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# Productive and Economic Comparison Between Aquaponics and Hydroponics in Different Seasons
# Comparación Productiva y Económica entre Acuaponía e Hidroponía en Diferentes Estaciones

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## SUMMARY

The productive and economic performance of experimental aquaponic and hydroponic (NFT Technique) systems for the production of tilapia (*Oreochromis niloticus*), lettuce (*Lactuca sativa*) and cucumber (*Cucumis sativus*) are evaluated. Two plant production cycles and a single fish production cycle were analyzed. The systems were compared regarding production and economic benefits. Production of 21.33 kg m$^{-3}$ of fish, 9.75 pieces of lettuce m$^{-2}$, and 0.0083 kg m$^{-2}$ of cucumber was obtained in the aquaponic system. In the hydroponic system, a production of 10.49 pieces of lettuce m$^{-2}$ and 0.94 kg m$^{-2}$ of cucumber fruit was obtained. The benefit-cost ratios were 1.50 in the aquaponic system and 2.18 in the hydroponic system, while the aquaponic system was superior regarding net profit (US$ 36 693.32 ha$^{-1}$) than the hydroponic system (US$ 24 313.42 ha$^{-1}$). It is concluded that the hydroponic system had higher plant production; however, aquaponics is more profitable due to the production of fish and vegetables.

***Index words:*** *cucumber, lettuce, NFT system, profitability, tilapia.*

## RESUMEN

Se evaluó el rendimiento productivo y económico de sistemas experimentales acuapónicos e hidropónicos (Técnica NFT) para la producción de tilapia (*Oreochromis niloticus*), lechuga (*Lactuca sativa*) y pepino (*Cucumis sativus*). Se analizaron dos ciclos de producción de plantas y un único ciclo de producción de peces. Se compararon los sistemas en cuanto a producción y beneficios económicos. En el sistema acuapónico se obtuvo una producción de 21.33 kg m$^{-3}$ de peces, 9.75 piezas m$^{-2}$ de lechuga y 0.0083 kg m$^{-2}$ de pepino. En el sistema hidropónico se obtuvo una producción de 10.49 piezas de lechuga m$^{-2}$ y 0.94 kg m$^{-2}$ de pepino. Las relaciones beneficio-costo fueron de 1.50 en el sistema acuapónico y de 2.18 en el hidropónico, mientras que el sistema acuapónico fue superior en cuanto a beneficio neto (US$ 36 693.32 ha$^{-1}$) que el hidropónico (US$ 24 313.42 ha$^{-1}$). Se concluye que el sistema hidropónico tuvo una mayor producción de plantas; sin embargo, el acuapónico es más rentable debido a la producción de peces y hortalizas.

***Palabras clave:*** *pepinos, lechuga, sistema NFT, rentabilidad, tilapia.*



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## INTRODUCTION

The benefits of combining aquaculture and plant production have been known for thousands of years, but in the last 30 years, the use of closed systems that circulate nutrient-rich water between fish tanks and plants has received considerable attention (Turcios and Papenbrock 2014; Delaide, Goddek, Gott, Soyeurt, and Jijakli, 2016; Junge, König, Villarroel, Komives, and Jijakli, 2017; Greenfeld, Becker, McIlwain, Fotedar, and Bornman, 2019). Aquaponics is the mutually beneficial integration of hydroponics (i.e., soilless systems for crop production) and aquaculture (i.e., aquatic animal husbandry) to produce plant and animal products simultaneously (Love, *et al.*, 2015). In an aquaponic system, aquatic animals excrete waste, and bacteria convert the waste into nutrients (through nitrification and denitrification) to be used in plant crops (hydroponics) that absorb the nutrients allowing to reuse and improve water quality for aquatic animals (Enduta, Jusoh, Ali, and Nik, 2011; Rakocy, 2012; Love *et al.*, 2015; Greenfeld *et al.*, 2019).

Some aquaponics studies producing tilapia (*Oreochromis niloticus*) and lettuce (*L. sativa*) have been conducted (Cani, Azevedo, Pereira, Oliveira, Chaves, and Braga, 2013; Goddek *et al.*, 2015; da Silva- Cerozi, and Fitzsimmons, 2016; Delaide *et al.*, 2016; Suárez-Cáceres *et al.,* 2021; Sánchez-Morales *et al*. 2024). Lennard and Leonard (2006) found that the Nutrient Film Technique (NFT) system is less efficient for nutrient removal and lettuce production than the medium or floating raft system. Schmautz *et al*. (2016) obtained significantly lower tomato production with the NFT than with the floating raft system but higher than in the medium-based system (Maucieri *et al.,* 2018). Nevertheless, NFT is an appropriate technology for aquaponics based on capital cost and ease of use (Lennard, and Leonard, 2006; Nicoletto *et al.*, 2018).

Research efforts continue to improve commercial-scale management for specific species in aquaponic culture. In addition to tilapia, other fish species have been used to grow different plants in aquaponic systems, such as rainbow trout (Forchino, Lourguioui, Brigolin, and Pastres, 2017), catfish (Da Rocha, Biazzetti-Filho, Stech, and Paz da Silva, 2017), and carp (Paudel, 2020). Crustaceans such as shrimp have also been used for aquaponics (Mariscal-Lagarda *et al.*, 2012). Some works have conducted economic and profitability analyses in aquaponic and hydroponic systems for a specific region, such as Rakocy, Bailey, Shultz, and Cole (1997), Rupasinghe and Kennedy (2010), Love *et al*. (2015), Tokunaga, Tamaru, Ako, and Leung, (2015), Dasgupta, and Bryant (2017), Quagrainie, Flores, Kim, and McClain (2018), Asciuto, Schimmenti, Cottone, and Borsellino (2019), Lobillo-Eguíbar, Fernández-Cabanás, Bermejo and Pérez-Urrestarazu (2020) and Babatunde, Deborah, Gan, and Simon (2023). This investigation compares hydroponic and aquaponic systems regarding production and profitability for cultivating tilapia, lettuce, and cucumber. In terms of production, Estrada-Perez, Zavala-Leal, González-Hermoso, and Ruiz-Velazco (2024) compared an aquaponic and hydroponic system, but with different densities than this study; however, in economic terms, there are no antecedents of such a comparison in the literature.

## MATERIALS AND METHODS

### Location

The experimental system was located inside a greenhouse at the Unidad Académica Escuela Nacional de Ingeniería Pesquera, Universidad Autónoma de Nayarit (21° 29′ 54.48″ N 105° 12′ 01.22″ W), in Matanchen in the State of Nayarit, México. In this region, in summer (July-September), the air temperature ranges between 25 and 32 °C, with a relative humidity between 79.28 and 81.97%. In autumn (October-December), the air temperature is 25.54 °C with an average humidity of 80%. In winter (January-March), the average air temperature ranged between 20.5 and 25 °C, and the relative humidity ranged between 71 and 82% (CICESE-UAT, 2024).

### Environmental Variables in the Greenhouse

Daily at 6:00 a.m. and 6:00 p.m., ambient temperature (TA) and relative humidity (RH) were recorded using a TFA model 30-5003 thermohygrometer placed at the height of the plant crop. During the summer-autumn cycle of plant culture, the mean environmental temperature was 29.61 °C ± 0.31, and the relative humidity was 69.61% ± 3.35. In an autumn-winter cycle, the mean environmental temperature was 21.93 °C ± 0.60, and the relative humidity was 74.42% ± 0.64.

### Aquaponic System

The crops were raised using recirculation systems combined with an NFT subsystem (Nutrient Film Technique). Each system had an area of 5.4 $m^2$ and was composed of a 1 $m^3$ polyethylene tank capacity (for fish farming or UNS), a clarifier tank (100 capacity), a biofilter tank (100-L capacity), and a solids subsystem (100-L capacity). The NFT subsystem consisted of six 10.16 cm in diameter by 3 m long PVC tubes. The flow was driven to each system component by a PVC pipe. All the fish tanks were aerated by oxygen diffusers (two per culture tank), powered by an air blower (1 HP). Further system details can be consulted in Castillo-Castellanos *et al.* (2016).

### Hydroponic System

The hydroponics system worked the same way as the aquaponic system, with the same area, but the clarifier and biofilter contained only water. The Steiner (1984) universal nutrient solution was poured weekly into the 1 m 3 tanks (without fish) in the hydroponic system. The solution concentration was 50% during the first four weeks and 75% in the remaining weeks (Castillo-Castellanos *et al.*, 2016).

### Evaluation of the Productive Performance of the Systems

Production cycles of lettuce and cucumber were carried out during the summer-autumn (September-October) and autumn-winter (December-January) seasons. A single production cycle of fish was carried out from September to January.

A 2×2 completely randomized factorial design (system x season), with three replicates for each production system, was used, where the treatments were the systems (aquaponics and hydroponics) and the seasons (summer-autumn and autumn-winter). The dependent variables were water quality (temperature, dissolved oxygen, and pH) and the productive performance of the plant (lettuce: leaf length, number of leaves, and leaf biomass in dry weight; Cucumbers: plant length and dry weight). The cultivated species were Tilapia (*Oreochromis niloticus*) Spring variety, Lettuce (*Lactuca sativa*) Parris island variety, and Cucumber (*Cucumis sativus*) Carolina variety.

Male fish (78.1 g mean initial weight) were used for the aquaponic component, with a seeding density of 30 fish $m^{-3}$. Growth in weight (g), biomass (kg $m^{-3}$), and survival of the organisms (%) were determined weekly. The fish were fed with balanced feed (35 and 30% protein according to the growth stage), following the feeding tables of the manufacturer (Purina®). Fish weight was measured using a Velab digital scale model VE-5000 precision ± 0.01 g, and the growth rate (*Tc*) was determined with the following equation:

$$Tc = (wf - wi)/tf \tag{1}$$

Where *wf* is the final weight of the organisms, *wi* is the initial weight of the organisms, and *tf* is the time at the end of the trial. Fish final biomass (*bf*) was calculated as:

$$bf = wf \cdot nf \tag{2}$$

Where *wf* is the final weight of the organisms and *nf* is the number of organisms surviving at the end of the culture.

For the hydroponic component of the aquaponic system, lettuce and cucumber seeds were first sown in expanded polystyrene containers with a capacity of 200 cavities using peat moss and vermiculite as substrates. The seedlings were watered daily until they reached an optimum size for transplanting (i.e. when presenting two true leaves). Subsequently, the seedlings were transplanted to the hydroponic subsystem, placing them every 30 cm in the holes of the PVC tubes and using wadding as a substrate for fixing. A harvest date was established for the plants, which was 35 days for lettuce and 49 days for cucumber plants from transplanting the seedlings to the hydroponic subsystem.

Thirty-six component holes (PCV tubes) were used for 36 lettuce plants and 24 for cucumbers. A random sample of 30% of the total population was taken for plant measurements. In lettuce plants, the number of leaves and plant length were determined weekly using a Vernier (Stanley®). Total plant weight (biomass dry weight g) was also determined at harvest, yield in grams per piece was calculated, and survival was determined weekly for both plant species. When the cucumber plants were harvested, a fluxometer was used to measure the length of the stem, the fruits produced by the cucumber plants were weighed, measured in length and thickness, and the total number of fruits per plant was counted to determine the productive yield (kg $m^{-2}$). In the hydroponic system, the same parameters were determined for the plants as in the aquaponic system.

### Statistical Analysis

Data normality and variance homogeneity were evaluated using the Shapiro-Wilk and Levene tests. A two-way ANOVA was used to determine the possible effect of the systems and the production cycles on plant productive performance (Lettuce leaf length, number of leaves and leaf biomass by dry weight; Cucumber plant length and dry weight) and water quality variables: dissolved oxygen (DO), electrical conductivity (EC), temperature (T) and (pH), setting significance at $\alpha = 0.05$. The Tukey HLS test was used for post-hoc comparisons. Correlations were made between fish and plant production parameters (growth and survival) with water quality variables, according to Zar (2010). The analysis was carried out using Statistica 6.0 (StatSoft, 2001).

### Economic Analysis

Crop production was estimated for a one-hectare productive area based on the experimental results, assuming a 6-month cycle for tilapia production and 35 and 49 days for lettuce and cucumber production, respectively. The database available in the National System of Information and Market Integration (SNIIM) of the Ministry of Economy was used for the prices of the products (SNIIM, 2024) and the costs of different commercial suppliers.

Utility (*U*) and benefit-cost ratio (*B/C*) were determined according to Parkin (2006). The utility was calculated as:

$$U = I - C \tag{3}$$

Where *I* is the total income and *C* is the production costs of the crop.
The benefit-cost ratio was obtained according to:

$$B/C = I/C \tag{4}$$

In turn, income for tilapia was calculated as:

$$It = bt \cdot pt \tag{5}$$

Where *bt* is the biomass of the tilapia and *pt* is the commercial price by 2022.
For cucumbers, revenues were calculated as follows:

$$Ic = bc \cdot pc \tag{6}$$

Where *bc* is the biomass of the cucumber and *pc* is the commercial price by 2022.
In the case of lettuce, income was calculated as:

$$IL = pL \cdot pL \tag{7}$$

Where *pL* is lettuce pieces and *pL* is the commercial price per piece by 2022.
Production costs depended on fixed costs (*Cf*) and variable costs (*Cv*) (Tables 1, 2) and were calculated using the equation:

$$C = Cf + Cv \tag{8}$$

Where: "*Cv*" are miscellaneous materials, energy, labor, and maintenance, and "*Cf*" are fry, fertilizers, feed, and fuel, among others considered during the year 2022.

## RESULTS AND DISCUSSION

### Fish Production

A production of 21.33 kg $m^{-3}$ of fish was obtained (Table 3). Fish mortality was 0.66% during the first plant production cycle and 2.36% during the second cycle. The final mean weight of tilapia was 736.00 g with a mean length of 32.15 cm. In addition, a condition factor of 2.21 was determined (Table 3). A correlation analysis showed a positive correlation between final tilapia weight and dissolved oxygen (r = 0.99, $p < 0.05$).

**Table 1. Fixed and variable costs of hydroponic and aquaponic systems per hectare.**

| Concepts | Quantity | Unit Cost) | Total cost ($US) |
|---|---|---|---|
| | | - - - - - - - - - - - - - - - $US | - - - - - - - - - - - - - - - |
| Fixed costs aquaponic system | | | |
| Electric power (Kw $h^{-1}$) | - | - | 4692.00 |
| Office | - | | 351.29 |
| Labor force | - | - | 5854.80 |
| Variable Costs Aquaponic System | | | |
| Gasoline (L) (Emergency power plant) | 1650 | 1.00 | 1650.00 |
| Variable costs of tilapia production | | | |
| Fry (individuals) | 55 555 | 0.05 | 2777.75 |
| Feed (kg) | 53 720 | 0.94 | 50 496.80 |
| Harvest cost (kg) | 39 500 | 0.06 | 2370.00 |
| Variable costs Plant production | | | |
| Planting substrate peat moss (kg) | 1722 | 1.16 | 1997.52 |
| Lettuce seeds (packages) | 60 | 0.82 | 49.20 |
| Cucumber seeds (packages) | 1144 | 0.82 | 938.08 |
| Planting material (per system) | 833 | 2.63 | 2190.79 |
| Fixed costs hydroponics system | | | |
| Electric power (Kw $h^{-1}$) | - | - | 2560.45 |
| Office | - | - | 351.29 |
| Labor force | - | - | 5854.80 |
| Variable costs hydroponics system | | | |
| Planting substrate peat moss (kg) | 861 | 1.16 | 998.76 |
| Lettuce seeds (packages) | 30 | 0.82 | 24.60 |
| Cucumber seeds (packages) | 572 | 0.82 | 469.04 |
| Gasoline (L) (Emergency power plant) | 1650 | 1.00 | 1650.00 |
| Fertilizers (kg) | 7296 | 0.66 | 4815.36 |
| Planting material (per system) | 833 | 2.63 | 2190.79 |

**Table 2. Total production costs of hydroponic and aquaponic systems per hectare.**

| Total production costs by cropping system | Cost ($US) |
|---|---|
| Aquaponic system | |
| Fixed costs | 10 898.09 |
| Variable costs | 62 470.14 |
| Total costs | 73 368.14 |
| Hydroponic system | |
| Fixed costs | 8 766.54 |
| Variable costs | 10 148.55 |
| Total costs | 18 915.09 |

**Table 3. Average ± SD values of tilapia growth parameters during the production cycle (September-January) in aquaponic system (Area of 5.40 $m^{-2}$).**

| Growth parameters | Growth parameters |
|---|---|
| Survival (%) | 97.08 ± 2.46 |
| Starting weight (g) | 78.10 ± 7.17 |
| Final weight (g) | 736.00 ± 161.70 |
| Daily weight gain (g $day^{-1}$) | 4.70 ± 5.02 |
| Initial size (cm) | 16.29 ± 1.27 |
| Final size (cm) | 32.15 ± 2.26 |
| Production (kg $m^{-3}$) | 21.33 |
| Food consumed (kg $m^{-3}$) | 29.01 |
| FCR | 1.36 |

In a study conducted using an aquaponic system, El-Saidy, and Hussein (2015) report a production of *O. niloticus* of 10.97 kg $m^{-3}$, with an average final weight of 219 g and a length of 22 cm. Such production was obtained after 44 weeks using an initial weight of 7.5 g and a 50 fish $m^{-3}$ stocking density. The authors report a lower biomass yield than the one obtained in this study (21.33 kg $m^{-3}$ with a 30 fish $m^{-3}$ stocking density). Similarly, the final fish weights and sizes in this investigation (736 g and 32 cm) were also higher than those reported by the authors. Those differences can be attributed, among other factors, to the different initial weights and stocking densities (El-Sayed, 2006).

## Water Quality

A significantly higher dissolved oxygen concentration was found in the hydroponic system (Table 4). Moreover, a significant interaction between the systems and cycles showed that the difference in dissolved oxygen between the systems was amplified during the autumn-winter cycle (Table 4; Figure 1a).

Electrical conductivity and temperature did not show a significant interaction ($p$ > 0.05) between cycles and systems; however, the electrical conductivity was significantly higher in the hydroponic system, while the temperature was significantly higher in the summer-fall cycle (Table 4). The pH was significantly higher in the autumn-winter cycle and in the hydroponic system, and a significant interaction indicated that the difference between the systems was amplified during the autumn-winter cycle (Figure 1b).

**Table 4. Analysis of variance of water quality variables.**

| Factor | EC | T |
|---|---|---|
| | μs $cm^{-1}$ | °C |
| Cycle | | |
| Summer-Autumn | 1.01 ± 0.25a | 30.23 ± 0.13 a |
| Autumn -Winter | 1.29 ± 0.27a | 25.05 ± 0.25 b |
| System | | |
| Hydroponics | 1.66 ± 0.21a | 27.56 ± 1.20a |
| Aquaponics | 0.63 ± 0.02b | 27.72 ± 1.14a |
| Two-way anova ($p$-value) | | |
| Cycle | 0.208 | 0 |
| System | 0.001 | 0.617 |
| Cycle by system | 0.334 | 0.696 |

[†] DO = dissolved oxygen; EC = electrical conductivity; T = temperature. Different letters indicate significant differences between treatments.

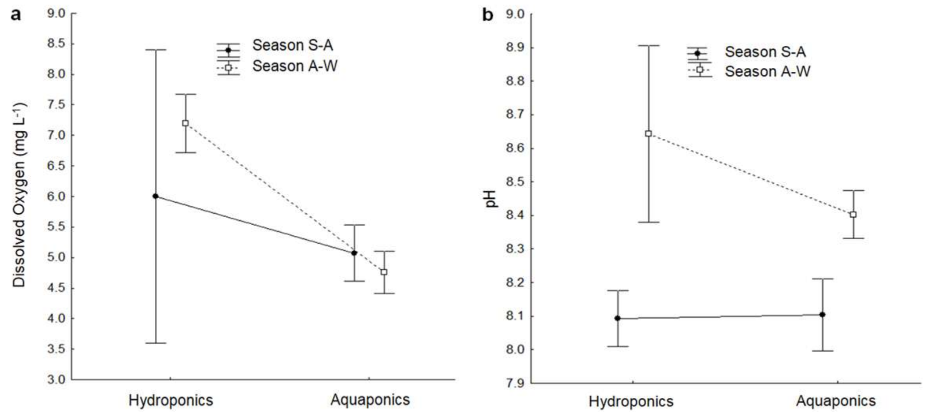


**Figure 1. (a) Dissolved oxygen concentrations (mg L$^{-1}$) in water between systems and cycles. (b) pH concentrations in water between systems and cycles.**

In this study, the higher plant production obtained using the hydroponic system compared with the aquaponics system could be attributed to differences in nutrients concentrations (Gutiérrez, 2012) between the systems since the hydroponic system received the necessary amount of nutrients, while in the aquaponic system, plants only depended on the nutritional input generated by nitrogenous waste from tilapia culture (e.g., ammonium, nitrites, nitrates).

Water parameters are essential for the development of plants and fish in aquaponic and hydroponic systems. Temperature, oxygen, and pH are the parameters with the most significant influence on the growth process of plants and fish (Somerville, Cohen, Pantanella, Stankus, and Lovatelli, 2022). The recommended temperature range for tilapia is 20 – 30 °C (Lazard, 1996; Rakocy, 2007), for lettuce 14 – 27 °C (Somerville *et al.*, 2022), and for cucumbers, 20 – 35 °C (Paris, Daunay, and Janick, 2012). According to Tyson, Simonne, Treadwell, White, and Simonne (2008), dissolved oxygen between 4 and 8 mg L$^{-1}$ is adequate, especially to promote the nitrification process for fish and plants; pH between 6.5 to 8 is ideal for fish and 5.5 to 6.5 for plants (e.g., cucumber), and lettuce can thrive at a pH between 6 and 7 (Somerville *et al.*, 2022). In this research, temperature and dissolved oxygen were adequate for the organisms, while pH remained in adequate ranges for fish but resulted in slightly stressful conditions for plants.

The difference in plant production between the different cycles in both hydroponics and aquaponics was mainly due to survival, in which temperature and pH played an important role, which were not within the optimal values required (not the tolerances) for both plants. According to the above, it has been established that the optimum temperature for lettuce is 15 °C - 22 °C (FAO, 2014) and pH 6.0-6.5 (Aubert, 1997). Those high pH values possibly effected the absorption of nutrients in lettuce, causing low growth and chlorosis (Nikolic and Pavlovic, 2018), resulting in yellowing of the leaves and mortality; it can be seen that during the summer-autumn cycle the pH was higher in the hydroponic system than in the aquaponic system, when there was higher mortality in the lettuce plants in the hydroponic system. On the contrary, in the autumn-winter cycle, lettuce production was higher in the hydroponic system than in the aquaponic system. According to the evidence in the present work, the level of dissolved oxygen in the water was lower than in the hydroponic system. Plants cultivated in hydroponic systems could encounter oxygen insufficiencies, such as when employing the NFT, a reduction in oxygen levels was noted (Suhl *et al.*, 2019). Furthermore, as roots become intertwined, the flow velocity of the nutrient solution decreases, signifying a reduced rate of oxygen transport to the densely packed root layers (Blok, Jackson, Guo, De Visser, and Marcelis, 2017). In the case of cucumber plants, high temperatures increase vegetative growth to a greater extent than desirable but decrease fruiting (Graves, 1983).

The pH (Figure 1b) exceeded the optimum level to maintain the availability of nutrients for plants. Sultenfuss, and Doyle (1999) state that the most accentuated effect of phosphorus deficiency is reduced growth and leaf number. In this research, the plants produced in the aquaponic system were smaller than in the hydroponic system. Even though the pH in the aquaponic system was higher than the recommended optimum, it produced plants, although with some deficiencies. High pH values slightly decrease the availability of potassium (K), phosphorus (P), calcium (Ca) and magnesium (Mg) but significantly reduce the availability of micronutrients such as manganese (Mn), zinc (Zn), copper (Cu), and especially iron (Fe) (Bugbee, 2004); this can alter the nutrient balance in plants and consequently reduce their growth rate (Gillespie, Kubota, and Miller, 2020).

The electrical conductivity observed in this investigation was 0.63 ± 0.02 μS $cm^{-1}$ for rearing tilapia and 1.66 ± 0.38 μS $cm^{-1}$ for plant culture, which are within the limits recommended by Nelson (2008) for tilapia (0.3 - 0.8 μS $cm^{-1}$) and hydroponics (1.5 and 1.8 μS $cm^{-1}$). Timmons, Ebeling, Wheaton, Summerfelt, and Vinci (2002) state that values lower than 0.3 μS $cm^{-1}$ can be toxic for tilapia.

## Plant Production

There was significantly higher lettuce production in the hydroponic system regarding plant length, number of leaves, and dry leaf biomass (Table 5). Dry leaf biomass was also significantly higher in the summer-autumn cycle (Table 5). There was no interaction between systems and cycles for lettuce plants (Table 5).

On the other hand, survival of lettuce plants in the hydroponic system was 59.25 ± 24.27% during the summer-autumn cycle and 98.14 ± 1.60% in the autumn-winter cycle, with a significant difference ($p$ = 0.05) between cycles. In aquaponics, survival was 95.37 ± 8.02% in the summer-autumn cycle and 52.77 ± 16.66% in the autumn-winter cycle, representing a population decrease of 40.74 %, with a significant difference between cycles ($p$ = 0.016). Significant differences were also found between systems in both growing cycles. During the summer-autumn cycle, higher survival was found in the aquaponic system ($p$ = 0.070), while higher survival was found in the hydroponic system during the autumn-winter cycle ($p$ = 0.009).

Cucumber plants were significantly longer during the summer-autumn cycle and when using the hydroponic system (Table 6). Significantly better results were obtained with the hydroponic system regarding fresh leaf biomass and length (Table 6). There was no interaction between systems and cycles for cucumber plants (Table 6). Survival of Cucumber plants in the hydroponic system was 94.43 ± 6.36% during the summer-autumn cycle and 93.03 ± 4.79% in the autumn-winter cycle, no significant difference was found ($p$ = 0.77) between cycles. In aquaponics, survival was 98.61 ± 2.40% in the summer-autumn cycle and 37.96 ± 26.39% in the autumn-winter cycle with a significant difference between cycles ($p$ = 0.0166). Higher survival was found in the hydroponic system during the autumn-winter cycle ($p$ = 0.040) above the aquaponic system. No Significant differences were found between systems during the summer-autumn cycle ($p$ = 0.34).

Keeping crops in protected environments aims to avoid pests and maintain optimal temperatures for the cultivation systems. According to Petrea *et al*. (2013), plant growth in an aquaponic system is similar to that of traditional cultivation as long as adequate plant densities are used. However, water temperature has shown a significant effect on the growth of both plants and fish in conventional farming systems and aquaponics (Vasdravanidis *et al.*, 2022). Temperatures at 21 °C are more suitable for aquaponics, since fish and plant growth are higher. Conversely, low temperature (11 °C) harms plant nutrient uptake, fish metabolism, biological filter efficiency, and microbial system parameters (Khalil, 2018).

**Table 5. Analysis of variance of lettuce growth variables.**

| Factor | Length | Number of leaves | Leaf biomass by dry weight |
|---|---|---|---|
| | cm | | g |
| Cycle | | | |
| Summer-autumn | 10.39 ± 1.66a | 9.82 ± 1.19a | 68.14 ± 25.40a |
| Autumn-winter | 13.87 ± 1.55a | 10.27 ± 1.56a | 43.69 ± 18.11b |
| System | | | |
| Hydroponics | 15.37 ± 1.10a | 12.91 ± 0.73a | 102.44 ± 12.80a |
| Aquaponics | 8.89 ± 0.98b | 7.18 ± 0.26b | 9.39 ± 1.86b |
| Two-way anova (p-value) | | | |
| Cycle | 0.606 | 0.606 | 0.039 |
| System | 0.000 | 0.000 | 0.000 |
| Cycle by system | 0.485 | 0.485 | 0.123 |

† Different letters indicate significant differences between treatments.

**Table 6. Analysis of variance of the growth variables of cucumber plants.**

| Factor | Length | Leaf biomass by dry weight |
|---|---|---|
| | cm | g |
| Cycle | | |
| Summer-autumn | 103.83 ± 23.71a | 225.68 ± 87.55a |
| Autumn-Winter | 82.95 ± 20.64b | 243.97 ± 80.27a |
| System | | |
| Hydroponics | 141.98 ± 7.14a | 417.21 ± 26.95a |
| Aquaponics | 44.80 ± 6.06b | 52.44 ± 10.56b |
| Two-way anova (*p*-value) | | |
| Cycle | 0.016 869 | 0.571 295 |
| System | 0.000 001 | 0.000 002 |
| Cycle by System | 0.306 531 | 0.553 708 |

† Different letters indicate significant differences between treatments.

## Plant Production per m²

A Total production of 9.75 pieces of lettuce $m^{-2}$ and 0.0083 kg $m^{-2}$ of cucumber was obtained in the aquaponic system. In the hydroponic system, a production of 10.49 pieces of lettuce $m^{-2}$ and 0.94 kg $m^{-2}$ of cucumber fruit was obtained.

On the other hand, Hernández, and Hernández (2005) obtained lettuce yields (3.24 kg $m^{-2}$ with 5.9 plants $m^{-2}$) in a hydroponic system, which are higher than those produced in this investigation (1.10 kg $m^{-2}$ with 6 plants $m^{-2}$). That may be attributable, in addition to differences in planting densities, to temperatures and pH, since Hernández, and Hernández (2005) maintained temperatures of 23 °C and pH of 6.3, which are lower than those prevailing in this study (27.5 and 8.3 °C).

## Plant Production Per Hectare

The production of lettuce obtained in hydroponics in the Summer-Autumn cycle was 25 926 pieces lower than in the Autumn-Winter cycle, and 104 938 pieces were estimated for both cycles (Table 7). The total production of the aquaponic system was 97 531 pieces $ha^{-1}$, with a difference of 27 160 pieces $ha^{-1}$ between cycles, with higher production during the Summer-winter cycle (Table 7). The difference in production between systems was 7407 pieces $ha^{-1}$, with a higher yield in the hydroponic system than in the aquaponic system.

Cucumber fruit production in the hydroponic system yielded a total of 9450 kg $ha^{-1}$, while in aquaponics, it yielded 83.39 kg ha-1 only in the summer–autumn cycle (Table 7). Hydroponic cucumber production in the Summer-autumn cycle was 2730 kg higher than in the Autumn-winter cycle (Table 7).

## Economic Analysis

Table 8 shows the results of the economic analysis of both production systems. The results indicate that the income estimated for the aquaponic system was US$ 64 625 higher than that of the hydroponic system due to the combination of the three products. In the hydroponic system, the income from cucumber and lettuce was US$ 27 805 higher than the income from plants in the aquaponic system.

The benefit-cost ratio was 0.68 higher in the hydroponic system; however, in terms of net benefit, the aquaponic system was US$ 12 380 higher.

The economic analysis indicated that aquaponics requires higher operating costs than hydroponics, which agrees with Quagrainie *et al.* (2018). In fact, they are not profitable on a small scale (Lobillo-Eguíbar *et al.*, 2020; Babatunde *et al.*, 2023); for this reason, this analysis was conducted on a larger scale. In this study, no investment costs were considered since both systems had the same characteristics and used the same space; the only difference

**Table 7. Production of lettuce (pieces ha$^{-1}$) and cucumbers (kg ha$^{-1}$).**

| Lettuces | | | | | |
|---|---|---|---|---|---|
| Summer-Autumn | | Autumn-Winter | | Total Production | |
| Aquaponics | Hydroponics | Aquaponics | Hydroponics | Aquaponics | Hydroponics |
| 62 346 | 39 506 | 35 185 | 65 432 | 97 531 | 104 938 |
| Cucumbers | | | | | |
| Aquaponics | Hydroponics | Aquaponics | Hydroponics | Aquaponics | Hydroponics |
| 83.39 | 60 900 | 0 | 33 600 | 83.39 | 9450 |

**Table 8. Economic analysis of hydroponic and aquaponic production systems.**

| Item | Value |
|---|---|
| Aquaponic system | - |
| Tilapia | - |
| Tilapia biomass (kg ha$^{-1}$) | 39 500 |
| Selling price per kilo of tilapia ($US) | 2.34 |
| Revenue from sale of whole fish ($US ha$^{-1}$) | 92 430 |
| Lettuce and cucumbers | - |
| Lettuce (pieces ha$^{-1}$) | 97 531 |
| Cucumbers (kg ha$^{-1}$) | 83.39 |
| Unit price lettuce ($US) | 0.175 |
| Price per kilo of cucumber ($US) | 0.117 |
| Revenue from the sale of lettuce and cucumbers ($US ha$^{-1}$) | 17 136 |
| Total revenue from the sale of aquaponics products ($US ha$^{-1}$) | 109 566 |
| Net profits ($US ha$^{-1}$) | 36 693.32 |
| Benefit-cost ratio | 1.5 |
| Hydroponic system | - |
| Lettuce and cucumbers | - |
| Lettuce (pieces ha$^{-1}$) | 104 938 |
| Cucumbers (kg ha$^{-1}$) | 9435 |
| Unit price lettuce ($US) | 0.41 |
| Price per kilo of cucumber ($US) | 0.205 |
| Total revenue from the sale of hydroponic products ($US ha-1) | 44 941 |
| Net profits ($US ha$^{-1}$) | 24 313.42 |
| Benefit-cost ratio | 2.18 |

was that in the hydroponic system, the tank did not contain fish. In other studies, investment costs have been considered when there are different equipment between aquaponic systems compared to hydroponic systems (e.g., water heaters, biomedia, and media bag, and dissolved oxygen probe, among others, which represents an investment cost 8% higher than a hydroponic system (Quagrainie *et al.*, 2018) (Lobillo-Eguíbar *et al.*, 2020). In general, it has been established that plant production is higher in hydroponic systems than in aquaponics (Love *et al.*, 2015). In this study, the production and quality of lettuce and cucumber from the hydroponic system were higher than those from aquaponics. The economic benefits from the plants were mainly differentiated by selling price, particularly by size, which resulted in a higher economic return from the plants in the hydroponic system over the aquaponic system (benefit ratio in the hydroponic system of 2.18). However, the aquaponic system is more profitable in net profits due to the higher income obtained from selling fish at higher prices (final weight ≥ 500 g).

Higher prices associated with fish and plants obtained from environmentally responsible practices could improve the economic performance of the aquaponic system, although such a price increase depends on many variables.

## CONCLUSIONS

It is concluded that, in terms of plant production, the hydroponic system is superior to what can be produced in an aquaponic system. However, in economic terms, indicators such as net profit are superior in the aquaponic systems since the income from fish production significantly compensates for the lower plant production.

## ETHICS STATEMENT

Not applicable.

## CONSENT FOR PUBLICATION

Not applicable.

## AVAILABILITY OF SUPPORTING DATA

Not applicable.

## COMPETING INTERESTS

The authors declare that they have no competing interests.

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## AUTHORS' CONTRIBUTIONS

Conceptualization and methodology: J.M.J.R.V., and A.H.LL.; Investigation, N.E.P., and J.M.J.R.V.; Writing-original draft preparation, J.M.J.R.V., and N.E.P.; Writing-review and editing, A.H.LL., J.M.J.R.V., and N.E.P.; Supervision, A.H.LL.; Funding acquisition, J.M.J.R.V.

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