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Hybrid aquaculture and its effects on physicochemical and biological water parameters and on the productivity of *Dormitator latifrons* and *Lactuca sativa* var. *Crisp*.

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ABSTRACT

The research was carried out at the Instituto Superior Tecnológico "Luis Arboleda Martínez" (Jaramijó, Manabí, Ecuador), with the aim of evaluating the interactive effect of hybrid aquaculture using RAS-NFT technologies (Recirculating Aquaculture Systems – Nutrient Film Technique) on the physicochemical and biological parameters and productivity of *Dormitator latifrons* and *Lactuca sativa* var. *Crisp*. An aquaponic system of a 2000 L main reservoir, decanter, biofilter, degasifier, NFT modules and secondary reservoir was implemented, physicochemical and biological parameters of the water were monitored for five months at six points, applying the INEN 2176:2013 standard. The results showed the ability of the system to maintain water stability. The pH ranged from 7.63 to 8.19; total dissolved solids (TDS) ranged from 367 to 457 mg/L; electrical conductivity (EC) between 7.08 and 7.68 mS/cm; salinity was reduced from 4954 to 4580 ppm in NFT, then increased by evapotranspiration; and the temperature stabilized at 26.6 °C after dropping to 24.6 °C in the siphon. Dissolved oxygen (DO) decreased to 0.81 mg/L in the siphon, but recovered to 5.82 mg/L in the secondary reservoir. Alkalinity ranged from 44 to 60 mg/L, total hardness was reduced from 318 to 283 mg/L, chlorides from 91 to 79 mg/L, and turbidity remained stable except in the siphon (73.6 NTU). Total coliforms decreased from 137 to 73 CFU. The effect of the compartment (system components) by multivariate analysis (MANOVA) determined significance ($p \leq 0.001$) on the physicochemical variables of the water. All multivariate statistics (Pillai Trace, Wilks Lambda, Hotelling Trace and Roy's Major Root) confirmed that the compartments of the aquaponic system are not homogeneous, indicating differences according to location. In terms of production, fish increased their biomass by 72.06%, while lettuce reached a weight of 940 g in the first harvest, while the second recorded 1081 g. Socially, community training achieved 87% attendance, with improvements of 30–35 percentage points in knowledge. The feasibility of integrating NFTs and RAS as sustainable production alternatives, optimizing water quality, biological efficiency and community participation, is demonstrated.

Keywords: aquaponics, *Dormitator latifrons*, *Lactuca sativa* var. *crispa*, NFT, RAS, physicochemical parameters, community participation.

INTRODUCTION

The need to reuse and propose sustainable aquaculture systems has become a global alert, considering that only 0.01% of available freshwater requires the optimization of the use of biosystems (Flores and Soto, 2024). In this context, aquaculture has reached a global production of 51.4 million tonnes, representing between 16.8% and 30% of the supply destined for direct human consumption. Since its inception, this industry has shown accelerated growth driven by the high demand for products in the most developed economies (Mendo et al., 2020).

Aquaponics is presented as a sustainable alternative for aquaculture production, as it allows food resources to be optimized and, in the case of Ecuador, small-scale activities support the food security of families (Barragán et al., 2021; Zárate et al., 2024). The aquaponic system is a technique that combines fish farming (aquaculture) with plant cultivation (hydroponics) in a closed cycle: fish waste nourishes the plants and the plants filter the water, which returns clean to the fish. NFT technology, in particular, flows a thin film of nutrient-rich water through the channels where roots develop, absorbing what is needed; however, this continuous flow requires constant monitoring to avoid accumulation of toxic waste or sudden changes in chemical parameters (Arias and Pardo, 2020).

Aquaponics provides an integrated source of protein (chame) and vegetables, offering fresh and nutritious food in controlled environments, by monitoring physicochemical parameters (such as pH, oxygen, temperature), an optimal environment for efficient and healthy production is ensured, reducing losses and improving food quality, which contributes to the availability of local and safe food (Somerville et al., 2022).

By implementing an aquaponic system with NFT technology, it fosters local economic development by creating jobs and opportunities in rural or urban areas, these systems can be operated on a small scale, promoting food production at the community level, which decreases dependence on imports and strengthens local economies, in addition, the sale of fresh products such as chame and vegetables can generate income for small farmers and local entrepreneurs. encouraging innovation and self-sufficiency (Sánchez and Gómez, 2023).

This system is highly efficient in the use of resources such as water and nutrients, by recycling fish waste to nourish plants, waste is minimized and environmental impact is reduced, which promotes sustainable agriculture and production, since NFT technology maximizes the efficiency of space and nutrients. making this aquaponic system suitable for areas with limited resources, which contributes to soil conservation and responsible water use (Gómez, 2024).

The physicochemical parameters of the water are decisive for the balance of an aquaponic system, since pH regulates the availability of nutrients and prevents toxicity, while the right temperature prevents stress in fish and favors the absorption of nutrients. Dissolved oxygen is essential for both fish and nitrifying bacteria, which transform toxic ammonia into nitrites and then into nitrates that can be used by plants. Likewise, electrical conductivity reflects the concentration of dissolved salts necessary for its growth (Osorio, 2016). In this sense, water analysis ensures an optimal environment for fish such as chame and plants, and it is essential to keep the parameters within appropriate ranges. NFT technology, although it favors the efficient use of nutrients, requires constant monitoring to prevent imbalances that compromise the stability of the system (Osejos Merino et al., 2018).

MATERIALS AND METHODS

Location

The research was carried out at the Instituto Superior Tecnológico "Luis Arboleda Martínez" located in the canton of Jaramijó in the province of Manabí, with coordinates WGS84/UTM Zone: 17S (southern hemisphere) – central meridian −81° Easting (E): 541 047.586 m, Northing (N): 9 895 077.192 m (Figure 1).

The research is non-experimental, focused on determining the behavior of physical, chemical and biological parameters in RAS and NFT systems with the production of plant and animal biomass.

Establishing the operating conditions of the aquaponics system with NFT and RAS technology

According to Vargas Peña and Flórez Pacheco (2024), the cultivation process begins with the water storage system, providing key information about the conditions that affect the crop. Various external factors, such as temperature, humidity and sunlight, influence the system, as well as internal variables such as pH, nutrient solution, circulation time, temperature, water oxygenation, water level in the tank and water flow (Mazzini et al., 2024).

Recirculating water systems in aquaculture (RAS) facilitate the production of aquatic species in tanks that have specific characteristics for fish welfare. These systems operate under strict controls and employ filters to purify recirculated water, although new water also needs to be added due to evaporation and splashing (Hernández, 2020).

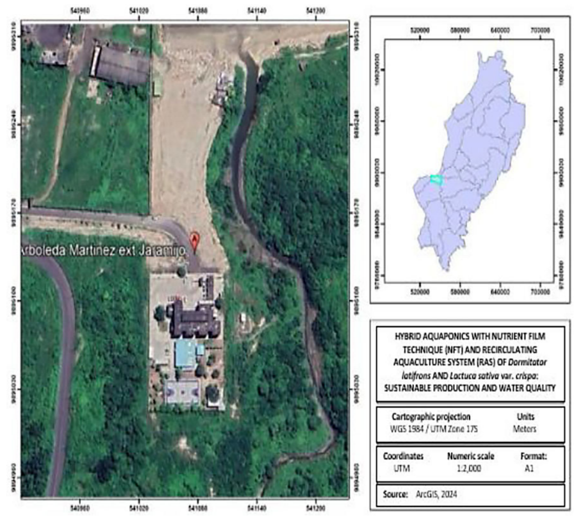

Figure 1. Geographic location map

Technical characteristics of the tanks

Tanks used in recirculation systems are oversized containers made of sturdy materials, designed to store water efficiently. Each tank plays a specific role within the system, such as the use of the biofilter, sedimentation or the cultivation of organisms, and its dimensions (diameter, height and thickness) are adjusted according to the needs of the system. Vargas et al. (2021) mention that it is feasible to measure the volume of water for each species introduced into the tanks.

Hydraulic characteristics of the system

The system works with the hydraulic implementation which is characterized by the different parts it contains, such as loads, pipes, pumps, aeration system, among others, which are the basis of the entire system for the behavior of the relationship between the introduced species (Mejía, 2024).

Biofilter

The biofilter is a fundamental part of any RAS system, understood as any type of filtration that helps to improve recirculation, living organisms are used to eradicate any type of impurities from the water, this process helps to transform toxic nitrogenous compounds generated by aquatic organisms through the nitrification process (García et al., 2021). That is why a biofilter was implemented in the NFT system that incorporated activated carbon as a hybrid medium, with the dual function of adsorption and microbial support, which favors the removal of dissolved organic compounds and micropollutants, while providing a porous surface for the growth of nitrifying and heterotrophic bacteria. accelerating the establishment of biofilm and improving efficiency in nutrient removal.

Recent studies have shown that the integration of activated carbon in biofilters shortens the nitrification start-up time and increases the ammonia nitrogen removal capacity compared to conventional systems (Papciak et al., 2024). In addition, research on bacteria immobilized in activated carbon shows a high efficiency in the removal of total phosphorus and nitrogenous compounds from aquaculture effluents, which confirms its applicability in high-performance aquaponic systems (Huang et al., 2023).

Management of the species Dormitator Latifrons

The process of acclimatization of species turns out to be a stressful stage, since it involves their adaptation to the new system, this process is influenced by factors such as variations in temperature, pH and salinity, which must be kept in optimal conditions to facilitate the transition over a period of 24 hours (Somerville et al., 2022).

The specimens of chame (*Dormitator latifrons*) were collected in the La Segua Wetland, obtaining a total of 250 specimens. The fish were transported in plastic containers with supplemental oxygenation in a vehicle to the ISTLAM aquaculture laboratory. Once in the laboratory, an initial biometrics was performed to record weight and height, selecting 100 representative individuals. Subsequently, a prophylactic disinfection treatment was applied by means of sodium chloride baths before entering the experimental system. The organisms were subjected to an acclimatization process in an aquaponic system with water recirculation (RAS) for 48 hours, under salinity conditions of 6.53 UPS. During this period, their external condition was monitored, assessing skin and fins for possible parasites or damage. Finally, the fish were placed in the experimental system with a condition of 0% salinity for the development of the research.

Management of Lactuca sativa var. Crisp

For the management of the crespa lettuce crop, a substrate composed of rice husks, ground eggshells and river sand was used, which was used for the initial sowing of the seeds in germinators. In total, 47 seeds were sown, which remained in this stage for 15 days, during which time they reached adequate development for transplantation. Subsequently, the seedlings were transferred to the NFT system**,** where they continued their growth and development under the conditions of the aquaponic system.

Physicochemical and biological parameters of water

Monitoring point

Within the aquaponic system, the physicochemical parameters of the water in all the components of the system were evaluated, these points are main reservoir (1), inlet, outlet and siphon decanter (2), biofilter (3), degasser (4), NFT inlet and outlet (5) and secondary reservoir (6), evaluating the parameters at these points is essential to detect and calculate the absorption and efficiency of the system as well as to avoid possible imbalances. identify problems in water treatment and ensure that conditions are suitable for the optimal development of aquatic species and plants (Hernández et al., 2024).

Frequency of monitoring

The methodology used was adapted to the characteristics of the place, the samples were collected in a timely manner at the points previously determined. The INEN 2176:2013 sampling standard was applied, the samples must be kept at room temperature, sterile glass containers of 400 ml were used, which were filled so that there are 50 ml between the sample and the lid, which allowed agitation (Instituto Nacional Ecuatoriano de Normalización [INEN], 2013) the monitoring of the system was carried out twice a week, over a period of five months.

Analysis of physicochemical and biological parameters

Table 1 presents the parameters evaluated during the research and the methods used in the Biotechnology Laboratory of the Technical University of Manabí (UTM).

Statistical analysis

Multivariate analysis of variance (MANOVA)

The MANOVA model was applied, a statistical tool that allows evaluating the effects of compartment, time and internal correlations of the system, providing statistical evidence on the dynamics of nutrients in each part evaluated (Jiang and Nguyen, 2021). This model integrates multivariate statistics (Pillai Trace, Wilks Lambda, Hotelling Trace and Roy's Major Root).

Plant-to-fish ratio

The method developed by the University of the Virgin Islands has proven to be a successful model due to its ease of implementation. However, there is no single optimal ratio for the fish-plant ratio, as it depends on factors such as the type of fish, the water flow rate and the efficiency of the biofilter. Generally, a 1:1 ratio is common, although it can be adjusted to 1:3 or 1:4 depending on system conditions (Santinón et al., 2023).

It is essential to balance the nutrient production generated by fish with the absorption capacity of plants. As both fish and plants grow, it is recommended to adjust this ratio: increasing the number of plants or reducing the number of fish to keep the fish's biomass constant and control feeding. Conversely, if plant numbers are low and excess food is supplied, nutrients can accumulate to toxic levels, requiring more frequent water exchanges (Medina et al., 2023).

In this study, the stocking ratio used was 1:1, planting 47 specimens of *Pacific fat sleeper* (*Dormitator latifrons*), obtained from the La Segua wetland, San Vicente, Ecuador. 47 lettuce seeds (*Lactuca sativa* var. *CRISPA*), previously germinated in plastic seedbeds at a rate of four seeds per container. Once the seedlings developed their first true leaves, they were transplanted into the hydroponic baskets with blonde turbid substrate and placed in the horizontal NFT system.

Absorption of nutrients by *Lactuca sativa* var. Crisp

To integrate these variables, net absorption was calculated using the following equation:

$$Absorción\ neta\ (g) = \\ = \frac{C_i \times V_i - C_f \times V_f}{1000} - P + R \quad (1)$$

where: *y* represent the initial and final concentrations of nutrients (ammonium, phosphorus and nitrites) in the water, $C_i C_f V_i$ and V_f the volumes of the solution, the production of nutrients contributed by the fish and the average removal performed by the biofilter, converting the mass differences from mg to grams, incorporating the excretion of the fish and adding the removal of the biofilter, thus obtaining the net absorption in grams. PR

TEP Technology

Knowledge technology, with participation in aquaponic systems, requires a comprehensive approach that combines community participation and learning assessment. Studies of Casanova et al. (2025), contemplate information and communication technology (ICT) initiatives in agriculture, such as sharing knowledge and improving technical skills, resulting in increased productivity and sustainability. In this context, empowerment and participation technologies (TEPs) are strategies that help motivate participants to take advantage of the productive and sustainable potential of the model, as indicated by the study of Díaz et al. (2025) highlighting that the use of digital platforms and mobile applications in environments encourages the active participation of the community, allowing the collective construction of knowledge and the application of solutions adapted to their reality.

The knowledge test allows you to reinforce key concepts (Giraldo et al., 2021), the definition, components and benefits of the system were addressed, as well as its cycle, the fish-plant relationship and the monitoring of water parameters, providing the necessary conceptual and practical basis. Operation and maintenance, fish feeding, plant care and disease prevention were also included, strengthening practical skills.

RESULTS

Structure of the aquaponic system

Model and description

Figure 2 presents the structure of the aquaponic system that was used in the research. This model integrates the technology of a recirculating aquaculture system (RAS) for the rearing of chame (*Dormitator latifrons*) with a nutrient film technique (NFT) system for the cultivation of lettuce (*Lactuca sativa* var. *Crispa*).

RAS and recirculation system flowchart

According to the process of the aquaponic system, the following flowchart is presented:

Description

The aquaponic system with RAS and NFT technology integrates components that maintain the water-fish-plant balance through an efficient and sustainable recirculation process. The main reservoir of 2000 L, built with materials such as PVC or fiberglass, allows fish farming and water aeration. This then passes through a 360 L decanter, which retains the solids generated by excretion and leftover feed, allowing clean water

Table 1. Physicochemical and biological parameters

Parameter	Measurements	Method
Physical-chemical		
pH	-	Potentiometry
Total dissolved solids (TDS)	mg/L	Conductometry
Salinity	mg/L	Conductometry
Temperature	°C	Conductometry
Dissolved oxygen	mg/L	Oximetry
Colour	Pt-Co	Spectrophotometry
Turbidity	NTU	Spectrophotometry
Total hardness	mg/L $CaCO_3$	Tritation
Alkalinity	mg/L	Tritation
Chlorides	mg/L	Tritation
Nitrites	mg/L	Tritation
Ammonium	mg/L	Tritation
Biological		
Total coliforms	MPN/100 ml	Most probable number method

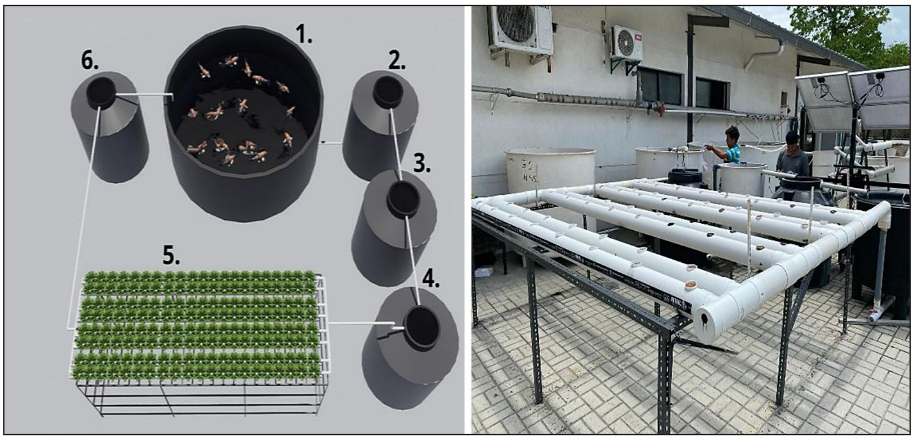

Figure 2. Description of RAS (recirculating aquaculture system) technology
1. Main reservoir: breeding of chames (*Dormitator latifrons*); 2. Decanter: removal of coarse solids; 3. Biofilter: biological nitrification; 4. Degasser: removal of dissolved gases; 5. NFT system: Nutrient Film Technique; 6. Secondary reservoir: water collection and recirculation

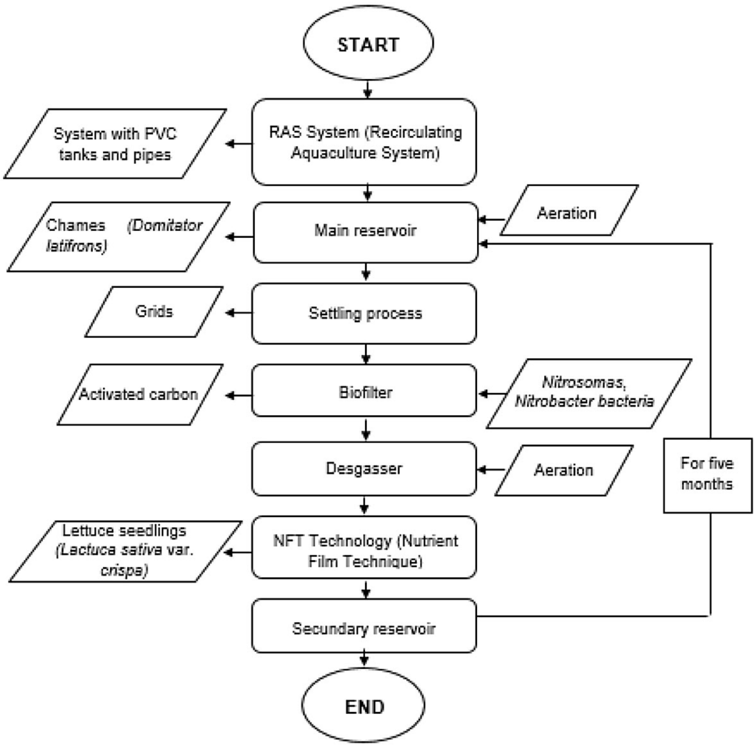

Figure 3. Description of the aquaponic system

to continue flowing (Capanema and Carvalho, 2022). Subsequently, it passes through a 500 L filtration system with activated carbon and a biofilter of the same volume, where nitrifying bacteria transform ammonium into nitrates (Floriano et al., 2023; Da Silva Rodrigues de Assis et al., 2023; Monsees et al., 2019). The 500 L degasser then removes dissolved gases, and in the NFT module, the plant roots absorb nutrients and oxygen to optimize their growth. Finally, the water passes through a secondary reservoir of 500 L, which oxygenates it in cascade before returning to the main tank.

The effluent from the biofilter is directed to an aeration system by hydraulic fall, which in addition to oxygenating the water, acts as a degassing mechanism, facilitating the elimination of gases such as CO_2 (Sánchez et al., 2014; Márquez and García, 2022). Finally, in the NFT (nutrient film technique) system, nutrients are continuously recycled, preventing losses and reducing soil pollution (Nirmal and Ahmad, 2024; Palmitessa et al., 2024).

Physical-chemical and biological parameters of water

Figure 4 illustrates the pH fluctuations in the recirculation system, starting at a slightly alkaline value in the Main Reservoir (8.1125), which then descend in the Decanter and Siphon, reaching their lowest point (7.6313). Subsequently, this parameter rises notably in the Biofilter and in the Degasifier, reaching its peak of 8.0988 being more alkaline, before falling again in the input and output of the NFT (7.9188 and 7.8313 respectively) due to the activity of the nutrient biofilm. Finally, it stabilized in the Secondary Reservoir with a value of 8.1975, demonstrating that the system manages to maintain the pH within an acceptable range.

Figure 5 shows the variations of total TDS throughout the system, starting with 390.14 mg/l in the Main Reservoir, experiencing an initial increase to 439.94 mg/l at the Decanter inlet that is later reduced to 399.71 mg/l. The TDS value follows an upward trajectory through the Siphon (431.34 mg/l) and reaches its peak in the Biofilter (457.61 mg/l), where microbial activity increases the concentration of dissolved solids. Subsequently, the TDS decreases in the Degasser (409.95 mg/l) and reaches its lowest level at the input of the NFT (367 mg/l), which could indicate a previous nutrient uptake by plants or dilution, before increasing again to 398.58 mg/l at the exit of the NFT due to water uptake by vegetation. Finally, the value stabilized in the Secondary Reservoir at 401.84 mg/l, demonstrating that the system has a consistent range in its stages.

Figure 6 shows that there is thermal variation in the temperature of the water throughout a process, starting with a high temperature of 27.43 °C in the Main Reservoir and in the decanter, then the decrease in the output of the decanter and the lowest point in the siphon (24.63 °C). Subsequently, the temperature is recovered in the Biofilter and the Degasifier, reaching 26.41 °C, during the recirculation of the NFT it is stabilized at the inlet and outlet with values of 26.15 and ending in the Secondary Reservoir with a temperature of 26.61 °C. On the other hand, Figure 7 illustrates the variations in dissolved oxygen levels, starting with a high concentration of 5.44 mg/L in the Main Reservoir, decreasing in the Decantation stages and at its lowest point the Siphon with just 0.81 mg/L. It increases its oxygen levels considerably in the degasser (4.84 mg/L.) demonstrating the recovery capacity by deoxygenating the water in the Biofilter and the Degasifier. Finally, there is a slight decrease within the NFT system until the exit, culminating in an increase and stabilization in the secondary reservoir of 5.82 mg/L.

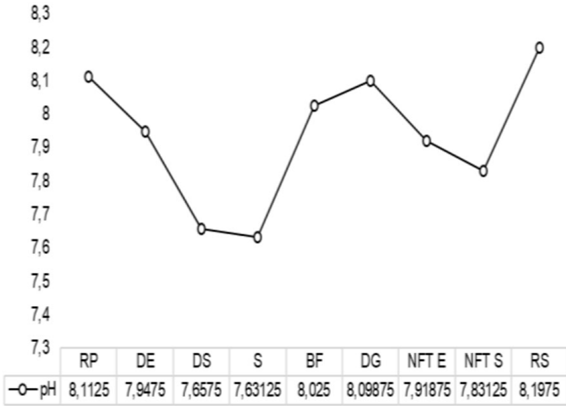

Figure 4. pH behavior in system recirculation

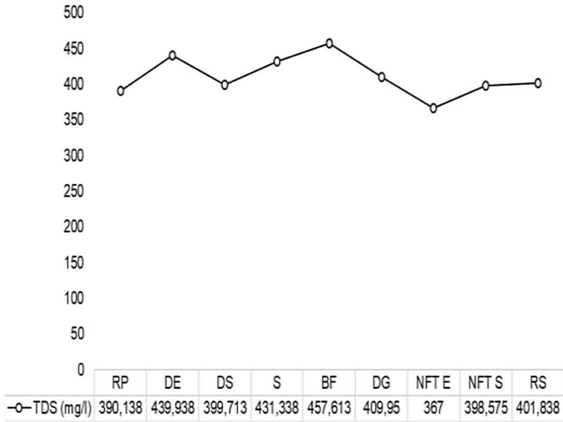

Figure 5. Behavior of TDS (total dissolved solids)

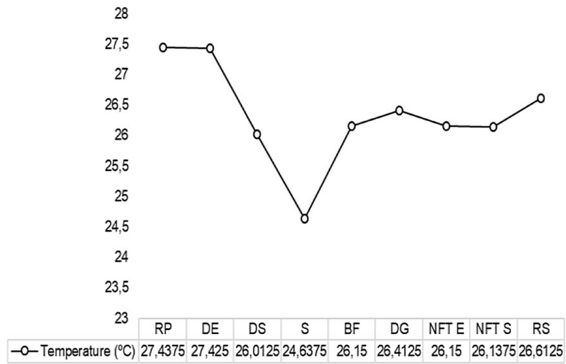

Figure 6. Temperature behavior

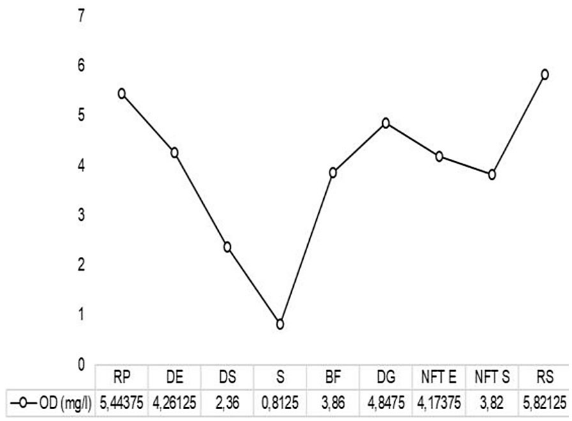

Figure 7. DO (dissolved oxygen) behavior

Note: Main reservoir (RP), inlet decanter (DE), outlet decanter (DS), siphon (S), biofilter (BF), degasser (DG), inlet NFT (NFT E), outlet NFT (NFT S), second reservoir (RS).

Figure 8 shows the salinity throughout a process, the concentration in the Main Reservoir and at the outlet of the Decanter is (4954 ppm), it tends to decrease progressively at the four points of the system, reaching the entry of the NFT as its lowest point with a value of 4580.5 ppm, and then having an increase in its output (4712.7 ppm) due to the evapotranspiration process, finally it has a slight decrease in the Secondary Reservoir again, demonstrating that the NFT is a determining factor in the accumulation of salts. Figure 9 shows the behavior in the conductivity variations, obtaining as a base a value of 7.45 mS/cm in the main reservoir and at the decanter inlet. Increasing the output of the NFT with values of 7.68 mS/cm, to then descend in the following stages and reach its lowest point at the entry of the NFT (7.08 mS/cm). Subsequently, an increase in the output of the NFT (7.32 mS/cm) is observed due to the

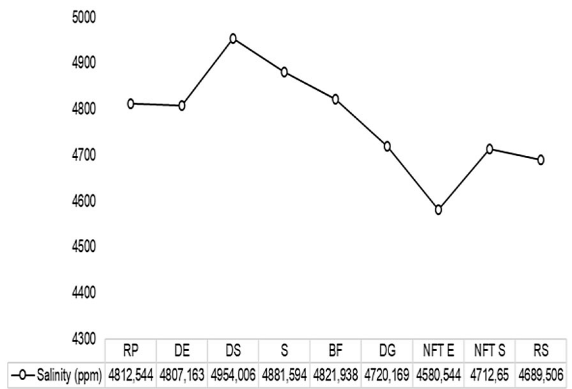

Figure 8. Salinity behavior

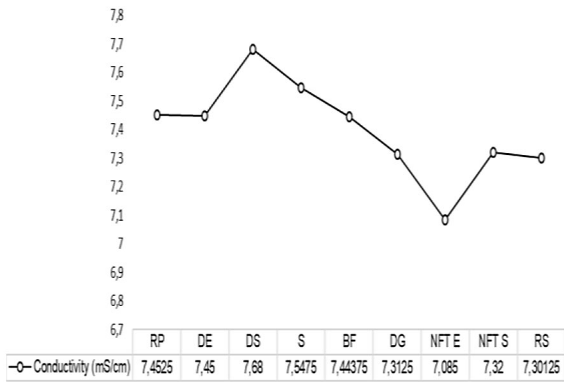

Figure 9. EC behaviour

concentration of ions caused by the absorption of water and nutrients from the plants, likewise in the final stage it stabilizes slightly in the Secondary Reservoir (7.30 mS/cm), making known the importance of the NFT as a crucial factor in the ionic dynamics of water.

Figure 10 shows that there is only one variation in the siphon recirculation system, which occurs due to sediments, it reaches a value of 73.59 NTU, however, it remains stable in the other components of the system, which indicates that the system has stability in this parameter. On the other hand, Figure 11 shows the concentration of chloride at eight points in the aquaponic system, revealing fluctuations. The initial concentration in the Main Reservoir is 85.281 mg/L, but it rises to 91.418 mg/L in the decanter, indicating an accumulation of salts. As water flows through the decanter outlet and siphon, the concentration drops to a range of 84–85 mg/L and remains remarkably stable in the biofilter and NFT system. The behavior culminates with a notable decrease to 78,873 mg/L in the Secondary Reservoir.

Figure 12 shows the dynamics of alkalinity in water. It starts at 46.95 mg/L in the Main Reservoir, but rises to more than 60 mg/L in the decanter. The level remains high in the siphon and biofilter, but a drop in the degasser is observed, to 44.675 mg/L, behavior determined by the nitrification process in the biofilter and the release of CO_2 in the degasser. Alkalinity is slightly maintained at the inlet and outlet of the NFT channels, and the system ends at 50.2 mg/L in the Secondary Reservoir, crucial values to buffer the pH and health of both the fish and plants. Regarding color, it starts at 48.375 Pt/Co in the Main Reservoir and undergoes an initial reduction in the decanter. However, the most notable point is the sudden peak of 59.375 Pt-Co in the siphon,

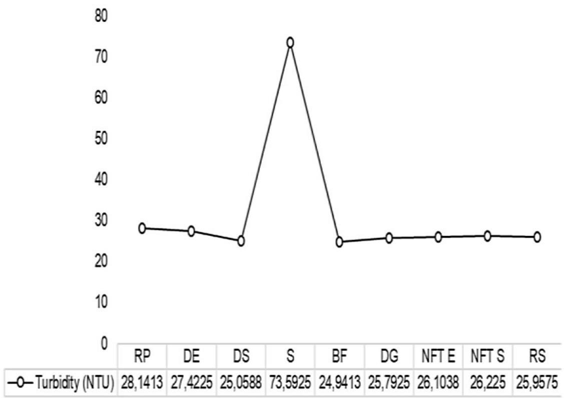

Figure 10. Turbidity behavior

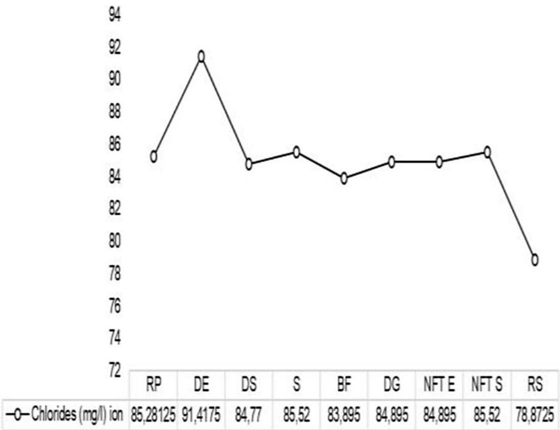

Figure 11. Chloride behavior

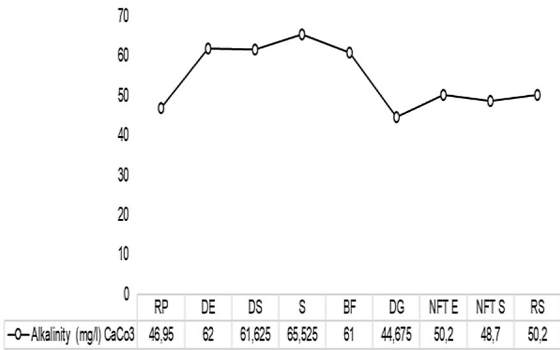

Figure 12. Alkalinity behavior

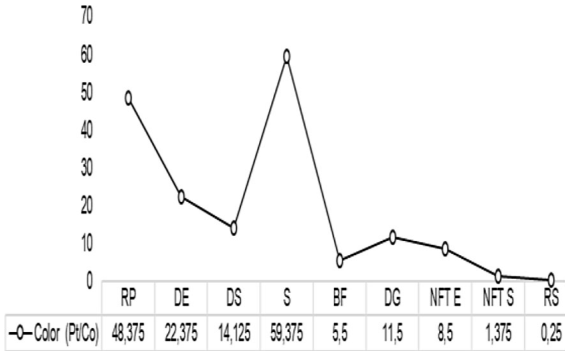

Figure 13. Color behavior

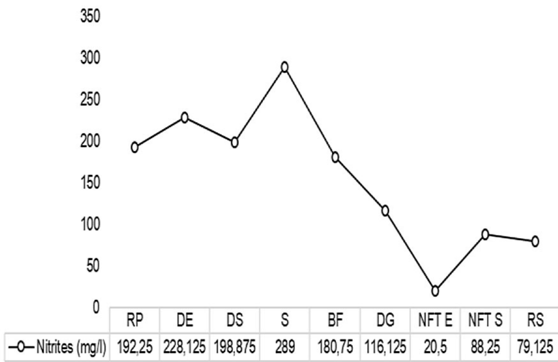

Figure 14. Behavior of nitrites

suggesting a release of accumulated organic matter, then the color is reduced to 5.5 Pt-Co in the biofilter that in addition to nitrification, also removes color-giving compounds, and continues to decrease through NFT channels thanks to uptake by plant roots and bacterial activity. The process concludes with a low color value of 0.25 Pt-Co in the Secondary Reservoir (Figure 13).

Figure 14 shows the initial value of 192.25 mg/L, slightly increasing at the decanter inlet, as well as a decrease in the output (198.875 mg/L). There is a large concentration that increases to its value in the siphon (289 mg/L) giving a great job for the biofilter, then considerably lowers to the point of the input NFT being a value of (20.5 mg/L). Despite this behavior, the final value of nitrites in the Secondary Reservoir (79.125 mg/L). The phosphate graph (Figure 15) shows that the initial concentration is low, but shoots up to a massive peak of 206.56 mg/L in the Outlet Decanter, indicating the release of this nutrient from the decomposition of organic matter and fish excreta accumulated at this point. However, the system demonstrates remarkable stability through the biofilter, degasser and NFT channels. This rapid and continuous reduction is evidence of the efficient uptake of phosphates by plants, which is an essential nutrient for their growth, culminating in a low level of 3.35 mg/L in the Secondary Reservoir.

The ammonium graph (Figure 16) shows a high peak of 6.5 mg/L in the siphon, associated with the decomposition of accumulated organic matter. However, the system responds efficiently:

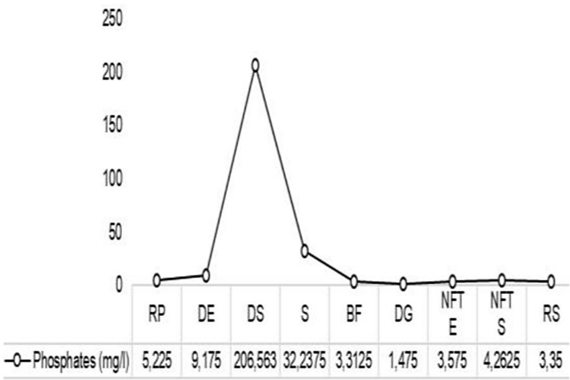

Figure 15. Phosphate behavior

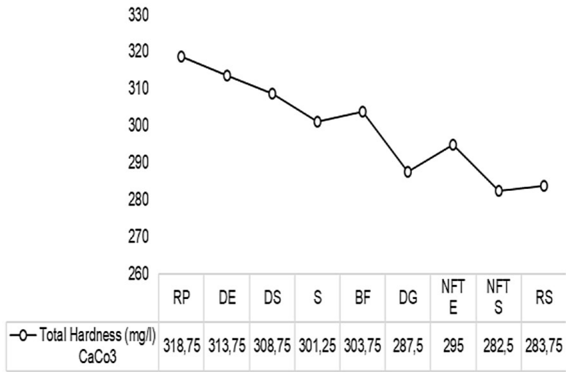

Figure 17. Total hardness behavior

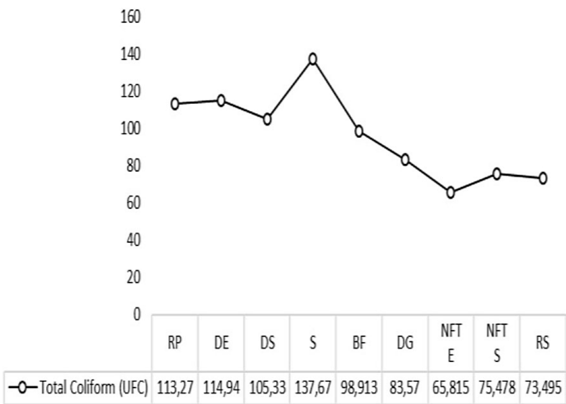

Figure 18. Behavior of total coliforms

in the biofilter, achieving a reduction. From there, concentrations remain low and stable in the degasser and NFT channels, where plant roots take advantage of it. Finally, in the Secondary Reservoir the level drops to 1 mg/L. The total hardness (Figure 17) shows a decrease throughout the system. The water starts with a relatively high level of 318.75 mg/L in the Main Reservoir and decreases as it progresses through the different stages, highlighting a marked drop in the degasser (287.5 mg/L) and a constant reduction in the NFT channels. The lowest value is recorded in the Secondary Reservoir with 283.75 mg/L. Throughout the aquaponic system, the concentration of total coliforms (Figure 18) begins with an equilibrium in the first two points (113.27 and 114.93 CFU) having a slight decrease in the output of the decanter, later showing a variation in the siphon, this being the highest point with values of 137.67 CFU, then begins a decrease to the point of the NFT, reaching its lowest point with values of 65.81 CFU at the inlet and 75.47 at the outlet, this being the most efficient part within the whole system, finally the concentration stabilizes in the Secondary Reservoir at 73.49 CFU, demonstrating that, despite the intermediate fluctuations, the general system is effective in reducing the load of coliforms.

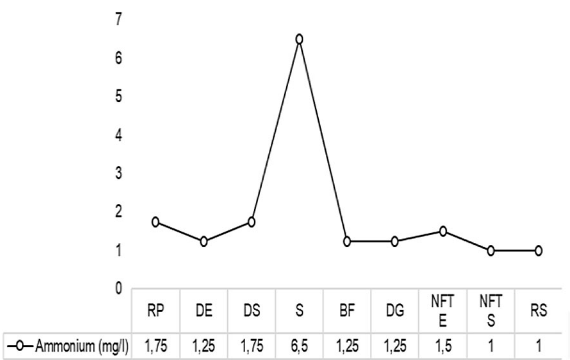

Figure 16. Behavior of ammonium

Statistical analysis

The multivariate fixed-effect model allowed us to infer that not all variables respond in the same way to location within the system. While some, such as oxygen, ammonium, phosphorus, pH, and turbidity, show significant compartment dependence, others, such as TDS, salts, or conductivity, are more homogeneous. The multivariate analysis of variance (MANOVA) revealed that the compartment has a highly significant effect ($p \leq 0.001$) on the physicochemical variables of the water (pH, TDS, temperature, oxygen, ammonium, phosphorus, among others). All multivariate statistics (Pillai Trace, Wilks Lambda, Hotelling Trace and Roy's Major Root) confirmed that the compartments of the aquaponic system are not homogeneous, indicating differences according to location.

Table 2 shows that the parameters dissolved oxygen, turbidity, coliforms and ammonium have high F values and p significance < 0.001, with an adjusted R^2 greater than 0.4, indicating a high dependence on the compartment and reflecting that the location influences the concentration and variability of these parameters. On the other hand, parameters such as TDS, salinity, conductivity, chlorides, total hardness and color, do not show significant differences between compartments (p > 0.05 and R^2 adjusted close to zero or negative), indicating that these values are relatively homogeneous throughout the system and less sensitive to location. And parameters such as pH, phosphates and temperature present moderate significance (0.01 < p < 0.06) with intermediate adjusted R^2, suggesting a partial influence of the compartments, which could reflect location-dependent absorption, filtration and chemical regulation processes. Taken together, these results show that compartment/location is a critical factor for certain key system parameters, while others remain relatively stable.

The S compartment (siphon) is a critical point where there are significant differences in: pH (slightly lower than degasser), dissolved oxygen (higher), turbidity (lower). These results suggest that S is a compartment with better oxygenation and clarification.

Analysis of compartment comparisons (Tukey)

The results show that the siphon (S) registers the lowest DO (1.65 mg/L), forming an independent homogeneous group. The decanters, biofilter and NFT (DS, BF, NF, DE) have intermediate values (3.58 to 4.78 mg/L), without significant differences between them, while the reservoirs and the degasser (RP, DG, RS) exhibit the highest values (5.35 to 5.41 mg/L), constituting another homogeneous group. This pattern reflects an ascending gradient of oxygenation throughout the system, with statistically significant increases between the three groups.

Regarding turbidity, the results indicate that most compartments (RS, DS, DG, BF, DE, RP, NF) have low and very similar values (19.76 to 21.96 NTU), forming a homogeneous group. In contrast, the siphon (S) achieves considerably higher turbidity (64.59 NTU). However, despite this evident difference in the averages, the levels of significance indicate that there are no statistically significant differences. Regarding the concentration of Coliforms, it is observed that the compartments RS, NF, DG, BF, DE, DS and RP have relatively similar values (21.95 to 38.60), grouping into homogeneous subsets. The siphon (S), on the other hand, registers a much higher value (144.90), clearly higher than the rest. However, the significance values (0.996 and 1.000) show that these differences are not statistically significant.

For phosphorus levels, the DG, BF, RS, NF, RP and DE compartments show relatively close values (3.00 to 6.67), integrating homogeneous subsets. In contrast, siphon (S) (17.66) and DS (85.45) have much higher values. Despite this, the significance values (0.998 and 0.078) indicate that these differences do not reach statistical significance. Finally, for ammonium, the RS, DG, BF, NF, DE, RP and DS compartments show similar values (1.01 to 1.60), forming a homogeneous group, while the S stands out with a considerably higher value (7.02). However, the significance values (1,000 and 1,000) confirm that there are no statistically significant differences.

Chame biomass (*Dormitator latifrons*)

In the aquaponic system evaluated, the growth of chame (*Dormitator latifrons*) was monitored in a period of five consecutive months,

Table 2. Multivariate analysis

Parameters	F (Compartment)	Gis.	R² Adjusted
pH	2.545	0.030	0.197
TDS	0.448	0.865	-0.096
Temperature	2.167	0.060	0.157
Dissolved Oxygen	11.560	0.000	0.627
Turbidity	5.779	0.000	0.432
Total coliforms	6.223	0.000	0.454
Phosphorus	3.051	0.012	0.246
Ammonium	5.823	0.000	0.434

which allowed to analyze the stability of the system in terms of animal performance. In January, an initial biomass of 2513 g was recorded, reaching intermediate values of 3599 g, 5676.3 g and 7703.8 g in the months of February, March and April, respectively, until reaching a final biomass of 8993.6 g in May. The total increase in biomass corresponded to a net increase of 6480.6 g, which is equivalent to 72.06%, considering the initial biomass and the biomass gained (Figure 19).

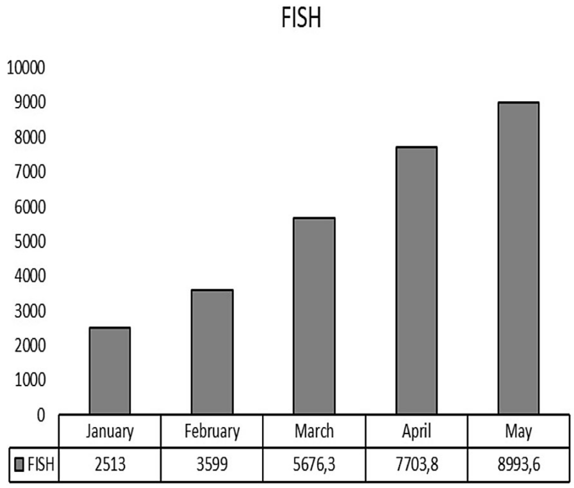

Figure 19. Biomass in *Dormitator latifrons*

Net nutrient absorption by *Lactuca sativa* var. Crisp

The analysis of the results shows that, while ammonium and phosphorus presented positive net absorption (70.33 g and 69.63 g, respectively), indicating a correct availability of nutrients for plants, nitrite showed a negative value (-65.27 g), which shows accumulation in the system (Tables 3 and 4). This finding suggests that although the biofilter was effective overall, there is a potential risk to fish due to nitrite elevation, so it would be advisable to adjust the biological filtration capacity.

Biomass in *Lactuca sativa* var. Crisp

Figure 20 shows the yield of the two crops of lettuce, where the first (C1) reached a total weight of 940 g, while the second (C2) registered 1081 g. These results show an increase of 141 g in the second harvest, equivalent to an approximate 15% increase in production. Higher yield in C2 indicates an improvement in system performance, suggesting greater nutrient availability and utilization throughout the crop cycle.

Community engagement and use of TEP

The analysis of community participation and use of Empowerment and Participation Technologies (TEP) shows a high level of involvement of the participants in the aquaponics project. Average workshop attendance was 13 people per session, out of a total of 15 participants, indicating community engagement in training activities. Likewise, the use of digital platforms by 12 people reflects that most of the participants adopted technological tools to record queries and reports, which shows the effectiveness of TEPs in promoting participation and knowledge exchange (Table 5).

Regarding the evaluation of learning through the knowledge test, the results reflect an improvement in the knowledge and understanding of the participants. The initial average in the different concepts evaluated ranged between 50% and 60%, while the final average reached between 85% and 90%, showing increases of 30 to 35 percentage points (Table 6). This shows that the implemented methodology that combined workshops, use of TEP and practical evaluation was effective in strengthening both the theoretical understanding of the aquaponic system (cycle, fish-plant relationship and nutrient management) and the practical skills related to the operation and maintenance of the system.

DISCUSSION

Atique et al. (2022) compared aquaponic structures with recirculating systems and hydroponics

Table 3. Nutrient balance in the aquaponic system

Nutrient	Ci (mg/L)	VI (L)	Cf (mg/L)	Vf (L)	P(g)	R (g)	Difference C·V (g)	Net absorption (g)
Nitrite (NO_2^-)	20.5	2000	88.25	2000	0.78	71.01	-135.5	-65.27
Ammonium (NH_4^+)	1.05	2000	1	2000	0.78	71.01	0.1	70.33
Phosphorus (PO_4^{3-})	3.57	2000	4.26	2000	0	71.01	-1.38	69.63

Table 4. Net absorption balance

Nutrient	Net absorption (g)	Interpretation
Nitrite (NO_2^-)	-65.27	Accumulation → risk for fish
Ammonium (NH_4^+)	70.33	Positive removal → safe water
Phosphorus (PO_4^{3-})	69.63	Positive removal → plants receive nutrients

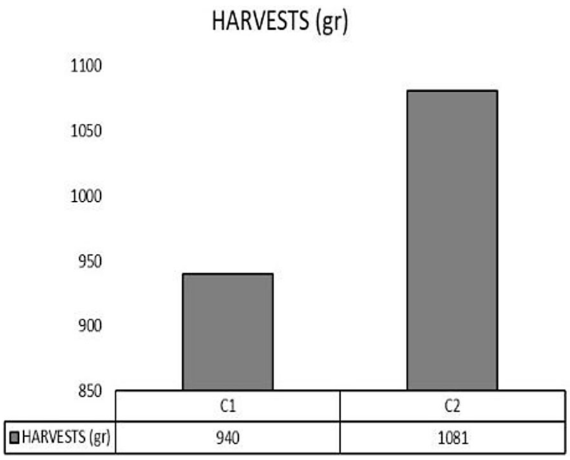

Figure 20. Biomass in *Lactuca sativa* var. Crisp

separately and reported significant improvements in plant performance, fish growth, and water quality. In addition, from the perspective of water sustainability, Schoor et al. (2024) demonstrated that the integration of NFTs in aquaponics reduces the water footprint used, which positions it as a strategy against water scarcity. Similarly, trials with NFT systems (tilapia, catfish, and foliar cultures) indicated that this design achieves higher feed conversion rates, leaf area, and yield per area in culture (Outa et al., 2024).

Nair et al. (2024) state that the pH remained within an adequate range for fish and plants, with values between 7 and 8 in the aquaponic system, favoring plant growth and nutrient availability, without affecting fish biomass or process efficiency. The water temperature is generally maintained between 26 and 27 °C, reflecting a state of equilibrium suitable for the development of both fish and plants. However, occasional variations, such as in the siphon, where the temperature drops to 24 °C, a value that is outside the predominant range at the other points of the circuit, are attributed to local conditions and differences in the thermal insulation of certain components. According to Lama et al. (2025), fish have a tolerance range of 10 to 32 °C and plants develop optimally in a range of 16 to 30 °C. However, it is important to note that although these general conditions allow for the coexistence of organisms in the system, thermal variations can influence the metabolic processes of fish and consequently indirectly affect plant growth.

According to Reyes et al. (2020), they state that TDS values are within a range greater than 350 mg/l, which is acceptable for the system. However, the authors state that TDS within values below 1000 mg/l are optimal for the fish and plants of the system. Thus, the research of Lama et al. (2025) shows that TDS affects fish if they reach values below 50 mg/l.

On the other hand, significant fluctuations in dissolved oxygen (DO) levels were observed throughout the system, with values mostly below the optimal range of > 5 mg/L recommended by Palmitessa et al. (2024). These findings coincide with Putra et al. (2025) reporting DO of 6.48 mg/L in a system with conventional aeration, while Naomi et al. (2020) reached 7.94 mg/L by implementing fine bubble generators, evidencing that the incorporation of aeration technologies can significantly improve DO levels. Likewise, recent research underlines the importance of maintaining values close to saturation to prevent root diseases and promote beneficial microbial activity in the biofilter (Nitu et al., 2024).

Regarding salinity, the results obtained showed values between 4580 ppm and 4954 ppm, far exceeding the recommended range for the optimal development of the crops. Palmitessa et al.

Table 5. Indicators of community participation and use of empowerment technologies (TEPs)

Indicator	Value	Unit	Observation
Average workshop attendance	13	people/workshop	Out of a total of 15 participants
Use of digital platform	12	Active people	Online query logging and reporting
Number of community solutions applied	5	Solutions	Improvements in fish feeding and plant watering

Table 6. Learning assessment (knowledge test)

Concept evaluated	Starting average	Final average	Increment
Aquaponic system definition and cycle	55%	88%	+33%
Fish-plant relationship and nutrient management	50%	85%	+35%
System operation, maintenance	60%	90%	+30%
Practical application of knowledge	52%	87%	+35%

(2024) state that concentrations above 1300 ppm can negatively affect plant growth and yield, evidencing that the values recorded in this study exceed the tolerable limits for the crops present. In contrast, fish also have a greater tolerance to these high salinity concentrations, being able to withstand them without significantly affecting their physiology (Subramanian et al., 2025).

When analyzing the salinity in the system, it is revealed that the values at the NFT outlet (4712 ppm) and in the Secondary Reservoir (4689 ppm) decrease compared to the previous points, suggesting that the recirculation and flow through the NFT act as a partial salinity regulation mechanism, balancing the concentration of salts in the system and contributing to maintaining more stable conditions for organisms.

The values of electrical conductivity (EC) in the aquaponic system are significantly above the ranges considered optimal, registering between 7 and 7.6 mS/cm. According to Lopchan et al. (2025), concentrations that exceed recommended levels can affect both plant growth and fish health, due to excess ions such as nitrates, calcium, and other dissolved nutrients. In well-balanced aquaponic systems, EC values typically range from 0.1 to 2.0 mS/cm for overall proper operation; for plants, the optimal ranges are approximately between 1 and 4 mS/cm, ensuring efficient plant growth, while for fish, the ideal EC is around 0.1 to 2.0 mS/cm, data that make it necessary to give a better fit to the set of nutrients and maintain conditions that help the health of fish and plants.

Gamarra et al. (2025) state that the optimal range of turbidity for the growth of fish (tilapia) and lettuce in aquaponic systems is between 15 and 22 NTU, since higher levels can affect photosynthesis and the health of aquatic organisms. This recommendation contrasts with the results of Devi et al. (2024), who reported variable turbidity between 2.56 and 5.22 NTU, with higher values indicating stress in the fish. In the present research, a turbidity of 73.59 NTU was observed in the siphon of the recirculation system, a value considerably higher than those reported in the recent scientific literature. This finding is attributed to sediment buildup, underscoring the need for efficient filtration to keep turbidity within ideal ranges.

The chloride dynamics in the NFT aquaponic system reflects an increase from 85,281 mg/L in the Main Reservoir to 91,418 mg/L in the decanter, which Samarakoon et al. (2020) indicate as a temporary accumulation of salts, attributable to sedimentation and partial evaporation. On the other hand, stabilization at 84–85 mg/L in the biofilter and NFT evidences the ability of these components to homogenize the nutrient solution, avoiding fluctuations that would affect nutrient absorption (Spyrou et al., 2025; Krastanova et al., 2022). The final decrease to 78,873 mg/L in the Secondary Reservoir suggests efficient absorption by plants and dilution associated with recirculation, maintaining safe levels within the ideal range of 75-90 mg/L as expressed by Resh (2013) and Mohapatra et al. (2020).

For Soliman et al. (2025) they reveal that alkalinity plays a crucial role in pH stabilization affecting fish health and plant growth, acting as a buffer by neutralizing the acids generated during metabolic and biological processes. The values obtained in this research (46.96 to 65.525 mg/L) are in line with the ranges reported by Zhu et al. (2022), who obtained values between 31–78 mg/L as CaCO3. These results agree that aquaponic systems can operate efficiently within wider ranges and slightly lower than traditionally ideal (50–150 mg/L), according to Lopchan Lama et al. (2025). However, Debroy et al. (2025) warn that values outside this ideal range cause pH fluctuations, negatively affecting both fish and plants.

Although there are no specific ideal color ranges for NFT systems (Palmitessa, 2024; Mohapatra et al., 2021), the color of the water in the system showed an initial value between 48.375 Pt-Co in the main reservoir, reaching a peak of 59.375 Pt-Co in the siphon and decreasing to 0.25 Pt-Co in the secondary reservoir, this trend is consistent with other recirculation systems, where the reduction of coloring compounds is attributed to biofiltration and root absorption (Yanes et al., 2022; Ibrahim, 2023). The peak in the siphon indicates release of accumulated organic matter, while the sustained decrease reflects the efficiency of the system in removing compounds responsible for color, ensuring optimal conditions for plant growth and fish health.

On the other hand, the results obtained from nitrites show that, although they reached high concentrations (192.25–289 mg/L), the NFT aquaponic system showed significant reduction capacity (20.5 mg/L at the NFT input). This coincides with recent research that highlights the efficiency of aquaponic systems compared to conventional ones in the control of nitrogenous compounds. For example, Deswati et al. (2020) reported nitrite concentrations between 0.232 and 0.329 mg/L in aquaponics, all below the critical threshold of 1 mg/L, an ideal range expressed by Lama et al. (2025), compared to higher values in conventional systems (0.515–0.729 mg/L), demonstrating that the aquaponic system favors nitrification and maintains ideal ranges for fish and plant health.

Regarding phosphates, the high concentration at the exit of the decanter (206.56 mg/L) is attributed to the release of phosphorus due to the accumulation of excreta and food debris, a phenomenon reported in studies by Xia et al. (2023) and Xue et al. (2023). The significant reduction to 3.35 mg/L in the secondary reservoir demonstrates the efficiency of the biofilter, the degasser and the plants in the absorption of the nutrient, being consistent with the findings of Lobanov et al. (2021), who obtained phosphate concentrations < 1 mg/L, highlighting the high root assimilation capacity of phosphorus in aquaponics (Ibrahim et al., 2023). Palmitessa et al. (2024) mention that the integration of the NFT technique, filtration and recirculation processes ensures that phosphate levels remain stable for plant development without compromising water quality for fish.

In the ammonium variable, a peak of 6.5 mg/L was observed in the siphon and a decrease to 1 mg/L in the secondary reservoir, coinciding with observations of aquaponic systems with NFTs reported in the literature. Heise et al. (2021) found that *Comammox Nitrospira* bacteria contribute to maintaining low ammonium concentrations through complete nitrification, achieving stability similar to that observed in this system. On the other hand, Deswati et al. (2023) reported fluctuations of 0.45 to 9.26 mg/L in biofloc systems, highlighting that microbial dynamics influence ammonium levels. In line with the recommendations of Lopchan Lama et al. (2025), keeping ammonium below 1 mg/L favors fish and plant health, confirming that the evaluated system operates within optimal ranges (Nair et al., 2025).

The progressive decrease in total hardness, from 318.75 mg/L to 283.75 mg/L, suggests carbonate precipitation processes and mineral consumption along the water flow, a behavior consistent with reports in aquaponic systems (Mohapatra et al., 2020). Although these values exceed the ideal range of 50–150 mg/L recommended for NFT systems (Lama et al., 2025), the fact that other studies report significantly higher hardnesses, such as in the research of Kumar et al. (2022) with results of 578.25–635.75 mg/L, highlight that hardness is a parameter that can be modulated by system design and biological interaction. In this context, the values observed in the study are viable for the tolerance of adapted species in hard waters, which underlines the importance of crop and fish selection to ensure success and a favorable environment in the system.

During the research, the results of the total coliforms evaluated in the system showed a balance at almost all monitoring points. The highest concentration obtained in this study was 137 CFU/100 mL, which is significantly below the detection limit established by Weller et al. (2020), which is 2496 CFU/100 mL. The results of this research are also below the range they found, which ranged from 6.3 CFU/100 mL to 2496 CFU/100 mL. According to Saxena et al. (2015), the presence of total coliforms is not a direct indicator of fecal pathogens, but it can be used to assess the cleanliness and integrity of distribution systems, since these organisms are able to survive and grow in water, especially in systems with biofilms.

The behavior of the weight of the chame (*Dormitator latifrons)* evidenced, with a sustained growth between January and May, coincides with what has been reported in recent studies on the performance of the chame in aquaponic systems. Vargas-Ceballos et al. (2024), where they demonstrated that stocking density significantly influences the growth and physiological parameters of the species, highlighting that moderate densities favor yield without compromising fish health. Similar results have been observed in other species cultured under aquaponic systems, where efficient biofiltration and an adequate supply of dissolved oxygen allow stable growth rates to be maintained (Mao et al., 2023).

Likewise, research on decoupled systems indicates that the optimization of specific physicochemical parameters for the fish can improve feed conversion and productive performance (Goddek et al., 2019). On the other hand, the biological synthesis of *D. latifrons* prepared by Badillo-Zapata et al. (2022) It implies that factors such as nutritional quality and health are determinants in growth, which explains the positive trend observed in this study (Aréchiga-Palomera et al., 2022).

In trials with lettuce in aquaponic systems, Maucieri et al. (2018) found that nitrate concentration and pH management directly influence productivity, showing that an adequate balance allows simultaneously optimizing fish and plant performance. Similarly, Yep and Zheng (2019) They highlight that the synchronization between the growth of the fish and the absorption of nutrients by the lettuce is key to maintaining the sustainability and efficiency of the system. In this case, the progressive increase in both biomasses reflects that there was a functional coupling, although with greater benefit for the chame, which opens the possibility of adjusting the plant-fish relationship to improve vegetable production without affecting fish growth.

The positive absorption of ammonium observed in this experiment is consistent with what was reported by Heise et al. (2021), who found very low concentrations of this nutrient (< 23 μM) due to the action of bacteria *Nitrospira comammox*, capable of oxidizing ammonium directly to nitrate and preventing its toxic accumulation. Similarly, the ammonium reduction recorded in this study (−7.349 mg/L) is consistent with that described by Thakur et al. (2023), who showed that the availability of ammonium-oxidizing bacteria favors a rapid conversion of the ion, contributing both to the stability of the system and to plant absorption.

In contrast, the marked accumulation of nitrites ($\Delta = -47{,}328$ mg/L) constitutes a risk, since this compound is highly toxic to fish. While Heise et al. (2021) reported that in efficient NFT systems, nitrification keeps nitrites in minimum ranges (< 19 μM) thanks to the activity of *Nitrospira*, in this case the accumulation suggests a limited capacity of the biofilter or non-optimal environmental conditions for the oxidation of nitrite to nitrate. The described coincides with Ibrahim et al. (2023), who point out that, when the oxidation capacity of nitrites is limited, accumulations can exceed plant absorption and compromise the efficiency of the biofilter, in addition to the adverse physiological effects documented by (Zhang et al. (2020) who showed that nitrites induce methemoglobinemia in tilapia, reducing the capacity to transport oxygen in the blood.

Finally, Lopchan et al. (2025) express in their research that phosphorus has values between 46–62% assimilated in biomass (35–45% in fish and 11–25% in plants), a considerably higher proportion than in hydroponics, which prevents its accumulation in water and favors a constant plant supply. In a complementary way, Vanacore et al. (2024) They showed that lettuce grown in aquaponic and floating systems maintains stable concentrations of nutrients, including phosphorus, as long as the conditions of the system are controlled. These findings support that the stable phosphate behavior observed in this study reflects a balance between the production generated by the fish and the absorption by the plants, guaranteeing a sustained contribution and without critical accumulations for water quality.

CONCLUSIONS

The implemented NFT-RAS hybrid system showed a functional design that integrated reservoirs, decanter, biofilter, degasser and NFT modules, which allowed a continuous and controlled circulation of water. This configuration ensured simultaneous processes of sedimentation, partial nitrification and oxygenation, although limitations were detected in the complete conversion of nitrites, an aspect that requires optimizing the capacity of the biofilter. From a technical point of view, the system showed structural and operational robustness, guaranteeing the interaction between fish and plants with minimal water replenishment, confirming its applicability as a sustainable alternative in small and medium-scale environments.

The physicochemical parameters remained within acceptable ranges for fish and plants: moderate alkaline pH (7.6–8.2), temperature between 24.6–27.4 °C and stability in salinity, hardness and alkalinity. Dissolved oxygen was recovered from critical decreases in the siphon (0.81 mg/L) to adequate values in the secondary reservoir (5.82 mg/L), while turbidity and color decreased throughout the recirculation. Nutrients showed efficiency in use, with ammonium reduced to 1 mg/L and phosphates to 3.35 mg/L, although nitrites indicated limitations in nitrification, in addition to reducing total coliforms. The spatial gradients of parameters confirm that the dynamics of the compartments and differentiated influences on water quality since, through multivariate statistical analysis, it was evidenced that the compartments of the aquaponic system are not homogeneous, showing significant variations in dissolved oxygen, turbidity, coliforms, phosphorus and ammonium ($p \leq 0.001$; R^2 adjusted > 0.4) depending on location.

In terms of production, *Dormitator latifrons* achieved a biomass increase of 72.06%, while *Lactuca sativa* var. *CRISPA* recorded a 15% increase in production with each harvest, values that reflect the efficiency of aquaponic integration. In the social sphere, community participation had a positive impact, with an attendance of 87% and significant improvements in the level of technical and practical knowledge of the participants, strengthening the technological appropriation and sustainability of the project.

The combination of NFTs and RAS stabilized the physicochemical and biological parameters and guaranteed the production of fish (*Dormitator latifrons*) and lettuce (*Lactuca sativa* var. *Crispa*), promoting community training in the context of efficient water management, reduction of toxic nutrients, agricultural and aquaculture productivity, and strengthening of local capacities, positioning hybrid aquaponics as an alternative for food security and environmental management.

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