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YIELD COMPARISON AND EFFICIENT USE OF NITROGEN IN TWO AQUAPONIC SYSTEMS

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ABSTRACT

The fundamental principle of aquaponics is based on the nitrogen cycle, where fish waste ammonium (NH_4^+) is transformed into nitrites and nitrates, which are absorbed by plants. However, when the pH is greater than 7, NH_4^+ becomes ammonia (NH_3), which can be harmful to fish. In this regard, it was proposed to evaluate the effectiveness of two aquaponic systems consisting of a floating raft and a tezontle bedding in transforming ammonium into nitrates. Two production cycles were conducted. During the first cycle, significant differences among treatments were observed in the leaf area index (LAI), yield, and fresh weight of the lettuce (*Lactuca sativa* L.) plants. In the second cycle, differences were also found in dry weight, width, and length of the leaf (Tukey, $\alpha = 0.05$). The lettuce yields obtained across treatments during the first production cycle were 3.7 and 3.96 kg m^{-2}, while in the second cycle they increased to 4.05 and 6.8 kg m^{-2}. Nitrogen use efficiency was 49.05 and 38.13 % in the first cycle and 57.86 and 36.6 % in the second cycle. Tilapia (*Oreochromis niloticus* L.) yields were 7.36 and 7.413 kg m^{-3}. The results indicate that the tezontle bedding system was better in terms of yield and other performance indicators.

Key words: *Lactuca sativa* L., *Oreochromis niloticus* L., nitrates, ammonium, nitrites, leaf area index.

INTRODUCTION

Agriculture faces challenges such as climate change, population growth, and environmental pollution. As one of the leading contributors to environmental degradation, this sector has driven the development of sustainable and eco-friendly production systems. Among these, aquaponics has emerged as a promising approach that enables the efficient use of water, soil, and energy resources (Rodríguez-González *et al*., 2017). Aquaponics is a type of circular agriculture that involves closed recirculation of water and nutrients (Lennard and Goddek, 2019). This technique is

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particularly promising in cities, as it can be implemented on a small scale on rooftops, in backyards, and in other small spaces. It also generates sources of proteins, vitamins, and minerals, making it suitable for self-consumption.

Aquaponics integrates aquaculture, which involves the farming of aquatic animals, and hydroponics for the production of vegetables by using the effluent generated in the aquaculture system. The essential components of an aquaponics system are the fish tank, biofilter, and hydroponics unit. The nutrients excreted by the fish or transformed by microbial activity in the fish pond are recirculated throughout the system and assimilated by the plants, while the remaining solid excretions need to be mineralized by microorganisms (Maucieri *et al*., 2018; Li *et al*., 2021).

Nitrifying bacteria that adhere to the biofilter convert waste into nutrients. The more surface area the particles have for bacteria to develop, the more efficient the nitrification process will be at converting ammonium into nitrites and then nitrates. Bacteria break down nitrogen compounds such as ammonium (NH_4^+), ammonia (NH_3), and nitrites (NO_2^-). Through the process of nitrification, these compounds are converted into nitrates (NO_3^-), which serve as essential nutrients for plant growth. This bioconversion ensures that harmful nitrogen species are removed from the effluent, preventing fish poisoning while simultaneously providing plants with the nutrients necessary for development (Li *et al*., 2021; Bautista-Olivas *et al*., 2021).

The hydroponic unit can consist of a floating raft or a substrate bed. Tezontle beddings are commonly used in greenhouse production due to its favorable physicochemical properties: it is a chemically stable material with a near-neutral pH, provides adequate aeration, and exhibits moisture retention capacity that varies with particle size. At the same time, tezontle acts as a biofilter, thus optimizing the space allocated to the system. However, tezontle beddings are difficult to handle and relatively expensive for larger scales. Furthermore, sediment accumulation may lead to clogging, particularly when fish population densities exceed bed load capacity, requiring separate filtration systems. In addition, higher rates of water evaporation and replacement are often required when using tezontle as a substrate (Millares *et al*., 2017).

In contrast, the floating raft method utilizes buoyant sheets made of materials, such as expanded polyethylene or plastic, designed to float on the water surface. Holes are drilled into these sheets to hold the plants, allowing their roots to remain in direct contact with the nutrient-rich water throughout the entire production cycle. This continuous exposure ensures a consistent nutrient supply and promotes uniform plant growth. The floating raft system is widely used in commercial operations and is particularly suitable for leafy crops such as lettuce. Moreover, water loss through evaporation is minimal, reducing the frequency and volume of water replacement required (Li *et al*., 2021).

Tilapia (*Oreochromis* spp.) is the most commonly used fish species in aquaponic systems due to its relatively short production cycle (six to nine months from hatch to harvest), high tolerance to fluctuations in water quality parameters, and resilience to low dissolved oxygen levels (Rodríguez-González *et al*., 2017). On the other hand, lettuce (*Lactuca sativa* L.) is one of the most important horticultural crops due to its short growth cycle (around 30 to 40 d under greenhouse conditions) when cultivated at temperatures between 14 and 24 °C and pH between 5 and 6.8 (Moreno-Simón and Zafra-Trelles, 2014). Several lettuce production cycles can be obtained per tilapia production cycle.

Monsees *et al*. (2019) compared an aquaponic system to a conventional hydroponic control for lettuce cultivation and found differences in the number of leaves and leaf area, with a 32 % lower yield in hydroponics compared to the aquaponic system. Bautista-Olivas *et al*. (2021) reported that lettuce grown in a hydroponic system produced higher yields (1.85 kg m^{-2}) than those grown in an aquaponic system (1.08 kg m^{-2}). This difference was attributed to the immediate availability of nutrients in hydroponics through controlled fertilization. However, hydroponics involves higher fertilizer costs and requires technical knowledge for proper nutrient management, while aquaponics is more environmentally friendly and does not rely on external fertilizer inputs.

The objective of this study was to compare the performance, efficiency of nitrogen utilization, and effectiveness of ammonium (NH_4^+) conversion to nitrates (NO_3^-) in two aquaponic systems used for lettuce and tilapia production. Both systems operated under closed recirculation conditions, one employing a floating raft and the other a tezontle substrate bed. The working hypothesis is that tezontle substrate beds in small-scale aquaponic systems increase nutrient availability, promote ammonium conversion to nitrates, and improve plant growth when compared to floating raft systems.

MATERIALS AND METHODS

The experiment was conducted in a 20 m long and 9 m wide zenithal greenhouse at the Autonomous University of Chapingo (19° 29′ 23′′ N, 98.8° 53′ 37′′ W), at an altitude of 2262 m. A randomized experimental design with three replicates was used, incorporating six experimental units and two treatments.

Treatment 1 (T1): Floating raft. This system consists of three main components: a fish tank with a capacity of 150 L, a plant bed with a volume of 75 L measuring 1.2 × 0.6 × 0.4 m, and a biofilter containing red tezontle with dimensions of 0.79 × 0.5 × 0.27 m and a water retention capacity of 55 L to support the nitrification process (Figure 1A).

Treatment 2 (T2): Tezontle bedding. This system is a simple recirculating aquaponic setup consisting of a 150-L fish tank and a plant bed measuring 1.2 × 0.6 × 0.4 m filled with red tezontle, which has a water retention capacity of 75 L (Figure 1B).

For effluent circulation, each system was equipped with a ¾-inch PVC pipe and a 0.25 HP submersible pump providing an average flow rate of 2.1 L min^{-1}. A GF-370 air pump with a water pressure of 1600 mm was used to maintain continuous aeration for 24 h in both the floating raft plant bed and the fish tank of each system. The experiment began on October 24, 2022, with 16 tilapia (*Oreochromis niloticus* L.) fish per pond,

Figure 1. Aquaponic systems used in the study. A: Treatment 1 (T1), floating raft system; B: treatment 2 (T2), tezontle bedding system.

weighing 158.74 g and measuring 19 cm on average. They were left for a week without lettuce cultivation to allow the systems to stabilize.

On October 31, 21 'Ruby Sky' lettuce seedlings were transplanted into the three replicates of each treatment, for a total of 63 plants per treatment. Harvesting was carried out 28 d after transplanting in both production cycles. The first cycle was harvested on November 28, 2022. The second cycle was transplanted on December 5, 2022, and harvested on January 2, 2023. The fish were harvested 68 d after planting in both treatments.

Throughout the 68-d tilapia production cycle and both lettuce cultivation cycles, weekly monitoring and maintenance activities were conducted to ensure optimal system performance. These activities included fish biometric measurements, plant and water sampling, and daily feeding of the fish with a commercial diet formulated according to recommended nutritional standards (Table 1).

Table 1. Proximate composition and mineral content of the commercial fish feed used during the tilapia (*Oreochromis niloticus* L.) fattening stage.

Feed fattening stage	Protein (%)	Fat (%)	Cu	Fe	Zn	Mn	B	P (%)	N (%)	S (%)
			(mg kg^{-1})							
Nutripec® 35/07	35	7	25.0	464.5	283.25	61.0	123.5	1.59	0.36	0.63
Nutripec® 32/06	32	6	27.5	298.5	281.60	57.5	99.5	1.29	0.25	0.36

Cu: copper; Fe: iron; Zn: zinc; Mn: manganese; B: boron; P: phosphorus; N: nitrogen; S: sulfur. Samples were evaluated at the National Laboratory for Agricultural and Forestry Research and Services (LANISAF) at the Autonomous University of Chapingo, Mexico.

Fish biometry

For 10 weeks, 10 fish per pond were randomly selected, placed in a container with water, and their weight and length were recorded. They were then returned to the fish pond.

Fish feeding

The feed amount was determined weekly based on the total fish biomass (Moreno-Simón and Zafra-Trelles, 2014), considering a feeding rate corresponding to 2 % of the tilapia body weight, following FAO (2023) recommendations. The fish were fed twice daily, divided into two equal rations:

$$AF = B \times TA \times d$$

where AF represents the amount of feed, B is the biomass (g), TA is the feed rate (%), and d is the number of days.

Feed conversion ratio

The feed conversion ratio (FCR) is an indicator of production costs based on the amount of feed consumed by fish in relation to live weight gain throughout the production cycle. A high FCR value indicates high production costs and is therefore unprofitable. According to Salazar-Murillo *et al*. (2023), the feed conversion ratio is calculated as:

$$FCR = \frac{T_{feed}}{\Delta\ Biomass}$$

$$\Delta\ Biomass = B_f - B_i$$

where T_{feed} represents the total feed supplied (kg), B_f is the final biomass (kg), and B_i is the initial biomass (kg).

Growth rate and specific growth rate percentage

According to Moreno-Simón and Zafra-Trelles (2014), the growth rate (GR, cm d^{-1}) and specific growth rate (% GR) are calculated as follows:

$$GR = \frac{L_f - L_i}{T_f - T_i}$$

$$\%\ GR = \frac{ln(L_f) - ln\ (L_i)}{T_f - T_i}$$

where L_i is the initial length (cm), L_f is the final length (cm), T_i is the initial time (d), and T_f is the final time (d).

Plant sampling

Three plants were randomly selected from each experimental unit, for a total of 18 plants sampled per week, for five weeks. The roots were separated from the base of the stem and leaves. Each sample was measured for leaf length and width, root length, and fresh weight of roots and leaves. A LI-COR LI-3100 leaf area integrator was used to obtain the leaf area. The plant material from each repetition was dried in a Binder 108 ED400 oven at 65 °C for 48 h until a constant dry weight was obtained.

Water sampling

To obtain the ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-) content in the effluent and plant bedding, a water sample (50 mL) was taken from the middle of the fish pond and the outlet of the plant bedding. Every week during the lettuce production cycles, a sample was sent to the National Laboratory for Agricultural and Forestry Research and Services (LANISAF) at the Autonomous University of Chapingo.

Nitrogen use efficiency

Nitrogen use efficiency (NUE) was calculated according to the equation proposed by Yang and Kim (2019):

$$NUE = \left(N_f - \frac{N_u}{N_a}\right) * 100$$

where N_f represents the total nitrogen accumulated in plant tissue at the final harvest (g), N_u is the total nitrogen content in the initial plant tissue (g), and N_a denotes the total amount of nitrogen applied (g).

Statistical analysis

Data were analyzed using mean values obtained from each replicate for all evaluated variables. A one-way analysis of variance (ANOVA) was conducted, and mean differences among treatments were determined using Tukey's *post hoc* test at a significance level of $\alpha = 0.05$. All statistical analyses were performed using Minitab version 19.

RESULTS AND DISCUSSION

Lettuce growth performance

Significant differences ($p \leq 0.05$) were found in most growth parameters between treatments (Table 2), indicating that the tezontle bedding system promoted higher photosynthetic activity and greater biomass accumulation. As a result, increased plant size corresponded with higher dry matter production (Escobar-Bahamondes *et*

Table 2. Comparison of means for different growth parameters of lettuce (*Lactuca sativa* L.) at harvest under two aquaponic systems: T1 (floating raft) and T2 (tezontle bedding) across two production cycles.

System	NL	LL (cm)	LW (cm)	LA (cm^2)	LAI	FLW (g)	DLW (g)	Yield ($g\ m^{-2}$)
First lettuce production cycle (October 31, 2022–November 28, 2022)								
T1	17.0^{a}	18.40^{a}	14.20^{a}	2474.35^{a}	7.22^{a}	135.76^{a}	13.93^{a}	3959.54^{a}
T2	16.0^{a}	17.06^{a}	13.73^{a}	2276.41^{b}	6.64^{b}	126.96^{b}	13.24^{a}	3702.87^{b}
CV (%)	7.44	5.32	2.39	5.89	5.89	4.74	3.61	4.74
Second lettuce production cycle (December 5, 2022–January 2, 2023)								
T	18^{a}	20.30^{a}	16.27^{a}	3596.15^{a}	10.49^{a}	208.46^{a}	18.95^{a}	6079.95^{a}
T2	17^{a}	17.02^{b}	13.98^{b}	2578.58^{b}	7.52^{b}	138.84^{b}	14.24^{b}	4049.63^{b}
CV (%)	5.72	0.12	0.55	12.08	12.08	15.86	12.84	15.86

Means with the same letter in the same column do not represent significant differences according to the Tukey test ($p \leq 0.05$). CV: coefficient of variation. NL: number of leaves; LL: leaf length; LW: leaf width; LA: leaf area; LAI: leaf area index; FLW: fresh leaf weight; DLW: dry leaf weight.

al., 2020). Overall, this system outperformed the floating raft across both production cycles for the variables evaluated.

From the second sampling of the first production cycle, T2 (tezontle bedding) showed a greater number and width of leaves compared to T1 (floating raft). Leaf length in T2 increased significantly 14 d after transplanting and continued to grow until harvest. In the second production cycle, an improvement was observed in all three variables, with T2 consistently outperforming T1.

According to Ahmed *et al*. (2021), increases in leaf area index are influenced by factors such as radiation interception, temperature, water availability, and nutrient supply. In this study, the photosynthetically active radiation (PAR) during the day ranged from 0.14 to 842.45 $\mu mol\ m^{-2}\ s^{-1}$ with an average of 138.78 $\mu mol\ m^{-2}\ s^{-1}$, and the ambient temperature ranged from 5.8 to 31.9 °C with an average of 17.2 °C. The difference between systems was determined by the effluent composition.

Nitrogen is one of the main nutrients affecting plant development (Bautista-Olivas *et al*., 2021), which can be found in three basic forms: ammoniacal nitrogen, nitrates, and nitrites. However, high levels of ammonium (NH_4^+) and nitrites (NO_2^-) can be toxic to fish and plants (Guzmán-Duchen and Montero-Torres, 2021). However, these compounds remained below 1 $mg\ L^{-1}$ in both treatments for both production cycles. On the other hand, in aquaponic systems, nitrogen assimilation by plants occurs in the form of nitrates (NO_3^-) and, to a lesser extent, ammonium (NH_4^+) (Benimeli *et al*., 2019). As NH_4^+ is toxic to plant cells, it is converted into organic compounds.

Plants can assimilate high levels of NO_3^-, which are stored in the metabolic reservoir in the cytoplasm and the storage reservoir in the vacuoles. Some species accumulate more nitrates due to highly efficient absorption, limited reduction capacity, or both (Sallenave, 2016). Nitrogen is highly mobile within the plant, and when supply is insufficient, it is redirected to young leaves, causing chlorosis and reduced yield (Lara-Izaguirre *et al*., 2019). For fish, high nitrogen waste levels promote pathogens that reduce growth and overall yield (Ornelas-Luna *et al*., 2017).

The main indicator of aquaponic system performance is the conversion of toxic compounds into plant-available forms, such as NH_4^+ to NO_3^-. In the first lettuce production cycle (weeks 1–5), the floating raft system (T1) had an average NH_4^+ concentration of 0.11 mg L^{-1} in the fish pond. Between weeks five and six, after harvest and without plants, NH_4^+ levels increased in both the pond and growing bed, indicating reduced transformation and lower NO_3^- consumption. This occurs because the absence of plants limits the surface area for nitrifying bacteria and removes the nitrate consumption gradient that drives nitrification, slowing the nitrogen cycle and reducing biofilter efficiency (Bautista-Olivas *et al*., 2021). Conversely, in weeks four and five, NO_3^- levels dropped from 140 to 47 mg L^{-1}, reflecting high nitrate uptake during the final growth stage (Figures 2 and 3).

The initial NO_3^- concentrations in the effluent during the first production cycle were 110 mg L^{-1} for T1 and 90 mg L^{-1} for T2. By the end of the cycle, these values changed to 47.7 and 220 mg L^{-1}, respectively. A similar trend was observed in the second production cycle, with average NO_3^- concentrations of 135.26 mg L^{-1} for T1 and 173.9 mg L^{-1} for T2 (Figures 2 and 3).

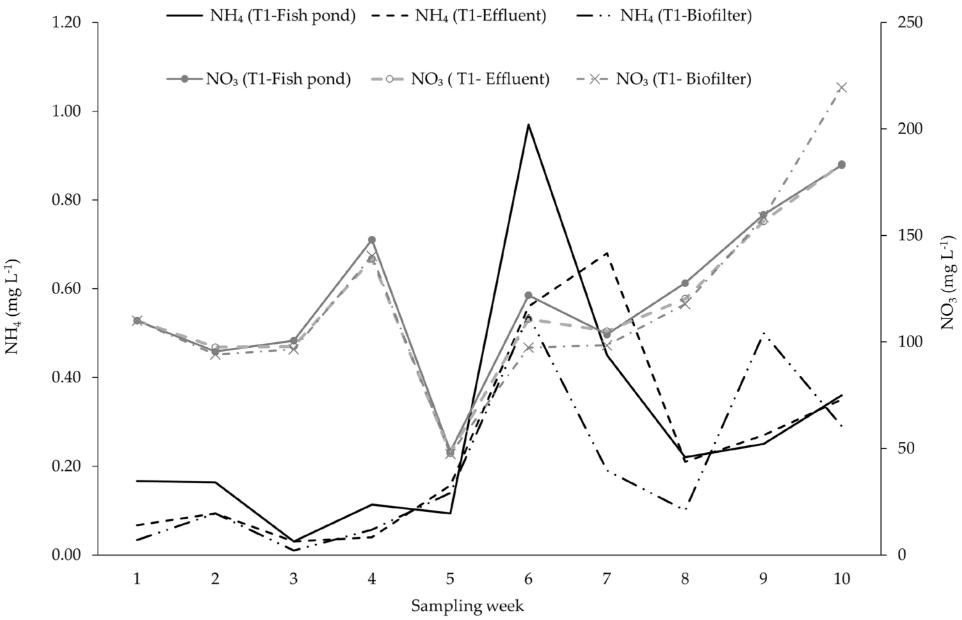

Figure 2. Dynamics of ammonium (NH_4^+) and nitrate (NO_3^-) concentrations in the effluent, fish pond, and biofilter during the tilapia (*Oreochromis niloticus* L.) production cycle in the T1 (floating raft) system.

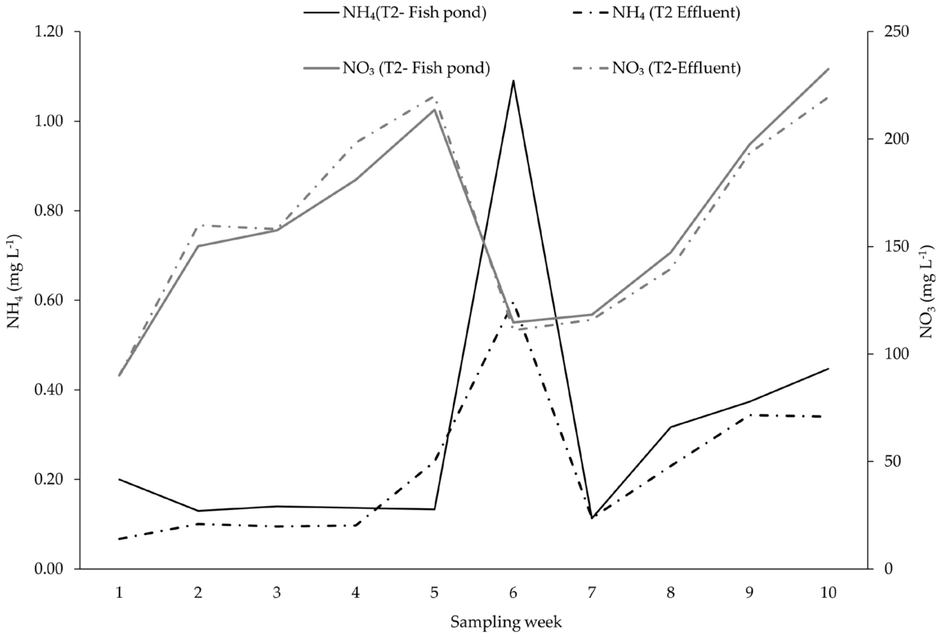

Figure 3. Dynamics of ammonium (NH_4^+) and nitrate (NO_3^-) concentrations in the effluent and biofilter during the tilapia (*Oreochromis niloticus* L.) production cycle in the T2 (tezontle bedding) system.

During the second production cycle, initial NH_4^+ concentrations in the fish pond were 0.17 mg L^{-1} for T1 and 0.2 mg L^{-1} for T2, rising to 0.35 and 0.45 mg L^{-1} by the end of the harvest. The maximum average NH_4^+ levels in the effluent for both cycles and treatments remained within recommended limits (<1 mg L^{-1}) (Somerville *et al*., 2014). The tezontle bedding system supported better microbial development and more efficient nitrification compared to the floating raft.

Tilapia farming

The daily feed conversion rate depends on both the weight and number of fish in the pond (Moreno-Simón and Zafra-Trelles, 2014). This indicator provides a measure of feed efficiency, allowing rations to be adjusted to ensure proper consumption, reduce energy waste, and maximize return on investment. Overfeeding can lead to increased excretion of protein-rich urine and feces, which upon decomposition produce toxic nitrogenous compounds, such as ammonium (FAO, 2023).

An adequate feeding regimen ensures that fish receive the necessary nutrients without overfeeding, which directly affects fish and plant health, water quality, productivity, and overall system profitability. Fish feed represents a major production cost, accounting for approximately 60 % of tilapia production expenses (Zafra-Trelles *et al*., 2019). The daily feed calculation resulted in an initial weekly feed portion of 355.96 g for T1 and 355.21 g for T2, and a final weekly amount of 511.25 g for T1 and 510.23 g for T2. However, the actual average feed consumed during the production cycle was only 62.31 % for T1 and 63.04 % for T2 of the calculated amounts, indicating relatively low feed intake in both treatments.

Production efficiency was evaluated using the feed conversion ratio (FCR). In this study, FCR values of 1.91 and 1.96 were obtained for T1 and T2, respectively. Although these values fall within the range between 1.39 and 2.14 reported by Zafra-Trelles *et al*. (2019), there is room for improvement, as nearly 2 kg of feed are required to produce 1 kg of tilapia, resulting in higher production costs.

The growth rate (GR) and percentage of specific growth rate per day (% GR) observed in this study were relatively low compared to values of 0.27 and 2.4 % d^{-1} reported by Hernández-Naranjo *et al*. (2021). Tilapia in T1 showed a slightly higher GR of 0.2 d^{-1} and % GR of 0.01 % d^{-1} compared to T2, which had a GR of 0.19 d^{-1} and % GR of 0.009 % d^{-1} throughout the production cycle. Overall, both treatments exhibited low specific growth rates.

In the analysis of variance in treatments T1 and T2, no significant differences ($p \leq 0.05$) were found for fish in terms of weight (228.24 and 227.78 g $fish^{-1}$), length (22.91 and 22.83 cm), and yield (7.41 and 7.36 kg m^{-3}). From the initial to the final week, the average weight gain was 69.04 g in T1 and 69.5 g in T2, which is reflected in the yield values. However, fish in T2 showed a slightly better response across the measured variables, likely due to the larger biofilter area in this system, which improved nitrification, nutrient conversion, and overall water quality.

The low tilapia production observed, likely due to reduced feed consumption, can be attributed to factors affecting water quality, including dissolved oxygen (DO), pH, temperature, and concentrations of NH_4^+, NO_2^-, and NO_3^-. Dissolved oxygen remained within optimal levels (6–8 mg L^{-1}), preventing competition for oxygen. According to Aleksić and Šušteršič (2020), a pH range of 6–8.5 is optimal for fish growth and the nitrification process, while nutrient absorption by plants is effective at slightly lower pH values (5.5–7.5). In this study, T1 had an initial pH of 7.85 and a final pH of 6.21, averaging 6.3, whereas T2 ranged from 7.7 to 6.21, with an average of 6.32. Although these values fall within the optimal range for plant nutrient uptake, they were near the lower limit for tilapia growth in both treatments.

During the first production cycle, average water temperatures in the fish pond were 28.17 °C during the day and 22.3 °C at night, while in the second cycle they averaged 27.19 °C (day) and 21.86 °C (night). According to Sallenave (2016), tilapia require temperatures between 27.8 and 29 °C during winter to achieve optimal growth. Rodríguez-González *et al*. (2017) found that temperature fluctuations can cause behavioral changes in fish, leading to slower growth, reduced feed intake, and altered activity of nitrifying bacteria, which in turn affects nutrient availability and the quality of both lettuce and fish. In this study, suboptimal temperatures occurred only at night, when fish are not feeding, and therefore likely did not significantly impact overall production.

During the tilapia production cycle, NO_2^- concentrations in the fish pond for T1 remained at 0.8 mg L^{-1} during the first three weeks, decreased to 0.47 mg L^{-1} in week four, and returned to 0.8 mg L^{-1} by the end of the cycle, resulting in an average concentration of 0.76 mg L^{-1}. In T2, NO_2^- levels ranged from 0.23 to 0.47 mg L^{-1}. The maximum average concentrations of NH_4^+ and NO_2^- in the fish pond for both treatments were within the recommended limits reported by Aleksić and Šušteršič (2020) (Table 3).

Table 3. Range of ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-) concentrations in the effluent and fish pond during two lettuce (*Lactuca sativa* L.) production cycles for T1 (floating raft) and T2 (tezontle bedding), compared with recommended values.

(mg L^{-1})	Cycle 1		Cycle 2		Recommended values*
	Effluent				
	T1	T2	T1	T2	
Ammonium	0.02–0.16^b	0.07–0.24^a	0.21–0.68^a	0.11–0.60^a	<1
Nitrites	0.47–0.80^a	0.27–0.47^b	0.63–0.80^a	0.23–0.47^b	<1
Nitrates	47.25–139.05^b	90–220.07^a	105.07–183.50^b	111–219.50^a	5–150
	Fish pond				
Ammonium	0.03–0.17^b	0.13–0.20^a	0.22–0.97^b	0.11–1.09^a	<1
Nitrites	0.47–0.80^a	0.27–0.47^b	0.63–0.80^a	0.23–0.47^b	<1
Nitrates	48.63–147.95^b	90–213.60^a	103.53–183^b	114.67–232.50^a	5–150

Means with the same letter in the same row do not represent significant differences according to the Tukey test ($p \leq 0.05$). *Aleksić and Šušteršič (2020).

The maximum nitrate concentration in the nutrient solution in T1 during both production cycles remained above 140 mg L^{-1}, while in T2 the maximum nitrate concentration in the effluent remained above 220 mg L^{-1}. Although nitrate concentrations in T1 stayed within the recommended ranges (Table 3), Sallenave (2016) found that effluent nitrate levels above 90 mg L^{-1} do not pose toxicity risks, as plants can store excess nitrate until needed. The NH_4^+ concentrations in the fish pond over the 10-week tilapia production cycle ranged from 0.17 mg L^{-1} (initial) to 0.36 mg L^{-1} (final) in T1, with a spike to 0.97 mg L^{-1} in week six, coinciding with the absence of plants. In T2, NH_4^+ started at 0.2 mg L^{-1} and increased to 0.45 mg L^{-1} by the end of the cycle, showing a similar peak of 1.09 mg L^{-1} in week six.

In terms of nitrogen use efficiency (NUE), the values obtained in this study were similar to those reported by Zou *et al*. (2016), who found efficiencies of 53.3 and 56.6 % in aquaponic systems supplemented with nitrifying bacteria, highlighting enhanced bacterial activity in nitrogen transformation. The results also exceeded those reported by Yang and Kim (2019), who recorded a NUE of 30.7 % when evaluating three feeding strategies (progressive, intermediate, and uniform). In their study, feeding rates were below optimal levels for maintaining suitable water quality and fish growth: the progressive feeding strategy increased feed proportionally to fish weight, the intermediate increased it by 0.7 %, and the uniform treatment maintained a constant feed rate throughout the production cycle.

In this study, maximum NUE values of 57.2 % were obtained for T1 and 46.95 % for T2 during the first production cycle, while values of 57.86 and 36.86 % were recorded for the second cycle, respectively. These results indicate superior performance for the T1 system in both production cycles. According to Zou *et al*. (2016), higher NUE values are typically associated with greater abundance and activity of nitrifying bacteria, which are favored by increased oxygen availability. Similarly, Yang and Kim (2019) reported that uniform feeding enhances nutrient availability, improves water quality, and consequently increases plant quality and yield. In the present study, feed quantities were calculated based on fish biomass; however, actual feed consumption was slightly lower than the estimated amount.

Lettuce yields during the first production cycle were higher in T2 (3.96 kg m^{-2}) compared to T1 (3.7 kg m^{-2}) (Figure 4A). Similarly, in the second production cycle

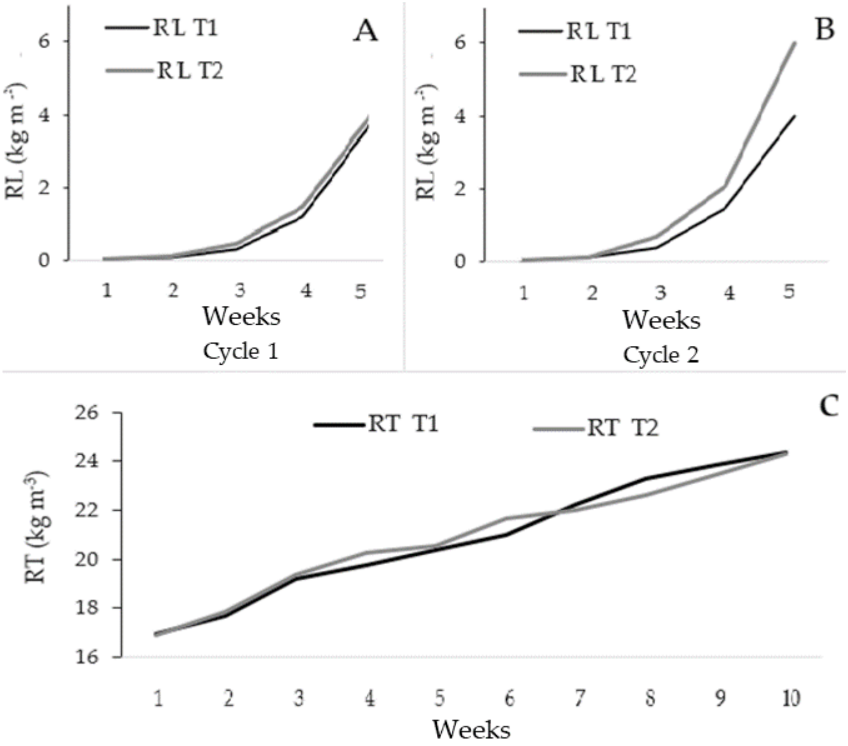

Figure 4. A: Lettuce (*Lactuca sativa* L.) yield (RL) in the first production cycle; B: Lettuce yield (RL) in the second production cycle; C: Tilapia (*Oreochromis niloticus* L.) yield (RT) over the whole production cycle.

(Figure 4B), T2 achieved a higher yield (6.08 kg m^{-2}) than T1 (4.05 kg m^{-2}), indicating a more efficient nitrification process and enhanced nitrate uptake in the T2 system (Table 2). Although plants exhibited satisfactory growth and development in both treatments, the superior performance of T2 suggests greater nitrate absorption and improved nitrogen use efficiency. According to Lara-Izaguirre *et al*. (2019), nitrogen is a key element regulating plant growth and development, primarily assimilated in the form of nitrates.

The lettuce yields obtained in both treatments in this study were higher than those reported by Jordan *et al*. (2018) for a hydroponic system (2.88 kg m^{-2}). Similarly, Bautista-Olivas *et al*. (2021) found a lettuce yield of 1.85 kg m^{-2} for hydroponic and 1.08 kg m^{-2} for aquaponic conditions, managed a biomass of 1.5 kg m^{-3} in fish, and 19 lettuces per m^2. In contrast, Jordan *et al*. (2018) obtained better results in hydroponics, which was due to the use of fertilizers in the nutrient solution and the elevated ambient temperatures during the experimental period (June–July). These conditions likely increased thermal stress on the fish, reducing feed intake and consequently lowering the organic load in the nutrient solution, which limited nutrient availability for plants. Lennard and Goddek (2019) compared lettuce growth under hydroponic and aquaponic systems across different seasons (summer, winter, and spring), using a density of 15 plants per m^2. In all cases, lettuce performance in the aquaponic system was comparable to that in the hydroponic system. However, during winter, the hydroponic setup yielded better results due to reduced fish feeding activity and lower water temperatures, which limited nutrient availability in the aquaponic system. Similarly, Barbosa *et al*. (2020) evaluated an aquaponic system to compare tilapia and lettuce yields under varying fish tank volumes, with an initial fish biomass of 4 kg m^{-3} and 19 lettuce plants per m^2. They found no significant differences in lettuce yield or fish performance among the treatments, which may be due to consistent water quality and uniform fish stocking density across systems. In this work, the increase in tilapia biomass throughout the production cycle rose from 16.93 to 24.29 kg m^{-3} in T1 and 24.34 kg m^{-3} in T2 (Figure 4C).

The weight and biomass of vegetables depend on several factors, including the type of substrate used in aquaponic cultivation, the season, the type of aquatic organism produced in aquaponics, and the quantity and quality of the feed (Barbosa *et al*. 2020). The pH of the water, electrical conductivity, ammonium, dissolved oxygen, and water temperature must also be controlled, as these factors directly affect the nutrient solution and influence the development of fish and plants (Somerville *et al*., 2014). The yields obtained in this study for both tilapia and lettuce were compared with those reported by other authors (Table 4). Among the treatments evaluated, T2 (tezontle bed) demonstrated the best overall performance.

Table 4. Comparative yields of lettuce (*Lactuca sativa* L.) and tilapia (*Oreochromis niloticus* L.) obtained in this study and reported by other authors under different production systems and environmental conditions.

Author	Production system	Location			Yields	
					Lettuce (kg m^{-2})	Tilapia (kg m^{-3})
Lennard and Goddek (2019)	Aquaponics	Australia			5.77	-
	Hydroponics				5.46	
Jordan *et al*. (2018)	Aquaponics	Brazil			2.58	-
	Hydroponics				2.88	
Barbosa *et al*. (2020)	Aquaponics	Brazil			1.62	4.44
					1.42	4.88
Bautista-Olivas *et al*. (2021)	Aquaponics	Mexico			1.08	-
	Hydroponics				1.85	
This study (2022–2023)	Aquaponics	Mexico	1st cycle	T1	3.70	7.36
				T2	3.96	7.41
			2nd cycle	T1	4.05	
				T2	6.80	

CONCLUSIONS

The results showed that the tezontle bed is the most effective alternative for small-scale aquaponic systems, as it promotes nutrient availability, the conversion of ammonium to nitrates, and superior vegetable growth compared to the floating raft system, thus partially confirming the proposed hypothesis. In contrast, the floating raft treatment required additional nutrients and a more efficient biofilter to achieve optimal nitrogen transformation and system stabilization, limiting its productive performance.

The separation of the biofilter from the growing bed in the floating raft system reduced nitrate availability and leaf area development. For the aquaculture component, fish growth, weight, and survival did not differ significantly between treatments; however, fluctuations in water pH affected overall performance, showing the importance of continuous monitoring to ensure balanced conditions for both fish and plants.

Although the floating raft treatment had higher nitrogen use efficiency, it did not result in increased biomass accumulation, suggesting possible nitrogen retention in plant tissues and incomplete transformation for growth. Future studies should examine nitrogen assimilation and accumulation dynamics to optimize nutrient utilization and enhance the integrated productivity of aquaponic systems.

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