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OPTIMIZED AQUACULTURE DATA MANAGEMENT WITH IoT: CLOUD STORAGE AND PROCESSING

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Abstract – The Internet of Things (IoT)-based water quality monitoring system (IoT) [1], designed to optimize management in aquaculture environments, integrates an Arduino UNO R4 WiFi board [2] with sensors for pH [3], turbidity [4], dissolved oxygen [5], and temperature [6], enabling the acquisition and transmission of data in real time to a cloud database [7]. To this end, an API was developed in Node.js within the Visual Studio Code environment [8], responsible for managing communication between IoT devices and Firebase [9], a NoSQL platform [10] used for fast and scalable information storage.

Wireless transmission [11] is carried out through the microcontroller's integrated connectivity [12], ensuring continuous updating of the measured parameters. A web application was also designed to facilitate data visualization, historical report generation, and the sending of alerts in case of possible anomalies. Operational tests demonstrated the stability of the system, the accuracy of measurement capture, and the integrity of data transmission. Overall, the results demonstrate the technical feasibility and potential of the system as a support tool for sustainable water quality management [13] in aquaculture areas.

Keywords-- IoT, Sensors, Water Quality, Database, Wireless Transmission, Web Application.

Abstract -- The Internet of Things (IoT)-based water quality monitoring system, aimed at optimizing management in aquaculture environments, integrates an Arduino UNO R4 WiFi board with pH, turbidity, dissolved oxygen, and temperature sensors, enabling real-time data acquisition and transmission to a cloud database. To this end, a Node.js API was developed within the Visual Studio Code environment to manage communication between IoT devices and Firebase, a NoSQL platform used for fast and scalable data storage.

Wireless transmission is achieved through the microcontroller's integrated connectivity, ensuring continuous updating of the measured parameters. A web application was also designed to facilitate data visualization, generate historical reports, and send alerts in the event of potential anomalies. Functional tests demonstrated the system's stability, measurement capture accuracy, and data transmission integrity. Overall, the results demonstrate the technical feasibility and potential of the system as a support tool for sustainable water quality management in aquaculture environments.

Keywords – IoT, Sensors, Water Quality, Database, Wireless Transmission, Web Application.

INTRODUCTION

The growth of aquaculture in Mexico has been driven by the need to diversify food production sources and strengthen the country's food security. The state of Tabasco, located in southeastern Mexico, is a region with a vast hydrological network that includes rivers, lagoons, and wetlands, making it an ideal area for the development of aquaculture activities. According to data from the National Institute of Statistics and Geography (INEGI) [14], Tabasco has more than 400 kilometers of coastline and an extensive network of water bodies covering approximately 10% of its total surface area. This wealth of water has allowed aquaculture to consolidate itself as an important economic activity in the state, generating jobs and contributing to the food security of the population.

Tilapia (Oreochromis spp. and Tilapia sp) were introduced to Mexico in 1964 from the United States and were first kept at the Temascal Fish Farm in Oaxaca. It is one of the species that is of great importance in the production of animal protein in tropical and subtropical waters around the world, particularly in developing countries.

Tilapia (Oreochromis niloticus) is one of the most farmed species in Tabasco due to its adaptability to the region's climatic conditions and high demand in the local and national markets. According to the 2022 Statistical Yearbook of Aquaculture and Fisheries, published by the National Aquaculture and Fisheries Commission (CONAPESCA) [15], tilapia production in Mexico reached 180,000 tons in 2021, with Tabasco ranking as one of the leading producing states, contributing approximately 8% of national production. However, despite its potential, aquaculture in the region faces significant challenges that limit its growth and sustainability.

In this context, tilapia (Oreochromis niloticus) has established itself as one of the most widely farmed species due to its resilience, rapid growth, and high market demand. However, water quality in breeding ponds remains a critical factor that directly influences the productivity and profitability of aquaculture systems. Inefficient management of physicochemical water parameters, such as pH, temperature, dissolved oxygen concentration, and turbidity, can create adverse conditions that affect the growth and survival of fry [16].

Monitoring these parameters is essential to ensure fish welfare and production sustainability. However, in many aquaculture farms, monitoring is done manually, which limits the accuracy and frequency of measurements, increasing the risk of sudden fluctuations in water conditions. According to the Strategic Agenda of the National Technological Institute of Mexico for Clean Water and Sanitation [17], the implementation of technological systems in water management is an urgent necessity to ensure its efficient use in strategic sectors such as aquaculture.

Faced with this problem, the use of emerging technologies, such as the Internet of Things (IoT) [1], offers an innovative solution for automating data collection and analysis in a timely manner, improving responsiveness to variations in water quality. The use of sensors and cloud platforms makes it possible to optimize aquaculture production processes and reduce losses caused by unexpected changes in water conditions [13].

The cloud-based IoT prototype [1] enables continuous monitoring and management of water quality in tilapia fry rearing ponds. The solution integrates specialized sensors for measuring key physicochemical variables, a web platform for viewing and analyzing the collected data, and a timely alert system for values outside the optimal ranges. This tool gives aquaculture producers greater control over their processes, optimizing pond management and promoting sustainability in tilapia production [13].

DEVELOPMENT

For the development of the Internet of Things (IoT)-based water quality monitoring system [1] aimed at optimizing management in aquaculture environments, the Scrum methodology [18] was implemented. This methodology is defined as an agile framework for managing complex projects, which allows value to be created and adaptation to changing needs through incremental deliveries called "sprints." It focuses on effective collaboration between teams and customers, delivering functional products in short cycles for continuous adjustment and improvement.

Phase 1 – Start (Sprint 0 Planning).

This phase focused on:

- Identifying problems and objectives: three key problems were detected: manual water monitoring of water, lack of remote access, and lack of digital security.
- Initial product backlog, established as user stories:
  - As an aquaculture operator, I want to monitor pH, turbidity, oxygen, and temperature in real time.
  - As an administrator, I want to generate historical water quality reports.
  - As a user, I need automatic alerts when parameters deviate.
- Technological definition: selection of Arduino UNO R4 WiFi, Firebase (NoSQL), and API in Node.js.

Phase 2 – Sprint Planning and Product Design (Sprint 1).

In this phase, Sprint 1 was planned to cover requirements gathering and UML modeling, where use case, sequence, class, and component diagrams were developed to define the communication between Arduino, API, and Firebase. Similarly, the IoT communication protocols (WiFi, MQTT [19], AMQP, CoAP [20], etc.) were defined.

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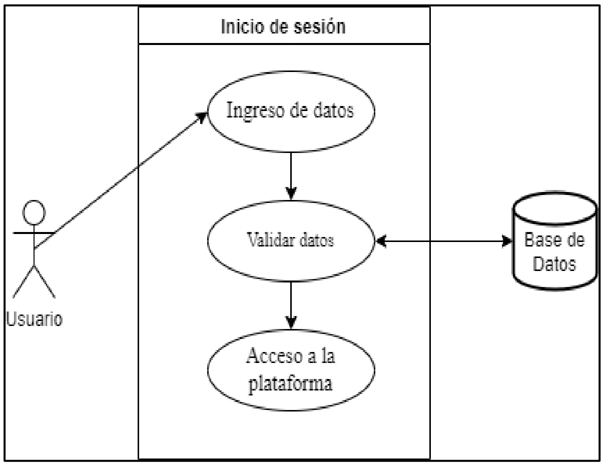
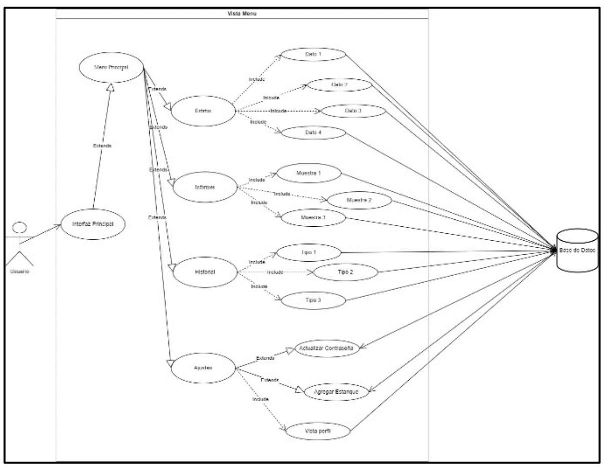
Figure 1. *Use Case: Login.*



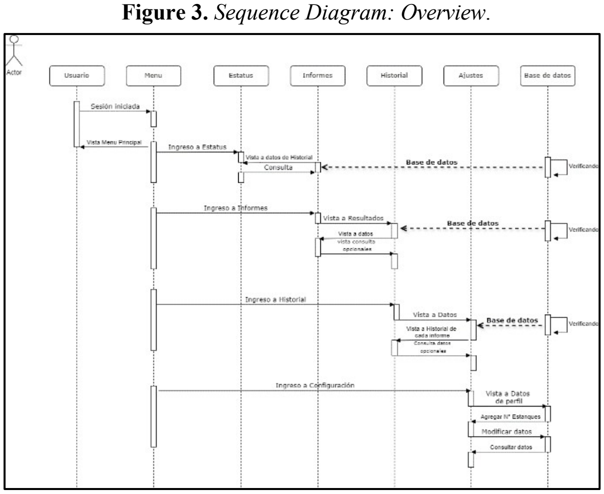
Source: *Own creation*, 2025.

Figure 2. *Use case: Main interface.*



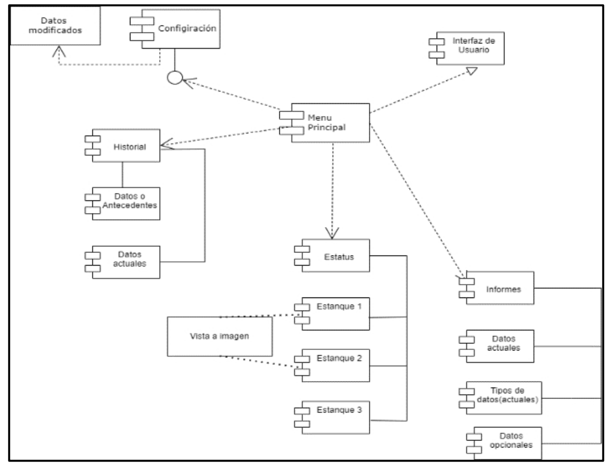
Source: *Own creation*, 2025.

Figure 3. *Sequence Diagram: Overview.*



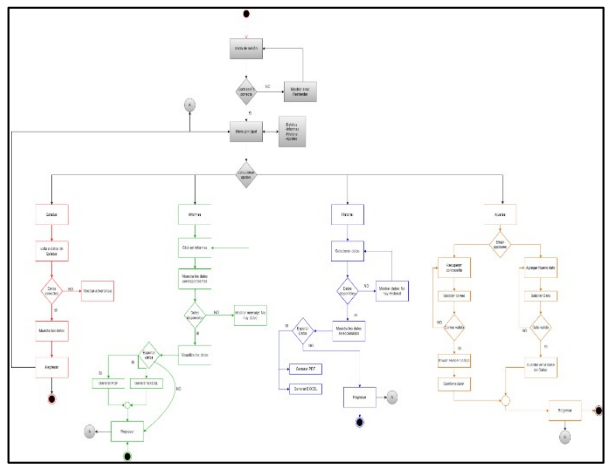
Source: *Own creation*, 2025.

Figure 4. *Sequence diagram: Overview.*



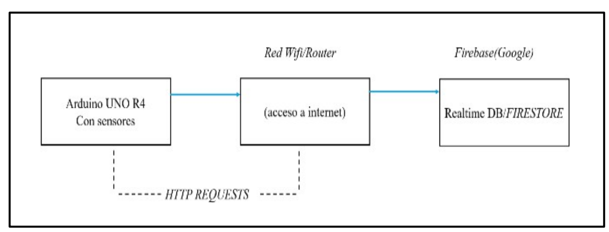
Source: *Own creation*, 2025.

Figure 5. *General Activities Diagram.*



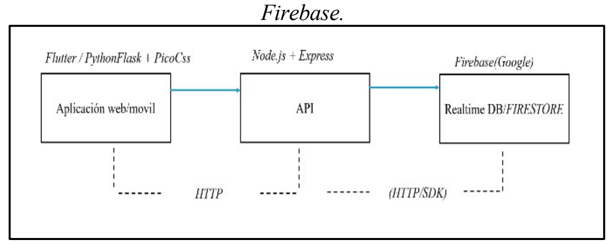
Source: *Own creation*, 2025.

Figure 6. *Base architecture of Arduino UNO R4, WIFI, and Firebase.*



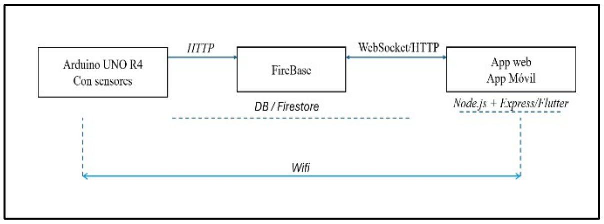
Source: *Own creation*, 2025.

Figure 7. *Base architecture in web application, API, and Firebase.*



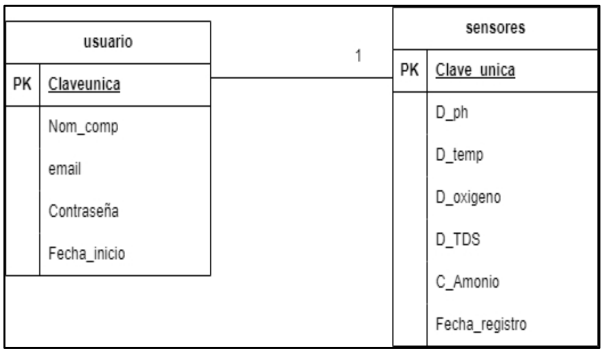
Source: *Own creation*, 2025.

Figure 8. *Base architecture of Arduino UNO R4, WIFI, Firebase, and applications.*



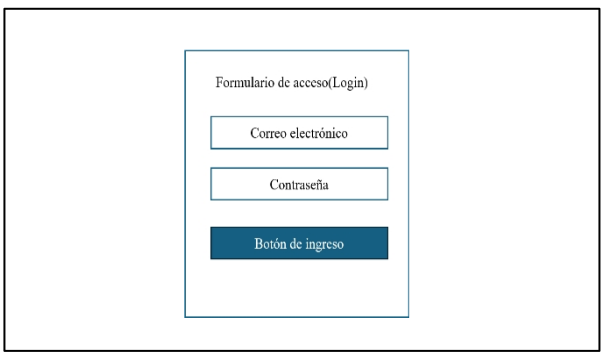
Source: *Own creation*, 2025.

Figure 9. *Class Diagram*.



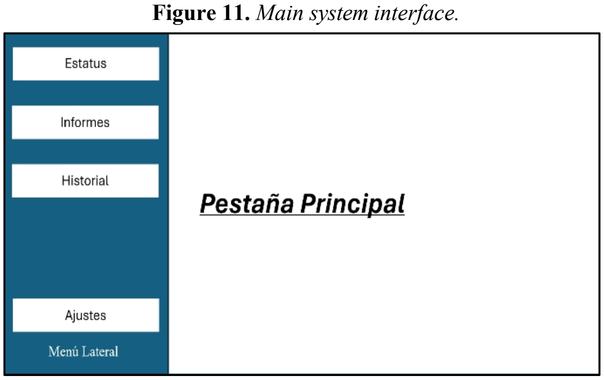
Source: *Own creation*, 2025.

Figure 10. *Login interface*.



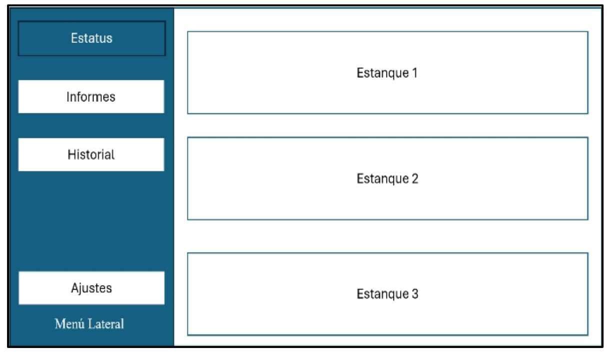
Source: *Own creation*, 2025.

Figure 11. *Main system interface.*



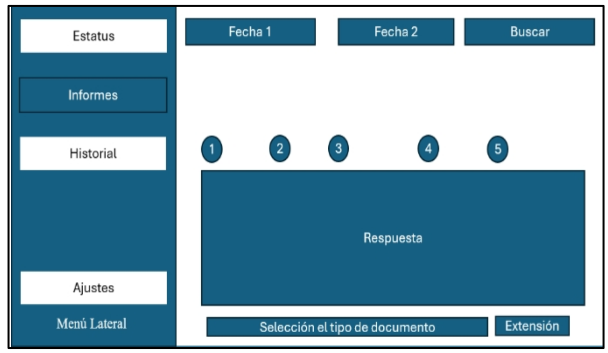
Source: *Own creation*, 2025.

Figure 12. *Pond interface*.



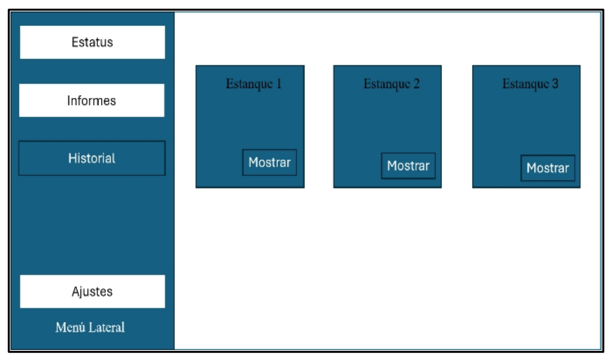
Source: *Own creation*, 2025.

Figure 13. *Reports interface*.



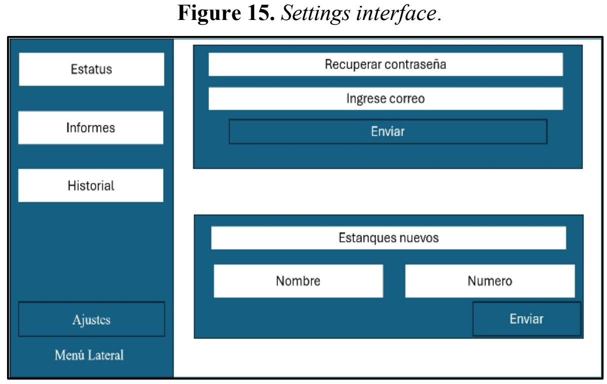
Source: *Own creation*, 2025.

Figure 14. *History interface*.



Source: *Own creation*, 2025.

Figure 15. *Settings interface*.



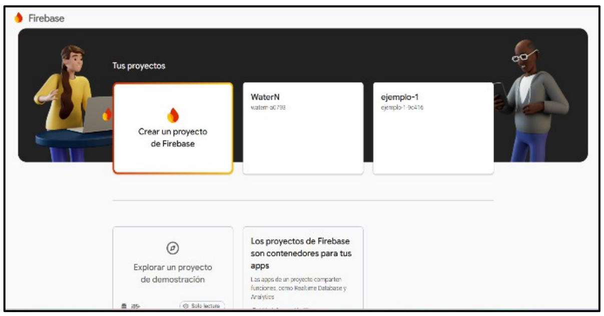
Source. *Own creation*, 2025.

Phase 3 – Iterative Development (Sprints 2–3).

This phase of the methodology focused on the development of:

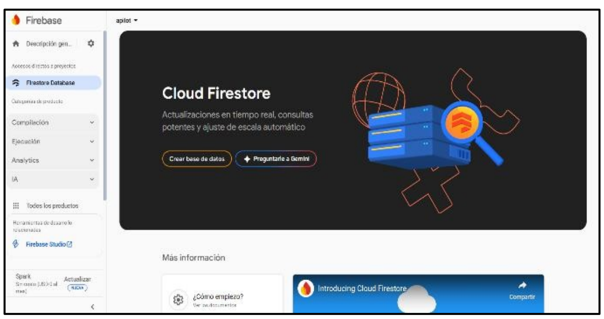
- Sprint 2: Creation of the database in Firebase.
  - Collections and nodes (users, sensors, ponds) were defined.
  - Real-time read/write tests were performed.
- Sprint 3: Development of the API in Node.js and connection with Arduino.
  - The endpoints (GET, POST, PUT, DELETE) were programmed.
  - Secure communication with SSL encryption and Firebase authentication was implemented.
  - Tests were performed with real pH, turbidity, and temperature sensors.

Figure 16. *Firebase: project creation.*



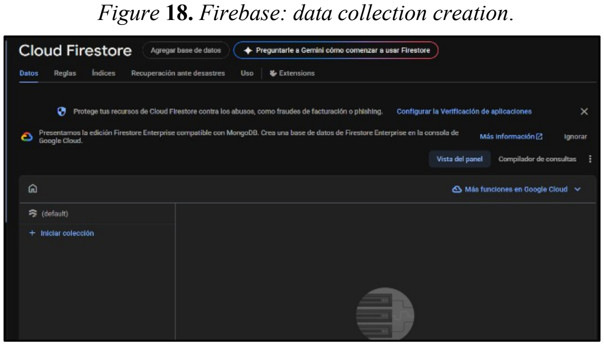
Source: *Own creation*, 2025.

Figure 17. *Firebase: database creation.*



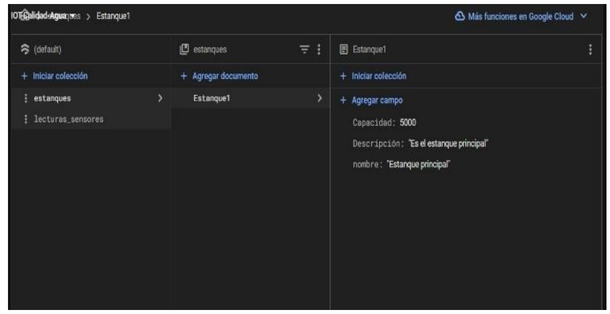
Source: *Own creation*, 2025.

Figure **18.** *Firebase: data collection creation.*



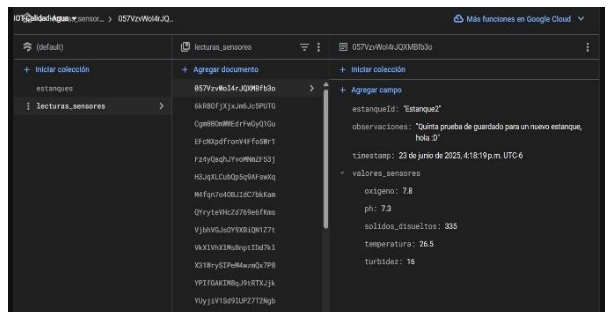
Source: *Own creation*, 2025.

Figure 19. *Firebase: collection created with data.*



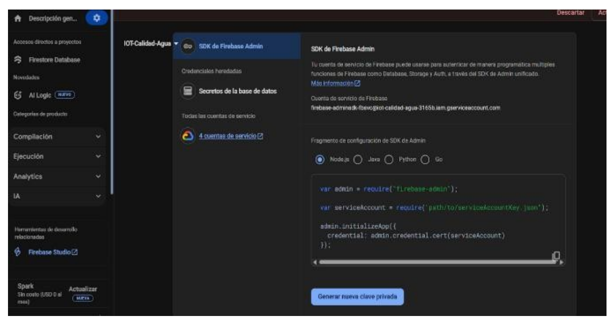
Source: *Own creation*, 2025.

Figure 20. *Firebase: view of the collection created with data.*



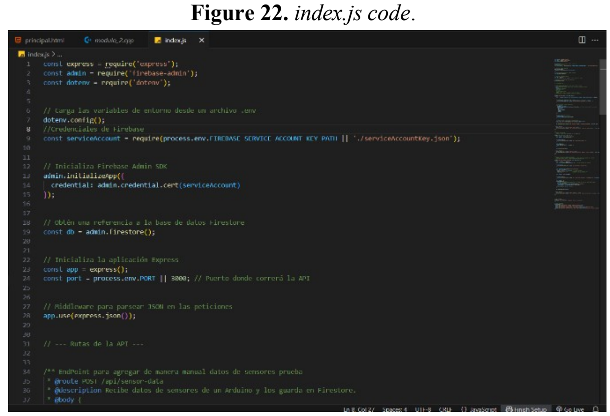
Source: *Own creation*, 2025.

Figure 21. *Service account for your Node.js backend.*



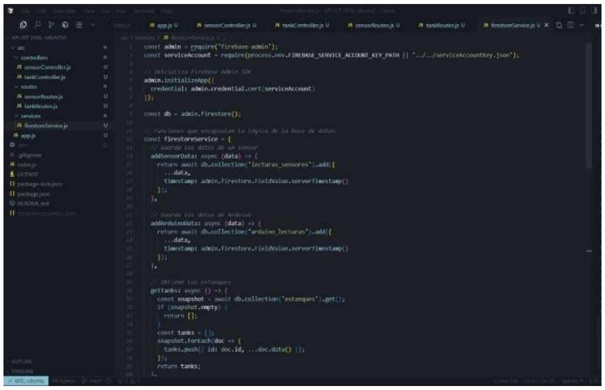
Source. *Own creation*, 2025.

Figure 22. *index.js code.*



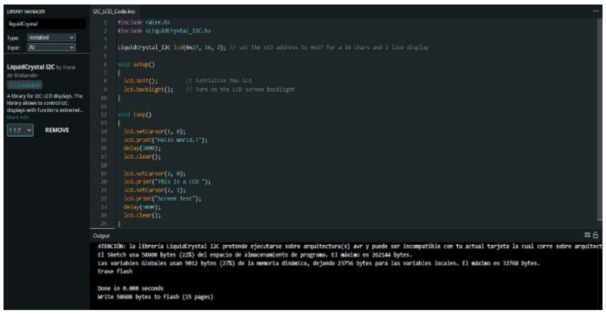
Source: *Own creation*, 2025.

Figure 23. *Controller.js code*.



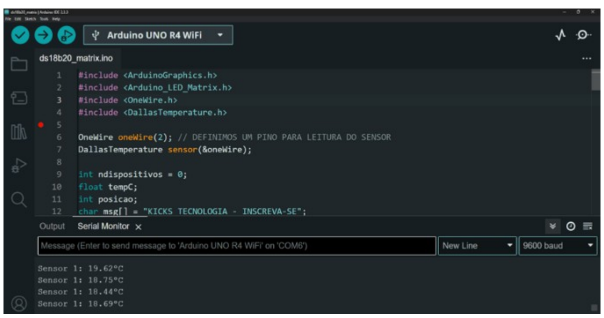
Source. *Own creation*, 2025.

Figure 24. *Arduino programming*.



Source: *Own creation*, 2025.

Figure 25. *Programming and testing the temperature sensor on Arduino.*

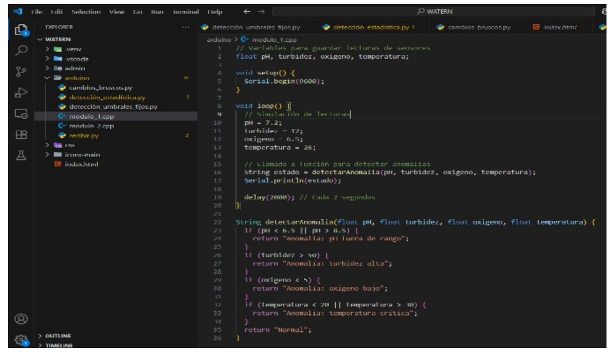


Source: *Own creation*, 2025.

Figure 26. *Programming and testing the pH sensor on Arduino*.

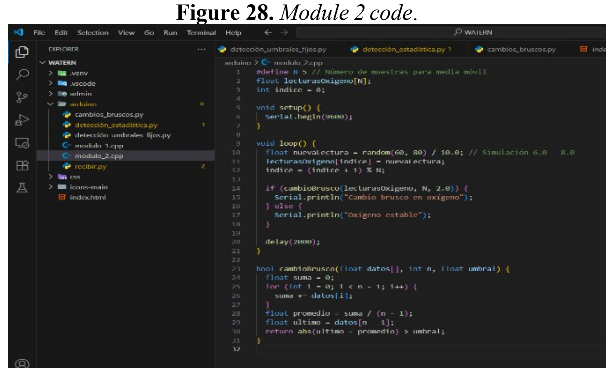
Source: *Own creation*, 2025.

Figure 27. *Module 1 code*.



Source: *Own creation*, 2025.

Figure 28. *Module 2 code*.



Source: *Own creation*, 2025.

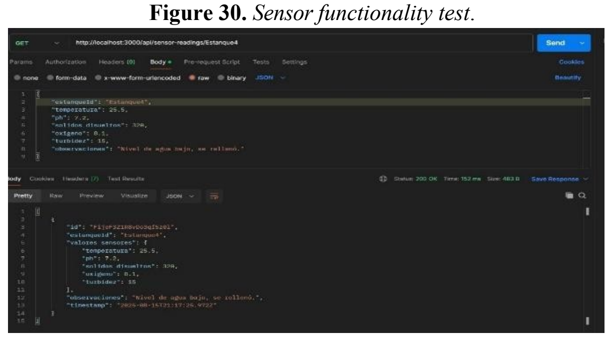
Phase 4 – Sprint Review and Validation (Sprint 4).

In this phase, the modules were verified for proper functioning, i.e., functional tests were performed, real-time measurements and anomaly alerts were validated, and a joint review with the client was conducted with immediate feedback.

Figure 29. *User functionality test*.

Source: *Own creation*, 2025.

Figure 30. *Sensor functionality test*.



Source: *Own creation*, 2025.

DISCUSSION AND ANALYSIS OF RESULTS

The use of sensors and connected devices in aquaculture began to be explored more frequently in Mexico around the 2010s. The need to monitor critical variables such as temperature, dissolved oxygen, pH, and salinity drove the adoption of these technologies.

At the national level, Mexican aquaculture is experiencing sustained growth and increasing importance for food security. According to official figures, in 2023 Mexico produced more than 1.9 million tons of fish and aquaculture species, with an economic value of over 42 billion pesos, confirming the sector's importance in the country's supply and exports. In the same year, shrimp production, the backbone of national aquaculture, reached a preliminary 243,400 tons, consolidating Mexico's position among the leading regional producers. Tilapia production, meanwhile, maintained its social and productive role by concentrating a significant proportion of the subsector's professionals and contributing an estimated value of billions of pesos, with strong roots in small and medium-scale production units. These local trends are in line with the global dynamics reported by the FAO, which documented in 2022 the historic turning point when aquaculture surpassed capture fisheries for the first time as the main source of aquatic animals for human consumption [21].

The implementation of digital technologies in rural areas of Mexico has grown rapidly: by 2023, 81.2% of the population aged 6 and over used the internet.
85.5% in urban areas and 66.0% in rural areas, with a statistically significant increase in rural areas compared to 2022. This progress opens up new possibilities for the implementation of Internet of Things (IoT) solutions in geographically dispersed aquaculture farms, where variability in water quality and input costs require continuous monitoring and data-driven decision-making. IoT systems that use pH, dissolved oxygen, temperature, and turbidity sensors, connectivity, and data analytics allow for the detection of suboptimal conditions in a more timely manner, enabling the optimization of feeding and reduction of mortality, thereby improving productivity and animal welfare under responsible management schemes [22]. Here are some examples:

The project entitled Wireless Monitoring and Control System in Aquaculture Farms: Project for obtaining a degree developed by David Duarte Correa at the Autonomous University of Querétaro; it focuses on the instrumentation and technification of aquaculture farms through a wireless monitoring and control system, making it accessible to national producers [23].

The Automation and Control for Pumping in Shrimp Farms project, implemented at the Loma de las Cayotas company, seeks to automate the pumping process for shrimp oxygenation, reducing errors and accidents and optimizing the efficiency of shrimp farming [24].

The Aquaculture Water Quality Management and Monitoring System Based on IoT Technologies and Software Engineering project is used in aquaculture production. It consists of a mobile application and a control prototype made up of a microcontroller card and the elements connected to it, allowing the main variables of an artificial aquaculture habitat to be monitored in order to control the elements for recirculation and maintain optimal levels of these variables.

Finally, in the case of the project Application of Embedded Systems and IoT for the Monitoring of Dissolved Oxygen in Aquaculture Ponds in Eldorado, Sinaloa: Project for obtaining a degree developed by Jesús Antonio Navar Pintor at the Autonomous University of Zacatecas in the Academic Unit of Electrical Engineering, it uses the architecture of a LoRaWAN
[25] network architecture for the Internet of Things (IoT), which encompasses the creation of edge devices, to the development of a LoRa network, the validation of system measurements in the collection of dissolved oxygen values that are vital for the optimal growth of marine species, and finally, implements the system in aquaculture ponds dedicated to the production of Vannamei shrimp, facilitated by the María Esperanza cooperative.

These projects reflect the progress and innovation in aquaculture automation in Mexico, contributing to more efficient and sustainable production.

Therefore, after analyzing the above results, it can be determined that the cloud-based IoT system that allows for the timely monitoring and management of physicochemical parameters of water quality in tilapia fry breeding ponds guarantees optimal conditions for the growth of the species and reduces risks associated with changes in these parameters, which has a significant impact on producers in the municipality of Centro, Tabasco, aligning with the Sustainable Development Goals (SDGs) of the UN 2030 Agenda [26] and the strategic axes of the government of the Republic of Mexico; this makes it different from existing systems.

1. Phase 1 – Start (Sprint 0 Planning): information was gathered to establish the requirements for the development of the cloud-based IoT system that allows for the timely monitoring and management of physicochemical parameters of water quality in tilapia fry ponds.

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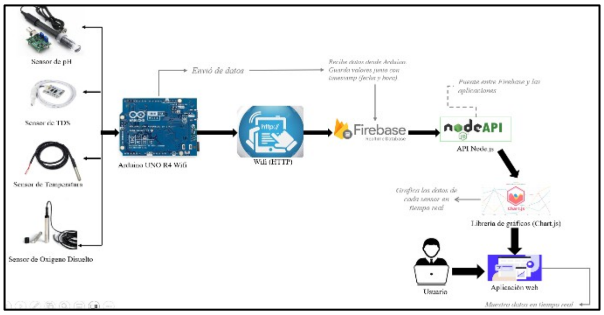
Based on these requirements, decisions were made regarding the functionalities to be developed, the users or people involved, the technologies to be used, and the type of design for the web system and control system.

2. Phase 2 – Sprint Planning and Product Design (Sprint 1): The requirements obtained in the initial phase (sprint 0 planning) facilitated the analysis and design of the cloud-based IoT system that allows for the timely monitoring and management of physicochemical parameters of water quality in tilapia fry breeding ponds.

Figure 31. *IoT System Architecture.*



Source: *Own creation*, 2025.

3. Phase 3 – Iterative Development (Sprints 2–3): The IoT system was developed based on the design created in phase 2 – sprint planning and product design (sprint 1).

Next, IoT system screens:

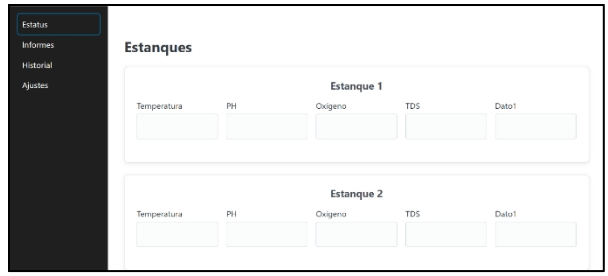
When starting up the cloud-based IoT system that allows for the timely monitoring and management of physicochemical parameters of water quality in tilapia fry breeding ponds, the main view is the following screen, which shows the user logging in.

Figure 32. *System home screen.*

Source: *Own creation*, 2025.

The Status interface is where the Arduino UNO R4, together with the sensors and the communication medium, will display the respective data for each pond.

Figure 33. *Status interface.*



Source: *Own creation*, 2025.

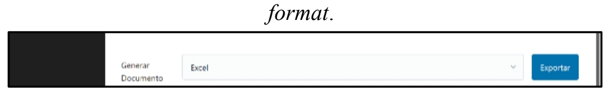
In the reports interface, the type of data to be obtained is selected using the required dates, and the data for each pond is displayed.

Figure 34. *Reports interface.*

Source: *Own creation*, 2025.

The report interface also has a section where the report can be generated in an Excel or PDF document.

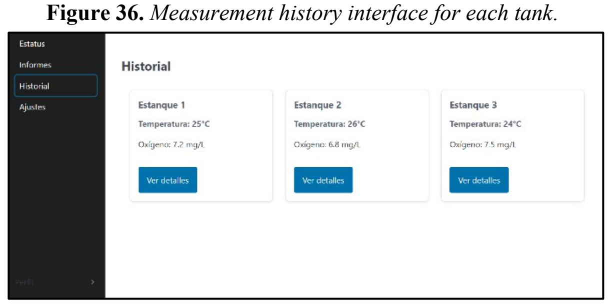
Figure 35. *Interface for generating the report in Excel or PDF format.*



Source: *Own creation*, 2025.

To view the history of measurements taken in each tank, use the history interface shown below.

Figure 36. *Measurement history interface for each tank.*



Source: *Own creation*, 2025.

If you need to adjust the system or recover your password, you can do so from the settings interface, shown below.

Figure 37. *Adjustment interface*.

Source: *Own creation*, 2025.

4. Phase 4 – Sprint Review and Validation (Sprint 4): For the deployment in production of a cloud-based IoT system that allows for the timely monitoring and management of physicochemical parameters of water quality in tilapia fry breeding ponds, the owner of the Medellín Tabasco Aquaculture Farm was contacted to authorize the implementation of the system. This process involved preparing the production environment, configuring the system, ensuring security, supervising it, and validating real-time measurements and anomaly alerts, as well as reviewing it together with the client and providing immediate feedback. The IoT system was successfully deployed.

CONCLUSIONS

The development of an Internet of Things (IoT)-based system and cloud technologies for monitoring and managing physicochemical parameters in tilapia fry rearing ponds proved to be an effective, accessible, and high-impact tool for local aquaculture. The prototype allowed for the timely recording and analysis of critical variables such as pH, temperature, dissolved oxygen, and turbidity, generating alerts in the event of variations that could compromise the health of the organisms. In this way, the objectives set were achieved, ensuring optimal conditions for the growth of the fry and contributing to the reduction of production losses.

The application of IoT technologies in aquaculture not only modernizes traditional production practices, but also drives the transition towards more sustainable and efficient systems. From a broader perspective and one of social commitment, this progress is perfectly in line with several of the essential goals of the UN's 2030 Agenda [26]: SDG 2 on eradicating hunger, SDG 6 on ensuring access to clean water, SDG 9 on promoting infrastructure and innovation, and SDG 14 on caring for our oceans. It also aligns our efforts with the strategic guidelines of the Mexican administration, which seek to strengthen food self-sufficiency, promote technological innovation, work toward environmental sustainability, and strengthen the inclusion of all sectors.

In particular, this project has a social focus: it seeks to ensure that technology does not remain only in cities, but also reaches rural areas. By doing so, we not only improve the competitiveness of the sector, but also ensure that producers themselves learn to use these digital tools, which is essential for their development.

The results obtained suggest that the integration of this system can significantly increase aquaculture productivity and reduce environmental impact, representing an important step towards the consolidation of smart aquaculture in Tabasco.

The following are proposed as future lines of research: 1. Expand the coverage of the system through the use of artificial intelligence for predictive analysis of water quality parameters, allowing for the anticipation of possible alterations and the optimization of feeding and oxygenation strategies.

As a second line of research, it is proposed to integrate solar energy modules to ensure the autonomous operation of the system in rural areas with electrical limitations, as well as to develop a mobile application [27] that allows producers to manage data from any device.

Finally, validations are planned in different types of water bodies and aquaculture species in order to adapt the model to various environmental conditions and strengthen its applicability in production contexts throughout the country.

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