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The IoT revolution in aquaculture: Technological advances in automated feeding and water quality monitoring in shrimp ponds

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Abstract: This study focuses on implementing an automated feeding system based on IoT technology in the shrimp farming sector in Ecuador. pH, temperature, turbidity, and salinity sensors are employed for continuous monitoring of water conditions, variables critical for the survival and development of shrimp. The ESP32 board is responsible for collecting, and processing data from these sensors, and transmitting them to IoT platforms such as Arduino Cloud and ThingSpeak for monitoring and control. The internal real-time clock of the ESP32 enables the programmed automatic operation of the feeder, facilitating precise and timely feeding adjustments. The results, validated at the Camachasa farm, have demonstrated the efficiency of the proposal, thereby solidifying IoT technology as an effective solution for the challenges faced by the Ecuadorian shrimp farming sector.

Keywords: Aquaculture, innovation, Internet of Things, automation.

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1. Introduction

Aquaculture is widely practiced in the coastal regions of Ecuador, particularly in the provinces of El Oro, Guayas, and Santa Elena. In these areas, it is observed that the majority of traditional shrimp production methods heavily rely on human expertise. Tasks such as controlling the timing of the hydraulic wheel aerator, feeding, and water quality testing involve human intervention and consume a significant amount of time for producers. Consequently, any sudden failure in these processes can result in substantial losses for farmers (Boyd et al., 2021). A promising solution lies in the implementation of Industry 4.0 in the aquaculture sector, utilizing IoT (Internet of Things) technology for water condition measurements. This approach has revolutionized the way shrimp production is monitored and managed. The combination of advanced technologies has enabled more precise, efficient, and sustainable control of aquatic crops, consequently improving production (Biazi & Marques, 2023).

In the context of adopting Industry 4.0 in the shrimp farming sector, interconnected sensors and devices are utilized to gather real-time data related to crucial variables that impact the habitat and development of shrimp (Chen et al., 2022; Flegel, 2019; Prapti et al., 2022). These sensors precisely measure fundamental parameters such as temperature, oxygen levels, pH, among others. The collected information is efficiently transmitted through a communication network to a centralized platform, facilitating comprehensive data management and control. This innovative approach, integrating various technologies, not only allows continuous monitoring of habitat conditions and feeding but also enables a proactive response to potential fluctuations in critical variables for shrimp production. In many cases, the centralized management platform provides advanced analysis and visualization tools, empowering producers to make informed decisions based on data. Furthermore, the potential integration of early warning systems helps mitigate risks by alerting about potential issues in production before they have a negative impact. The aforementioned points highlight some of the key aspects that Industry 4.0 contributes to aquaculture (Haji Daud et al., 2022; Teja et al., 2020; Tsai et al., 2022).

Several studies highlight the importance of technology in shrimp production, with a particular focus on monitoring water quality. For instance, in research (Shareef & Reddy, 2019), a system was developed that integrates various sensors, including dissolved oxygen, pH, and water temperature. This system utilizes Modbus TCP/IP communication to transmit the collected data, providing information to administrators through web interfaces and mobile devices. While wired data transmission resolves signal issues, it also introduces limitations in field size and complexities in setup.

Another innovative approach (Saha et al., 2018) links IoT technologies with the use of Arduino and Raspberry Pi in monitoring water quality in aquaculture environments, considering variables such as temperature, pH, electrical conductivity, and color. This study, employing diverse sensors and devices, along with Android applications for remote visualization, significantly contributes to the advancement of efficient technological solutions for managing and monitoring key parameters in aquaculture. The comprehensive combination of hardware and software proposed in this work stands out as a successful strategy for implementing IoT in the aquaculture sector.

In Abinaya et al. (2019), the focus is on designing an Internet of Things (IoT) system that enables advanced monitoring and control of water parameters in aquacultural environments. The system can detect and manage temperature, pH, dissolved oxygen, water level, detect unpleasant odors, and measure ammonia in the water. Sensor nodes collect real-time data and send it to an Arduino processor for analysis. If the parameters exceed desired values, the system activates corresponding controllers to implement corrective measures. Additionally, they have cloud connectivity through a Wi-Fi modem, allowing remote access to the values on a control platform. Furthermore, notifications are sent to interested parties via short messages through a GSM modem.

Another significant approach is precision feeding in aquaculture, as different species in various growth stages demand specific amounts of food. Inefficient feeding management increases costs and leads to environmental issues by contaminating pool water. Climate changes and inadequate food supplies can negatively impact shrimp growth. The study (Chiu et al., 2022) addresses these challenges by introducing an innovative feeding management system based on the Internet of Things (IoT) and Artificial Intelligence (AIoT). An existing fish feeder is enhanced by incorporating a precision feeding AIoT system. The system placement on the water surface of the breeding pond allows for the measurement of fluctuations in the application area. A buoy equipped with a three-axis accelerometer detects surface water fluctuations when fish seek food. The fish feeder receives the wirelessly transmitted data, which adjusts the feeding time based on the received information. This intelligent approach optimizes fish feeding by adjusting the quantity, thereby reducing costs associated with aquaculture. This system represents a significant advancement toward more efficient and sustainable fish feeding management in aquaculture environments.

The evidence supports the claim that smart farming has increased productivity and streamlined monitoring in the agricultural industry. Likewise, one of the ways to address this is increasing productivity and quality in shrimp farming by applying intelligent technologies on aquaculture which indeed it has show as an efficient strategy, considering that worldwide there are higher demands for seafood each years. This is addressed in our study by implementing Industry 4.0 within the shimp farming sector to gather real time data for key factors that affect water quality and shrimp development such as temperature, oxygen, pH level along with salinity & turbidity through sensors an IOT devices. These data are then communicated over a communication network to be used in efficient management and analysis, allowing us for making decisions. IoT integration affects the automation of feeding systems besides water monitoring. For example, automated controls to reduce the amount of feed and oxygen required based on conditions increase efficiency while driving lower resource usage.

The proposal for an IoT-based system in aquaculture stands out due to its comprehensive approach to monitoring multiple critical variables, such as temperature, pH, salinity, and turbidity, allowing for more complete management of water conditions essential for shrimp survival. Unlike previous studies that focus on individual sensors or data transmission, this system automates both feeding and movement control, reducing the producer's workload and optimizing operational efficiency. Further, customizable alerts allow a proactive response to negative volatility — heads up positions are adjusted before they can cause any damage.

The paper is organized as follows: In Section 2, the materials and methods of how to build a full process prototype. In Section 3, the analysis and results are introduced followed by Conclusions in last section.

2. Materials and methods

This section presents the methodology based on the work (Blacio et al., 2021), addressing a review of previous research, the design and execution phases of the automated monitoring system for water and feed quality for shrimp. The selected components and their coherence with the study's objective are detailed: proposing an efficient architecture for monitoring in aquaculture. The research begins by identifying challenges in the monitoring systems of shrimp pools in the province of Santa Elena, Ecuador. It is emphasized that in the region, the evaluation of water quality and feed inspection is done manually, leading to higher production costs and, in many cases, the use of inefficient traditional systems. Aware of these issues, the design of the IoT architecture proceeds, referencing the model from (Montaño-Blacio et al., 2023).

2.1. System components

The proposed system relies on various physical components to facilitate its design and implementation.

The ESP32 NodeMCU board serves as the central core of the system. Based on the ESP32 microcontroller, it achieves seamless integration of Wi-Fi and Bluetooth capabilities. This microcontroller reads data from various sensors, including pH, temperature, salinity, and turbidity. Subsequently, it transmits this information about water conditions to an IoT platform through an Internet connection. Additionally, it can control a relay switching device for the automatic feeder.

Regarding the instrumentation, we have the DS18B20 temperature sensor, responsible for converting environmental signals into electrical signals representing temperature values. This sensor can be submerged in water due to its factory encapsulation and provides temperature data to the microcontroller. Additionally, there is the analog pH module, equipped with a BNC connector for probe connection, tasked with measuring water acidity levels through electric pulses subsequently interpreted into pH levels. The TDS sensor measures salinity levels in terms of total dissolved solids (TDS) in water, with this value being an essential basis for assessing water purity. Lastly, the SEN0189 turbidity sensor is designed to evaluate water turbidity by analyzing light dispersion and transmittance. This sensor is crucial for detecting suspended sediments, such as algae, providing a critical parameter for assessing water quality.

In addition, the prototype features a navigation system that utilizes an Arduino Uno as the system's brain. This device receives coordinates from the GPS sensor and orients itself using a digital compass. Both elements, positioned as antennas at the top of the prototype, send commands to the L298D controller to execute the movement of the feeding dispenser.

2.2. Monitoring architecture design

The overall monitoring system, as illustrated in Figure 1, features an IoT architecture starting from the physical layer with the sensors, followed by the routing layer that establishes communication between the Home Gateway and the end node using the HTTP protocol and Wi-Fi connection (802.11g protocol compatible with both devices). The application layer, on the other hand, handles the visualization and retrieval of data on the IoT platform, both on ThingSpeak and Arduino IoT. Additionally, the microcontroller uses a digital pin to activate or deactivate the relay module, enabling the switching of the motor to rotate the feeder, synchronized through the integrated RTC.

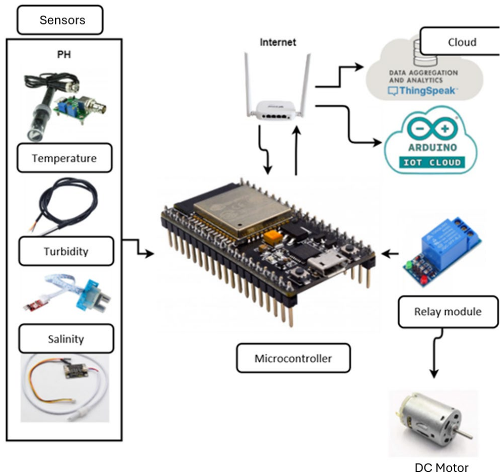

Figure 1. General data monitoring scheme.

The overall circuit reads the four sensors adapted to the development board. All sensors are powered on the VCC pins with regulated 3.3V provided by the ESP32 NodeMCU development board, constituting the first form of connection. The second connection involves the GND or ground signal connected to the GND pin, while the analog pins of the sensors are connected to the analog input ports of the board.

2.3. Electronic design for position control

Figure 2 depicts the component scheme comprising the navigation system, with the Arduino microcontroller, a GPS sensor responsible for obtaining geographical location points of the device, and a digital compass or magnetic sensor providing Earth's north reference to allow the device to orient itself in a specific direction. Regarding the output devices or actuators, an H-bridge L298D is employed to control two motors, each with a maximum capacity of 3A. Both motors operate synchronously, propelling the prototype forward or turning as needed. This action is achieved through the H-bridge, which receives TTL signals from the Arduino microcontroller card, constantly updating sensor data to manage the device's position based on predefined coordinates in the algorithm.

The Haversine formula is employed to calculate the distance between two points on the surface of a sphere, representing the shortest distance on the Earth's surface. It assumes the Earth is completely round, although in practice, it is not due to the presence of hills (Kasture et al., 2014).

Knowing the coordinates of two points on the Earth's surface in latitude and longitude is necessary to determine their distance.

The first two formulas (1)(2) represent the general equation of Haversine and the trigonometric identity of Haversine. The subsequent formulas (3)(4)(5) are necessary for a more convenient calculation in the application of the algorithm, as they constitute a breakdown of the two equations above.

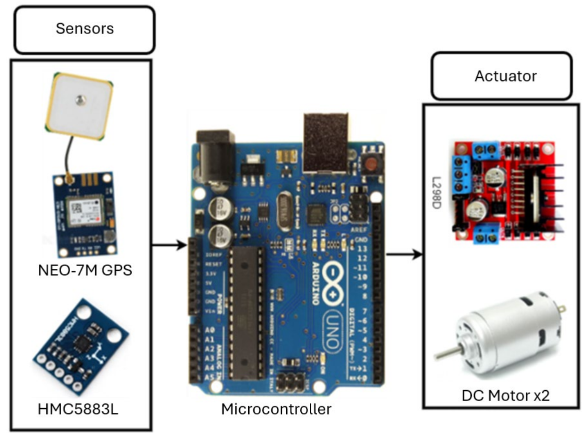

Figure 2. The overall system diagram for the navigation system.

$$hav(d/r) = hav(\varphi\_2 - \varphi\_1) + cos(\varphi\_1).cos(\varphi\_2).hav(\lambda\_2 - \lambda\_1) \quad (1)$$

$$hav\left(\frac{d}{r}\right) = sin^2\left(\frac{\theta}{2}\right) = \frac{1-cos(\theta)}{2} \quad (2)$$

$$a = sin^2\left(\frac{\Delta\varphi}{2}\right) + cos(\varphi_1).cos(\varphi_2).sin^2\left(\frac{\Delta\varphi}{2}\right) \quad (3)$$

$$c = 2.arctan\,2\left(\sqrt{a}, \sqrt{1-a}\right) \quad (4)$$

$$d = r.c \quad (5)$$

$\varphi_1 = Point\ 1\ Latitude$ $\quad \lambda_1 = Point\ 1\ Longitude$
$\varphi_2 = Point\ 2\ Latitude$ $\quad \lambda_2 = Point\ 2\ Longitude$
$d = arc(Distance)$ $\quad r = Earth\ radius$
$\Delta\varphi = \varphi_2 - \varphi_1$ $\quad \Delta\lambda = \lambda_2 - \lambda_1$

The formula allows for the determination of the initial bearing, also known as the forward azimuth, which, if followed in a straight line along a great circle arc, will lead from the starting point to the destination point. This algorithm is implemented in Arduino Uno to enable the prototype to move autonomously, facilitating its movement throughout the shrimp farm for automatic feeding.

2.4. Implementation of the system

The proposal is implemented in the structure shown in Figure 3. Each protruding corner is equipped with a buoy to facilitate the prototype's flotation on the water's surface, allowing the sensors to submerge a few centimeters below the surface.

Figure 3. Prototype structure.

In Figure 4, the complete integration of the hardware into the structure is observed, encompassing both the feeder control system and the automatic navigation system, along with water quality monitoring.

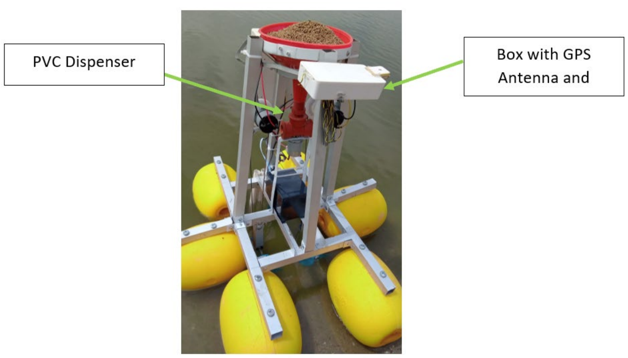

Figure 4. Implemented final prototype.

3. Analysis and results

The tests are conducted at the facilities of Camachasa, a private company dedicated to shrimp farming, located in the Parish of Chanduy, Santa Elena Province. During the tests, water conditions are monitored, and experiments are carried out in two different scenarios within the same area. Additionally, the operation of the integrated navigation system in the prototype is verified.

In the first scenario, the prototype is positioned at the edge of the pool to take measurements of water conditions and validate the values obtained by the sensors. In the second scenario, the prototype moves 23 meters from the edge towards the interior of the pool to assess potential variations in sensor measurements.

• Cloud connection results

The range of the feeder prototype in relation to the Home Gateway device was evaluated. According to the manufacturer's specifications, the device allows for a wireless connection of 30 to 60 meters. This enables measuring the signal range when the prototype is at a certain distance within the shrimp pool.

Figure 5 shows the data and a heat map of the received signal strength indicator (RSSI) while moving the prototype within the pool. The optimal connection points are identified, where the RSSI values approach zero, establishing fixed points with optimal signal for the movement of the prototype.

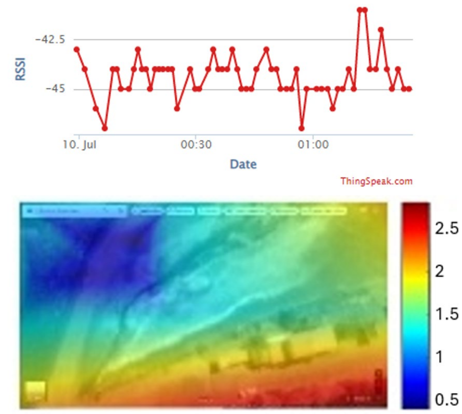

Figure 5. RSSI data and heat map.

It is evident that the maximum distance is 52.47 meters with an RSSI signal strength of -71 dBm, and the minimum distance is 22.7 meters with an RSSI signal strength of -32 dBm, representing optimal signal reception for the device's operation.

• Real-time monitoring results

Wi-Fi communication is configured between the end node and the Home Gateway, ensuring that data is successfully transmitted to the IoT platform's cloud. The time interval for the arrival of a new data point varies between 10 and 20 seconds.

In Figure 6, the data is displayed on the dashboard. The left graph represents pH values, while the right graph shows real-time salinity values.

Figure 6. Arduino IoT Cloud parameters dashboard.

ThingSpeak serves as the data backup platform in this project. Its dashboard, though simple, proves practical by displaying the variables captured by the sensors in real-time, as shown in Figure 7. Each graph is automatically refreshed with the arrival of new data, a process that takes between 15 and 20 seconds. This interval is constrained by the limitations of the license, as the free version imposes it as the minimum time for data retrieval.

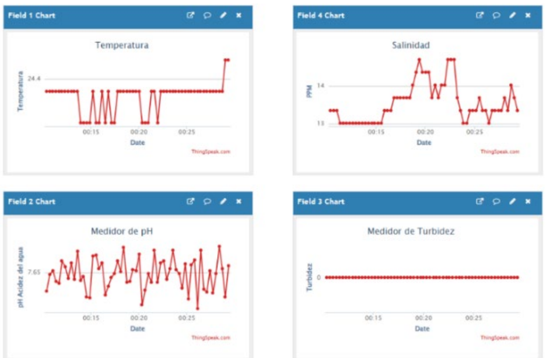

Figure 7. Dashboard of parameters of the ThingSpeak IoT platform.

From the IoT platform, sensor data is extracted by exporting a file in Excel containing the complete history of the data. This facilitates the visualization of sensor variables from the beginning of the monitoring. Subsequently, a comparison of data is conducted between both scenarios to identify potential changes that may have occurred during the measurements. To ensure the functionality and effectiveness of the prototype, optimal water quality conditions are established, serving as a key reference (Table 1). These conditions are compared with certified instrumentation to verify the accuracy of the prototype and ensure its proper operation.

Table 1. Optimal shrimp survival ranges.

Variable	Value
Temperature	21-30°C
Water Acidity	7.5 – 9 pH
Salinity	500 – 1600ppm

Testing shrimp pool of 16g (Scenario 1)

Figure 8, Temperature section, shows the temperature data graph over 30 minutes. A smooth variation is observed, and the temperature values remain at an average of 29.7°C, reaching peaks of 30.06°C without significant changes.

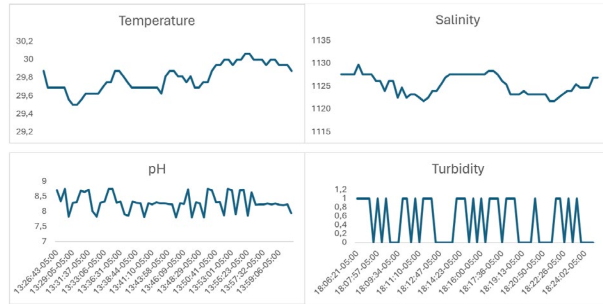

Figure 8. Variables measured in Scenario 1.

Figure 8, pH section, shows significant changes due to water turbulence caused by mixing with bottom sediments. The pH values range from 7.8 to 8.7, with an average of 8.2, which is the most stable value and allows for the optimal survival of the shrimp, as indicated in Table 1.

In Figure 8, the Salinity section the salinity levels at the edge of the pool are evident, ranging between 1121 ppm and peaking at 1129 ppm. The most stable salinity value averages at 1127 ppm, within acceptable ranges for shrimp survival according to Table 1.

The turbidity of the water fluctuates over time, as illustrated in Figure 8, Turbidity Section. These changes are attributed to the disturbance of sediments and their mixing with the water, driven by wind-induced turbulence along the shore.

Testing shrimp pool of 16g (Scenario 2)

In figure 9, Temperature section, stability in temperature levels is observed. During the initial 3 minutes of the prototype's movement, there is a decline from 29.87°C to 28.25°C. Between 14:03 and 14:31, the prototype remains stationary, providing stable values of 28.8°C. Towards the end of the graph, the temperature drops due to the manipulation of the device.

The shallow water depth and windy conditions cause variations in the pH level readings, as shown in figure 9, pH section. The values fluctuate between 7.03 and 8.06, with the most stable pH value being 7.7.

In figure 9, the Salinity section illustrates the behavior of the salinity sensor, with values ranging from 1116 ppm to 1127 ppm. The most stable salinity value remains at an average of 1123 ppm.

In Figure 9, Turbidity Section it is observed that turbidity maintained an optimal water level by staying below the threshold throughout the entire time interval. This is due to the absence of sediment levels in the water that could affect the sensor threshold.

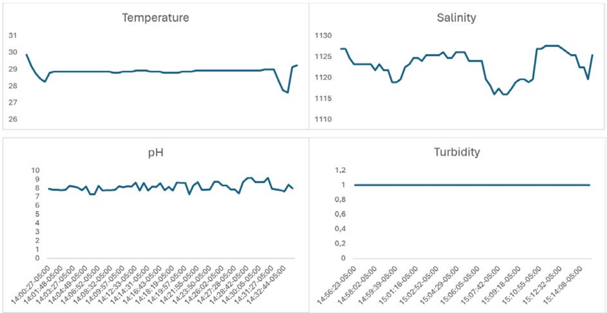

Figure 9. Variables measured in Scenario 2.

It is determined that, despite changes in the sensing of water conditions in both scenarios, there is no extreme variation that would adversely affect shrimp growth. This results in acceptable ranges for shrimp survival.

- Testing of the feeding system

The feeder prototype initiates its operation with an approximate 3-minute waiting period to establish GPS communication with satellite antennas. Motor activation occurs through a switch, allowing the flow of current from the battery to the controller and avoiding unnecessary energy consumption. During its movement, the prototype navigates towards specific points, although deviations may occur due to weather conditions.

The displacement is executed by propellers autonomously controlled by the microcontroller, using coordinates from the GPS sensor and those established in the navigation algorithm. The feeding system, managed by the ESP32 Node-MCU, sends signals to the relay module to turn the dispenser on and off according to predefined times. Shrimp feeding is programmed to occur every hour. Figure 10 illustrates the tests.

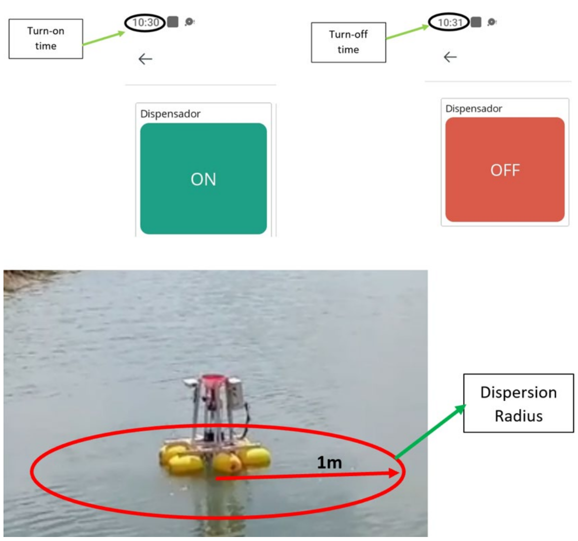

Figure 10. Feeding dispersion, relay module activated.

During the dispersion process, the relay is activated, initiating the rotation of the feeder's motor and allowing the food to be expelled within a radius of approximately 1 meter around it (see figure 10).

Aquaculture is an industry undergoing remarkable transformations thanks to new technologies, particularly the use of IoT. Although the reviewed studies cover various aspects of smart aquaculture, particularly water quality monitoring and feeding automation, this research is more comprehensive and specifically focuses on the development of a system that includes mobility and an automatic feeder for shrimp farming in Ecuador.

For example, while ISAS (Tsai et al., 2022) improved shrimp survival rates through water quality monitoring and aeration automation, my approach is more directly focused on feeding, a critical component of aquaculture production. By linking a mobile feeder with specific sensors, I reduced feed waste and adjusted the amount of food to an appropriate level, achieving better growth. On the other hand, while (Teja et al., 2020) indicates the need for monitoring in small farms, it focuses on measuring data rather than on the automation of the feeding process itself. Since feeding is critical for operational efficiency and cost reduction, automating this operation is essential for small producers.

While (Saha et al., 2018; Shareef & Reddy, 2019) focus on water quality monitoring, neither has a system that integrates automated feeding. The essence of an automated feeding system is crucial for achieving sustainable increases in shrimp production. By monitoring conditions, feeding is continuously adjusted according to water parameters. Although (Haji Daud et al., 2022) also addresses water quality data and its impact on shrimp production, it lacks the necessary parameters for a feeding system. Consequently, my research on monitoring and automated feeding represents an advancement, presenting a system that not only monitors but also acts on real-time data.

Furthermore, (Chiu et al., 2022) presents a precision feeding system, but it applies to pellet management for fish. Finally, while (Abinaya et al., 2019) focuses on monitoring and controlling multiple water parameters, my research is different as it encompasses a real-time automated feeding system that responds dynamically to conditions, significantly improving production efficiency.

While there are several valuable contributions in the literature on smart aquaculture that I previously discussed, the proposed research stands out for addressing feeding automation in shrimp farming with an innovative approach. This solution effectively tackles the specific challenges faced by the sector in Ecuador, ensuring a feeder system that dynamically responds to water conditions to optimize sustainable and profitable production in aquaculture and to address the limitations of current systems.

4. Conclusions

The system successfully configured a Home Gateway enabling wireless communication between the final Node, identifying optimal connection points with a range of 57.42m. The heatmap verified the signal power intensity, peaking at -70dBm. The final Node was configured using the Arduino IoT cloud development environment, demonstrating data collection with a latency of 5 to 10 seconds, which doesn't critically impact the prototype's functionality given the non-critical nature of water condition readings. The navigation algorithm operated as theorized, showing proper functionality through the serial monitor despite occasional deviations in open-field tests due to wind-induced water currents. The feeding system was validated through dispenser activation and deactivation based on the algorithm's set times. However, a 10-second delay during startup and shutdown was noted, attributed to the limitations of the free IoT platform license.

The choice of Wi-Fi technology in this project was motivated by its accessibility and ease of implementation. However, it is recognized that this choice limits the use of the system in larger environments, such as larger ponds or in remote locations. To overcome these limitations, future iterations of the system could consider the implementation of other communication technologies, such as LoRaWan, which offers a longer range and lower power consumption. This transition would allow the system to be extended to large-scale aquaculture applications, where distances and connection reliability are critical. Furthermore, the integration of technologies such as LoRaWan would open the door to the implementation of distributed sensor networks, empowering real-time monitoring and control of multiple shrimp farming locations.

To improve the autonomy of the system, it would be beneficial in future work to explore renewable energy options, such as the integration of solar panels. This could be especially useful in remote environments or where access to electricity is limited.

Although the technology options implemented in the prototype provide a good starting point, there is considerable scope for system improvement and expansion through technologies such as LoRaWAN, improvements in durability and power optimization, as well as careful planning to overcome integration and scalability challenges.

Conflict of interest

The authors have no conflict of interest to declare.

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