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Architecture of a LoRaWAN IoT RTU for water quality control in aquaculture systems

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Abstract*– Modern aquaculture faces significant challenges associated with continuous water quality monitoring, particularly in rural areas where electrical and telecommunications infrastructure is limited. This article presents the design, implementation, and experimental validation of a Remote Terminal Unit (RTU) based on the Internet of Things (IoT) and Long Range Wide Area Network (LoRaWAN) technology for the continuous monitoring of critical water quality variables such as pH, dissolved oxygen, and temperature in aquaculture systems. The proposed solution integrates multi-parameter sensors, a low-energy consumption architecture, and both local and remote configuration and calibration mechanisms. Data is transmitted via LoRaWAN to The Things Network, enabling real-time monitoring of pond biochemical conditions under variable environmental scenarios. Experimental validation was conducted in real aquaculture ponds, comparing RTU measurements with certified reference equipment; results demonstrated high correlation, with maximum deviations of less than 0.3 pH units, ≤0.2 mg/L for dissolved oxygen, and within ±1 °C for temperature. Field tests further confirmed reliable long-distance communication and reduced energy consumption, ensuring viability for prolonged autonomous operation. This robust architecture contributes to aquaculture productivity sustainability and aligns with Sustainable Development Goals related to efficient water management, food security, and technological innovation.

***Keywords*– Aquaculture monitoring, Dissolved oxygen, Internet of Things (IoT), LoRaWAN, Remote Terminal Unit (RTU), Smart aquaculture, Water quality monitoring**

I. Introduction

The sustained growth of aquaculture worldwide has led to fish and aquaculture production reaching historic highs, consolidating its position as a strategic activity for global food security [1]. This increase in production has intensified the need for more rigorous control of environmental variables present in farming systems, such as temperature, dissolved oxygen, pH, and electrical conductivity [2], [3], which directly affect the health, growth, and productivity of aquatic species. In this regard, international organizations agree that the sustainability of the sector depends, to a large extent, on the adoption of technologies that enable efficient management based on reliable, real-time data [4]. In this context, continuous monitoring of water quality using emerging technological solutions has become a key element in optimizing production and mitigating environmental and health risks.

Traditionally, the measurement of physicochemical variables in water has been carried out using portable multiparameter probes, which are widely used due to their versatility and accuracy. However, the need for frequent calibrations, together with the dependence on manual and spot measurements, limits their application in continuous and distributed monitoring schemes. These restrictions hinder the early detection of critical events, which can lead to episodes of stress or mass mortality in aquaculture systems [5]. Various journalistic and technical reports show that the lack of timely monitoring, combined with factors associated with climate change, has caused significant economic losses in the aquaculture industry [6], highlighting the need for automated, robust, and continuously operating monitoring systems.

In response to these limitations, automated monitoring solutions based on Remote Terminal Units (RTUs), Programmable Logic Controllers (PLCs), and SCADA systems have been proposed, which have proven highly effective in industrial environments. However, their adoption in aquaculture systems presents significant constraints, including high implementation costs, high energy consumption, and operational complexity that hinders their scalability [7], [8]. Additionally, these solutions often rely on wired communication infrastructures or cellular networks, which are unstable, costly, or non-existent in rural and remote areas where much of the aquaculture activity takes place [9].

At the same time, recent research has explored the use of IoT architectures and open platforms for monitoring environmental variables in different production contexts [10]. Although these approaches have demonstrated technical feasibility, many of the proposed solutions lack prolonged experimental validation or do not explicitly consider the adverse environmental conditions typical of aquaculture, such as high humidity, continuous exposure to water, and corrosion processes [11]. Furthermore, recurring limitations have been identified associated with the absence of mechanisms for sensor drift correction, unrobust electronic encapsulation, and inefficient energy consumption management, factors that compromise the long-term reliability and sustainability of the systems.

Given this scenario, long-range, low-power communication networks are emerging as a promising technological alternative. In particular, LoRaWAN has been widely studied due to its ability to offer wide coverage ranges with reduced energy consumption, making it particularly suitable for rural and remote environments [12], [13]. Several studies report successful applications of LoRaWAN in the monitoring of water resources and production systems, highlighting significant improvements in energy efficiency and communication range [14], [15]. However, challenges remain related to latency, link reliability in humid climates, and the efficient integration of multiple analog sensors within a single terminal unit, which are critical aspects for aquaculture applications [16].

Based on this state-of-the-art analysis, a clear scientific gap is identified: the absence of an integrated IoT RTU architecture that simultaneously optimizes multisensor acquisition, energy management, and long-range communication using LoRaWAN, explicitly considering the environmental and operational constraints of aquaculture systems. Within this framework, the present work aims to design a LoRaWAN-based IoT RTU for the continuous monitoring of critical water quality variables in aquaculture systems, contributing to the development of more efficient and robust technological solutions adapted to the real conditions of the sector.

II. General Description of the System

This paper presents the design of a Remote Terminal Unit (RTU) based on IoT technology and LoRaWAN communications, intended for monitoring water quality by acquiring critical physicochemical variables, specifically temperature, pH, and dissolved oxygen. The RTU has been designed as an autonomous, low-energy consumption system suitable for operation in aquaculture environments, as well as in remote environmental monitoring applications, as shown in Fig. 1 and Fig. 2.

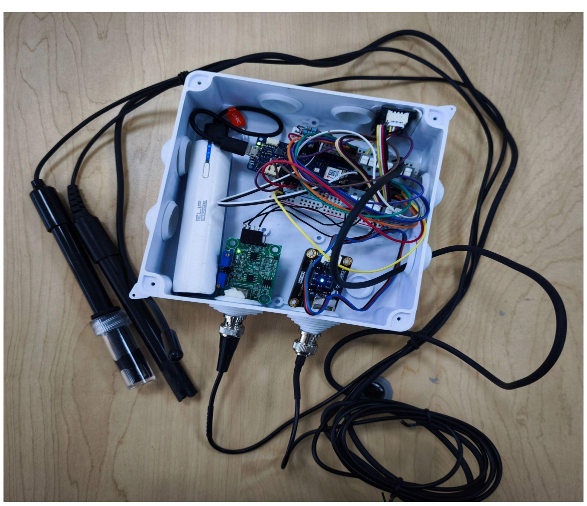

Fig. 1 Proposed RTU prototype for the system

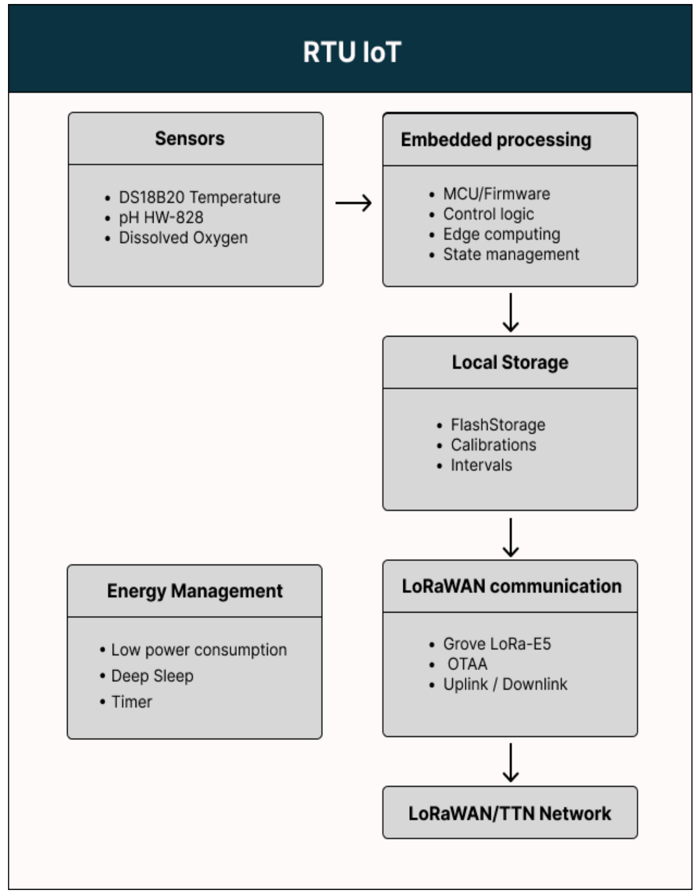

Fig. 2 Architecture of the proposed IoT system

The RTU allows for remote and local configuration and calibration of sensors. Remote configuration is performed through The Things Network (TTN) LoRaWAN infrastructure using Downlink messages, while local configuration is performed using a Serial interface, providing operational flexibility, facilitating maintenance tasks, and enabling integration with various IoT platforms.

From a structural point of view, the RTU adopts a modular architecture, integrating pH, dissolved oxygen, and temperature sensing subsystems, along with analog signal acquisition and conditioning modules, embedded processing, LoRaWAN communications, and an autonomous energy management system. This modular approach is widely used in distributed IoT systems for environmental monitoring due to its scalability, robustness, and ease of maintenance [17].

The RTU connects to a commercial LoRaWAN gateway, which acts as a bridge between the field device network and the cloud infrastructure. This scheme allows for persistent data storage and subsequent visualization through multi-platform interfaces. Previous studies have shown that this architecture improves system reliability and reduces latency in remote water quality monitoring applications [18].

III. LoRaWAN RTU Architecture and Operation

A. General Architecture of the RTU

The proposed Remote Terminal Unit (RTU) has been designed under a three-layer functional architecture, an approach widely adopted in industrial and environmental IoT devices due to its structural clarity, modularity, and ease of experimental validation, as shown in Fig. 3.

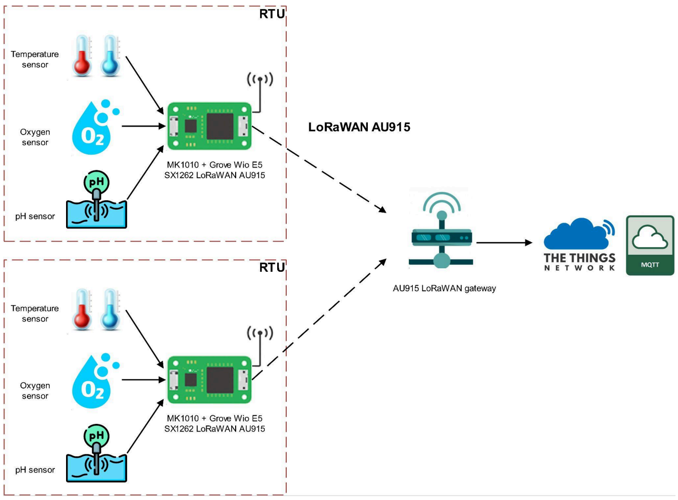

Fig. 3 Functional Topology of the RTU: Acquisition, Communication, and Visualization

The data acquisition layer consists of sensors connected to the Arduino MKR WiFi 1010 microcontroller, which is responsible for reading, conditioning, and processing analog and digital signals.

The communication layer uses a Grove LoRa-E5 module, configured as a LoRaWAN device, responsible for transmitting the acquired data to The Things Network (TTN) network infrastructure. This layer enables long-range communication with low energy consumption, a key feature for prolonged deployments in aquaculture environments.

Finally, the visualization layer corresponds to a dashboard developed in Python, which receives uplink messages from TTN, decodes the defined binary payload, and presents the information in a structured manner to the user, allowing remote monitoring of the environmental variables measured by the RTU.

B. RTU Operating Cycle

The RTU operates cyclically, following a low energy consumption pattern suitable for continuous monitoring applications. In each operating cycle, the RTU checks whether the configured transmission interval has been reached.

Once this interval has been reached, the RTU initiates the data acquisition process. The DS18B20 sensor provides the temperature measurement, the pH sensor delivers an analog signal that is converted to a pH value through a calibration process, and the dissolved oxygen sensor measures the oxygen concentration in mg/L.

The acquired values are then packaged into an optimized binary payload designed to minimize the size of the transmitted message. In addition to the environmental measurements, the payload incorporates the configured transmission interval and a status byte, called statusFlags, which allows reporting relevant events associated with the operation, configuration, and calibration of the RTU, as illustrated in Fig. 4.

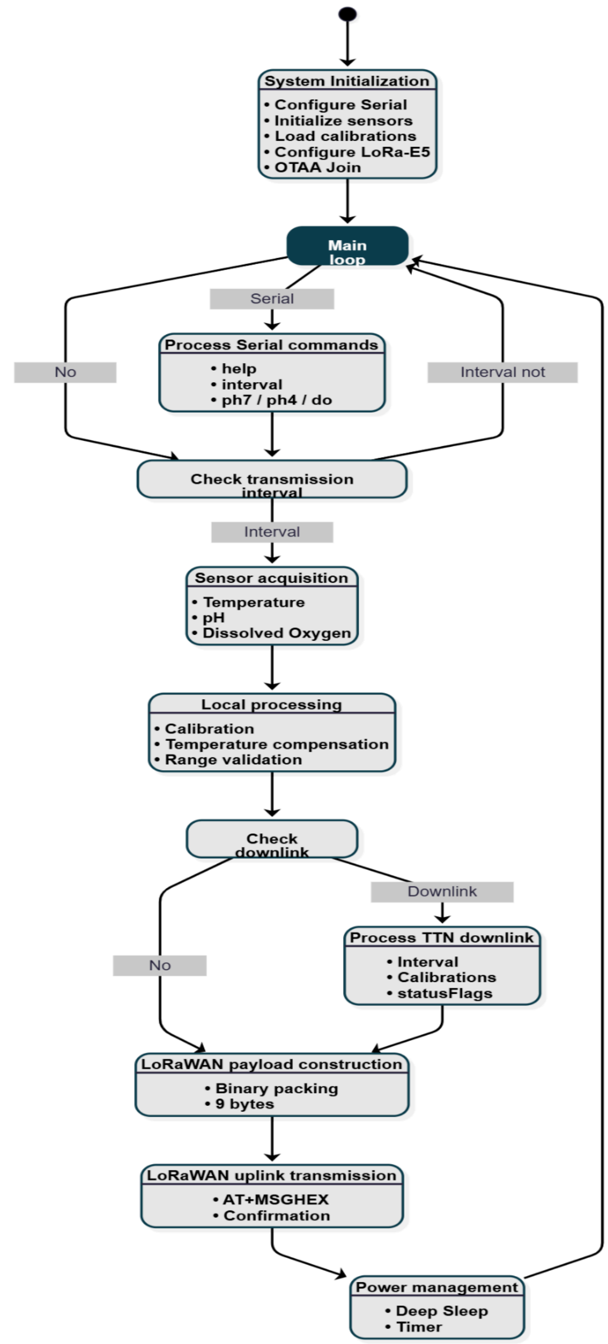

Fig. 4 IoT RTU operation flowchart

C. *RTU Communication Protocol*

Communication between the RTU and the LoRaWAN network is carried out via uplink and downlink messages. Uplinks transport the data acquired by the sensors from the RTU to The Things Network (TTN), while downlinks enable remote modification of the RTU's operating parameters (e.g., transmission interval or execution of calibration routines). This operation is illustrated in the RTU's local interface (see Fig. 1) and in the TTN traffic log (see Fig. 2).

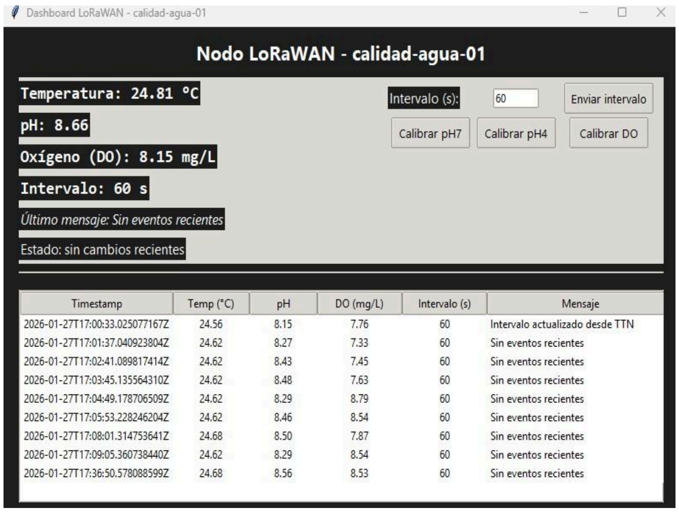

Fig. 5 Local dashboard of the LoRaWAN node.

Fig. 6 Uplink/Downlink messages recorded in The Things Stack.

The communication protocol and uplink payload format have been designed to be compact, efficient, and easily decodable, ensuring reliable operation during testing and experimental deployment, as detailed in Table I.

TABLE I
UPLINK PAYLOAD FORMAT

Field	Bytes	Description
Temperature	2	Temperature value in °C × 100 (int16)
pH	2	pH value × 100 (int16)
Dissolved Oxygen	2	Concentration in mg/L × 100 (int16)
Interval	2	Transmission interval in seconds (uint16)
statusFlags	1	Status byte indicating system events

IV. CONFIGURATION AND CALIBRATION

The RTU can be configured and calibrated both remotely, using downlink messages sent via The Things Network (TTN) LoRaWAN network, and locally via the serial interface. This dual mode facilitates device commissioning, experimental validation, and maintenance tasks.

For system validation, the measurements provided by the dissolved oxygen, pH, and temperature sensors integrated into the RTU were compared with certified commercial instruments. The accuracy of the system was evaluated by the maximum deviation between the two measurements, defined as

$$\Delta_{max}=\max|x_{RTU}-x_{ref}|$$

where xRTU corresponds to the measurements obtained by the remote unit and xref to the values indicated by the standard equipment, this parameter allows the worst case of discrepancy to be identified and the reliability of the system to be evaluated. The measurement ranges and maximum deviations observed during the experimental calibration process are summarized in Table II.

TABLE II
ANALYSIS OF MEASUREMENT RANGES FOR COMMERCIAL EQUIPMENT COMPARED TO EXPERIMENTAL RTU EQUIPMENT

Variable	RTU measurement (range)	Standard Value (range)	Maximum deviation
Dissolved oxygen (mg/L)	7.31 - 8.09	7.0 - 7.1	≈ 1.09 mg/L
pH	6.19 - 6.45	6.35 - 6.52	< 0.33 Units
Temperature (°C)	24.37 - 24.62	24.0 - 25.5	<± 1.13 °C

Note: The values correspond to measurements obtained during the experimental calibration process compared with commercial standard equipment.

For the dissolved oxygen (DO) sensor, the measurements recorded by the RTU ranged from 7.31 mg/L to 8.09 mg/L, while the standard values remained between 7.0 mg/L and 7.1 mg/L, resulting in a maximum deviation of approximately 1.09 mg/L during the initial calibration process. However, after calibration and during field validation, the deviation decreased to approximately 0.3 mg/L, indicating improved accuracy under operational conditions.

In the case of pH, the values measured by the RTU varied between 6.19 and 6.45, compared to reference values between 6.35 and 6.52, showing a maximum difference of less than 0.33 pH units. For temperature, the values recorded by the system ranged from 24.37 °C to 24.62 °C, while the standard measurements were between 24.0 °C and 25.5 °C, with variations of less than ±1.13 °C.

Each configuration or calibration action performed generates an internal event that is reported in the next uplink message via the statusFlags byte, allowing the operational status of the RTU to be traced during experimental testing.

Overall, the results confirm that the accuracy achieved by the RTU is adequate for continuous water quality monitoring applications in aquaculture systems.

A. Calibración del Sensor de pH

The HW-828 pH sensor used in the RTU requires two-point calibration: pH 7 (neutral point) and pH 4 (acidic point). Calibration is based on acquiring the average voltage through the ADC and determining the electrode slope at 25°C. Calibration at pH 7 (neutral point)

1) Calibration at pH 7 (neutral point)

Twenty ADC samples were obtained at 30-millisecond intervals, and the average voltage V7 was calculated using:

$$V_7 = \frac{1}{20}\sum_{i=1}^{20} ADC_i \frac{3.3}{1023}$$

This value represents the output of the electrode when it is in a neutral buffer solution and is stored as a center point in the system memory.

2) Calibration at pH 4 (acid point)

Using the same sampling procedure, the average voltage V_4 was obtained:

$$V_4 = \frac{1}{20}\sum_{i=1}^{20} ADC_i \frac{3.3}{1023}$$

3) Calculation of electrode slope at 25°

The electrode slope, S25, indicates how many volts vary per unit of pH.

$$S_{25} = \frac{V_4 - V_7}{4-7}$$

The negative slope confirms the expected behavior of the electrode in acidic solutions (higher voltage in less acidic solutions).

4) Temperature compensation

For an arbitrary temperature T, the slope was adjusted by:

$$S(T) = S_{25}[1 + 0.003(T - 25)]$$

This coefficient of 0.003 corresponds to the typical thermal correction factor for glass electrodes based on the Nernst equation

5) Final pH calculation

Finally, the pH measured by RTU was determined by:

$$pH(T) = 7 + \frac{V - V_7}{S(T)}$$

where V is the instantaneous voltage obtained by the ADC. This equation implemented in firmware provides a temperature-corrected measurement based on the two calibration points, ensuring accuracy and stability over time.

B. Mathematical model for measuring dissolved oxygen

The RTU implements a simplified linear model for estimating dissolved oxygen (DO), based on a single calibration performed in oxygen-saturated water. The general equation used in the firmware is expressed as

$$DO(T) = \frac{V_{read}}{V_{sar}}.\ DO_{sat}(T)$$

Where V_{read} is the instantaneous voltage measured by the ADC, V_{sat} is the voltage recorded during calibration in saturated water (using the do command), and $DO_{sat}(T)$ represents the theoretical solubility of oxygen in water at temperature T.

Solubility is calculated using a cubic approximation frequently employed in embedded systems:

$$DO_{sat}(T) = 14.46 - 0.41022T + 0.007991T^2 - 0.000077774T^3$$

Finally, to avoid non-physical values and ensure numerical stability, the firmware applies a cutoff to the final measured value of dissolved oxygen:

$$0 \leq DO \leq 25\ mg/L$$

This procedure allows the consistency and reliability of DO calculation to be maintained under various environmental conditions and variations in sensor properties.

C. Local Configuration via Serial Terminal

The LoRaWAN-based RTU allows local configuration and calibration via a serial interface, which is particularly useful during laboratory testing and in scenarios where LoRaWAN connectivity is not available. In this context, interaction with the system is carried out through a set of predefined commands and data structures, which are described in Table III.

TABLE III
SERIAL INTERFACE COMMANDS

Command	Description
help	Displays the list of available commands
interval=SEC	Sets the transmission interval (10–3600 s)
ph7	pH 7.0 calibration
ph4	pH 4.0 calibration
do	Dissolved oxygen calibration

V. EXPERIMENTAL SETUP

The experimental validation of the proposed system was carried out in real aquaculture ponds under variable environmental conditions, with the objective of evaluating its performance in representative operating scenarios. The tests were conducted in a freshwater cultivation pond commonly used for fish production, ensuring that the experimental conditions reflected typical small-scale aquaculture environments.

A. Experimental Procedure

This work follows an experimental applied research approach under real-world aquaculture conditions. The experimental validation of the proposed RTU was conducted through a structured procedure designed to evaluate measurement accuracy, communication reliability, and system stability.
The experimental procedure consisted of the following steps:

1) System Deployment:
The RTU was installed at the edge of the aquaculture pond, while the sensing probes for temperature, pH, and dissolved oxygen were immersed at a fixed depth to obtain stable and representative measurements of the water body.

2) Reference Instrument Setup:
Certified commercial multiparameter equipment with traceable calibration was deployed in parallel with the RTU sensors to serve as reference instrumentation, ensuring metrological traceability and reliability of the comparison data.

3) Sensor Calibration:
Prior to data acquisition, the RTU sensors were calibrated using standard buffer solutions (pH 4 and pH 7) and oxygen-saturated water for dissolved oxygen, following the procedures described in Section IV of this document.

4) Data Acquisition:
The RTU was configured to acquire and transmit data at predefined intervals. Measurements from both the RTU and the reference equipment were recorded simultaneously over a continuous observation period of one hour.

5) Data Transmission and Logging:
Sensor data collected by the RTU were transmitted via LoRaWAN to The Things Network (TTN), where they were stored and visualized through a custom monitoring dashboard, following the description in section III of this document.

6) Performance Evaluation:
The accuracy of the RTU measurements was evaluated by comparing them with the reference values using the maximum absolute error and mean absolute error (MAE) metrics. Additionally, temporal consistency and communication reliability were analyzed during the observation period.

This procedure ensures the reproducibility of the experiment and provides a systematic framework for evaluating the performance of IoT-based monitoring systems in aquaculture environments.

Fig. 7 Record of the on-site water quality measurement process in an aquaculture system, carried out during the experimental phase of the study. Data acquisition was performed directly in the cultivation pond using multiparameter monitoring equipment, ensuring the representativeness, reliability, and validity of the values obtained under real operating conditions.

Fig. 7. Record of the on-site water quality measurement process in an aquaculture system, carried out during the experimental phase of the study. Data acquisition was performed directly in the cultivation pond using certified multiparameter monitoring equipment, ensuring representativeness and validity under real operating conditions.

VI. Results and Siscussion

To quantitatively assess the performance of the proposed RTU, the experimental validation was based on direct comparison with certified reference instruments using error-based metrics commonly adopted in environmental monitoring systems. The primary metric employed was the maximum absolute error, which allows evaluation of the worst-case deviation between the proposed system and the reference equipment. The maximum absolute error is defined as:

$$\Delta_{max} = \max \left| x_{RTU}(i) - x_{ref}(i) \right|$$

where $x_{RTU}(i)$ represents the measurement obtained by the IoT-based RTU at sample i, and $x_{ref}(i)$ corresponds to the value provided by the certified reference instrument at the same sampling instant.

This metric was selected because, in aquaculture applications, short-duration deviations or peak errors may lead to critical operational decisions, such as oxygenation control or emergency responses. Therefore, assessing worst-case behavior is more relevant than global statistical indicators such as correlation coefficients or mean squared errors.

Additionally, to provide a global accuracy assessment, the mean absolute error (MAE) was computed for each monitored parameter. The MAE is defined as:

$$MAE = \frac{1}{n} \Sigma \mid x_{RTU}(i) - x_{ref}(i) \mid$$

where n represents the number of samples collected during the observation period. This metric complements the maximum absolute error by quantifying the average deviation of the RTU measurements with respect to the reference instruments.

The results obtained during the 1-hour continuous observation period reveal a high correlation between RTU measurements and certified reference equipment values, as summarized in Table IV.

TABLE IV
FIELD VALIDATION RESULTS (1-HOUR POND MONITORING)

Parameter	RTU – Measured range	Reference equipment – Measured range	MAE(Mean Absolute Error)	Observation period
Dissolved oxygen (mg/L)	7.09 – 7.31	7.00 – 7.10	≈ 0.15 mg/L	1 hour
pH	6.19 – 6.45	6.35 – 6.52	< 0.11 units	1 hour
Temperature (°C)	24.37 – 24.62	24.0 – 25.5	±0.63 °C	1 hour

For dissolved oxygen (DO), RTU readings ranged from 7.09 mg/L to 7.31 mg/L, while reference values remained between 7.0 and 7.1 mg/L, resulting in a mean absolute error (MAE) of approximately 0.15 mg/L. For pH, RTU values ranged from 6.19 to 6.45, while reference values ranged from 6.35 to 6.52. The MAE was calculated as 0.15 units, and for temperature, the variations did not exceed ±0.63 °C. These results fall within acceptable ranges for continuous monitoring in aquaculture systems. Fig. 8 shows the dashboard interface, which displays real-time measurements and their temporal evolution.

Fig. 8 Dashboard with real-time monitoring of pH, temperature, and DO during the experimental test.

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The LoRaWAN communication system demonstrated reliable performance during testing, enabling regular data transmission without significant losses, even under variable environmental conditions typical of aquaculture. Fig. 9 illustrates the LoRaWAN coverage map in the RTU deployment area, confirming the estimated signal strength and observed link stability.

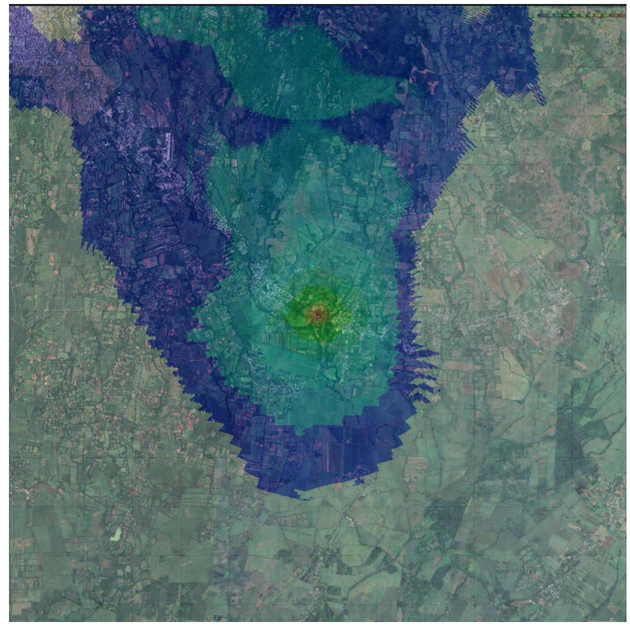

Fig. 9 LoRaWAN coverage map in the aquaculture environment, showing link availability and stability.

Additionally, the low average power consumption (15.2 mW) supports approximately 6 months of autonomous operation using a 3000 mAh 18650 battery. The wide LoRaWAN coverage (Fig. 9) also enables multiple devices to operate simultaneously on the same network, making the system suitable for scalable aquaculture deployments.

Future work will focus on implementing local data storage mechanisms to improve data backup during connectivity interruptions. Field tests also highlighted the need to enhance prototype waterproofing against splashes, humidity, and adverse environmental conditions to ensure long-term reliability.

VII. CONCLUSIONS

In this article, a Remote Terminal Unit (RTU) based on IoT and LoRaWAN communication was developed and experimentally validated for the continuous monitoring of critical water quality parameters in aquaculture systems. The results obtained under real operating conditions demonstrated high agreement between the measurements of the proposed system and certified reference instruments, with deviations within acceptable margins for continuous monitoring applications of pH, dissolved oxygen, and temperature.

The implemented architecture demonstrated robust performance in terms of communication reliability, low energy consumption, and extended autonomous operation capability, making it particularly suitable for rural and remote environments where electrical and telecommunications infrastructure is limited. Furthermore, the inclusion of local and remote calibration mechanisms, along with a modular structure, provides flexibility, scalability, and ease of maintenance compared to conventional solutions.

From an applied perspective, the system contributes to improving the operational management and sustainability of aquaculture, directly supporting Sustainable Development Goals 2, 6, and 9 through efficient water use, the strengthening of food production, and the adoption of technological innovation. Future plans include long-term validation, strengthening environmental encapsulation, and incorporating advanced analytics for smart aquaculture systems.

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