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Optimization of energy consumption in a pisciculture system with Biofloc technology using a programmable logic controller (PLC)

Optimización del consumo energético en sistema piscícola con tecnología Biofloc mediante un controlador lógico programable (PLC)

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Abstract: Programmable logic controllers (PLC) are designed to monitor and regulate industrial processes. These electronic systems with programmable memory store control instructions, allowing specific functions to be executed based on the information received by the controllers. In fish farming, energy-intensive processes such as oxygenation and water recirculation are required. However, these processes can be automated using PLCs, adjusting the operating times and intensity of the equipment, allowing energy consumption to be reduced under optimal conditions for aquaculture production. The objective of the study was to implement a PLC-based automation system to monitor and control the Blowers in order to optimize energy consumption and improve the operational efficiency of the system. The methodology focused on the automation of the aeration of the fish farming system with biofloc technology. The results showed a significant reduction in energy consumption, leading to a decrease in production costs.

Keywords: Automation, Biofloc, PLC, Fish farming, Programming.

Resumen: Los controladores lógicos programables (PLC) están diseñados para supervisar y regular los procesos industriales, estos sistemas electrónicos con memoria programable almacenan instrucciones de control, permitiendo ejecutar funciones específicas según la información que reciben los controladores. En la piscicultura, se requieren el uso intensivo de energía para procesos como la oxigenación y la recirculación de agua. Sin embargo, estos procesos son posible de automatizarlos mediante PLC, ajustando los tiempos de operación y la intensidad de los equipos, permitiendo reducir el consumo energético, bajo las condiciones óptimas para la producción acuícola. El objetivo del estudio fue implementar un sistema de automatizado basado en PLC para monitorear y controlar los Blowers con el fin de optimizar el consumo energético y mejorar la eficiencia operativa del sistema. La metodología se centró en la automatización de la aireación del sistema piscícola con tecnología biofloc. Los resultados mostraron una reducción significativa en el consumo energético, conllevando a una disminución en los costos de producción.

Palabras clave: Automatización, Biofloc, PLC, Piscicultura, Programación.

1. INTRODUCTION

Aquaculture production worldwide has grown at an average annual rate of approximately 3.2%, surpassing the population growth rate [1]. In Colombia, fish farming has been implemented for several years; however, it faces challenges related to the adequacy, sustainability, and implementation of production systems. One of the main difficulties lies in the high energy consumption required to maintain optimal system conditions [2], [3], [4].

The Biofloc Technology System (BFT), also known as a symbiotic system, represents an innovative approach in aquaculture. This system is based on the creation of a microbiological environment in which aggregates of microorganisms—such as bacteria, protozoa, and other organisms—develop. Flocs are also formed, playing a key role by reducing the need for external feed, as they convert excess feed and fish excreta into an additional protein source. This process is enabled by heterotrophic bacteria, which metabolise organic waste generated by the fish, transforming it into protein-rich feed [5], [6], [7]. However, one of the limitations of the system lies in its implementation costs, particularly high energy consumption.

For this reason, there is a clear need within aquaculture to improve efficiency in terms of dissolved oxygen (DO), particularly in BFT systems, where heterotrophic and nitrifying microorganisms coexist. The primary function of these microbes is the transformation of nitrogenous compounds into feed or biomass. However, a major challenge associated with high microbial concentrations is the elevated oxygen demand, as not only do the fish or shrimp require oxygen, but the microbial balance also depends on constant and efficient aeration [8], [9].

Given the current challenges, automation becomes highly relevant due to technological advancements. In this context, the implementation of systems capable of monitoring, recording, and controlling variables such as DO emerges as a viable alternative for improving operations, by activating intelligent systems only when conditions demand it [10]. One of the key components in such systems is the programmable logic controller (PLC), which is designed to supervise, regulate, and control industrial processes. These programmable memory-based electronic devices store control instructions, allowing them to execute specific functions based on information received from sensors or other system components [11], [12]. This enables more effective monitoring, contributing not only to fish health but also to the stability of the microbial community and water quality [13].

In BFT-based aquaculture, the intensive use of energy is essential for processes such as oxygenation and water recirculation. However, these processes can be automated through PLCs, adjusting operating times and equipment intensity. This allows for a reduction in energy consumption while maintaining optimal conditions for aquaculture production. Therefore, the objective of this study was to implement a PLC-based automated system to monitor and control the blowers, aiming to optimise energy consumption and enhance the operational efficiency of the system.

2. METODOLOGY

The study was conducted in a fish farming system located near the municipality of Aguachica, Cesar, at an altitude of 160 metres above sea level, with an average annual temperature of 28 °C. The system comprises two ponds, each with a capacity of 74,000 litres of water.

To initiate the BFT process, a water maturation phase was carried out, involving continuous aeration for a period of 40 days. During this time, feed with 45% protein content and molasses were supplied in order to stimulate the development of beneficial bacteria within the culture system. Once the physicochemical parameters of the water reached the required conditions (as outlined in Table 1), the stocking of fish commenced, with a density of 4,500 tilapia fingerlings per pond, each with an average weight of 0.61 g.

***Table 1:** Recommended physicochemical conditions for the pond-based cultivation of Oreochromis sp.*

Condiciones físico y químicas de sistema Biofloc			
Parameter	**Mínimun**	**Óptimal**	**Maximun**
pH	5.0	6.0 – 8.5	11
Temperature (°C)	20	28 – 32	42
Ammonia (ppm)	0.0	0.0	2.0
Nitrites (mg/L)	0.0	0.0	5.0
Nitrates (mg/L)	0.0	0.0	300 – 400
Dissolved Oxigen (mg/L)	1.6	4 – 8	≥9

***Source:** Adapted from Saldaña. [14]*

Experimental design: The groups were organised following a 2×4 factorial design, considering two conditions of the BFT system (with and without automation) and two response variables: oxygenation and energy consumption (Figure 1).

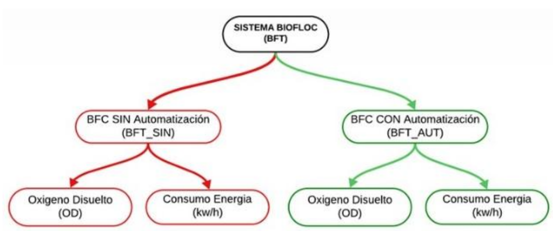

***Fig. 1.** Experimental design diagram*
***Source:** Authors' own elaboration.*

In aquaculture, stagnant water poses several problems, as the lack of circulation creates a favourable environment for the accumulation of harmful bacteria and the formation of toxic gases [15]. In order to prevent these adverse conditions and avoid the concentration of harmful substances, air blowers are used to ensure the homogeneous distribution of dissolved oxygen (DO) throughout the culture ponds. These devices function by delivering DO through poly-diffuser hoses, allowing not only for efficient oxygenation of the medium but also for the constant movement of suspended solids, thereby maintaining a suitable environment for the microorganisms within the system.

Aeration system implementation: In Group I: BFT without automation (BFT_NOAUTO), the aeration system consisted of a 1.2 HP blower operating continuously at a constant speed. In contrast, Group II: BFT with automation (BFT_AUTO) utilised an aeration system comprising two 1.2 HP blowers and two 1.5 HP variable frequency drives, all controlled by a PLC. This setup ensured that at least one blower operated at minimum revolutions to maintain optimal oxygen levels, while the second remained on standby, ready to activate in the event of a failure or under critical conditions (Figure 2).

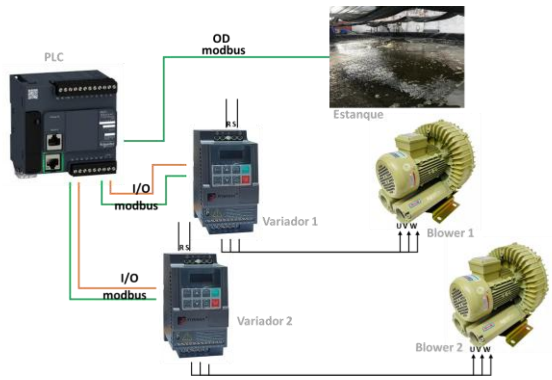

***Fig. 2.** Flow diagram of blower operation in Group II (BFT_AUTO)*
***Source:** Authors' own elaboration.*

Monitoring of active energy (AE) and dissolved oxygen (DO): Data on active energy consumption and DO levels were collected daily from both systems throughout the 182-day production cycle. Energy consumption data were obtained via the direct connection of the blowers, which transmitted operational status and consumption values through a communication system. The PLCs stored this information at set intervals, which was later exported as CSV files for further analysis. DO measurement was performed using an oximeter without PLC connectivity, which necessitated manual data recording on paper sheets, followed by digitalisation for analysis.

Statistical analysis: An ANOVA was applied to evaluate the main effects of automation and system condition on the response variables, as well as their interaction.

3. RESULTS AND ANALYSIS

Energy consumption in Biofloc systems is critical for maintaining water quality, as these systems require continuous aeration to ensure adequate levels of dissolved oxygen. This, in turn, guarantees that physicochemical parameters remain within optimal ranges. In this regard, the results on energy consumption (Figure 3) show that the BFT_NOAUTO system, represented by the red line, maintained a constant energy usage between 16 and 18 kW/h throughout the entire production cycle. In contrast, the BFT_AUTO system, illustrated by the blue line, exhibited a progressive pattern: it started with values ranging from 10 to 13 kW/h and increased gradually over the course of the cycle.

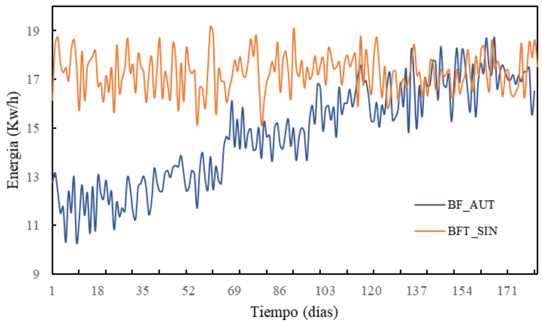

***Fig. 1.** Consumo energético de los sistemas BFT_AUT y BFT_SIN*
***Source:** Authors' own elaboration.*

Mogállón et al. (2020) conducted a study in which they analysed images of microbubbles and foam (ME) using a data analysis programme (MATLAB) and an image filtering algorithm. Their objective was to determine the relationship between the water column height in the pond, the amount of foam generated, and electrical consumption. The results indicated that, among the measured variables, system efficiency can be optimised. They concluded that higher production of ME in water columns ranging from 0.40 to 0.85 m resulted in energy savings of 5% to 8% in the system ($F = 231.64$, $df = 1{,}180$; $p < 0.05$, $p = 8.77\times10^{-41}$) [16].

In the present study, energy savings were observed during the initial months of production, which progressively increased in the final stage. This may be associated with the increase in fish size, which requires greater energy input to maintain optimal culture conditions (Figure 4). In this regard, Hughes (2023) notes that juvenile fish have a less demanding metabolism compared to adults, resulting in lower oxygen consumption due to reduced metabolic demand [17].

In this context, the implementation of BFT systems has not only proven to be a viable alternative for improving operational efficiency—as demonstrated by the findings of this study—but also represents a highly effective strategy to enhance the sustainability of fish farming in Colombia. Hernández et al. (2023) highlight that aquaculture has shown the highest growth rate within the national livestock sector over the past decade and that BFT systems significantly contribute to the natural control of water quality, biosecurity, and nutrient reuse through nitrification processes and the production of high-value bacterial protein [18]. Furthermore, positive effects have been recognised in fish immunostimulation, feed conversion, growth, and reproductive performance. These benefits, combined with the automation of key processes such as aeration, reinforce the potential of automated BFT systems to transform aquaculture into a more efficient and resilient practice.

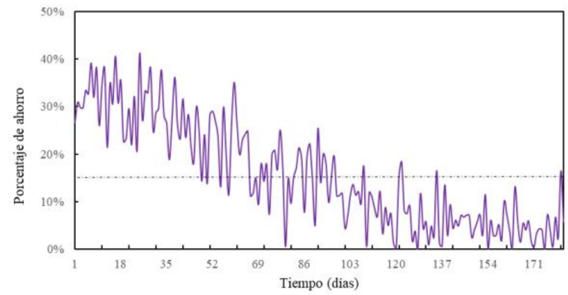

***Fig. 4.** Percentage of energy savings in the BFT_AUTO system*
***Source:** Authors' own elaboration.*

Significant differences were found in the behaviour of dissolved oxygen between the BFT_NOAUTO and BFT_AUTO systems ($F = 144.31$, $df = 1{,}180$; $p < 0.05$, $p = 3.30\times10^{-28}$), as shown in Figure 5, where these systems are represented by the red and green lines, respectively. In the BFT_NOAUTO system, initial dissolved oxygen levels ranged between 7 and 8 mg/L; however, a progressive decline was observed throughout the production cycle, reaching values close to 5 mg/L towards the end. In contrast, the BFT_AUTO system maintained constant dissolved oxygen levels, around 5 mg/L, over the entire cycle. This highlights that the automated BFT system (BFT_AUTO) offers significant advantages in terms of energy efficiency, particularly during the early months of the production cycle. This finding is particularly relevant, as energy consumption associated with aeration represents one of the most significant costs in aquaculture production.

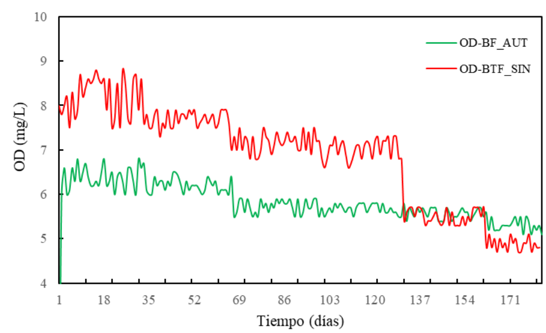

***Fig. 5.** Dissolved oxygen behaviour in BFT_NOAUTO and BFT_AUTO systems*
***Source:** Authors' own elaboration.*

With regard to energy savings, significant differences were observed between the two systems (t-test = 15.21; df = 1, 362; $p < 0.05$, $p = 3.30\times10^{-41}$). The results show that the majority of the energy savings achieved with the BFT_AUTO system occurred during the first three months of the production cycle, in comparison to the BFT_NOAUTO system.

This finding suggests that automation has an immediate impact on reducing energy consumption, which may be attributed to the more efficient use of aeration equipment according to the actual needs of the system. Furthermore, the increasing oxygen demand as the fish grow likely contributed to the progressive rise in energy consumption towards the end of the cycle.

In addition to the benefits observed in the present study with the BFT_AUTO system based on PLCs, it is important to highlight other more integrated technological solutions, such as the AcAS system described by Sasikumar et al. (2024a). This one-stop aquaculture automation system enables users to easily monitor and control culture conditions through a customisable graphical interface. It incorporates high-precision industrial sensors (pH, conductivity, redox potential, and dissolved oxygen), connectivity with modern technologies (Wi-Fi, LoRa/ZigBee, 4G/5G), and data storage capabilities, facilitating real-time decision-making [19].

With regard to physicochemical parameters associated with energy consumption, the nitrogen cycle is particularly influential in fish growth and health, and therefore in meat quality [20]. It is thus essential to maintain these parameters within the recommended ranges (see Table 1).

Figure 6 presents the results for the systems under evaluation. In the BFT_AUTO system, the recorded values remained within the recommended ranges for the cultured species, with a maximum ammonia peak of 1 mg/L, nitrite up to 2 mg/L, and nitrate reaching a maximum of 70 mg/L. These findings are consistent with those reported by Avnimelech (2009), who stated that BFT systems can maintain ammonia concentrations below 1.5 mg/L, thanks to the activity of heterotrophic bacteria, which efficiently assimilate nitrogenous compounds [21]. Similarly, Tasleem et al. (2024) highlight that nitrite concentrations below 5 mg/L and nitrate levels of ≤60 mg/L do not produce adverse effects in fish. These findings confirm that the BFT system is capable of efficiently controlling nitrogen compounds, contributing to a stable and healthy aquatic environment for the microbial community within the culture system [22].

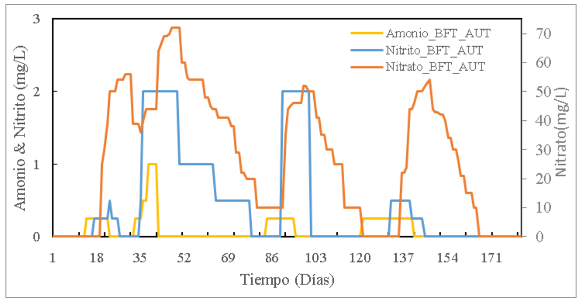

Fig. 6. *Ammonia, nitrite, and nitrate behaviour in the BFT_AUTO system*
Source: *Authors' own elaboration.*

In contrast, Figure 7 shows the results for the BFT_NOAUTO system, where maximum concentrations of ammonia, nitrite, and nitrate were observed at 0.5 mg/L, 1 mg/L, and 5 mg/L, respectively. These values fall within the acceptable limits for aquaculture. Notably, when compared with the BFT_AUTO system, the BFT_NOAUTO system exhibited less fluctuation in nitrogen compounds, indicating more stable water quality. These findings are consistent with those reported by Putra et al. (2020), who observed ammonia, nitrite, and nitrate concentrations of 0.02 mg/L, 0.43 mg/L, and 3.20 mg/L, respectively. These values are comparable to those observed in the present study, further supporting the effectiveness of the BFT system in controlling nitrogen compounds through the use of carbon sources such as molasses, which promote heterotrophic microbial activity [23].

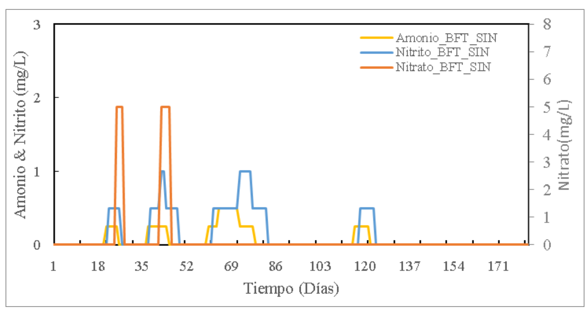

Fig. 7. *Ammonia, nitrite, and nitrate behaviour in the BFT_NOAUTO system*
Source: *Authors' own elaboration.*

Based on the above, the results obtained in this study using the BFT_AUTO system demonstrate a positive trend towards automation in aquaculture, showing significant improvements in energy efficiency and DO control. Similarly, a study on BFT-based shrimp farming reported that a sensor-based automation system substantially improved production parameters, including specific growth rate (28.66%), protein efficiency (0.49 ± 0.01), and survival rate ($65 \pm 2.6\%$), compared to manual practices (Sasikumar et al., 2024b). They also reported a notable reduction in nitrogen compounds (ammonia, nitrite, and nitrate), suggesting enhanced water quality management [24]. These findings are in line with the benefits observed in the present study, where the use of programmable logic controllers (PLCs) enabled the maintenance of more stable DO levels and the optimisation of energy consumption. Although the system implemented in this research was simpler than that described by Sasikumar et al., the results confirm that even basic levels of automation can generate positive impacts in BFT systems.

Therefore, the results obtained in this study reaffirm the potential of automation via PLCs in BFT aquaculture systems to enhance energy efficiency and operational control. However, it is acknowledged that this experience corresponds to an initial validation phase conducted under controlled conditions and with a limited number of experimental units. While certain key variables, such as pH and temperature, were monitored manually, their integration into future versions of the automated system represents a valuable opportunity to strengthen real-time control and advance towards more intelligent and interconnected aquaculture production schemes.

As can be inferred, the PLC-based automation demonstrated in this study proves to be a viable strategy for optimising energy consumption in BFT systems, particularly in regions where electricity costs significantly affect production margins. This solution can be adapted to different geographical contexts, including areas with warm climates and limited water availability. Its implementation does not require highly specialised infrastructure, making it scalable for small- and medium-scale aquaculture operations. From a cost–benefit perspective, although the initial investment in sensors, variable frequency drives, and the programmable logic controller may represent a moderate increase in installation costs, the operational benefits—including energy savings, reduced technical failures, and optimised oxygen utilisation—clearly justify its adoption in the medium term. Furthermore, by improving culture efficiency and stabilising production conditions, it contributes indirectly to the environmental and economic sustainability of the system.

4. CONCLUSIONS

This study evaluated the implementation of a PLC-based automation system to optimise energy consumption and maintain appropriate levels of dissolved oxygen in Biofloc (BFT) aquaculture systems. The implementation of the automatic control system enabled more precise management of aeration, reducing energy consumption without compromising the physicochemical parameters essential for the growth of aquatic organisms.

The analysis of the relationship between dissolved oxygen and energy consumption suggests that automation not only optimises the use of energy resources but also enables more efficient water quality management. As the fish grow, energy demand increases, highlighting the need for dynamic adjustment of aeration capacity—precisely what the automated system allows.

PLC-based automation in BFT aquaculture systems represents an effective strategy for improving operational efficiency, reducing energy costs, and ensuring optimal environmental conditions for culture. The implementation of similar technologies is recommended in other aquaculture systems to support sustainable production and more efficient resource use.

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