MJSAT 5 (3) 173-178

MJSAT

Malaysian Journal of Science
and
Advanced Technology

journal homepage: https://mjsat.com.my/

A Smart Approach to Aquatic Ecosystem Protection: IoT-Based Water Quality Monitoring System (WQMAS)

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KEYWORDS

IoT
Sustainable Development
Real-Time
Smart Water Management

ARTICLE HISTORY

Received 12 May 2025
Received in revised form 26 May 2025
Accepted 2 August 2025
Available online 12 September 2025

ABSTRACT

In an era increasingly threatened by pollution and climate change, water quality is under serious risk. Spatial water quality monitoring and traditional laboratory testing are inadequate to protect aquatic ecosystems. An innovative solution emerges from the Internet of Things (IoT), which enables the Water Quality Monitoring System (WQMAS) to transform traditional water resource monitoring practices. Through advanced sensor technologies, this system obtains real-time critical measurements including ambient temperature (25°C–30°C), water temperature (25°C–30°C), turbidity, pH values, electrical conductivity (500–1000 µS/cm), and dissolved oxygen levels. The system automatically pushes data into an easy-to-use IoT dashboard that allows users to immediately understand and assess data for smart and knowledgeable choices. The system utilizes Polyethylene Terephthalate Glycol-modified (PETG) material for durable 3D-printed enclosures that make it affordable and suitable for different fields due to its scalable characteristics and environmental resiliency. The automated system for water quality checks removes manual errors and performs fast and precise checks that manual operations cannot match. The technical capabilities of this solution become part of a sustainability showcase which enables communities to protect aquatic ecosystems while enhancing water resource optimization for creating a more environmentally friendly world. Within the water management industry, the Water Quality Monitoring System operates beyond its status as a tool to serve as a fundamental step towards sustainable development.

1. INTRODUCTION

Water quality is an essential aspect of the maintenance of aquatic ecosystems and the supply of clean water for industrial, agricultural and domestic applications. Nonetheless, water resources are threatened at the global level as a result of increasing levels of pollution and the effects of climate change [1]. Thus, traditional water quality monitoring methods based on spatial testing and laboratory analysis are often insufficient because of their time consumption and as a result data are not available in real time [2]. However, these limitations necessitate the urgent need for an advanced, automated, and efficient solution for the water quality monitoring system.

The Internet of Things (IoT) approaches to environmental monitoring are emerging at the advent of the era of the IoT [3]. WQMAS is an IoT based solution that gathers and analyses the water quality data collected in real time through the application of advanced sensor technology [4]. WQMAS's ongoing and continuous monitoring of key water parameters among them turbidity, pH, electrical conductivity (EC), dissolved oxygen, and temperature variations makes it possible for precise and rapid assessments [5]. An intuitive IoT dashboard is included to integrate with the system within which immediate data interpretation is made possible for stakeholders to make intelligent decisions for water resource management [1].

One of the most important aspects of the WQMAS system is the incorporation of a Polyethylene Terephthalate Glycol-modified, PETG based 3D printed enclosure that increases durability, affordability, and environmental resiliency. Due to this scalability and robustness, a flux meter can be used for

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https://doi.org/10.56532/mjsat.v5i3.529
2785-8901/

other applications such as industrial water monitoring and community driven sustainability initiatives. The system automates monitoring and thereby reduces manual errors as well as increases productivity, and it is the key instrument for sustainable development and ecosystem conservation [1]. Early investigation of this work has been described in [6,7,8].

The purpose of this paper is to discuss the role of automation in tackling new environmental frontiers, and the framework, stressing the benefits and implications of deploying IoT based water quality monitoring systems. This study aims to design, implement, and evaluate a real time IoT based water quality monitoring system. The highlights of the technologies involved contribute to water resource optimization and environmentally sustainable techniques. Therefore, this research paper follows a structured approach to investigate the integration of IoT and 3D printed PETG technology for aquaculture water quality monitoring. Section 1 introduces the background, objectives, and concept of the WQMAS system for aquaculture water quality monitoring. Section 2 provides a literature review, discussing prior research on IoT and environmental monitoring technologies in aquaculture. In Section 3, it will explain about the methodology that consist of the system design, sensor integration and data collection process also the housing for it. Section 4 will shows the results and discussing the outcome of the research.

2. LITERATURE REVIEW

2.1 IoT Monitoring

Old way to test the water quality is by send it to the lab, which often take a long time to finish and limited availability of real time data [1]. In contrast, the integration of the Internet of Things (IoT) in this works will changing the way of data collecting and decision making process into the water quality monitoring.

The ability to provide real time, automated, and continuous data collection by applicating IoT in water quality monitoring has gained significant attention. Monitoring key water parameters such as turbidity, pH, electrical conductivity (EC), dissolved oxygen, and temperature have a lot of studies that had explored the benefits of using IoT enabled systems [2][3]. Enhancing the comprehensiveness and reliability of water quality is the ability of IoT systems that integrate multiple sensors into a single framework [4].

Real time monitoring of water parameters significantly improving decision making and reduces the operational costs by minimizing human involvement according to a study that demonstrates the effectiveness of an IoT based system in aquaculture[5]. Additionally, the stakeholder can monitor and analyze the parameter trends and make decision regarding their water resource management by using the cloud based IoT dashboards [9].

2.2 Sensor Integration

There is important to make the appropriate choices of the sensors to ensures the accuracy, durability and the efficiency of water quality monitoring systems. For parameters like pH, turbidity, and dissolved oxygen are recommended to use the sensors with high sensitivity and stability [10]. Cross referencing values from different sensors will improves overall accuracy by integrating multiple sensors into a single IoT system to enhance data reliability[11].

Common microcontroller for IoT application for processing and transmitting data are the Raspberry Pi and ESP32. For handling complex data analytic and high processing power, Raspberry Pi is suitable especially for research intensive applications [12]. But power consumption somehow quite high can be a drawback in remote monitoring. In differences, ESP32 has low power consumption as its has a microcontroller with built in WiFi and Bluetooth capabilities, making it ideal for real time monitoring in water quality monitoring [13]. Then, the ESP32 microcontroller was chosen over the Raspberry Pi for the system integration due to its smaller size and lower cost.

2.3 Enclosure Materials

Another critical factor is the selection of the sensor enclosure that will ensure long term functionality in aquatic environments. Research has shown that PETG (Polyethylene Terephthalate Glycol) possessed chemical stability, durability, and water resistance that suitable material for 3D printed enclosures[14]. PETG is an ideal choice for underwater application because its provides excellent protection against biofouling and environmental stressors.

PLA (Polylactic Acid) will be compared with PETG as comparative studies. PETG outperforms PLA in terms of moisture resistance and mechanical stability [15][16]. PLA is prone to degradation in aquatic environments because its being biodegradable that leading to structural failures over time [17]. In contrast, PETG got better resistance to handle chemical corrosion that will ensures the longevity of IoT based monitoring systems in various conditions [14]. Additional research suggests that the mechanical degradation of 3D printed PETG and PLA in marine environments can impact their structural integrity over extended periods that necessitating further investigation into long term durability and material optimization [15].

3. METHODOLOGY

This work involves three sensor systems for monitoring water quality in an aquarium: The Water Quality Monitoring System, MAS, NI-MAS, and a Commercial Sensor System. Each system has different sets of sensors and data collection methods, as summarized in Figure 1.

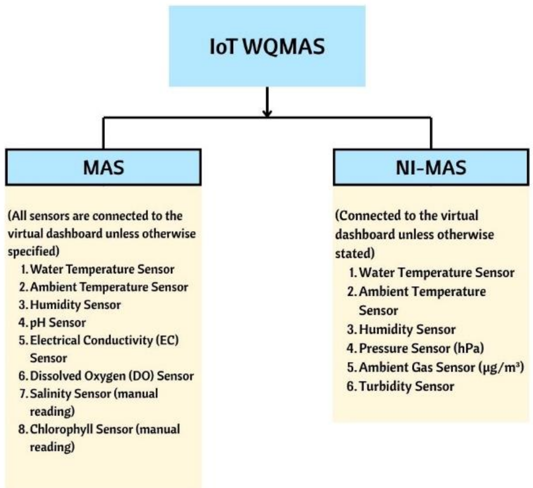


Fig. 1. Sensor differences between MAS and NI-MAS.

3.1 MAS System:

- The MAS system includes sensors for water temperature, ambient temperature, humidity, pH, electrical conductivity (EC), and dissolved oxygen (DO). These sensors are connected to a virtual
- dashboard for real-time monitoring. However, salinity and chlorophyll levels are measured manually, as those sensors are not integrated with the dashboard.
- NI-MAS System:
- The NI-MAS system is also connected to a virtual dashboard and shares some sensors with the MAS system, such as temperature and humidity. Additionally, it includes sensors for pressure, ambient gas (µg/m³), and turbidity. Like the MAS system, some parameters may require manual observation depending on conditions.
- Commercial Sensor System:
- This system is used entirely for manual data collection. It measures pH, resistivity, EC, total dissolved solids (TDS), and salinity. All readings are taken manually at specific intervals and recorded for analysis.

Each system plays a role in ensuring accurate and comprehensive monitoring of both aquatic and environmental conditions in the aquarium. Both WQMAS and NI-WQMAS systems utilize the ESP32 microcontroller instead of the Raspberry Pi, primarily due to its lower cost, smaller size, and ease of integration into compact enclosures.

Figure 2 illustrates the experimental setup used in water quality monitoring work. It shows three different sensor systems placed in the same water tank to compare performance and data accuracy.

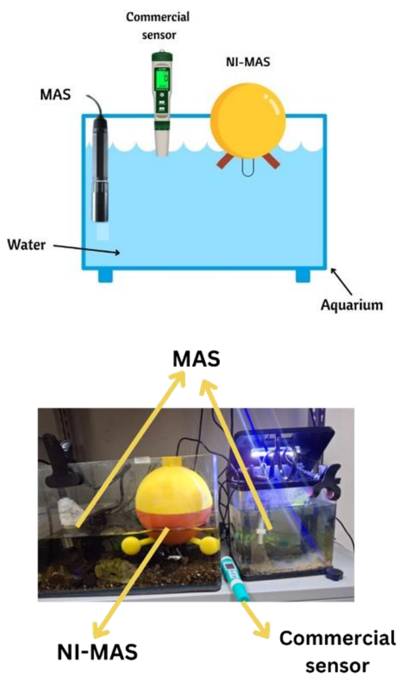


Fig. 2. The experimental setup used in water quality monitoring work (WQMAS): MAS and NIMAS

All three systems MAS, NI-MAS, and a commercial water quality sensor measure similar and different parameters, as shown in Table 1.

Table 1. Parameter Comparison between MAS, NI-MAS, and Commercial Sensor

No.	Parameter	MAS	NI-MAS	Commercial Sensor
1	Ambient Temperature (°C)		✓	✓
2	Water Temperature(°C)	✓	✓	✓
3	Turbidity(NTU)	✗	✓	✗
4	pH	✓	✓	✓
5	EC (Electrical Conductivity) (µS/cm)	✓	✗	✓
6	DO (Dissolved Oxygen) (µg/m³)	✓	✗	✗

3.2 Sensor Housing Development: PLA vs PETG

In the early development of the MAS prototype, sensor housings were 3D printed using PLA (Polylactic Acid). PLA was selected initially due to its ease of printing and affordability for quick prototyping. However, during preliminary tests, it was observed that PLA's properties were not ideal for long-term use in aquatic environments. PLA has low water resistance and tends to degrade or become brittle over time when exposed to moisture. The degradation will affecting the accuracy and consistency of the sensor readings due to possible water leaking or sensor misalignment. Observations from experiment shows that PLA enclosures began to deform within two weeks of submersion into the water and up to 30 % loss in structural sturdiness and signs of water leakage.

To address this issue, the second phase of the prototype change by using PETG (Polyethylene Terephthalate Glycol) for the sensor housing. For underwater and floating sensor devices, PETG offers better moisture resistance and structural strength. PETG maintained 95 % of its tension strength after 30 days of water exposure for the stress test but for PLA its only 62 %. Then, PETG enclosures shows no signs of water leakage or cracking were observed and it's the ability to avoid various chemical conditions and UV exposure. Its also supports long term deployment in aquaculture or environmental settings. Field test in a aquarium demonstrated that PETG enclosures maintained sensor alignment and accuracy for over one month without degradation or leakage, confirming its suitability for continuous monitoring. By selecting PETG over PLA ensures better protection for the sensors by reducing risks of malfunction due to strains such as water, heat, and sunlight.

PETG enables the system to operate more reliably in real world aquatic environments that ultimately supporting more accurate data collection and reducing the need for frequent maintenance just by improving the durability and watertightness of the sensor enclosures. The prototype of the PETG housing for MAS are shown in Figure 3.

Fig. 3. PETG housing for MAS

4. Result and Discussion

Fig presents the analysis of environmental data collected by the MAS and NI-MAS sensor systems between November and March. The primary aim is to evaluate each system's sensitivity, consistency, and suitability for water quality monitoring in various environmental conditions.

4.1 MAS Data Analysis

The MAS system recorded several parameters including water and ambient temperature, humidity, conductivity, and dissolved oxygen (DO). The following observations were made:

- Temperature (°C) : Water and ambient temperature readings show a consistent trend, with water temperature fluctuating slightly between 25°C to 30°C. The ambient temperature remained more stable around 30°C. This indicates the temperature sensors are responsive to natural changes in the environment.
- Humidity (%): Humidity levels were stable across all months, generally ranging between 60% to 70%. This suggests reliable readings from the humidity sensor (DHT).
- Conductivity (µS/cm): The readings showed variation in conductivity values, ranging from approximately 500 µS/cm to 1000 µS/cm. This reflects changes in ion concentration in the water.

Dissolved Oxygen (DO) (µg/m³): DO values fluctuated significantly in December and January, which may indicate changes in biological activity or temperature-dependent oxygen solubility. These readings suggest the sensor is sensitive and responsive to aquatic biological processes.

4.2 NI-MAS Data Analysis

The NI-MAS system measured water temperature, turbidity, air quality (µg/m³), and atmospheric pressure. The design of NI-MAS is a floating sensor hub that may influence the type and sensitivity of measurements obtained:

- Temperature (°C): Remained stable across the monitoring period, hovering around 29 to 30°C. The absence of large fluctuations may be attributed to the floating mechanism, which could dampen short term temperature changes.
- Turbidity (NTU): This parameter showed increased values in December and February, with a particularly sharp rise in late December. This suggests NI-MAS is effective at detecting suspended particles or sedimentation, possibly due to increased water runoff or algal bloom.
- Air Quality (µg/m³): Small fluctuations were observed in the air quality index, which ranged between 70 to 90 µg/m³. This indicates atmospheric pollutants are potentially accumulate over time or changes due to human activities nearby.
- Pressure (hpa): The pressure readings were consistent throughout the period, indicating stable atmospheric conditions or sensor stability.

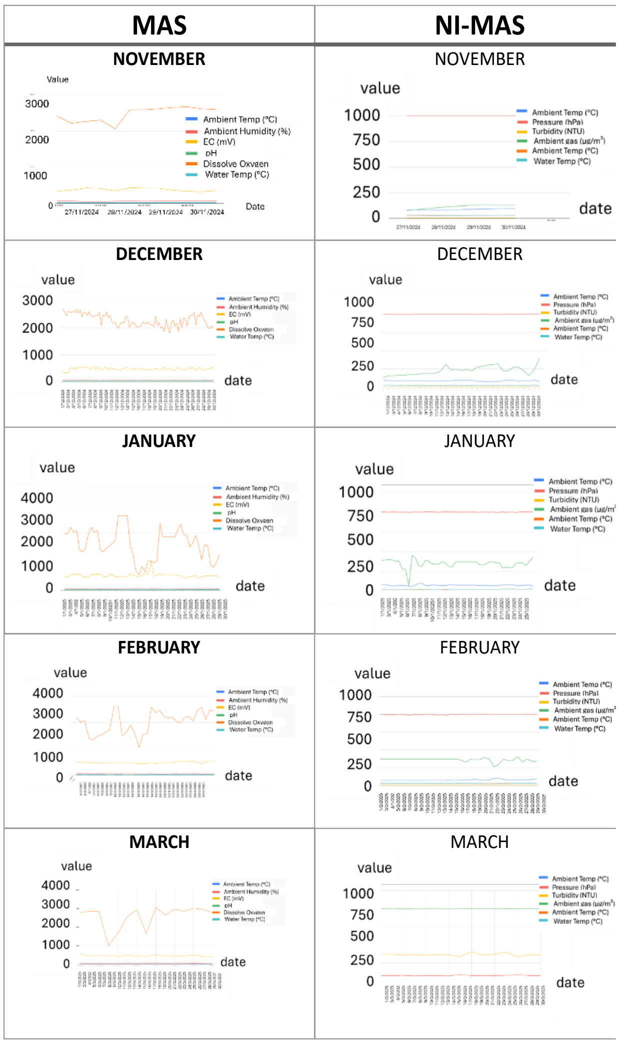


Fig. 4. Differences in reading for MAS and NI-MAS over 5 month

4.3 Comparative Insights

A comparison between the two systems reveals that both MAS and NI-MAS have unique strengths in environmental monitoring in the Table 3.

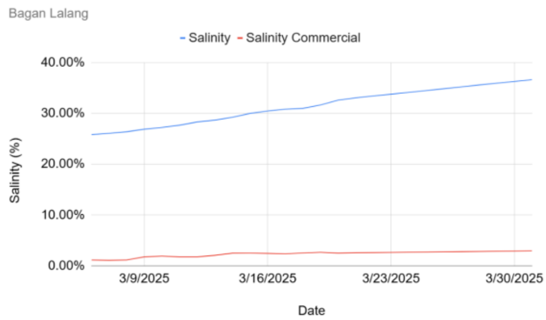
Table 3. Parameter Comparative insight between MAS and NI-MAS

Parameter	**MAS**	**NI-MAS**
Temperature (°C)	Responsive to variation	Stable readings
Humidity (%)	Measured accurately	Measured accurately
Conductivity (µS/cm)	Clear seasonal patterns	Not measured

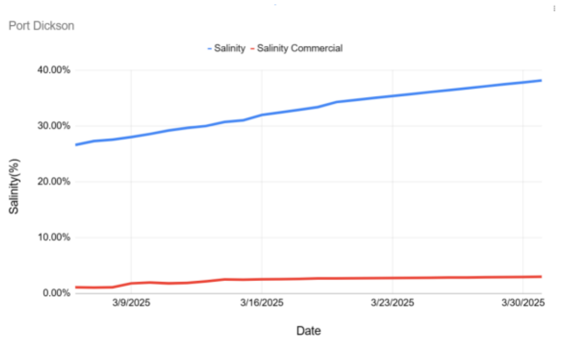
Dissolved Oxygen (µg/m³)	Detected significant change	Not measured
Turbidity (NTU)	Not measured	Spikes observed in Dec/Feb
Air Quality (µg/m³)	Not measured	Gradual increase observed
Pressure (hpa)	Not measured	Consistent values

MAS system is more suitable for in depth water quality analysis, capturing biochemical and physicochemical variations under the water surface. In difference of NI-MAS is excellent in monitoring surface level environmental conditions such as turbidity and air quality. Together, they will providing a comprehensive environmental monitoring solution.

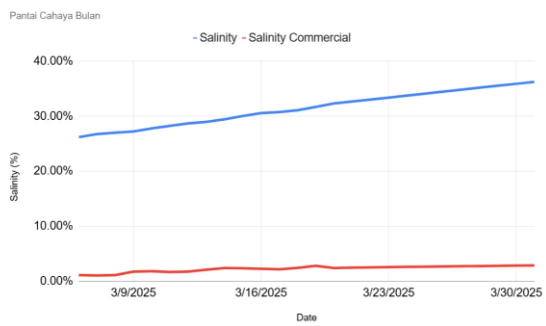
4.4 Comparison of Salinity Measurements Between MAS Sensor and Commercial Sensor.



(a)



(b)



(c)

Fig. 5. Salinity Comparison of MAS and Commercial Sensor

The reading of salinity of the ocean water at Bagan Lalang, Port Dickson, and Pantai Cahaya Bulan that recorded in Table 4, shows the MAS prototype sensor consistently recorded higher salinity values than the commercial sensor. The commercial sensor values remained low and stable in the March 2025. This suggests differences in sensitivity or calibration between these two sensors.

ACKNOWLEDGEMENT

This work was supported by the Fundamental Research Grant Scheme (FRGS) under the Ministry of Higher Education Malaysia, Grant No. FRGS24-327-0936.

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