

Aquaculture 4.0 in Costa Rica: automation, sensors and artificial intelligence for management in tilapia production

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Abstract– *The rapid development of aquaculture demands the implementation of innovative solutions that improve production efficiency while promoting sustainability. This research addresses the application of automated systems, sensor technologies, and artificial intelligence for management in tilapia farming in Costa Rica. Using real-time monitoring and predictive models, the system will allow for optimal regulation of water levels, maintenance of dissolved oxygen stability, and reduced mortality in production systems. Adopting Aquaculture 4.0 principles can strengthen operational efficiency, reduce labor, and resource use, and foster more sustainable and adaptable production at different scales within the country's aquaculture sector.*

Keywords– *Aquaculture 4.0, Tilapia production, Water management, Automation, Artificial intelligence*

I. INTRODUCTION

In recent years, aquaculture has become a key activity in Costa Rica's rural development, and tilapia production is among the sector's main products [1]. However, production systems have shortcomings and face recurring problems in water resource management due to variations in water levels, evaporation, physiological stress in fish, production mortality, and environmental sustainability. [2].

Furthermore, in addition to the factors mentioned above, modern aquaculture is constantly interacting with global trends that emphasize digitization, automation and process optimization, the latter being a set of tools known as Aquaculture 4.0 [3], sometimes causing the national aquaculturist to fall behind.

Therefore, this research aims to evaluate an automation system using information sensors and artificial intelligence for the intelligent management of tilapia ponds to improve the operational control of aquaculture, the welfare of the cultivated specimens, and help different aquaculturists to improve their production.

II. JUSTIFICATION

This research seeks to explore the benefits of ATO (Auto Top Off systems), the use of sensors for pond monitoring, and artificial intelligence applications in intensive tilapia aquaculture. In this type of aquaculture, the challenges lie in managing water levels, dissolved oxygen, and environmental stability in intensive production. Consequently, factors such as evaporation, temperature fluctuations, and human error can cause stress in the fish, reducing their growth and increasing their mortality [4].

Aquaculture farmers face difficulties in addressing all the issues, which has led to a decline in tilapia production.

Climate change also severely impacts aquaculture, harming fish production for consumption. However, Aquaculture 4.0, with its emerging technologies, offers hope to the sector by enabling the capture and interpretation of field data to predict and make more accurate decisions that will allow for increased productivity in a sustainable and profitable manner [5].

III. THEORETICAL DEVELOPMENT

The adoption of emerging technologies has become a growing trend in various manufacturing industries, including aquaculture. The use of sensors and devices to control and monitor processes in real time offers numerous benefits, such as resource optimization, increased efficiency, and cost reduction [6].

Consequently, efficient water management in tilapia aquaculture is essential to maximize productivity and product quality. Therefore, the application of new technological tools is beginning to revolutionize the sector, and in particular, Aquaculture 4.0 is paving the way, demonstrating great potential for improving the management and optimization of tilapia aquaculture.

A. Aquaculture 4.0

This involves, among other things, the integration of advanced digital technologies characteristic of Industry 4.0, such as sensors, system automation, real-time data analysis, and artificial intelligence, all with the aim of modernizing and facilitating aquaculture production processes [7]. However, this approach goes beyond simply maximizing productivity; it also promotes a more rational use of resources, improves the traceability of production systems, minimizes environmental impact, and enables appropriate decision-making based on accurate and contextualized information.

The main characteristics of Aquaculture 4.0 include: a) intelligent monitoring through which different sensors collect environmental data such as dissolved oxygen, pH (degree of acidity or alkalinity) and temperature, b) automation that provides automatic control mechanisms to optimize resources, c) predictive planning through which models and artificial intelligence are used to anticipate production management needs, and d) traceability and transparency that, through digital systems, track the entire production chain. [5]

B. Institutional framework in Costa Rica

The Costa Rican Institute of Fisheries and Aquaculture (INCOPESCA) is the public institution responsible for regulating, promoting, and sustainably developing fishing and

aquaculture activities in Costa Rica. It was created by Law No. 7384, and its main function is to ensure the rational use of aquatic resources, guaranteeing their long-term conservation and the balance between production, the environment, and social well-being [8].

Among its functions are the formulation and implementation of policies, regulations, and management plans for fishing and aquaculture, as well as the granting of permits, licenses, and concessions. The institute also supervises and monitors the sector's activities to ensure compliance with current regulations, combats illegal fishing, and promotes best practices in production. INCOPECA also fosters scientific research, technology transfer, and producer training to strengthen the sector's competitiveness. Furthermore, it collaborates with other national and international institutions in the sustainable management of marine and freshwater resources, contributing to the country's economic, social, and environmental development.

Similarly, INCOPECA established the National Fisheries and Aquaculture Development Plan 2025–2030, which considers technological innovation and modernization as fundamental elements for increasing the competitiveness and sustainability of Costa Rica's fisheries and aquaculture sector. In this context, the introduction of digital technologies, process automation, and the use of intelligent systems are promoted to increase productivity, ensure the responsible use of natural resources, and strengthen the capacity to adapt to climate change [8].

Similarly, the National Fisheries and Aquaculture Development Plan also seeks to promote applied research, knowledge transfer and continuous training of stakeholders, encouraging the adoption of tools such as sensors, real-time monitoring systems or data analysis, with the aim of moving from traditional production systems towards more efficient, sustainable management practices with a technical and scientific basis, as Alejandro Pérez, researcher at the Center for Research in Aquaculture and Fisheries Production (CIPAP) comments in a video posted on the Youtube platform [9].

C. Production systems in Costa Rica

Tilapia production in Costa Rica is classified into three types of systems: extensive, semi-intensive, and intensive, each distinguished by characteristics such as the level of technological application, stocking density, and desired scale of operation. Extensive systems, which employ more traditional technology and have the lowest initial operating costs, are based on earthen ponds and low stocking density (generally less than 1 kg/m²). These systems have reduced consumption of external inputs in terms of feed and other requirements, as they utilize nutrients from the aquatic environment. Finally, their production is limited to 2-5 tons per hectare per year and they are vulnerable to climatic fluctuations [10].

On the other hand, semi-intensive systems are of an intermediate category since they incorporate balanced feed to

supplement the fish's natural diet. They also include occasional aeration and improved water quality management through the control of parameters such as dissolved oxygen and pH. This raises stocking densities to 10-20 kg/m² and production to 10-15 tons per hectare, improving efficiency without requiring considerable investment [11].

Finally, intensive systems are those that boost productivity with high densities, above 30 kg/m², continuous aeration and real-time monitoring of several variables, achieving harvests of up to 50 tons per hectare, although they require more capital investment and more technical training [12].

All these types of systems have integrated tilapia aquaculture into the diverse production realities of Costa Rica, emphasizing sustainability and productivity. Likewise, there are tools and technologies that can help improve tilapia production; an explanation of these follows.

D. ATO systems

These are automated mechanisms designed to maintain a stable water level in aquariums, tanks, or aquaculture facilities by precisely and automatically compensating for losses caused by evaporation, splashing, or minor leaks. They operate using sensors that detect drops in the water level and activate a pump or valve connected to a reservoir, replenishing water until the optimal volume is reached. This ensures the uniformity of key indicators such as salinity, mineral levels, and the overall volume of the aquatic environment [13].

In fish production for human consumption, using an ATO system can offer certain advantages, especially in intensive or semi-intensive systems. Key advantages include water volume stability. In climates like Costa Rica's, with high temperatures, constant evaporation in indoor systems or small tanks can affect water levels. In this case, the ATO system maintains a stable water level, preventing waste buildup, keeping dissolved oxygen more stable, and reducing stress on the fish, which translates into improved growth.

Similarly, when the water level drops, the concentration of waste increases and the temperature and oxygen levels change. In this case, the ATO optimizes water quality by gradually compensating for these losses, preventing sudden spikes in fish production.

Similarly, the ATO prevents reduced mortality in production due to malfunctioning pumps, poorly positioned aerators, and excessive water heating, as it reduces avoidable deaths, especially in tilapia fry and during the early grow-out phases.

Finally, it saves on labor costs, as it decreases manual water refills, reduces human error, and allows staff to focus on feeding and monitoring the fish [14].

E. Emerging technologies

Today, several technologies are under development, defined by their innovative nature, rapid expansion, and high potential to generate radical transformations in society, the economy, and various industrial sectors in the coming years.

In the case of aquaculture, the most relevant technologies for this research will be discussed.

a) Sensors and the Internet of Things (IoT): Their application in aquaculture facilitates the incorporation of advanced technology that continuously records critical variables such as dissolved oxygen, temperature, pH, ammonia levels, and water volume. This equipment transmits information in real time to online platforms, enabling rapid and precise interventions to mitigate potential anomalies, thus strengthening operational management [15]. In intensive farming environments, this uninterrupted monitoring ensures greater environmental homogeneity, maximizes the efficiency of input use, and significantly reduces mortality losses resulting from abrupt changes in water quality. In this way, IoT and sensors not only increase productivity but also promote more sustainable practices by anticipating and correcting imbalances before they impact the performance of the entire system.

b) Data Analysis and Artificial Intelligence (AI): Data processing through analysis and artificial intelligence techniques allows for the proper management of large amounts of data obtained from sensors and devices in aquaculture production. In this way, through forecasting, instabilities in water quality and fish growth rates can be predicted and feeding protocols can be adjusted to maximize production. AI also allows for the early detection of diseases based on the analysis of patterns in fish behavior and physiological alterations, increasing operational efficiency, reducing operating costs, and promoting the environmental sustainability of aquaculture systems. These tools combine continuous monitoring and automated control, thus creating more efficient and competitive production [16].

c) Automation and robotics: these two areas are manifested through devices such as automatic feeders, programmed aerators, and remote controls for tank management. These technological solutions minimize the need for manual intervention, optimize precise nutrient portions, and ensure immediate responses to environmental disturbances. In certain environments, the adoption of automated feeders and aerators has demonstrated favorable results, driving higher levels of productivity and operational uniformity within the Aquaculture 4.0 framework [17].

IV. METHODOLOGY

The project focuses on applied research in technology to improve the management of tilapia aquaculture in Costa Rica. A qualitative approach was chosen, using exploratory and descriptive studies to address a problem little studied in the sector. Likewise, a mixed design is adopted that combines a systematic literature review (RSL) that, together with applied research, aims to technically support the development of an intelligent management prototype for tilapia production, allowing traceability between theoretical evidence and field findings.

A. Systematic review process

To support the components of the system (ATO, sensors and AI), a systematic review was carried out following a transparent selection and evaluation process, for which inclusion and exclusion criteria were used where studies published between 1998 and 2026 were taken into account that addressed Aquaculture 4.0 technologies (IoT, AI, sensors), water resource management in intensive and semi-intensive systems, tilapia production and aquaculture regulatory frameworks in Costa Rica, prioritizing sources that analyzed operational efficiency and environmental sustainability. Likewise, documents that did not focus on tilapia production, studies on marine aquaculture not applicable to continental ponds, and opinion articles without technical or scientific support were excluded.

B. Analytical synthesis and thematic analysis

The extracted data were grouped into thematic axes to identify the convergence between theory and reality of the sector in Costa Rica: a) axis 1: stability of the aquatic environment, through the review of the literature it was expected to evaluate the criticality of dissolved oxygen and the water level in order to justify the integration of ATO systems in order to compensate for evaporation and reduce physiological stress, b) axis 2: technological maturity and research gaps: through the bibliographic analysis it was intended to reveal the global growth in IoT, but also determine the existing gaps in the country regarding the implementation of these technologies, where manual records and technical ignorance normally prevail and c) axis 3: economic viability, this type of projects initially determines high cost as its main barrier, therefore, the research aims to establish the need to use open source platforms (Arduino) and low-cost technologies to guarantee accessibility to small producers.

C. Field investigation and traceability

To validate the theoretical synthesis, an empirical phase was carried out where the following parameters were included: a) population and sample, where emphasis was given to the owners of aquaculture farms in Guanacaste and Alajuela, regions located in the north of the country. Likewise, a purposive sample of 10 farms was selected to obtain depth in the operational data. b) instruments, observation and interviews were used as data collection instruments and c) data analysis, measurement techniques and visual tools such as mental maps were used to organize the farm processes and thus present the data in a more visual and simple way.

In the end, the objective was to obtain valuable information that would improve the management of aquaculture farms and promote technological innovation in the sector through a process that guarantees data traceability.

V. RESULTS

The most relevant aspects of the results obtained through observation and interviews are described below. These results are essential for developing a proposed aquaculture

automation system using information sensors and artificial intelligence for the intelligent management of tilapia ponds. The main objective of this stage was to gather information that would facilitate a better understanding of the technical requirements and associated challenges, with a view to the future implementation of the system on an aquaculture farm.

The interview instrument was used to assess the level of knowledge and adoption of these emerging technologies by fish farmers. The results demonstrated a widespread lack of awareness on the subject and the absence of similar systems on the farms, as shown in Figure 1. This situation represents a significant opportunity since the project can promote the incorporation of new technologies to achieve smarter and more efficient aquaculture management.

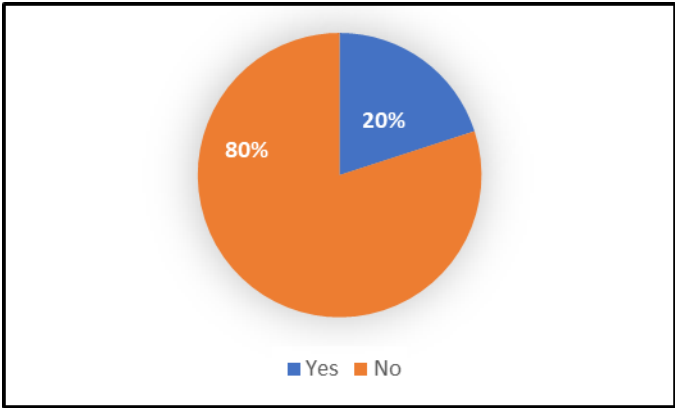


Fig.1 Did you use some type of technology in farm management.

During this research, it was observed that most fish farmers maintain paper records or lack organized control over their activities. This highlights the value of having a system that generates real-time information, making it essential for maintaining a farm history without relying on manual record-keeping. Therefore, this project aims to offer a technological solution that facilitates the monitoring and storage of relevant data, contributing to more efficient tilapia aquaculture management, as shown in Figure 2.

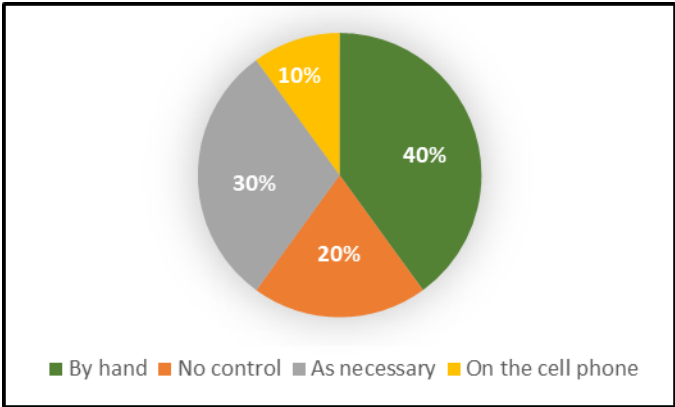


Fig.2 How do you manage your farm?

Common problems faced by fish farmers in their daily work were identified, which represents a significant advantage, since no one is better suited than they are to express which aspects most affect their production. Various problems related to their farms were analyzed, including water management issues and labor shortages to meet all their needs. These observations are especially positive for the project, as one of its main objectives is to provide fish farmers with real-time access to relevant data to help them improve their production, in addition to automating processes. In this way, the project seeks to address these problems and provide fish farmers with a tool that allows them to have better visibility and control over their farms, as shown in Figure 3.

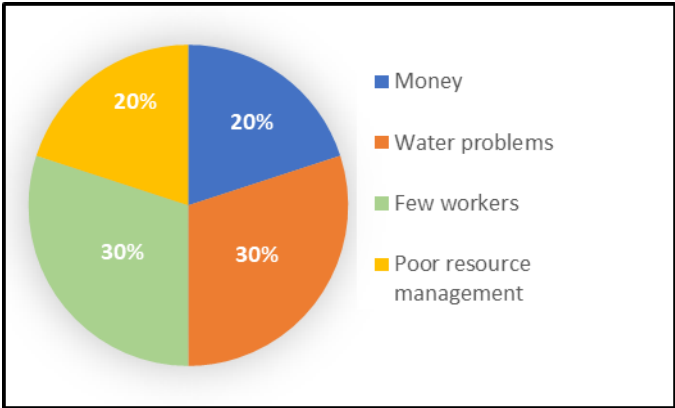


Fig.3 What are the main problems on your farm?

The diagnosis carried out in Guanacaste and Alajuela shows that aquaculturists still have very important deficiencies in water management, as well as in labor. The interviews show that there is a great lack of knowledge at a technological level, as well as a great predilection for keeping records on paper. This operational gap explains to us the importance of introducing aquaculture 4.0 to optimize tilapia production, whose specialty would be using digital tools that guarantee the traceability, efficiency and sustainability of the national aquaculture sector in relation to current institutional policies.

Consequently, some of the results indicated that fish farmers have limited budgets, which they must manage carefully throughout the year. Therefore, acquiring any type of technology could affect their financial stability. For this reason, in the initial stage of the project, when economic resources are limited, the option of using open-source platforms and low-cost technologies is considered.

Likewise, a prototype based on ATO systems and Arduino microcontrollers is proposed to automate the filling and monitoring of ponds. The system integrates oxygen, pH and temperature sensors to capture real-time data on critical variables. Using artificial intelligence, predictive algorithms would be executed to anticipate environmental fluctuations, optimizing the well-being of the tilapia and reducing operating costs through automated and digitized control of the aquatic environment.

On the other hand, another identified challenge is the limited knowledge on this topic, which presents an opportunity to develop seminars and promote the implementation of these technologies in the country. Through project outreach and training, the aim is to strengthen producers' understanding of technological innovations applied to the aquaculture sector, providing them with the necessary tools to make informed decisions and maximize their benefits.

In conclusion, having this information readily available is crucial for fish farmers, as the solution can bring substantial improvements to their daily work and facilitate decision-making that was previously beyond their reach [18]. Beyond the direct benefits for fish farmers, this project represents a transformative opportunity at the national level for tilapia production by integrating innovative and effective technologies. Its implementation would not only increase the efficiency and productivity of farms but also bring about a significant change in their management, fostering modernization and promoting more sustainable development in the sector.

VI. DISCUSSION OF RESULTS

We are currently witnessing the Fourth Industrial Revolution, a process that has not only transformed production systems and technologies across various sectors but has also profoundly impacted the agribusiness sector. As a result, the concept of Aquaculture 4.0 has emerged, integrating digital tools and technological advancements into fish production processes.

Understanding the concept of Aquaculture 4.0 is key for individuals and organizations that want to expand their operations more efficiently and sustainably, as it is based on the digitalization of the aquaculture sector with the aim of improving and optimizing the entire production chain [19].

Under the concept of Aquaculture 4.0, there is a set of techniques that aim to digitize the activity through devices, software, and systems capable of transforming the entire production process. These techniques mean greater agility in the work, improved economic efficiency, and a shift towards more sustainable practices.

It is important to mention that among the technologies encompassed by Aquaculture 4.0 is the use of sensors and Internet of Things (IoT) devices, which can significantly contribute to aquaculture management. Interestingly, since 2015, the number of connected and installed IoT devices has steadily increased, and projections indicate that by 2034, the figure will exceed 40 billion [20].

It is also worth mentioning that tilapia aquaculture production ranks among the most distinguished worldwide, reaching over 7.2 million tons in 2021 and generating a value exceeding US\$14.1 billion. This fish is the second most farmed species globally and exhibits an approximate annual growth rate of 7%, driven primarily by China and other Asian countries, which account for around 80% of total production [21].

Consequently, the adoption of technology on farms can generate very positive results, as it would radically transform tilapia production management. This transformation goes beyond simply using sensors to measure variables; it also improves the efficient management of information for optimal decision-making. By using advanced sensors, it is possible to monitor key variables, such as water level, temperature, and fish health, in real time. This continuous flow of data provides valuable information that guides farm management, allowing producers to adjust their aquaculture practices precisely and at the right time.

The incorporation of technological tools allows for increased operational efficiency and a considerable reduction in costs. By collecting and analyzing data in real time, areas for improvement can be identified and more informed decisions made, leading to more effective management and greater control of systems within farms. [22].

Similarly, aquaculture can significantly optimize energy efficiency and the responsible use of resources through the implementation of monitoring technologies. To make aquaculture operations more efficient, sensors can be installed to measure parameters such as temperature, dissolved oxygen, and water quality, among others. This optimizes aeration and water recirculation, which can reduce energy consumption. Furthermore, real-time monitoring facilitates more efficient management and promotes the integration of renewable energy sources.

Once the sensors collect data on the variables as previously indicated, this data must be stored and processed on a platform that makes it available to producers through information management tools. This tool can incorporate AI to visualize, monitor, and analyze the conditions of the ponds or recirculating systems in real time, facilitating timely decision-making. It is essential that it be free, open-source, and decentralized, and that it does not involve licensing costs [23].

Similarly, in terms of profitability, the implementation of technological tools can result in a rapid return on investment for fish farmers, as the combination of cost savings and increased production can place the farm in a prominent competitive position in the market.

Finally, the proposed automation system using sensors and artificial intelligence to improve operational control in tilapia aquaculture can yield tangible results and benefits in key areas, from optimizing feed and water quality to reducing mortality and using energy efficiently. Continuous monitoring of variables such as temperature, dissolved oxygen, and pH enables data-driven decision-making, improving productivity and strengthening the strategic and logistical aspects of production. Adopting these new tools will propel aquaculture companies toward a more technological, profitable, and environmentally responsible model, allowing Industry 4.0 to have a significant and inclusive impact on all stakeholders in the sector. Furthermore, it is not enough to simply consider the overall budget allocated to the fisheries and aquaculture sector; investment in research, development, and innovation should also be prioritized within the country's public policies.

This fosters technical training, applied research in coastal and rural regions, and the consolidation of knowledge for the intelligent use of emerging technologies. Likewise, it is necessary to promote collaboration among the public, private, and academic sectors to ensure the effective, sustainable, and comprehensive implementation of Industry 4.0 technologies in aquaculture [24].

VII. POSSIBLE PROTOTYPE FOR THE PROPOSAL

In accordance with the objectives of this project and after learning about aspects of Industry 4.0 technology, a possible prototype for the proposal is described below, highlighting three main parts: the ATO, the sensors, and the AI connection.

A. ATO (*Auto Top Off system*)

The system consists of an automatic control module or microcontroller that acts as the central processing unit. Due to its low cost and compatibility with free software, the Arduino board is recommended, although other compatible boards can also be used.

The main function of the microcontroller will be to maintain a constant water level and the physicochemical stability of the aquatic environment through a closed feedback system using an ultrasonic sensor. This system must operate based on the continuous detection of variations in the water level, activating a replenishment mechanism when a decrease in the water level is identified, mainly associated with evaporation processes.

For the water supply itself, the microcontroller activates a filling pump through a power stage using a relay or transistor, where the solenoid valve acts as a flow control mechanism within the hydraulic system, thus serving as a complementary shut-off and safety element. This scheme allows for precise and regulated control of the supplied volume, as well as strictly defined opening times through programming. The supply comes from an independent reservoir containing chlorine-free water or water treated by reverse osmosis, a process that removes heavy metals and other contaminants, guaranteeing ionic stability, chemical purity, and minimizing alterations in the physicochemical parameters of the tank water.

Finally, as an operational redundancy measure, a backup control based on a float is incorporated, which functions as a mechanical safety switch in case of possible failures of the ultrasonic sensor or the electronic controller, mitigating risks of overfilling.

B. Sensor system

The proposal incorporates a sensor architecture oriented towards the continuous acquisition of data on different critical variables to ensure the stability of the aquatic environment in the production of tilapia.

First, as mentioned in the previous section, the water level is measured using an ultrasonic sensor. This sensor sends a small sound pulse into the water and then "listens" to the echo that bounces back after hitting the surface. By measuring the

time, it takes for the echo to return, the sensor calculates the distance between itself and the water's surface. The shorter the return time, the closer the water; the longer the return time, the farther away the water is.

On the other hand, the dissolved oxygen (DO) concentration is obtained using a sensor that functions as a small chemical cell. In this case, the oxygen dissolved in the water passes through a sensor membrane and reaches an internal electrode. There, a chemical reaction occurs that generates a small electrical current, the greater the amount of oxygen present, the greater the current produced. The microcontroller detects this amount of current and converts it into a value displayed in milligrams per liter (mg/L) or as a percentage of oxygen saturation.

Next, the temperature is measured using a calibrated thermistor or digital sensor. In the case of a thermistor, its electrical resistance changes as the temperature increases or decreases, allowing the microcontroller to detect this change and convert it into degrees Celsius using a formula integrated into the programming. In the case of a digital sensor, the device measures the temperature internally and directly sends the value, already converted into digital data.

Finally, the pH is determined using a sensitive electrode that produces a small voltage depending on the concentration of hydrogen ions (H^+) in the water. The more hydrogen ions present (more acidic water), the greater the voltage difference; the fewer ions (more basic water), the smaller the voltage difference. The circuit then converts this voltage into a pH value, which is sent to the microcontroller, typically on a scale of 0 to 14.

It is important to mention that an LCD screen will be used to display the values obtained by the previously mentioned sensors. This 16×2 blue LCD module allows up to 16 characters to be displayed on each of its two lines and uses a single-port serial (I2C) interface.

C. AI control module

Artificial Intelligence (AI) is acquiring an important role in electronic systems that employ sensors, because it allows these devices to process information, learn from it and make decisions autonomously, since by integrating real-time data acquisition, predictive analysis can be performed for the automatic management of any environment [25].

In this proposal, this module would process signals from sensors measuring water level, dissolved oxygen, temperature, and pH, correlating them with historical records to anticipate evaporation variations and dissolved oxygen fluctuations.

The system will implement supervised learning algorithms and adaptive statistical models for the processing of multidimensional data from pH, temperature and oxygen sensors. By training with historical records and ideal crop parameters, the model will perform predictive analysis to anticipate critical fluctuations, dynamically calculating the optimal water addition rate, minimizing sudden changes in level and chemical composition. In addition, the module would implement diagnostic routines, comparing expected

values with measurements made to detect anomalies, sensor failures or atypical behavior in real time. In the event of critical events, the system can generate alerts that can be notified through digital interfaces or communication networks, guaranteeing early intervention to adequately maintain the hydrological and chemical stability of the production tanks.

Finally, it is important to mention that, although the implementation of a system with AI involves a greater initial investment, its benefits offset that cost over time. Automation reduces constant surveillance, reduces the probability of making errors and suffering failures, and increases the efficiency and quality of the system. In addition, predictive analysis improves decision making and increases the efficiency and quality of the system. Likewise, using open-source platforms could help eliminate software licensing expenses, offsetting the investment with long-term operational savings, optimizing resources and significantly reducing production mortality. Consequently, this technology not only modernizes the system, but also generates significant economic savings in the medium and long term.

D. Security measures

Furthermore, the proposal includes a section dedicated to safety measures within the automated water replenishment system, designed to prevent overfilling and protect both the electronic components and the tank structure. To this end, a mechanical float is included as an emergency mechanism independent of the electronic control; when the water level exceeds a critical point, this device opens or closes an electrical contact, immediately stopping the water flow safely and reliably.

Consequently, the microcontroller incorporates programming that establishes a maximum operating time for water replenishment, ensuring that the pump or solenoid valve operates only during predefined safe intervals. This combination of mechanical and logical safety guarantees a double layer of protection: even in the event of sensor or control algorithm failures, the system automatically interrupts the filling process before a spill occurs.

The integration of these mechanisms provides greater operational reliability and significantly reduces potential risks, preventing damage to the system and the aquatic environment.

E. Energy systems

Since many aquaculture facilities are in rural or hard-to-reach areas, it may be necessary to use solar panels to power the entire system. These devices capture solar radiation and convert it into electricity, allowing the equipment to operate autonomously. Solar panels, usually made with silicon photovoltaic cells, can convert sunlight into usable electrical energy [26].

For this type of application, a suitable option is the Renogy 100W solar panel, recognized for its good efficiency, resistance and ease of installation, characteristics that make it an excellent alternative for projects of this type.

In addition to solar panels, an energy storage system, such as batteries, is necessary to maintain a continuous power supply for all devices, even at night or on cloudy days. Following the range of equipment provided by Renogy, a suitable option is a 12V, 100Ah deep-cycle hybrid gel battery. This type of battery offers the advantage of using a gel electrolyte, which prevents spills and improves safety, as well as providing a longer lifespan and stable performance in solar systems.

F. Support infrastructure

The implementation of this prototype is economically viable for local producers, with a total estimated cost of approximately \$570 according to current references in the Costa Rican market, since it is designed specifically for farms with limited budgets. The expense is broken down into essential components such as the Arduino board (approximately \$30) [27], the Renogy solar panel (approximately \$120) [28], a gel battery approximately \$230) [29], and precision sensors for measuring pH and dissolved oxygen (approximately \$200). [30] Likewise, the return on investment (ROI) analysis is projected in the medium term, based on the reduction of tilapia mortality and the optimization of manual labor, factors that the FAO (Food and Agriculture Organization of the United Nations) identifies as determinants for profitability in Aquaculture 4.0. In this way, the initial investment translates into an improvement in the financial performance and competitiveness of the aquaculturist.

Finally, it is essential to have at least all the necessary physical infrastructure to support the sensors, protective boxes, cabling installation, and, ultimately, all the elements necessary to guarantee the installation and operation of the system. This infrastructure would be defined according to the topography of the property where the solution is implemented, including cabling and protective boxes, in addition to the necessary infrastructure [27].

G. Diagram of the proposal

Figure 4 shows the block diagram of the proposed aquaculture automation system using information sensors and artificial intelligence for the intelligent management of tilapia ponds, which includes all the components explained above.

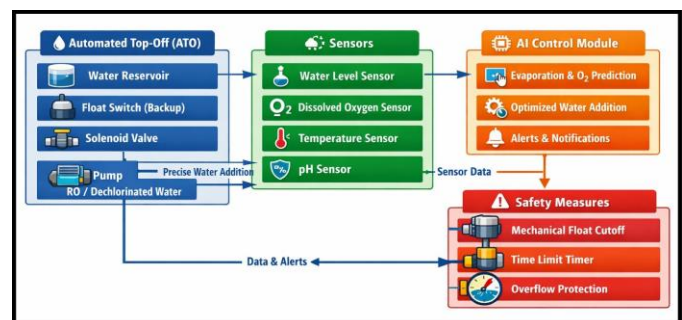


Fig.4 Diagram of the proposal

VIII. CONCLUSIONS

Today it is important to provide fish farmers with a clear understanding of how AI, sensors and automation can improve the efficiency of their production management, suggesting a focus on modernizing and optimizing traditional aquaculture practices.

Similarly, these technologies can help reduce costs in aquaculture systems by greatly improving pond management. Using sensors, it would be possible to identify critical changes or alterations in parameters such as water quality in a timely manner, allowing for localized and precise intervention. In this way, only the strictly necessary measures would be applied, reducing environmental impact, preventing water pollution, and promoting more sustainable and environmentally responsible aquaculture practices [28].

The adoption of emerging technologies can revolutionize how tilapia farmers access information about their aquaculture operations, providing them with real-time data that was previously unavailable. This data availability can improve informed decision-making and more precise management of farm operations, leading to improved tilapia production, increased output, and consequently, a significant increase in the farmer's finances [29].

Although the concept of Aquaculture 4.0 has not yet been officially incorporated into Costa Rican aquaculture policies, a growing strategic environment exists that favors its future implementation. This is due to the country's push for digitalization and the adoption of innovative technologies as part of its institutional and national priorities [30]. Therefore, projects of this type can focus on integrating smart technologies, institutionalizing digital governance frameworks, and promoting training programs that support the transformation of the aquaculture sector toward more sustainable, efficient, and competitive models, opening a world of possibilities that have not been considered until now and that could become the solution to some of the main problems facing society today.

CONFLICTS OF INTEREST

The author declare that he has no conflict of interest at a financial, personal, professional, or institutional level that could influence the judgment of objectivity.

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