

*Research Article*

## Comparing lettuce and cucumber production using hydroponics and aquaponic (tilapia) systems

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**ABSTRACT.** Aquaponics is the cultivation technique that integrates aquaculture with hydroponics. The present work compared two plant production cycles of a hydroponic component of an aquaponic system (tilapia-lettuce-cucumbers) vs. a hydroponic system. The tilapia growth trial lasted 22 weeks in the aquaponic system, during which two plant production cycles -lettuce-cucumber- (seven weeks) were performed. Water quality and environmental variables were recorded, evaluating weight growth and biomass produced in fish rearing. Leaf number, height, and weight were determined in lettuce plants. Stem length and fresh weight were measured in cucumber plants; length, fresh weight, and diameter were determined in cucumber fruit. The results showed that the average tilapia biomass per tank was  $33.76 \text{ kg m}^{-3}$  with an average final weight of  $592.26 \pm 25.45 \text{ g fish}^{-1}$ . Lettuce production ( $\text{plants ha}^{-1}$ ) was higher in aquaponics than hydroponics during the first cycle, while in the second one, it was greater in hydroponics. Significant differences (ANOVA,  $P < 0.05$ ) resulted between treatments in both cucumber production cycles with larger biomass growth in hydroponics than in aquaponics. Cucumber fruit showed larger weight ( $212.52 \pm 18.89 \text{ g}$ ) and length ( $14.15 \pm 1.75 \text{ cm}$ ) in hydroponics, thus greater yield ( $4.97 \text{ t ha}^{-1}$ ); hydroponics-grown cucumber plants had longer stem lengths ( $292.51 \pm 8.73 \text{ cm}$ ). In conclusion, the hydroponic system had higher plant production. However, aquaponics provided a double benefit since it produced fish and plants, and the plants used waste from fish rearing without contaminating the environment.

**Keywords:** aquaponics; hydroponics; tilapia; lettuce; cucumber; aquaculture

### INTRODUCTION

Aquaponics constitutes an intensive agricultural practice that promotes water recycling, nutrient recovery, and waste treatment by combining recirculating aquaculture with soilless vegetable production (Danaher et al. 2013, Da Silva 2020). Combining both food production systems simultaneously, nutrient requirements - essential for plant growth - are met, while waste generated by

fish production is managed in aquaculture (Shalan et al. 2018). Aquaponics solves several sustainability problems, such as limited water availability, environmental pollution, increased fertilizer costs, and depletion of fertile soils (Yep & Zheng 2019).

Since ancient times, fish have been harvested from rice fields as a concurrent crop in tropical Asia, China, and India. Fish culture practice in rice fields has had a checkered history dating back to 2000 years in China

(Fernando 1993). Aquaponics has been the subject of research over the past 20 years, starting with the pioneering works of Watten & Busch (1984). Since then, research has been developed mainly with *Oreochromis niloticus* and with different hydroponic crops that include sets of lettuce (Chaves et al. 2000, Castillo-Castellanos et al. 2016, Estrada-Perez et al. 2018), cucumber (Tyson et al. 2008, Castillo-Castellanos et al. 2016, Estrada-Perez et al. 2018), tomato (Roosta & Hamidpour 2011, Maucieri et al. 2018) and basil (Rakocy et al. 2004, Savidov et al. 2007, Hanson et al. 2008) varieties, among others. Previous aquaponic studies have used different fish varieties, such as carp *Cyprinus carpio* (Paudel 2020), catfish *Rhamdia quelen* (Rocha et al. 2017), rainbow trout *Oncorhynchus mykiss* (Forchino et al. 2017), and crustaceans as shrimp *Penaeus vannamei* (Mariscal-Lagarda et al. 2012), which have been reared with different plant species using low- (Fierro-Sañudo et al. 2018) and high- (Boxman et al. 2018, Pinheiro et al. 2020, Chu & Brown 2021) salinity water and contributing to knowledge development of this technique. For the plant growth area, the most common aquaponic recirculation systems use either bed with a substrate (pumice stone, sand, gravel, expanded clay) (FAO 2014, Kasozi et al. 2019). Another option is the nutrient film technique (NFT), where plant roots are exposed to a thin layer of nutrient-rich water that runs through horizontal pipes (Kasozi et al. 2019). In these culture systems, fish food provides most of the nutrients to the wastewater effluent: nitrogen (N), phosphorus (P), potassium (K), iron (Fe), manganese (Mn), and sulfur (S) (Roosta 2014). According to Yang & Kim (2020), either lettuce or cucumber require macronutrients (N, P, Ca, Mg, S) and intensive energy inputs for biomolecule synthesis, and other micronutrients (Goddek et al. 2015). NFT is an appropriate technology for aquaponics based on capital cost and ease of use (Lennard & Leonard 2006, Goda et al. 2015). The commercial sector's interest in aquaponics is growing since this cultivation technique has several advantages over common Recirculating aquaculture systems (RAS) and hydroponic systems using an inorganic nutrient solution (Roosta & Hamidpour 2011). Aquaponic systems could contribute towards commercial-scale fish and plant production, as well as a means of generating employment. These systems are often expensive to build and operate. However, by incorporating a secondary plant crop that receives most of the necessary nutrients at no additional cost (Muñoz-Gutiérrez 2012), aquaponics provides the possibility of maintaining high-quality fish and vegetable production

simultaneously, thereby, a great potential to become a sustainable technology (Wongkiew et al. 2017).

Therefore, this study aims to evaluate the productive performance of aquaponics for tilapia *O. niloticus* var. Spring in tilapia-lettuce-cucumber production compared to a hydroponic system. The results of this study make it possible to issue recommendations to exploit these species and sustain their future research.

## MATERIALS AND METHODS

### Location

The experiment was carried out in the Aquaponics Crop Unit at the Unidad Académica Escuela Nacional de Ingeniería Pesquera, in the municipality of San Blas, Nayarit, Mexico, located at 21°29'56"N and 105°12'00"W in a greenhouse with anti-aphid mesh sides and plastic cover. According to Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP 2014), the predominant climate in the study area is warm and humid with an average annual temperature of 25.6°C, 35°C maximum, 18°C minimum, and 89% average annual relative humidity.

The tilapia growth trial lasted 22 weeks (September 13, 2014 to January 3, 2015), during which two plant production cycles were carried out. The first production cycle was from September 6 to October 25, 2014, and the second was from December 13, 2014 to January 31, 2015.

### Experimental design

Two plant species, lettuce (*Lactuca sativa* var. Parris island) and cucumber (*Cucumis sativus* var. Carolina), were cultivated under the effect of two nutrient sources (treatments): a) tilapia *O. niloticus* var. Spring cultivation (aquaponics) effluent, and the b) universal nutrient solution (UNS) of Steiner (1984) (hydroponics) at 50% concentration in the first two weeks and 75% in the next five weeks (for both production cycles).

The crops were raised in recirculation systems (three independent systems for each treatment) combined with the NFT subsystem; each system had an area of 9.25 m<sup>2</sup> and was composed of a 1 m<sup>3</sup> polyethylene tank capacity (for fish farming or UNS), solid sedimentation tank (100 L capacity), nitrification tank (100 L capacity) and a subsystem of solids (100 L capacity). The NFT subsystem consisted of six 10.16 cm in diameter by 3-m long PVC tubes with 10 holes of 5.08 cm in diameter each to place the plants. The flow was driven to each system component by a PVC

pipe. A Quiet One® model 3000 pump was used for each system with a flow rate of  $47.82 \text{ L min}^{-1}$ . All the fish tanks were aerated by oxygen diffusers (two per culture tank), which were aerated by an air blower Pioneer® RS-0750 (1 Hp). The system design can be seen in Figure 1. More system details can be consulted in Castillo-Castellanos et al. (2016). The flow rates determined in the mass balance for each of the parameters considered are shown (Table 1).

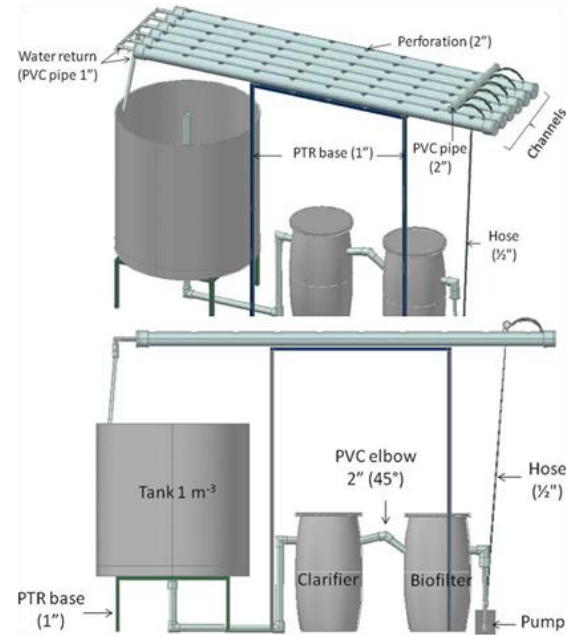
Each system worked with 60 plants per experimental unit, of which 24 were cucumber and 36 were lettuce. Three replicates were available for each culture system and treatment, distributed under a completely randomized design.

Environmental temperature and relative humidity were recorded daily at 06:00 and 18:00 h using a TFA thermohygrometer model 30-5003 (TFA Dostmann, DE) placed at the plant crop height. At the same time, the values of water quality variables - dissolved oxygen (DO), electrical conductivity (EC), and temperature (T) were recorded from the fish tanks and plant culture channels of each system and determined with a YSI Professional 2030 (YSI Inc., OH, USA). The pH was determined with a Hanna HI 98130 (Woonsocket, RI, USA) potentiometer. In addition, weekly water samples were taken to estimate nitrate ( $\text{NO}_3^-$ ), total ammonium nitrogen (TAN), and phosphate ( $\text{PO}_4^{3-}$ ) ions concentration, which were determined by spectrophotometry with a BioTek microplate reader model Synergy HTX (BioTek, Winooski, VT) using the methodology indicated in Strickland & Parsons (1977).

### Fish farming

The masculinized fish (*O. niloticus*, var. Spring) were previously purchased at a laboratory. Stocking density was  $60 \text{ fish m}^{-3}$  with an average individual weight of  $75.63 \pm 14.2 \text{ g}$ ; the feeding frequency was three times a day, and the food supplied was 35 and 30% protein according to fish size, where the amount of feed was adjusted to the weekly biomass produced, starting at 3.5% and ending at 1.8% (Purina®). Weekly fish growth was estimated by randomly sampling 40% of the population; fish were anesthetized under  $0.1 \text{ g L}^{-1}$  tricaine methane sulfonate with buffered (MS-222, Sigma Aldrich, USA) for weighing and measuring. Total length was obtained with an ichthyometer, and weight was determined with a digital balance (Velab model VE-5000, México, precision = 0.01 g).

Weight gain ( $W_g$ ) was calculated from the equation  $W_g = W_f - W_i$ , where  $W_f$  is the final weight, and  $W_i$  is the starting weight. The condition factor (K) was also calculated by equation  $K = 100 \times (W / L^3)$  (Ricker 1975),



**Figure 1.** Hydroponic and aquaponic system design. Resource: Castillo-Castellanos et al. (2016).

**Table 1.** Water flow estimated by mass balance according to total ammonia nitrogen production (TANP), total suspended solids production (TSSP), dissolved oxygen consumption (DOC), carbon dioxide production ( $\text{CO}_2\text{P}$ ) determined for  $60 \text{ organisms m}^{-3}$ .

	Production	Flow ( $\text{L min}^{-1}$ )
TANP	$16,286 \text{ mg TAN d}^{-1}$	18.849
TSSP	$147,262 \text{ mg TSS d}^{-1}$	12.174
DOC	$-217,948 \text{ mg DO d}^{-1}$	48.818
$\text{CO}_2\text{P}$	$299,679 \text{ mg CO}_2 \text{ d}^{-1}$	7.432

where K is the condition factor [ $W$  is the fish weight (g), and  $L$  is fish length (cm)]. All fish handling and husbandry procedures complied with the Guide for the Care and Use of Laboratory Animals: Eighth Edition (NRC 2011).

In addition, daily weight gain (DWG) was estimated in grams per day using the equation proposed by Gallo García (2007):  $\text{DWG} = (\text{final average live weight} - \text{initial average live weight}) / \text{elapsed days}$ .

Weekly fish survival (%) was determined from the difference by counting dead organisms. The survival percentage was calculated by equation  $S = (N_f / N_i) \times 100$ , where  $N_f$  is the final number of organisms, and  $N_i$  is the initial number of organisms. The final biomass was calculated as  $B_f = W_f \times N_f$ .

### Lettuce and cucumber cultivation

During both production cycles, lettuce and cucumbers were planted in peat moss substrate on polystyrene trays. The seedlings remained in the trays until three or four true leaves appeared (about four weeks); the plants extracted from the trays were subjected to a root wash to remove the root ball and transplanted into the cultivation channels. In each of the six NFT channels of both systems, four cucumber and six lettuce seedlings were placed alternately at 25 cm distance between plants.

Some morphological characteristics were measured to determine growth and biomass by randomly sampling 30% of the population of each cultivation system. In lettuce plants, the number of leaves and height (cm) were measured every week. At harvest, height (cm) and foliar weight (g) in fresh matter were measured in 100% of plants, and yield was calculated in grams per plants and number of plants per hectare. In cucumber plants, stem length (cm) was measured every week, while in harvested fruit, length (cm), fresh weight (g), and diameter (cm) were recorded. At the end of the production cycle of cucumber cultivation, plant stem length (cm) and fresh weight (g) (without root) were measured; finally, fruit yield was determined in tons per hectare.

Lettuce varieties were harvested after five weeks in the system, and cucumber fruit was harvested once it reached 12 cm in length or 3.8 cm in diameter. Cucumber plants were removed from the system after seven weeks of cultivation.

### Statistical analysis

Statistica 6.0 StatSoft Inc. Tulsa, OK, USA was used. Normality and homogeneity tests were performed with the tests Shapiro-Wilk and Levene ( $P = 0.05$ ), respectively. Both tests indicated that the data were homogeneous and distributed normally, so parametric statistics were used. Water quality parameters, nutrient values, and productive parameters of lettuce and cucumber plants were first analyzed using a one-factor analysis of variance (ANOVA).

## RESULTS

### Environmental variables

The results indicated that the average value of environmental temperature in the first production cycle was  $27.17 \pm 0.48^\circ\text{C}$  (at 06:00 h:  $23.85^\circ\text{C}$ ; and at 18:00 h:  $30.4^\circ\text{C}$ ), while in the second one, an average of  $22.30 \pm 0.67^\circ\text{C}$  (at 06:00 h:  $19.20^\circ\text{C}$ ; and at 18:00 h:  $28.6^\circ\text{C}$ )

was recorded, resulting in significant differences ( $P < 0.05$ ) between production cycles.

The mean relative humidity values of the first and second production cycles were  $70.79 \pm 1.75\%$  (at 06:00 h: 88%; and at 18:00 h: 55%) and  $72.90 \pm 0.87\%$  (at 06:00 h: 83%; and at 18:00 h: 59.50%), respectively, resulting in statistically significant differences ( $P < 0.05$ ).

### Water and nutrient quality variables

Differences ( $P < 0.05$ ) were found in DO, T, and EC, comparing water quality variables between treatments during the first production cycle, while no differences were recorded ( $P > 0.05$ ) in pH (Table 2). During the second production cycle, statistical differences were found between aquaponics and hydroponics ( $P < 0.05$ ) in DO, EC, and pH, while T was statistically similar ( $P > 0.05$ ) (Table 2).

Significant differences ( $P < 0.05$ ) were observed in DO, T, and pH, comparing the water quality variables of each treatment between production cycles. At the same time, EC was similar between cycles in both treatments ( $P > 0.05$ ).

When the concentration of nitrogen ions and  $\text{PO}_4^{3-}$  were compared between cycles, significant differences were obtained ( $P < 0.05$ ) in  $\text{NO}_3^-$  concentration between aquaponics and hydroponics culture channels at the first cycle (Table 3). Moreover, statistical differences ( $P < 0.05$ ) were found between the two treatments during the second production cycle, showing higher TAN and  $\text{PO}_4^{3-}$  concentrations in the plant culture channels in the aquaponics system (Table 3).

### Fish farming

Fish weight had an increase in daily weight of  $4.17 \pm 0.57$  g (Table 4), obtaining an average weight at harvest (22 weeks) of  $592.26 \pm 25.45$  g fish<sup>-1</sup> (Fig. 2). The condition factor at the end of the production cycle was 2.19, indicating the time for better condition or fish well-being (Table 4). Tilapia fish yield was  $33.76$  kg m<sup>-3</sup>.

### Growing plants

#### First production cycle: lettuce

Growth variables of lettuce plants, number of leaves, and height (Table 5) showed the highest growth in hydroponics, reaching the harvest with significant differences ( $P < 0.05$ ) between treatments. The final number of leaves was  $15.04 \pm 0.55$  in aquaponics and  $26.96 \pm 1.32$  in hydroponics, while height was  $17.31 \pm 1.09$  and  $39.50 \pm 2.74$  cm in aquaponics and hydroponics, respectively.

**Table 2.** Mean values  $\pm$  standard deviation (SD) of water quality variables for both production cycles. First letter: if different in groups, it shows significant differences ( $P < 0.05$ ) between treatments per production cycle. Second letter: if different in groups, it shows significant differences ( $P < 0.05$ ) between cycles by treatment. DO: dissolved oxygen; T: temperature; EC: electric conductivity; pH: hydrogen potential. A: acuaponics, H: hydroponics.

Variables	Treatment	First production cycle	Second production cycle
		Average $\pm$ SD	Average $\pm$ SD
DO (mg L <sup>-1</sup> )	A	3.86 $\pm$ 0.58 <sup>aa</sup>	4.94 $\pm$ 0.77 <sup>ab</sup>
	H	6.49 $\pm$ 0.25 <sup>ba</sup>	7.17 $\pm$ 0.44 <sup>bb</sup>
T (°C)	A	30.53 $\pm$ 0.70 <sup>aa</sup>	25.25 $\pm$ 0.73 <sup>ab</sup>
	H	30.06 $\pm$ 0.75 <sup>ba</sup>	24.95 $\pm$ 0.75 <sup>ab</sup>
EC (mS cm <sup>-1</sup> )	A	0.74 $\pm$ 0.08 <sup>aa</sup>	0.77 $\pm$ 0.08 <sup>aa</sup>
	H	1.82 $\pm$ 0.22 <sup>ba</sup>	1.87 $\pm$ 0.22 <sup>ba</sup>
pH	A	7.99 $\pm$ 0.12 <sup>aa</sup>	8.29 $\pm$ 0.37 <sup>ab</sup>
	H	8.00 $\pm$ 0.43 <sup>aa</sup>	8.60 $\pm$ 0.32 <sup>bb</sup>

**Table 3.** Mean values  $\pm$  standard deviation value (SD) of ammonium (TAN), nitrates (NO<sub>3</sub><sup>-</sup>), and phosphates (PO<sub>4</sub><sup>-</sup>) concentrations (mg L<sup>-1</sup>) in Nile tilapia (*Oreochromis niloticus*) fish tanks and culture channels in both treatments. First letter: if different in groups, it shows significant differences ( $P < 0.05$ ) between treatments per production cycle. Second letter: if different in groups, it shows significant differences ( $P < 0.05$ ) between production cycles by treatment. In fish tanks, they are compared between production cycles.

Ion	First production cycle			Second production cycle		
	Aquaponics		Hydroponics	Aquaponics		Hydroponics
	Fish tank	Channel	Channel	Fish tank (fishless)	Channel	Channel
TAN	1.62 $\pm$ 0.53 <sup>a</sup>	1.30 $\pm$ 0.30 <sup>aa</sup>	0.79 $\pm$ 0.28 <sup>aa</sup>	1.64 $\pm$ 0.55 <sup>a</sup>	2.24 $\pm$ 1.17 <sup>aa</sup>	0.49 $\pm$ 0.13 <sup>ba</sup>
NO <sub>3</sub> <sup>-</sup>	68.85 $\pm$ 4.3 <sup>a</sup>	77.81 $\pm$ 13.68 <sup>aa</sup>	31.01 $\pm$ 4.36 <sup>ba</sup>	121.65 $\pm$ 69.09 <sup>a</sup>	163.63 $\pm$ 103.36 <sup>aa</sup>	136.6 $\pm$ 37.09 <sup>ab</sup>
PO <sub>4</sub> <sup>-</sup>	3.09 $\pm$ 0.44 <sup>a</sup>	3.03 $\pm$ 0.67 <sup>aa</sup>	4.42 $\pm$ 1.40 <sup>aa</sup>	4.45 $\pm$ 1.82 <sup>a</sup>	5.52 $\pm$ 0.63 <sup>ab</sup>	2.22 $\pm$ 0.80 <sup>ba</sup>

Weight yield (g plant<sup>-1</sup>) of harvested lettuce was higher in hydroponics (122.65  $\pm$  51.25 g) than in aquaponics (16.08  $\pm$  10.01 g). However, lettuce performance in aquaponics was 23,400 plants ha<sup>-1</sup>, while it was 23,040 plants ha<sup>-1</sup> in hydroponics, slightly higher in aquaponics. In aquaponic treatment, 60.18  $\pm$  52.58% survival occurred, while 59.25  $\pm$  24.26% in hydroponics (Table 5).

#### First production cycle: cucumbers

The length and weight of harvested cucumber fruit had significant differences ( $P < 0.05$ ) between treatments, with lower values observed in aquaponics than in the control group. The average cucumber fruit length was 9.30  $\pm$  1.71 cm in aquaponics and 12.80  $\pm$  1.31 cm in hydroponics, while the average weight per fruit was 94.30  $\pm$  10.23 and 148.64  $\pm$  5.01 g in aquaponics and hydroponics, respectively. Cucumber fruit yield was 0.135 t ha<sup>-1</sup> in aquaponics and 4.97 t ha<sup>-1</sup> in hydroponics in the first production cycle.

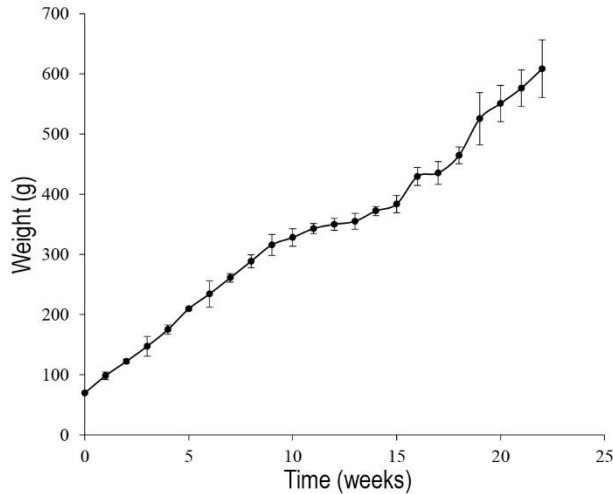
Cucumber plant stem length grew longer in hydroponics, reaching a final stem length of 292.51  $\pm$  8.73 cm,

**Table 4.** Performance results of Nile tilapia (*Oreochromis niloticus*) at final production.

Variable	Production cycle
Survival (%)	94.9 $\pm$ 1.65
Initial weight (g)	75.63 $\pm$ 14.2
Final weight (g)	592.26 $\pm$ 25.45
Daily weight gain (g d <sup>-1</sup> )	4.17 $\pm$ 0.57
Initial size (cm)	15.74 $\pm$ 1.08
Final size (cm)	30 $\pm$ 0.15
Weekly size gain (cm)	1.05 $\pm$ 0.02
Condition factor at the beginning	1.87
Condition factor in the end	2.19

while it was 112.52  $\pm$  5.05 cm in aquaponics (Table 5), resulting in significant differences ( $P < 0.05$ ) between treatments.

At the end of the cucumber growing cycle, fresh leaf biomass was obtained with significant differences ( $P < 0.05$ ) between aquaponics and hydroponics. In aquaponics treatment, a biomass of 44.70  $\pm$  3.79 g plant<sup>-1</sup> was observed, while a biomass of 416.72  $\pm$  19.59 g plant<sup>-1</sup> was obtained in hydroponics. In aquaponics,



**Figure 2.** Example of Nile tilapia (*Oreochromis niloticus*) growth curve corresponding to a stocking density of 60 fish per tank ( $1 \text{ m}^3$ ) in an aquaponic system.

the survival of cucumber plants ended at  $95.83 \pm 7.21$  and 100% in hydroponics (Table 5).

### Second production cycle: lettuce

In this stage, lettuce varieties in hydroponics acquired greater growth, showing statistical differences ( $P < 0.05$ ) between treatments. At harvest, the number of leaves in hydroponics was  $16.03 \pm 0.86$  and  $8.22 \pm 0.75$  in aquaponics; finally, height in hydroponics was  $21.44 \pm 0.63$  and  $9.34 \pm 0.46$  cm in aquaponics (Table 5).

Lettuce weight yield ( $\text{g plant}^{-1}$ ) showed significant differences ( $P < 0.05$ ) between treatments, which were higher in hydroponics ( $81.62 \pm 67.72$  g) than in aquaponics ( $4.09 \pm 4.08$  g) and yield in plants  $\text{ha}^{-1}$  was 19,800 in aquaponics and 38,160 in hydroponics. Finally, survival resulted in  $50.92 \pm 14.25\%$  in aquaponics and  $98.14 \pm 1.60\%$  in hydroponics (Table 5).

### Second production cycle: cucumbers

Only one harvest of cucumber fruit was obtained in hydroponics. The fruits had an average weight of  $212.52 \pm 18.89$  g with an average length of  $14.15 \pm 1.75$  cm. The reached yield was  $1.07 \text{ t ha}^{-1}$ .

Cucumber plant stem length had significant differences between treatments ( $P < 0.05$ ) since the fourth week of cultivation, of which the highest length in hydroponics reached a final value of  $269.81 \pm 6.28$  cm. In comparison,  $94.20 \pm 5.91$  cm was reached in aquaponics (Table 5).

At the end of the cucumber growing cycle, significant differences ( $P < 0.05$ ) were observed in

fresh biomass between aquaponics and hydroponics. The aquaponic treatment had a final average weight of  $51.37 \pm 5.68$  g, while higher cucumber plant biomass was obtained in hydroponics with a final value of  $419.22 \pm 20.85$  g per plant. Plant survival in aquaponics was  $91.66 \pm 7.21$  and  $93.05 \pm 4.80\%$  in hydroponics (Table 5).

## Comparison of plant cultivation between production cycles

### Lettuce cultivation

Significant differences ( $P < 0.05$ ) were found between production cycles when lettuce plant growth was compared with a greater number of leaves and height in the first cycle (Table 5). Biomass was also higher during the first cycle in both treatments.

The yield (parts per hectare) obtained in aquaponics was higher in the first cycle, surpassing the production of the second cycle with 3600 plants. In contrast, the greatest production in hydroponics occurred during the second cycle. If both production performance cycles were added for each treatment, hydroponics would have 61,200 plants  $\text{ha}^{-1}$  higher than that calculated for the aquaponic treatment of 43,200 plants  $\text{ha}^{-1}$  with a difference of 18,000 plants (Table 6).

### Cucumbers cultivation

Plant growth at the end of the crop showed no significant differences ( $P > 0.05$ ) between production cycles in aquaponics treatment, but they were found ( $P < 0.05$ ) in hydroponics with longer plant lengths at stage one (Table 5). Moreover, the plant biomass showed no statistical differences ( $P > 0.05$ ) at both cycles in each treatment.

During the second cycle, the hydroponics treatment showed greater growth and fruit biomass ( $212.52 \pm 18.89$  g and  $14.15 \pm 1.75$  cm) compared to the values obtained in the first cycle ( $148.64 \pm 5.01$  g and  $12.80 \pm 1.31$  cm). Only the control group obtained cucumber production with a five times lower yield in the second production cycle than the first, finding statistically significant differences ( $P < 0.05$ ) between production cycles. Plant survival decreased in both treatments in the second cycle. The aquaponic plant survival fell from 95.85 to 91.66%, and the witness decreased from 100 to 93.05% (Table 5).

The yield ( $\text{t ha}^{-1}$ ) obtained in aquaponics and hydroponics was higher in the first cycle, surpassing the production of the second cycle with 0.12 and  $3.9 \text{ t ha}^{-1}$ , respectively. If both production performance cycles were added for each treatment, hydroponics would

**Table 5.** Mean value  $\pm$  standard deviation value (SD) of lettuce leaf number and height; cucumber plant stem length and final survival of the aquaponics and hydroponics systems' first and second production cycle. First letter: if different in groups, it shows significant differences ( $P < 0.05$ ) between treatments per production cycle. Second letter: if different in groups, it shows significant differences ( $P < 0.05$ ) between production cycles by treatment. In fish tanks, they are compared between production cycles.

	First production cycle		Second production cycle	
	Aquaponics	Hydroponics	Aquaponics	Hydroponics
	Lettuce plants			
Number of leaves	15.04 $\pm$ 0.55 <sup>aa</sup>	26.96 $\pm$ 1.32 <sup>ba</sup>	8.22 $\pm$ 0.75 <sup>ab</sup>	16.03 $\pm$ 0.86 <sup>bb</sup>
Height (cm)	17.31 $\pm$ 1.09 <sup>aa</sup>	39.50 $\pm$ 2.74 <sup>ba</sup>	9.34 $\pm$ 0.46 <sup>ab</sup>	21.44 $\pm$ 0.63 <sup>bb</sup>
Survival (%)	60.18 $\pm$ 52.58 <sup>aa</sup>	59.25 $\pm$ 24.26 <sup>aa</sup>	50.92 $\pm$ 14.25 <sup>aa</sup>	98.14 $\pm$ 1.60 <sup>bb</sup>
	Cucumber plants			
Stem length (cm)	112.52 $\pm$ 5.05 <sup>aa</sup>	292.51 $\pm$ 8.73 <sup>ba</sup>	94.20 $\pm$ 5.91 <sup>aa</sup>	269.81 $\pm$ 6.28 <sup>ba</sup>
Survival (%)	95.83 $\pm$ 7.21 <sup>aa</sup>	100 $\pm$ 0.00 <sup>aa</sup>	91.66 $\pm$ 7.21 <sup>aa</sup>	93.05 $\pm$ 4.80 <sup>ab</sup>

**Table 6.** Final cucumber and lettuce production yields in aquaponic and hydroponic systems.

	Cucumber (t ha <sup>-1</sup> )		Lettuce (plants ha <sup>-1</sup> )	
	First production cycle	Second production cycle	First production cycle	Second production cycle
Aquaponics	0.14	0.02	23400	19800
Hydroponics	4.97	1.07	23040	38160

have 6.04 t ha<sup>-1</sup> higher than that calculated for the aquaponic treatment of 0.16 t ha<sup>-1</sup> with a difference of 5.88 t ha<sup>-1</sup> (Table 6).

## DISCUSSION

Rakocy et al. (2004) reported a higher *O. niloticus* production of 61.5 kg m<sup>-3</sup> at a density of 77 fish m<sup>-3</sup> than in this investigation. However, Marengoni (2006) mentions very similar survival, final weight, and size results on tilapia farming for the same period, except that the daily weight gain reported was 3.43 g d<sup>-1</sup>, and in this research, it was 4.06 g d<sup>-1</sup>. Besides, his research project was performed in cages.

Because of their low water volume, NFT systems are generally susceptible to abrupt changes in hydrological variables (Caló 2011). An NFT system cannot maintain water temperature in places with a large environmental temperature variation. Additionally, pH may undergo abrupt changes quickly, particularly affecting fish (Caló 2011). However, during the production cycle of *O. niloticus*, water quality variables were optimal (T, from 26 to 30°C; DO, 3 to 10 mg L<sup>-1</sup> and pH, 8 to 8.5) as reported by Comisión Nacional de Acuacultura y Pesca (CONAPESCA 2012). TAN tolerance levels for tilapia should be less than 2 mg L<sup>-1</sup> (Somerville et al. 2022). In this research, mean values of 1.63  $\pm$  0.54 mg L<sup>-1</sup> were found within the tolerable

range, consistent with Kotzen & Appelbaum (2010), who refer to values of 1.87 mg L<sup>-1</sup> for an aquaponic system with tilapia at the beginning and 0 mg L<sup>-1</sup> at the end of the crops.

The NO<sub>3</sub><sup>-</sup> are not toxic even at high concentrations from 150 to 300 mg L<sup>-1</sup> (Graber & Jungue 2009), but NO<sub>3</sub><sup>-</sup> toxicity in tilapia may occur if the concentration exceeds 300-400 mg L<sup>-1</sup> (DeLong et al. 2009). The results found in this research were within the tolerable range with maximum average values of 121.65  $\pm$  69.09 mg L<sup>-1</sup>. The PO<sub>4</sub><sup>-</sup> concentration for tilapia rearing should range from 0.5 to 1.5 mg L<sup>-1</sup> (CONAPESCA 2010). According to the results, concentrations two and three times higher than the acceptable level (maximum averages of 5.52  $\pm$  0.63 mg L<sup>-1</sup>) were recorded; however, in this study, it does not seem to have been a limiting factor for the growth and development of the fish.

The recommended EC for Nile tilapia is <2 mS cm<sup>-1</sup> (Timmons et al. 2002). This experiment recorded values lower than this (average value of 0.755  $\pm$  0.08 mS cm<sup>-1</sup>), which were within the recommended levels for tilapia and aquaponics: 0.3-0.8 mS cm<sup>-1</sup> (Nelson 2008). Values similar to the previous ones were found in Yang & Kim (2019) aquaponic experiments with *O. niloticus* and six plant species, including lettuce varieties.

Pinho et al. (2017) reported 95% under aquaponics conditions regarding tilapia survival. This work achieved a similar tilapia survival (94.9%). This experiment's total mortality (5.1%) of tilapia production was lower than 10%, representing the limit that tilapia production should not exceed (Kubitza 2009).

The similarity observed in growth and biomass between treatments, in both plant production cycles, from the beginning to the third week could be due to the aquaponic system having similar nutrient concentrations on the hydroponics system; the analyses demonstrated such a scenario for TAN,  $\text{NO}_3^-$  and  $\text{PO}_4^{3-}$  ions (Table 3). The difference from week four to harvest could be explained by hydroponics' increased nutrient concentrations from 50 to 75% since this treatment provided the ions required for adequate growth and biomass. In contrast, this contribution was regularly slow in aquaponics, increasing its concentration over time, according to work performed by nitrifying bacteria and fish effluent contribution (Caló 2011).

During the development of both production cycles, the aquaponics treatment showed lower lettuce plant growth and biomass than hydroponics, probably due to low nutrient availability in aquaponics (Table 3). This result agrees with Rakocy et al. (2004) who cultivated basil in aquaponics, and the limitation of some nutrients was notorious because chlorosis (yellowing) was observed in leaves, in addition to the plants growing slowly after transplantation until the nutrients in the system were stable, as previously mentioned. Although similar concentrations were observed in aquaponics and hydroponics and even greater TAN,  $\text{NO}_3^-$  and  $\text{PO}_4^{3-}$  ions, better growth results in systems aquaponics than in systems hydroponics were impossible in this study. Furthermore, whether or not other essential nutrients influenced lettuce plant growth in this work is difficult to determine because their concentrations were not known. Nevertheless, Rakocy et al. (2006) reported that low performance in aquaponics could be associated with low calcium ( $\text{Ca}^{2+}$ ), iron ( $\text{Fe}^{2+}$ ), phosphorus (P), and manganese ( $\text{Mn}^{2+}$ ) concentrations in the nutrient solution provided by the system. Rubio (2012) reported low lettuce plant weight values in aquaponics at an NFT recirculation system, similar to those obtained in the aquaponic treatment in this study.

On the other hand, another set of factors may have affected plant growth, such as high pH values. Nitrification decreases when pH is less than 6.4 and above 9.0 (Ruiz et al. 2003), and with a pH greater than 7.5, nutrient absorption, such as P,  $\text{Ca}^{2+}$ ,  $\text{Fe}^{2+}$ , and  $\text{Mn}^{2+}$  may be affected, with the risk of precipitating and

decreasing their availability (Baixauli & Aguilar 2002). In this study, likely low nutrient assimilation in the second production cycle (with no low concentration of TAN,  $\text{NO}_3^-$  and  $\text{PO}_4^{3-}$  ions since they were observed in adequate amounts, similar to or above the treatment hydroponics) has led to lower lettuce plant growth and biomass compared to the first cycle. It is also possible that these high pH values during the experiment have caused chlorosis (leaf yellowing) (Yang & Kim 2019) and mortality.

On the other hand, the variance analysis results indicated that some water-recorded variables, such as DO, T, and pH, influenced plant development between production cycles (Table 1). In the case of DO, the optimal interval to promote the nitrification process by bacteria is at a concentration from 4 to 8  $\text{mg L}^{-1}$  (Tyson et al. 2008). In this study, DO levels in aquaponics and hydroponics were within the optimal interval, particularly in the second production cycle and in hydroponics in both cycles.

An important factor is nutrient solution temperature, which determines the nutrient concentration absorbed by the plant, consequently influencing the photosynthetic system efficiency (Calatayud et al. 2004). In this study, root exposure of *L. sativa* var. Parris Island temperatures from 24.9 to 30.5°C positively correlated with height and leaf number variables in both treatments and leaf weight in aquaponics. Light radiation is an essential plant resource for photosynthesis (Valverde et al. 2005). Therefore, the accumulative effects of stressors can have numerous consequences for crops, ranging from short-term physiological responses in plants individually to long-term changes in plant structure and function (Carvajal et al. 2010).

Survival between aquaponics and hydroponics (60.18 and 59.25%, respectively; Table 5) in the first production cycle was higher than the value reported by Rubio (2012), which indicates survival of  $53.33 \pm 0.39\%$  for lettuce plant aquaponics in the NFT system. Low survival in aquaponics could be due to lettuce plant roots being exposed to large amounts of solids and consequently deprived of an adequate oxygen supply caused by the anaerobic decomposition of trapped waste (Khiari et al. 2020a). Removing such particles is one of aquaponics' most critical treatment processes; thus, suspended solids in contact with plant roots can clog them, preventing nutrient absorption (Caló 2011). This study did not have an additional sediment filter to remove suspended solids in the system.

The recommended EC for aquaponics systems is 0.3 to 0.8  $\text{mS cm}^{-1}$  (Nelson 2008). This experiment showed



average values from  $0.74$  to  $0.77 \pm 0.08 \text{ mS cm}^{-1}$  (first and second cycles, respectively), as recommended for production.

$\text{NO}_3^-$  is the main nitrogen ion form absorbed by plants. Thus, the accepted aquaponics range is  $5$  to  $150 \text{ mg L}^{-1}$  (FAO 2014). The results in this research study at the channels of the aquaponics system (where the lettuce varieties were placed) were  $77.81 \pm 33.73$  and  $163.63 \pm 216.58 \text{ mg L}^{-1}$  in the first and the second production cycle, respectively (Table 3). These values were tolerable and non-toxic to plants, within the accepted range for aquaponics in the first cycle and slightly higher in the second. However, Khiari et al. (2020b) showed strong evidence that P delays aquaponics' mineralization and nitrification period since no impact was observed on *Nitrobacter* and *Nitrosomonas* bacterial growth and thus  $\text{NO}_3^-$  availability in the system.  $\text{NO}_3^-$  concentrations in hydroponic solutions range from  $50$  to  $280 \text{ mg L}^{-1}$  (Resh 2004) and are acceptable up to a limit of  $100 \text{ mg L}^{-1}$  in an RAS system (Timmons et al. 2002). Nevertheless, studies have demonstrated that aquaponics  $\text{NO}_3^-$  varies between  $10 \text{ mg L}^{-1}$  and more than  $200 \text{ mg L}^{-1}$  without causing plant or fish stress (Liedl et al. 2004, Rakocy et al. 2006, Lam et al. 2015). In this study,  $\text{NO}_3^-$  concentrations ( $140.34 \pm 69.90$  and  $136.6 \pm 97.00 \text{ mg L}^{-1}$  in the first and second cycle, respectively) were adequate for hydroponics (Table 2).

P is one of the 17 essential elements required for plant growth and development (Raghothama 1999, Johri et al. 2015) and is taken up by the roots as  $\text{H}_2\text{PO}_4^-$  or to a lesser extent as secondary  $\text{HPO}_4^{2-}$  (Johri et al. 2015) and  $\text{PO}_4^{3-}$ . Aquaponic experiments report a  $\text{PO}_4^{3-}$  range from  $0$  to  $17 \text{ mg L}^{-1}$  (Lennard 2004, Villarreal et al. 2011, Buzby & Lin 2014). In this study, the average values of this experiment were  $3.03 \pm 2.37$  and  $5.52 \pm 4.57 \text{ mg L}^{-1}$  (first and second production cycle, respectively) at the channels of the aquaponics system (where lettuce varieties were located), which were within the permitted values for aquaponics (Table 3).

During the first cycle in hydroponics, low survival ( $59.25 \%$ ; Table 5) of lettuce plants was due to a high mortality rate days before harvest, which could have been attributed to an apparent fungal-looking apical rot problem (undiagnosed) that lettuce plants showed off and died before harvest day. Numerous field- and greenhouse-grown lettuce investigations have indicated the relationship between temperature, light intensity, duration, and relative humidity on tip burn. This Ca-related disorder occurs under specific environmental conditions (Collier & Tibbitts 1984, Schlaghauser et al. 1987, Bres & Weston 1992). According to Alvarado

et al. (2001), the problem seems more serious as the crop matures because dense foliage causes less airflow, increasing leaf moisture; additionally, if bacteria are present, rot develops on the dead leaf tip. However, in agreement with Baixauli & Aguilar (2002), such apical physiopathy can be caused by stressful situations of low luminosity followed by high luminosity periods or by rapid temperature increases leading to high breathing levels, producing water and thermal stress. During the second production cycle in the hydroponic system, survival was acceptable ( $98.14\%$ ), while the aquaponics system had a survival of  $50.92\%$ , lower than in the first cycle (Table 5). This result was probably due to the increased amount of solids in the system since more food was brought to the fish, which caused the roots to be covered with a layer of solids that prevented adequate water and nutrient absorption. As plants had withered and finally died, the presence of solids may have influenced the aquaponic cultivation since Chamorro-Legarda et al. (2011) also recorded growth difficulties in lettuce by the presence of sedimented solids (from the effluent of rainbow trout culture) at the bottom of the culture channels.

Concerning cucumber fruit average weight, Dursun et al. (2010) obtained  $126.7 \text{ g fruit}^{-1}$ , and Sánchez-del-Castillo et al. (2014) reported weight from  $268$ - $275 \text{ g}$  with cucumber under different hydroponic systems. According to this research, the average fruit weight obtained in the aquaponics system was  $148.64 \pm 5.01 \text{ g}$ , closer to the reported values. However, it was lower in aquaponics ( $94.30 \pm 10.23 \text{ g}$ ), while the average weight per fruit ( $212.52 \pm 18.89 \text{ g}$ ) was greater during the second hydroponics production cycle. Cucumber fruit length was higher in hydroponics ( $12.80 \pm 1.31$  and  $14.15 \pm 1.75 \text{ cm}$  in the first and second cycles, respectively) than in aquaponics ( $9.30 \pm 1.71 \text{ cm}$  in the first production cycle). During the second cycle in the aquaponic treatment, cucumber plants did not reach the fruiting stage, probably due to high saturation of solids in the root system, which probably prevented nutrient absorption and thus good cucumber fruit development, as mentioned above. Although similar levels of TAN,  $\text{NO}_3^-$ , and  $\text{PO}_4^+$  ions were observed in the water in aquaponics and hydroponics, the concentrations of the remaining nutrients needed for the proper cucumber cultivation development were not considered in this study. Even if these nutrients were present, they were not assimilated due to the high pH value and presence of solids that prevented plant development.

Tyson et al. (2008) recommended recirculation systems with pH management close to  $7.5$  and  $8.0$  for aquaponics in their work with cucumber and high

tilapia densities, favoring nitrification to convert ammonia residues to nitric nitrogen efficiently. Moreover, Okemwa (2015) suggests that by maintaining water pH closer to optimal for nitrification (pH 7.5 to 8.0) instead of the optimal for plant production (pH 5.5 to 6.5), plant yields are not reduced, and system sustainability could be improved. This study had higher pH levels than those mentioned (Table 2). Low temperature is one of the environmental factors influencing plant growth and development, mainly in temperate climate species, such as cucumber, a sensitive crop affected by cold exposure (Garstka et al. 2007, Skupień et al. 2017). The appropriate temperature for cucumber varies depending on the crop stages; for plant growth, the day temperature is 21°C, and for fruit development, the optimal day temperature is 19°C (Vasco-Morcillo 2002). Paris et al. (2012) mentioned a general interval for cucumber cultivation, which can be considered from 20 to 35°C. Although Vasco-Morcillo (2002) argues that above 30°C, plants can notice imbalances and night temperatures equal to or less than 17°C have resulted in defective leaves and fruit malformations. In the experiment referred to in this study, the average environmental temperature was  $27.17 \pm 0.48^\circ\text{C}$  during the day in the first cycle and  $22.30 \pm 0.67^\circ\text{C}$  in the second one, generally found within the range and at an optimal temperature threshold for cucumber fruit development.

The Servicio de Información Agroalimentaria y Pesquera (SIAP), an organism of the Government of Mexico, reported an average cucumber crop yield on irrigated soil in Nayarit of  $10.04 \text{ t ha}^{-1}$  in autumn-winter and  $16.17 \text{ t ha}^{-1}$  in spring-summer, recommending cultivation from May to July (SIAP 2020). Particularly, the pickle cucumber variety in San Blas, Nayarit, yielded  $12.32 \text{ t ha}^{-1}$  in 2015 (SIAP 2015). In this study, a maximum yield of  $4.97 \text{ t ha}^{-1}$  was obtained (Table 5), occurring in the hydroponic treatment and resulting in lower-than-expected production due to all the factors involved in plant production and growth evaluated. However, the planting dates for the spring-summer season were from April to September and the autumn-winter season from October to March (CONABIO 2006). Low cucumber fruit production in aquaponics and hydroponics could also be attributed to the greenhouse's absence of pollinating insects (bees or bumblebees), which affected crop yield in both treatments. Another agent, such as air, may have pollinated the fruits produced, but this medium is less efficient than insects. According to the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO 2006), pollen grains of cucumber flowers

are large, sticky, and heavy, so the wind cannot transport them. Thus, the participation of insects (entomophily vectors) is necessary to transport pollen, a quote that is consistent with USAID (2007), which states that cucumber plants depend on the movement of bees to transfer pollen between male and female flowers.

Cucumber plant growth appears to have had normal behavior in the hydroponics system and leaf biomass, greater than that of the aquaponic treatment. The difference between treatments could be attributed to the high contribution of suspended and sediment solids in the aquaponic system. Crops of high nutritional demand (fruit crops, cucumber) must use ripe aquaponic systems. A mature system can generate better-quality nutrients more steadily (Caló 2011). The high survival rates of cucumber plants in the two production cycles of both treatments evaluated (above 90%; Table 5) may be attributed to having a strong main root and fasciculate roots with quite superficial development that withstand greater resistance to the presence of solids compared to lettuce plants (Casilimas et al. 2012), allowing this species to absorb water and nutrients more efficiently.

Finally, the aquaponic system could have allowed good fish growth since they were maintained in the culture tanks in generally good conditions. However, for future studies, the system should be improved, specifically the clarifier or sedimentation tank, which somehow allowed the fine sludge to pass into the hydroponic component and affect plant roots. A pollination method is also necessary for fruit production since it is difficult for pollinating insects to enter when greenhouses are used. In conclusion, although the hydroponic system had higher plant production, the aquaponic system provided a double benefit since it produced fish and plants using waste from a fish culture without contaminating the environment.

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