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# Design of an autonomous multiparameter buoy with photovoltaic energy and remote communication based on IoT for aquaculture environments

## Diseño de una boya multiparamétrica autónoma con energía fotovoltaica y comunicación remota basada en IoT para entornos de acuicultura

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## ABSTRACT

A prototype of an autonomous multiparameter buoy was designed to address technological limitations in water quality monitoring in aquaculture environments. The objective was to develop a modular and sustainable system integrating photovoltaic energy and wireless communication to monitor critical parameters in real time: pH, temperature, dissolved oxygen, and electrical conductivity. The system consists of an emitter module, receiver module, and a data transmission platform to the cloud. Materials included reinforced PLA and PETG, and electronic components were powered by a 20 W solar panel connected to a 12 V 7 Ah battery. During testing, the prototype demonstrated a 48-hour energy autonomy and reliable LoRa transmission with a 500 m range in the direct line of sight. The modular design facilitates sensor integration and system adaptation to various conditions, benefiting small producers. However, challenges such as component resilience in harsh environments and optimizing energy autonomy under adverse conditions remain, presenting opportunities for future improvements in robustness and scalability.

**Keywords:** aquaculture 4.0; IoT; environmental monitoring; wireless sensors; sustainable technology

## RESUMEN

Se diseñó un prototipo de boya multiparamétrica autónoma para abordar las limitaciones tecnológicas en el monitoreo de la calidad del agua en ambientes de acuicultura. El objetivo fue desarrollar un sistema modular y sustentable que integre energía fotovoltaica y comunicación inalámbrica para monitorear en tiempo real parámetros críticos: pH, temperatura, oxígeno disuelto y conductividad eléctrica. El sistema consta de un módulo emisor, un módulo receptor y una plataforma de transmisión de datos a la nube. Los materiales incluyeron PLA reforzado y PETG, y los componentes electrónicos fueron alimentados por un panel solar de 20 W conectado a una batería de 12 V 7 Ah. Durante las pruebas, el prototipo demostró una autonomía energética de 48 horas y una transmisión LoRa confiable con un alcance de 500 m en la línea de visión directa. El diseño modular facilita la integración de sensores y la adaptación del sistema a diversas condiciones, beneficiando a los pequeños productores. Sin embargo, persisten desafíos como la resiliencia de los componentes en entornos hostiles y la optimización de la autonomía energética en condiciones adversas, lo que presenta oportunidades para futuras mejoras en robustez y escalabilidad..

**Palabras clave:** acuicultura 4.0; IoT; monitoreo ambiental; sensores inalámbricos; tecnología sostenible

## 1. INTRODUCTION

Aquaculture is a rapidly growing activity in global food production, accounting for 89% of fish destined for human consumption (FAO, 2024). This sector contributes to global food security by providing aquatic protein (T. Garlock et al., 2022; Obiero et al., 2019), and economic development in coastal and rural regions through job creation and economic diversification (Bennett et al., 2024; Engle & van Senten, 2022). Its expansion is driven by the increasing demand for aquatic products and the need to reduce exploitation of natural fishery resources (Laktuka et al., 2023).

In recent decades, aquaculture has adopted intensive and semi-intensive systems driven by technological advances that optimize production and favor sustainability (Biazi & Marques, 2023; Rowan, 2023). This activity faces challenges related to environmental management, the implementation of sustainable technologies, and the equitable distribution of benefits (TM Garlock et al., 2024; Naylor et al., 2023; Wong et al., 2024). The adoption of technological solutions is essential to improve performance, especially in regions with limited resources and high poverty (Araujo et al., 2022; Bunting et al., 2023).

In Peru, aquaculture has become an engine of economic development (Sociedad Nacional de Pesquería, 2020), particularly in rural and tropical regions (Quesquén-Fernández et al., 2022; Sánchez Calle et al., 2021). The country has a high potential because of its species diversity and favorable climatic conditions (BCRP, 2017; Organización de las Naciones Unidas para el Desarrollo Industrial, 2017). However, the sector faces technological and infrastructure limitations that hinder its sustainable development and integration into broader value chains (Gozzer-Wuest et al., 2021).

In the San Martín region of the Peruvian Amazon, aquaculture represents a relevant economic activity (Dirección Regional de la Producción de San Martín, 2022; Programa Nacional de Innovación en Pesca y Acuicultura, 2018), especially in rural communities dedicated to the production of species, such as tilapia (Arévalo-Hernández et al., 2023; García-Castro & Ascón-Dionisio, 2022; Ismiño-Orbe et al., 2024; Reyes-Bedriñana et al., 2022; Sotelo-Lescano et al., 2024). However, the limited availability of advanced monitoring technologies restricts efficiency in the management of production systems, negatively impacting the quality of products and environmental sustainability of the activity.

Thus, the identified knowledge gap lies in the limited availability of systems specifically designed to monitor aquaculture conditions, considering the technological needs and characteristics of the environment. Although advanced technologies have been developed in other regions (Chiu et al., 2022; Dupont et al., 2018; Eze et al., 2023; Lu et al., 2022), their high costs and poor adaptability to small producers generate a significant gap in the implementation of accessible and practical solutions.

Recent studies have explored approaches to overcome energy and technological limitations in aquaculture, especially in remote areas. Research focusing on the use of renewable energy and monitoring technologies has demonstrated their ability to improve the management of production systems (Bórquez López et al., 2020; Flores Mollo & Aracena Pizarro, 2018; Staude et al., 2024; Von Borstel Luna et al., 2017; Zhang et al., 2022), although challenges remain for their effective integration in resource-limited environments.

In this context, this study aimed to design an autonomous multiparameter monitoring buoy powered by photovoltaic energy and equipped with wireless communication, specifically adapted for rural and experimental aquaculture environments. This proposal seeks to bridge the identified technological gap by providing a sustainable solution for real-time monitoring of critical parameters and enhancing aquaculture productivity and sustainability in the San Martín region and similar areas. Improving the control of environmental variables is crucial because their fluctuations directly impact the growth and health of aquatic organisms. The lack of accessible monitoring systems limits the ability of producers to respond to changes in water conditions, which affects production efficiency. Accurate monitoring is essential to mitigate environmental risks and ensure the long-term sustainability of aquaculture activities.

## 2. MATERIALS AND METHODS

To ensure efficient water quality monitoring in aquaculture environments, the proposed system was developed with a modular and scalable approach. The design integrates energy-efficient components, real-time data acquisition, and reliable wireless communication to provide continuous monitoring of critical parameters. The system operates autonomously, leveraging photovoltaic energy and long-range communication technology to address the challenges of remote deployment.

### 2.1. System architecture and electrical diagram

The proposed system consists of three main components: transmitter, receiver, and data transmission modules to the cloud. Each component integrates specific subsystems to ensure efficient power management, data acquisition, wireless communication, and real-time visualization. The modular architecture allows flexibility in adapting to different environmental conditions and facilitates future upgrades by integrating additional sensors or communication protocols. Figure 1 shows the overall system architecture and the interactions between the modules.

The transmitter module is designed for data acquisition and transmission. This module incorporates a power management subsystem consisting of a solar panel, charge controller, and 18650 batteries. This subsystem ensures a stable power supply to the ESP32 microcontroller, which acts as the central-processing unit. Sensors connected to the ESP32 include pH, electrical conductivity, dissolved oxygen (DO), and temperature sensors. These sensors collected environmental data processed by the ESP32 before being sent to the LoRa transmitter module using a serial interface. The LoRa module handles the wireless transmission of the processed data over a radio frequency channel. This architecture ensures reliable data acquisition and transmission, even in remote aquaculture environments.

The receiver module captures and processes the data transmitted by the transmitter module. This module also includes a power management subsystem consisting of rechargeable batteries to power both the ESP32 and LoRa receiver modules. Once the data were captured by the LoRa receiver module, ESP32 processed it and prepared it for transmission over Wi-Fi. This module is connected to a local router, allowing the data to be integrated into a cloud-based system for analysis and visualization.

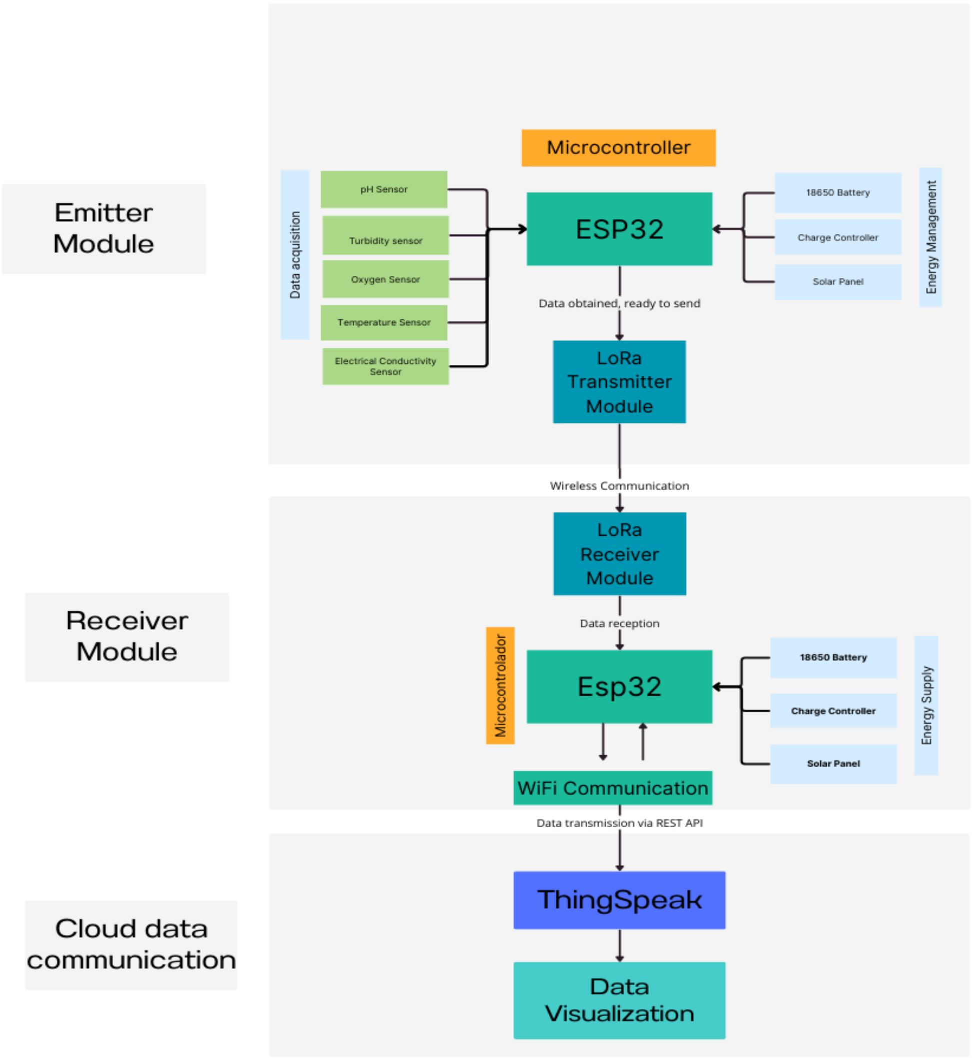

**Figure 1.** Architecture of the proposed system

Figure 2 shows the electrical schematic of the system, highlighting the interconnection of the main components. The solar panel generated power that was regulated by a charge controller and stored in a 18650 battery bank. Sensors for pH, conductivity, dissolved oxygen, temperature, and turbidity measurements were connected to the ESP32, which processed the information. This information was transmitted via radio frequency through the LoRa module, which was supported by an antenna to amplify the signal. The electrical design included a power module that efficiently distributed power between the sensors, ESP32, and communication modules, ensuring continuous operation of the system.

The processed data were transmitted to the cloud using a REST API, utilizing the ESP32's Wi-Fi capabilities. The cloud platform ThingSpeak acted as an intermediary for data storage and visualization. ThingSpeak receives the data packets and provides a real-time graphical representation of the monitored parameters. This modular design allows for seamless scalability and adaptability, ensuring compatibility with alternative protocols, such as MQTT, if required. The complete architecture facilitated maintenance, expansion, and possible system upgrades, promoting the sustainable management of aquaculture environments.

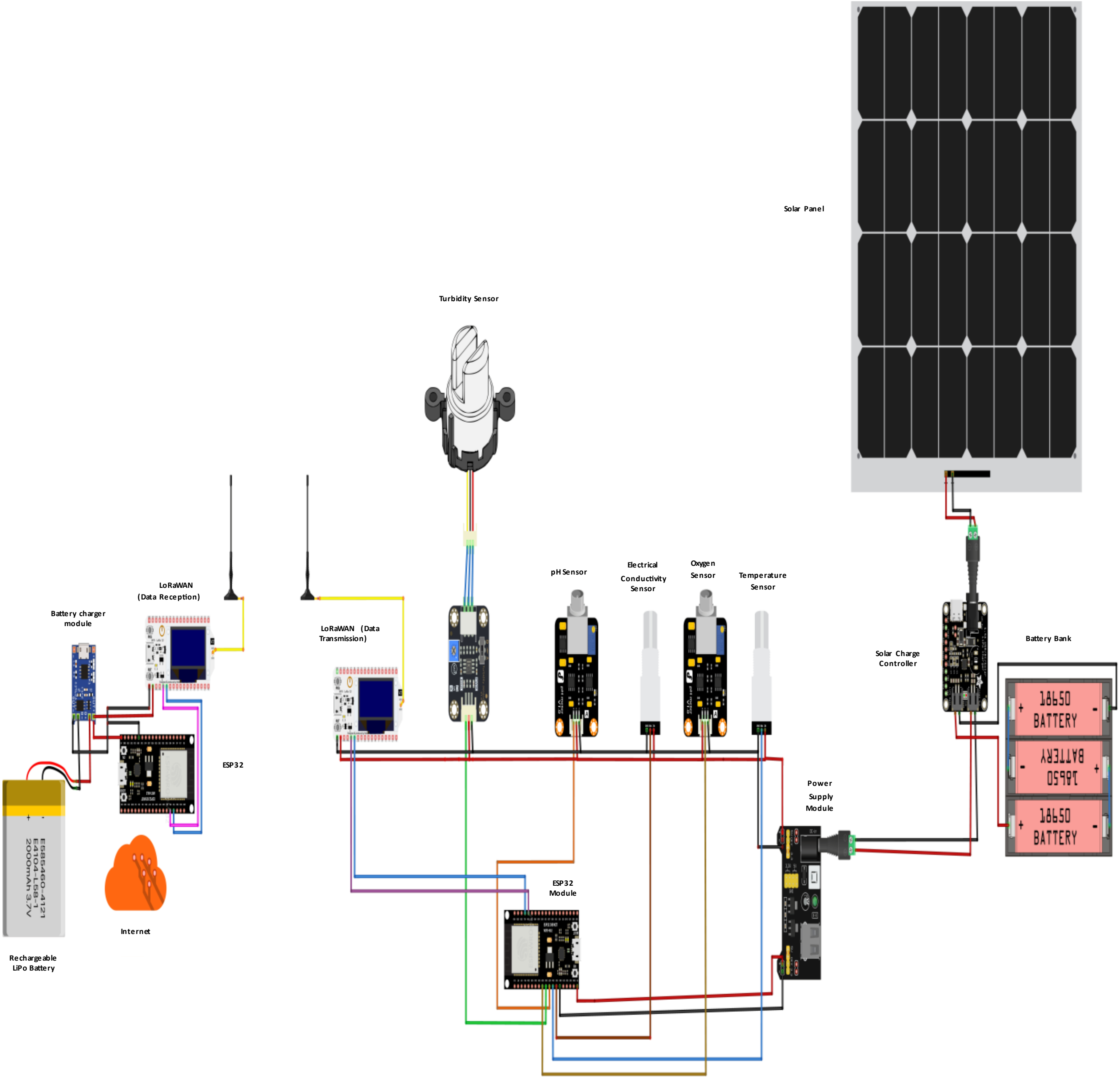

**Figure 2.** Electrical diagram of the multiparameter buoy prototype

## 2.2. Buoy prototype design

The designed multiparameter buoy prototype had a rigid structure manufactured by 3D printing, using materials such as reinforced PLA and PETG, which were selected for their moisture resistance and durability in aquatic environments. 3D printing technology allows precise and modular construction, facilitating adjustments and modifications to the design to adapt it to the specific needs of the project. The dimensions of the prototype were 70 cm in length, 30 cm in width, and 50 cm in height, and were optimized to ensure hydrodynamic stability and buoyancy in aquatic environments. The structure includes two main floats that act as support and balance elements, ensuring efficient operation in water bodies with calm or moderate currents. As shown in Figure 3, the design incorporates a robust frame and strategically positioned floats to maximize stability during operation.

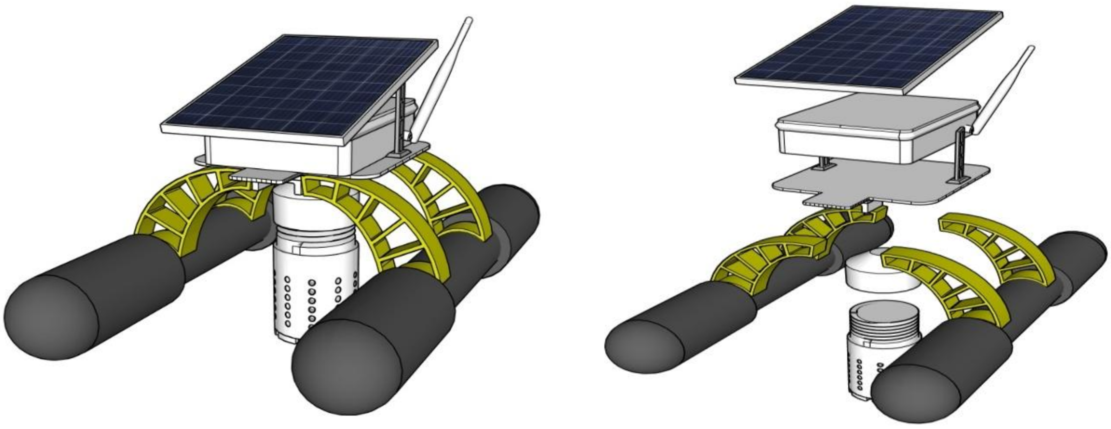

Figure 3. Conceptual design of the multiparameter buoy prototype

## Solar panel and energy management

The buoy was equipped with a 20 W photovoltaic panel mounted on an adjustable frame that optimized the collection of sunlight. The energy generated was stored in a 12 V, 7 Ah sealed lead-acid battery, which provided a continuous power supply for the sensors and electronic modules, ensuring uninterrupted operation of the system.

## Sensors

The buoy has a set of sensors to monitor critical water quality parameters as shown in Table 1:

**Table 1.** Technical specifications of the buoy prototype sensors

| Sensor | Measuring range | Precision |
|---|---|---|
| pH | 0 to 14 | ±0.01 |
| Electrical conductivity | 0 to 2000 µS/cm | N/A |
| Dissolved oxygen | 0 to 20 mg/L | ±0.1 mg/L |
| Temperature | -10 to 50 °C | ±0.5 °C |

All sensors were protected in a waterproof central module, located beneath the main platform, to avoid damage during operation as can be seen in Figure 4.

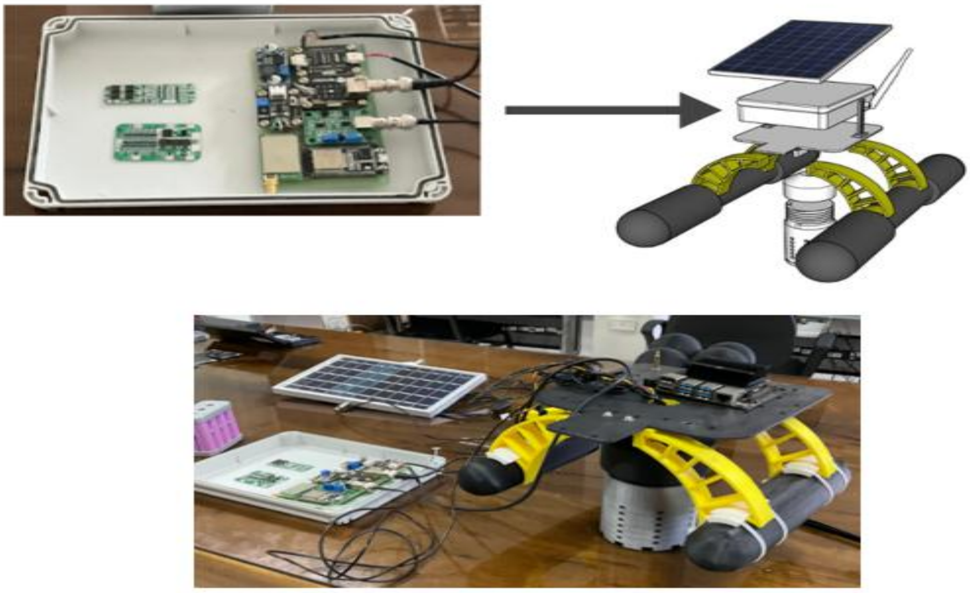

Figure 4. Location and protection of sensors in the central module

## Wireless communication

The system uses LoRa modules for data transmission via radio frequency, with a range of up to 500 m in the direct line of sight. The data collected by the ESP32 in the transmitter module were sent to the LoRa transmitter module, which communicates with a receiver module connected to a Wi-Fi network. The processed data were then transmitted to the cloud via a REST API using the ThingSpeak platform for storage and real-time visualization.

As shown in Figure 5, the system architecture enables efficient communication between the transmitter modules and the central receiver module, thereby optimizing the monitoring of critical parameters. Each transmitter module, equipped with a photovoltaic receiver, autonomously collects and transmits data, whereas the receiver module consolidates the information before sending it to the cloud for analysis. This modular configuration ensured a robust data flow that was adaptable to the needs of the aquaculture environment.

**Figure 5.** Conceptual design for sending data to the cloud

## 3. RESULTS

### Applications and functionalities

The buoy was designed to collect real-time multiparameter water quality data, enabling efficient, data-driven management of aquaculture environments. Monitored parameters include pH, dissolved oxygen, temperature, and electrical conductivity, with the sampling frequency adjustable based on operational requirements. This flexible approach ensured that the system could adapt to various environmental conditions and specific monitoring requirements. Furthermore, the modular architecture of the buoy makes it easy to maintain, allowing for scalable integration of additional sensors in the future, increasing the versatility of the system.

### Operation simulation

Initial testing of the prototype confirmed that the structure could support up to 200 g of additional weight, including electronics and sensors, without compromising its stability. The floats provided an adequate balance under moderate wind conditions, ensuring reliable operation in aquatic environments. The power management system proved to be efficient, guaranteeing autonomy for up to 48 hours in the absence of direct sunlight. As shown in Figure 6, the prototype was tested in a real aquatic environment, demonstrating its ability to operate effectively and collect multiparameter data in real time.

**Figure 6.** Testing of the buoy prototype in a real aquatic environment

## Data visualization

Figure 7 presents examples of data collected by the buoy sensors, including temperature, dissolved oxygen, turbidity, and conductivity levels. These data were recorded and visualized in real time using the ThingSpeak platform, allowing immediate analysis of the monitored parameters. This real-time visualization capability validates the functionality of the system to generate actionable and decision-relevant information for aquaculture management.

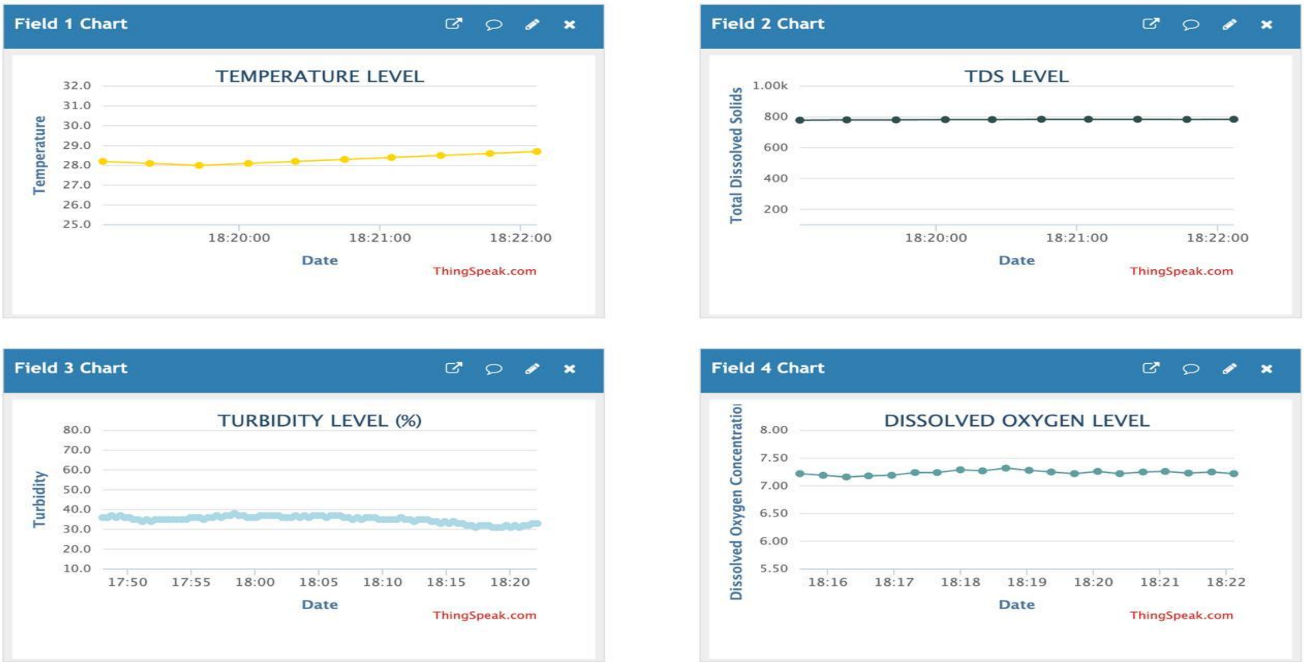

**Figure 7.** Visualization of real-time data obtained by the buoy sensors

## System challenges and discussion

The designed prototype demonstrated adequate energy autonomy for operation in remote aquaculture environments, lasting up to 48 h, without direct sunlight. This result is consistent with the findings of López et al. (2020); Zhang et al. (2022) highlighted the importance of optimizing renewable energy generation and storage in autonomous systems. However, under conditions of prolonged high cloud cover, autonomy could be limited, highlighting the need to explore complementary options such as the integration of hybrid energy generation systems. This challenge is critical for ensuring continuous operation in regions with significant climatic variability, such as San Martín.

The sensors installed on the buoy met the measurement ranges required for aquaculture monitoring and provided reliable data on pH, dissolved oxygen, temperature, and electrical conductivity. This aligns with studies such as that of Mollo and Pizarro (2018), who emphasized the need for robust and accurate sensors to cope with the changing conditions of water bodies. However, in scenarios with high sediment concentrations or extreme temperature fluctuations, the accuracy of the sensors can be compromised, suggesting the implementation of automatic calibration systems to mitigate this problem.

The LoRa modules in the system enabled reliable line-of-sight transmission up to 2 km, validating its effectiveness in rural and remote environments. This approach was consistent with that reported by Staude et al. (2024); Von Borstel Luna et al. (2017), who highlighted the usefulness of LoRa for environmental monitoring applications. However, the presence of physical obstacles can significantly reduce the signal quality, as pointed out by previous studies. Future integration of complementary technologies, such as ZigBee or Wi-Fi, could improve communication coverage and stability under adverse conditions.

The modular design of the buoy, which allows for the integration of additional sensors, and its focus on renewable energy highlights its potential for experimental and rural aquaculture settings. This addresses the technological gap highlighted in the literature (Chiu et al., 2022; Dupont et al., 2018; Lu et al., 2022) by offering an accessible and adaptable solution for smallholder farmers' needs. However, the durability of these components in harsh environments, such as high humidity and salinity, poses an additional challenge that requires improvements in the materials and coatings used to extend the life of the system.

Although digitalization has improved data storage and management capabilities in fish farms, the adoption of more advanced technologies remains limited. In addition, in Staude et al. (2024) and Von Borstel Luna et al. (2017), several companies in the sector have not yet defined which processes can be optimized with Industry 4.0, which generates a fragmented implementation. The buoy developed in this study represents a step towards the automation of water quality monitoring, integrating IoT for the collection and transmission of data in real time, allowing for improved decision-making and optimized production.

The transformation towards an Aquaculture 4.0 model involves not only the adoption of IoT sensors and networks but also the integration of advanced technologies such as artificial intelligence, robotics, and big data analytics. However, the high cost of acquiring imported equipment and lack of clear strategies for its integration remain significant barriers. This study demonstrates that the development of low-cost autonomous devices can reduce these barriers and facilitate technological transitions. The gradual implementation of emerging technologies will allow traditional fish farms to optimize their production processes without compromising their financial or operational stability.

## CONCLUSIONS

The present study demonstrated the feasibility of an autonomous multiparameter monitoring system for aquaculture that integrates photovoltaics, smart sensors, and IoT-based wireless communication. The developed buoy allowed for the collection of real-time data on pH, temperature, dissolved oxygen, and electrical conductivity, providing key information for the optimization of water quality in fish farms. Its modular design facilitates the integration of new sensors and their adaptation to different operating environments, representing a step forward in the automation of aquaculture monitoring.

Beyond the technical benefits, this study highlights the potential of Industry 4.0 technologies in the modernization of the aquaculture sector. The transition to Aquaculture 4.0 requires progressive adoption strategies that contemplate not only the development of low-cost autonomous devices, but also training in digital tools and strengthening technological infrastructure. Future work should focus on the integration of artificial intelligence for predictive data analysis, optimization of energy consumption and improving the resistance of materials used in autonomous monitoring systems in aquatic environments.

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The authors did not receive any sponsorship to carry out this study-article.

## CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest related to the development of the study.

## AUTHORSHIP CONTRIBUTION

Conceptualization; Data curation; Formal analysis; Fund acquisition; Research; Software; Validation, Visualization; Writing - original draft; Writing - proofreading and editing: Lévano-Rodriguez, D., Gonzales-Garay, J. H., Lévano-Casildo, M. and López-Gonzales, J. L.

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