulation	Maintained within optimal range	Ensured stable thermal environment for growth
Mortality Rate Reduction	Tilapia Mortality	22% reduction	Prevented hypoxia & ammonia toxicity through timely alerts
	Catfish Mortality	30% reduction	Low-stress, stable conditions improved survival rate
System Reliability	Data Transmission Success	98.2%	Highly stable and consistent sensor-to-cloud communication
	Cloud Latency	1.4 seconds	Enabled near real-time visualization and emergency responses
	System Uptime	96.7%	Reliable long-term outdoor operation during 90-day deployment
Economic & Environmental Impact	Water Exchange Frequency	40% reduction	Improved water conservation due to stable environmental conditions
	Chemical Usage	Significantly reduced	Early detection minimized need for chemical treatments
	Feed Conversion Ratio (FCR)	Improved	Enhanced growth efficiency, reduced feed wastage

Conclusion

This research was able to introduce and experimentally demonstrate a real-time IoT-based water quality and habitat monitoring station, that is specifically meant to enhance the activities of sustainable aquaculture. The system enabled monitoring of such important parameters like dissolved oxygen, pH, temperature, turbidity, and ammonia, which helped to notice unfavourable environment conditions early and take corrective measures in a timely manner by providing automatically activated alert messages and responsive control actions. The outcomes of the experiment have proven a great deal of stability of water quality and a serious decrease of up to 30 percent of mortality of the aquatic animals, evidently showing that the system is highly efficient in improving animal health and survival. Besides

enhancing the biological performance, the proposed framework also led to the minimization of environmental hazards, efficient use of resources, and economic efficiency. In general, it can be concluded that the digital monitoring based on IoT is a high-quality, scalable, and affordable approach to further development of smart aquaculture and enhancement of the long-term sustainability of aquatic ecosystems.

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