UPDATE ON TILAPIA AND VEGETABLE PRODUCTION IN THE UVI AQUAPONIC SYSTEM

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Abtract

The UVI commercial-scale aquaponic system has produced Nile and red tilapia continuously for 4 years. During that time, two trials have been conducted to evaluate the production of basil and okra. Tilapia were harvested every 6 weeks from one of four 7.8-m^3 rearing tanks. Nile and red tilapia were stocked at 77 and 154 fish/m^3, respectively. During the last 20 harvests, production of Nile and red tilapia averaged 61.5 and 70.7 kg/m^3, respectively. Mean harvest weight was 813.8 g for Nile tilapia and 512.5 g for red tilapia. Nile tilapia attained a higher survival rate (98.3%) and a lower red conversion ratio (1.7) than red tilapia (89.9% and 1.8, respectively). Projected annual production is 4.16 mt for Nile tilapia and 4.78 mt for red tilapia. Batch and staggered production of basil in the aquaponic system was compared to field production of basil using a staggered production technique. Annual projected yield of basil is 25.0, 23.4 and 7.7 kg/m^3 for batch, staggered and field production, respectively. Annual projected yield of basil for the aquaponic system is 5.34 mt for batch production and 5.01 mt for staggered production. However, batch production was not sustainable with the current fish output because nutrient deficiencies occurred. The okra trial compared the production from three varieties (Clemson, Annie Oakley and North South) and two planting densities (2.7 and 4.0 plants/m^2) in the aquaponic system. One variety (Clemson) was cultivated in a field plot at the low planting density. The highest production (3.04 kg/m^2) was attained by the variety 'North South' at the high density.

Projected annual production of 'North South' is 13.37 kg/m^2 and 2.86 mt per system. Field okra grew slowly and produced only 0.15 kg/m^2. The aquaponic system performed well over a sustained period of time. Aquaponic production of basil and okra was dramatically higher than field production.

Introduction

Aquaponics is the combined culture of fish and plants in recirculating systems. Nutrients, which are excreted directly by the fish or generated by the microbial breakdown of organic wastes, are absorbed by plants cultured hydroponically (without soil). Fish feed provides most of the nutrients required for plant growth. As the aquaculture effluent flows through the hydroponic component of the recirculating system, fish waste metabolites are removed by nitrification and direct uptake by the plants, thereby treating the water, which flows back to the fish-rearing component for reuse.

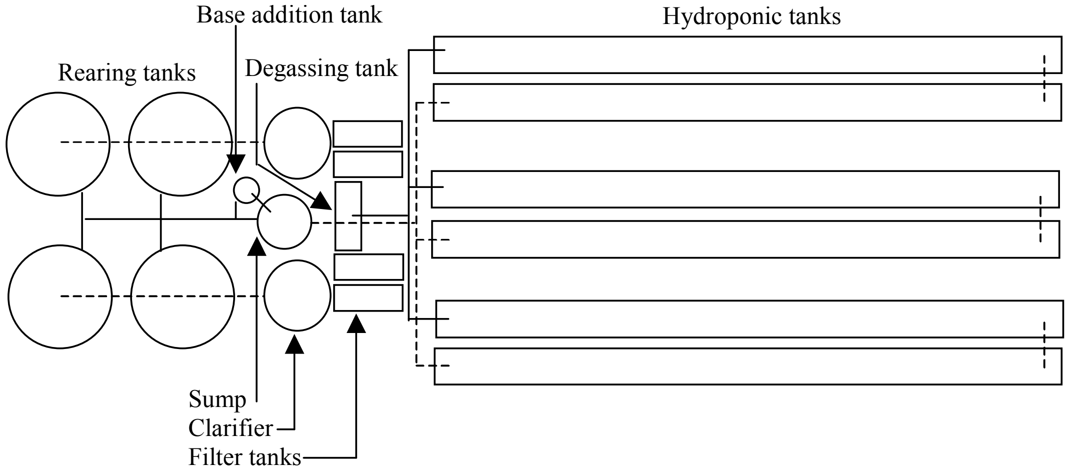
Aquaponics has several advantages over other recirculating aquaculture systems and hydroponic systems that use inorganic nutrient solutions. The hydroponic component serves as a biofilter, and therefore a separate biofilter is not needed as in other recirculating systems. Aquaponic systems have the only biofilter that generates income, which is obtained from the sale of hydroponic produce such as vegetables, herbs and flowers. In the UVI system, which employs raft hydroponics, only calcium, potassium and iron are supplemented. The nutrients provided by the fish would normally be discharged and could contribute to pollution. Removal of nutrients by plants prolongs water use and minimizes discharge. Aquaponic systems require less water quality monitoring than individual recirculating systems for fish or hydroponic plant production. Aquaponics increases profit potential due to free nutrients for plants, lower water requirements, elimination of a separate biofilter, less water quality monitoring and shared costs for operation and infrastructure.

A commercial-scale aquaponic system was developed at the University of the Virgin Islands in St. Croix. The status of the system was reported in the proceedings of ISTA 4 and 5 (Rakocy et al. 1997, Rakocy et al. 2000). The development of the system initially required many design changes. There have been no major changes in system design since ISTA 5. The system has produced tilapia continuously since that time. During the continuous production of tilapia, two short-term trials were conducted to determine the production capacity of basil and okra. This paper will report the highlights of this work.

Methods

The design of the UVI aquaponic system is shown in Figure 1. The water pump, which is located on the left side of the sump, pumps water a short distance to the fish rearing tanks. The flow to individual tanks is regulated by ball valves. As the carrying capacity of a fish- rearing tank is reached, a greater portion of the flow (378 L/min.) is diverted to that tank. Water flows from the fish-rearing tanks through the rest of the system by gravity and returns to the sump, which is the lowest point in the system.

Each fish-rearing tank has 22 air diffusers (14 L/min), which are cleaned weekly. There are four air diffusers in the degassing tank and one in the base addition tank. Each hydroponic tank has 24 air diffusers (10 L/min), which are positioned every 1.2 m in the center of the tank.



Tank Dimensions

Rearing tanks: Diameter: 3 m, Height: 1.2 m, Water volume: 7,800 L
Clarifiers: Diameter: 1.8, Height of cylinder: 1.2 m, Depth of cone: 1.1 m, Slope: 45º, Water volume: 3,785 L
Filter and degassing tanks: Length: 1.8 m, Width: 0.76 m, Depth: 0.61 m, Water volume: 700 L
Hydroponic tanks: Length: 30.5 m, Width: 1.2 m, Depth: 41 cm, Water volume: 11,356 L
Sump: Diameter: 1.2 m, Height: 0.9 m, Water volume: 606 L
Base addition tank: Diameter: 0.6 m, Height: 0.9 m, Water volume: 189 L
Total system water volume: 111,196 L
Flow rate: 378 Lpm, Pump: ½ hp, Blowers: 1½ hp (fish) and 1 hp (plants)
Total land area: 0.05 ha.

Pipe Sizes

Pump to rearing tanks: 10 cm
Rearing tanks to clarifier: 10 cm
Clarifiers to filter tanks: 10 cm
Between filter tanks: 15 cm
Filter tank to degassing tank: 10 cm
Degassing to hydroponic tanks: 15 cm
Between hydroponic tanks: 15 cm
Hydroponic tanks to sump: 15 cm
Sump to pump: 7.6 cm
Pipe to base addition tank: 1.9 cm
Base addition tank to sump: 3.2 cm

Figure 1. Layout of UVI Aquaponic System.

Settleable solids are removed from the clarifiers three times daily by opening a ball valve. Fine solids collect on orchard netting in the filter tanks and are removed one or two times weekly by draining the tank and washing the netting with a high pressure water spray. Effluent from the filter tanks passes through a fine-meshed plastic screens as it enters the degassing tank. The screens, which prevent tilapia fry from reaching the hydroponic tanks, are washed daily.

The pH is monitored daily and maintained at 7.0-7.5 by alternately adding calcium hydroxide and potassium hydroxide to the bass addition tank, where it dissolves and slowly enters the system. In the process of adding base, calcium and potassium ions are supplemented. The only other nutrient requiring supplementation is iron, which is added in a chelated form at a concentration of 2 mg/L once every three weeks.

Water lost through evaporation, transpiration and sludge removal is replenished with rainwater in the sump. Influent water is regulated by a float valve and measured by a water meter.

Tilapia are stocked in the rearing tanks at a rate of 77 fish/m^3 for Nile tilapia (*Oreochromis niloticus*) or 154 fish/m^3 for red tilapia and cultured for 24 weeks. Production is staggered so that one tank is harvested every 6 weeks, at which time they are weighed and counted. After harvest, the rearing tank is immediately restocked. The fish are fed three times daily with a complete, floating pellet containing 32% protein. The fish are fed *ad libitum* to satiation over a 30 minute feeding period.

Tilapia are produced continuously in this system to maintain stable bacterial populations. Hydroponic experiments are limited in duration. Between hydroponic experiments, the system is operated with a variety of demonstration crops or no crops at all. The hydroponic component has waste treatment capacity in excess of the amount generated at the recommended feeding rate and maintains acceptable ammonia and nitrite concentrations without the presence of plants.

Snails were introduced to the system several years ago, probably by birds. Snails consumed the nitrifying bacteria, which resulted in higher concentrations of ammonia and nitrite. Therefore, the hydroponic tanks were stocked with red ear sunfish fingerlings (*Lepomis microlophus*) to control the snail populations.

Hydroponic trials were conducted to evaluate the production of basil and okra. Basil trials occurred in 2002, and an okra trial occurred in 2003.

Two basil production trials were conducted during the periods of January 28 - May 20 and June 18 - September 20, 2002. Hydroponic basil was planted into a fully established and functioning system with a reservoir of nutrients generated from fish waste. In the first trial basil was produced by batch culture. Basil seedlings were planted at a density of 8 plants/m^2 in the entire 214-m^2 growing area. The plants were harvested three times by cutting and allowed to re-grow before a fourth and final harvest. The production period averaged 28.3 days. The main stem was cut at a height of 15 cm, which left sufficient leaves for re-growth. In the second trial a staggered production method was used. Every week one fourth of the growing area (53.5 m^2) was planted with basil seedlings at a density of 8 plants/m^2 until the system was fully planted. After a 28-day growing period, the plants were harvested at a height of 15 cm, allowed to re-grow and harvested a second time. There were a total of eight harvests. During the second trial, the staggered production procedure was followed for basil seedlings that were planted in an adjoining field at a density of 8 plants/m^2. The soil was prepared by applying dried composted cow manure (2-1-2) at a rate of 5.87 mt/ha. The plants were irrigated as needed with well water. Each of four plots consisted of three rows containing nine plants. Production data was collected from the seven inner plants from the middle row. Basil in the field trial was cultivated for 28 days. During all trials the plants were sprayed twice weekly with a commercial formulation of *Bacillus thuringiensis* to control caterpillars.

An okra production trial was conducted during the period of October 1 – December 22, 2003. Hydroponic okra was planted into a fully established and functioning system with a reservoir of nutrients generated from fish waste. Seedlings of three varieties of okra (North-South, Annie Oakley and Clemson Spineless) were transplanted into the system at two densities [2.7 plants/m^2 (low density) and 4.0 plants/m^2 (high density)] in six completely randomized blocks in a 3 by 2 factorial design. The low-density spacing was 33% less dense than the high-density spacing and is the recommended density for field production of okra. The plants grew in the aquaponic system for 33 days before the first harvest. Within each treatment replication a sample area of 2.1-m^2 was delineated, encompassing nine plants in the high-density plots and six plants in the low-density plots. Pods that were 8-cm and longer were cut with hand-held pruners from the sample area, counted and weighed *en mass*. Pod harvests were conducted every Monday, Wednesday and Friday for 49 days. There were a total of 22 harvests.

During the trial, okra seedlings were also transplanted into an adjoining field at a density of 2.7 plants/m^2. To prepare the soil, gypsum was applied at a rate of 4 mt/ha, and inorganic fertilizer (N-P-K of 21-7-7) was applied at a rate of 100 kg/ha. During the trial, field okra received four foliar applications of micronutrients (iron, magnesium and molybdenum). Six plots consisting of three rows were established. After transplanting, a layer of straw was placed over each plot to reduce the growth of weeds. The plots were irrigated as needed with well water using drip irrigation lines. Production data was collected from the six inner plants from the middle row. Field okra was cultivated for the same time period as okra in the aquaponic system. The first harvest of field okra occurred 54 days after transplanting and continued for 28 days. Harvests were conducted on Mondays, Wednesdays and Fridays of each week.

A pesticide (Sevin) was applied twice to the field plots to control ants. Field and aquaponic okra plants were sprayed twice a week with *Bacillus thuringiensis* to control caterpillars. During the last 6 weeks of the trial, field and aquaponic okra were sprayed once or twice weekly with a commercial formulation of potassium bicarbonate to control mildew.

In the basil trials standard methods were used to measure pH, total alkalinity, total dissolved solids (TDS), total ammonia-nitrogen (TAN), nitrite-nitrogen and nitrate-nitrogen once every 2 weeks at one location in the system. Dissolved oxygen (DO) and water temperature were measured periodically.

In the okra trial standard methods were used to measure the following water quality parameters once every two weeks: DO, water temperature, pH, total alkalinity, total suspended solids (TSS), turbidity, chemical oxygen demand (COD), TDS, electrical conductivity (EC), TAN, nitrite-nitrogen, nitrate-nitrogen, total phosphorous (TP), orthophosphate, potassium, calcium, magnesium, sulfate, chloride, iron, manganese, zinc, copper, boron, molybdenum and sodium. Samples for water quality analysis were collected at the influent and effluent of the hydroponic tanks to determine changes that occurred in water quality as culture water passed through the hydroponic component and the fish rearing and solids removal components. Water temperature, pH and total alkalinity were only measured at the influent to the hydroponic tanks because these parameters generally remain constant throughout the system.

Results and discussion

Tilapia production

Tilapia production data for 20 harvests are given in Table 1. The total harvest weight per tank for Nile and red tilapia averaged 480 and 551 kg, respectively. Based on these means, projected annual production would be 4.16 mt for Nile tilapia and 4.78 mt for red tilapia. Total harvest weight ranged from 387 to 632 kg for Nile tilapia and 448 to 688 kg for red tilapia. Some variability in total harvest weight was likely due to seasonal temperature fluctuation and the weight of fingerlings at stocking. There is a slight growth depression of tilapia from mid-December through mid-April when water temperatures decrease in the Virgin Islands, which are located at 18° North latitude. The mean weight of fingerlings stocked ranged from 43 to 138 g for Nile tilapia and 23 to 85 g for red tilapia. Feeding is another factor that may have contributed to variability in total harvest weight and slight underproduction. The fish were always fed three times daily, but the system was not managed as intensely as a commercial system would be, especially during periods between hydroponic experiments. It is possible that the fish were slightly underfed at times. With optimal *ad libitum* feeding, production may have been greater and less variable.

Red tilapia were stocked 154 fish/m^3 to produce smaller fish (512.5 g) for the West Indian market, which prefers a colorful whole fish that is served with its head on. At this density production averaged 70.7 kg/m^3, and the growth rate averaged 2.69 g/day. Nile tilapia were stocked at 77 fish/m^3 to produce a larger fish (813.8 g) for the fillet market. At this density production averaged 61.5 kg/m^3, and the growth rate averaged 4.40 g/day. The stocking rates appeared to be nearly optimal for the desired product size. Nile tilapia attained a higher survival rate (98.3%) and a lower feed conversion ratio (1.7) than red tilapia (89.9% and 1.8, respectively).

To achieve a desired minimum production of 5 mt, more research is needed on types of feed (e.g., higher protein levels) and the delivery of the feed. To achieve an annual harvest of 5 mt for Nile tilapia, the average harvest weight must be 978 g, an increase of 164 g over the current harvest weight. In addition to better feed and feed delivery, it may be necessary to stock larger fingerlings or increase the stocking rate slightly.

Basil production

Batch production of basil averaged 2.0 kg/m^2 per harvest (Figure 2). There was some mortality after each harvest, and final survival was 84.7%. Harvest by cutting weakened the plants and their roots became infected with *Pythium*. Before the first harvest, the roots appeared to be healthy. There was no indication of nutrient deficiency during the initial harvests. However, by the fourth harvest nutrient deficiencies were evident, especially in the second hydroponic tank of each set, indicating that some nutrient or nutrients became limiting as water traveled a distance of 61 m through each set of two hydroponic tanks. The deficiency was manifested as chlorosis (yellowing) of the leaves. Initially there was a large reservoir of nutrients and no deficiencies appeared early in the trial. However, during the production of four consecutive batches of basil, nutrient depletion occurred. During this period, the ratio between daily feed input and plant growing area was 81.4 g/day/m^2. Batch production of basil exceeded the nutrient generation capacity of the system. The cropping system was therefore changed to a staggered production to moderate nutrient uptake.

In the staggered production trial, the plants were cut once and allowed to regrow for a final second harvest. Production was two times higher in the second harvest (2.4 kg/m^2) than in the first harvest (1.2 kg/m^2). The average weight/plant was 167.1 g in the first harvest compared to 327.1 g in the second harvest. Basil exhibited slow growth after transplanting

Table 1. Production of Nile and Red tilapia in the UVI aquaponic system. Nile tilapia are stocked at 77 fish/m^3 and red tilapia are stocked at 154/m^3.

Harvest Date	Tilapia	Harvest Weight per tank (kg)	Harvest Weight per unit volume (kg/m^3)	Initial Weight (g/fish)	Final Weight (g/fish)	Growth Rate (g/day)	Survival (%)	FCR
02/07/2002	Nile	632	81.1	113	1070	5.70	98.8	1.8
03/21/2002	Nile	429	55.0	74	711	3.79	100.0	1.8
05/02/2002	Nile	417	53.4	76	701	3.72	99.2	1.7
06/13/2002	Red	528	67.7	23	476	2.52	92.5	1.8
07/25/2002	Nile	418	53.6	60	700	4.16	99.5	1.7
09/05/2002	Nile	461	59.1	76	781	4.22	98.3	1.9
10/17/2002	Nile	534	68.5	89	896	4.80	99.3	1.8
11/28/2002	Red	542	69.5	75	470	2.53	96.0	2.0
01/09/2003	Nile	460	59.0	67	769	4.18	99.7	1.7
02/20/2003	Nile	432	55.4	68	786	4.27	92.0	1.8
04/03/2003	Nile	387	49.6	61	654	3.53	98.5	1.7
05/14/2003	Red	448	57.4	52	441	2.32	84.6	1.9
06/24/2003	Nile	432	55.3	107	733	3.77	98.2	1.6
08/07/2003	Nile	480	61.6	71	825	4.49	97.0	1.6
09/18/2003	Nile	551	70.6	80	921	5.01	100.0	1.6
10/30/2003	Nile	443	56.8	59	768	4.25	96.2	1.7
12/11/2003	Red	688	88.2	85	663	3.40	86.5	1.6
01/22/2004	Nile	482	61.8	43	815	4.60	98.7	1.7
03/04/2004	Nile	551	70.6	85	924	4.99	99.3	1.7
04/15/2004	Nile	571	73.2	138	967	4.93	98.3	1.8
Mean	Nile	480	61.5	79.2	813.8	4.40	98.3	1.7
	Red	551	70.7	58.8	512.5	2.69	89.9	1.8

Figure 2. Basil and okra production in the UVI Aquaponic System.

while it became established. Cutting stimulated branching, and re-growth was faster. Mortality due to *Pythium* and aggravated by cutting was still a serious problem in this trial. After eight harvests there was no sign of nutrient deficiency. The ratio between daily feed input and growing area was 99.6 g/day/m^2, 22% higher than in the batch trial. Fish consumed more feed during the staggered production trial because water temperatures were as much as 5°C higher (29°C vs. 24°C) during the summer compared to winter/spring when the batch trial was conducted. The higher feeding ratio and the even uptake of nutrients created a sustainable production system, although *Pythium* was more severe due to higher water temperatures. Increasing the feeding ratio during the cool season would require the cultivation of more fish.

Field production of basil resulted in much lower yields (0.6 kg/m^2) and average weight (104.4 g) compared to aquaponics, but survival was 100%, as the plants did not have *Pythium* and could easily recover from cutting. As with the staggered production, the plants grew slowly after transplanting and only attained an average yield and weight/plant of 0.3 kg/m^2 and 49.8 g at the first harvest. Yield and weight/plant tripled to 1.0 kg/m^2 and 159.1 g by the second harvest.

A comparison of all three cropping systems showed that batch and staggered production of basil in an aquaponic system were comparable and both aquaponic crops were approximately three times more productive than field production (Table 2). Annual projected yield was 25.0, 23.4 and 7.8 kg/m^2 for batch, staggered and field production, respectively. Annual projected yield for the system was 5,341 kg for batch production and 5,008 kg for staggered production. However, batch production was not sustainable with the current fish output, and nutrient deficiencies would render much of the harvest unmarketable. Fresh basil with stems sells for $22.00/kg in the U.S. Virgin Islands. Therefore, gross income from staggered production would be US$515/m^2/year and US$110,210/system/year compared to field production with gross income of US$172/m^2/year and US$36,808/year for the same production area. Compared to field production, the aquaponic system would save substantial labor associated with weeding but would require additional labor for seedling replacement due to mortality. Total income from the system would be US$134,245 when fish are included. The basil would generate 4.6 times more income than the fish. However, the fish contribute additional value to the system through consistent nutrient generation and the elimination of the need for excessive water quality monitoring or frequent water replacement.

Table 2. Comparison of basil yield, mean plant weight, survival and gross income with three production methods (Rakocy *et al.*, 2004).

Production Method	Annual Yield (kg/m^2)	Annual Yield (kg/214 m^2/yr)	Mean Plant Weight (g)	Survival (%)	Income (US$/ m^2/yr)	Income (US$/214 m^2/yr)
Batch	25.0	5,341	286.5	84.7	550	117,700
Staggered	23.4	5,008	244.7	-	515	110,210
Field	7.8	1,669	104.4	100	172	36,808

Table 3. Means values and ranges of water quality variables during basil production trials. Units are in mg/L unless otherwise noted (Rakocy *et al.*, 2004).

Variable	Batch Culture	Staggered Culture
pH	7.4 (7.0-7.6)	7.1 (6.9-7.3)
Total-ammonia-N	2.2 (1.6-2.9)	1.7 (1.1-2.4)
Nitrite-N	0.7 (0.4-1.1)	0.9 (0.5-1.1)
Nitrate-N	42.2 (26.7-54.7)	42.9 (30.9-51.8)
Total dissolved solids	532 (490-560)	550 (490-560)
Alk (mg/L, as $CaCO_3$)	113.2 (65.6-206.7)	88.6 (65.6-115.6)

Water quality - basil trial

TAN and nitrite-N concentrations remained within safe limits for fish culture (Table 3). Nutrient concentrations were lower than the levels normally found in hydroponic systems, but they were generally acceptable for aquaponic systems because nutrients were produced daily, excreted directly by the fish or generated from the mineralization of organic matter. The slow removal of solids from the clarifiers and filter tanks provided sufficient time for substantial mineralization to occur. In addition to removing fine particulate matter, microorganisms in the filter tank also removed dissolved organic matter, preventing it from inducing excessive microbial growth on the plant roots.

In this aquaponic system water develops a tea color due to the accumulation of refractory organic compounds (e.g., tannic acid), but suspended solids levels are generally low (<10 mg/L) and the water remains clear. These characteristics were exhibited in all previous trials with lettuce. With basil the water became turbid, and DO levels in the rearing tanks decreased to a range of 4.0 to 5.0 mg/L. In previous lettuce trials DO concentrations ranged from 5.0 to 6.0 mg/L in the rearing tanks.

pH was maintained at an average value of 7.1 to 7.4 (Table 2). This value is considered to be high for a hydroponic system, but in an aquaponic system pH must be maintained above 7.0 to promote nitrification. Fish excrete large quantities of ammonia, which must be oxidized to nitrate to prevent toxicity. Nitrification produces acid and the pH decreased daily. To increase pH from the initiation of the first trial to the end of the second trial, including the inter-trial period, 22.5 kg of $Ca(OH)_2$ was added in 23 doses and 21.5 kg of KOH was added in 22 doses. Based on this data, the system would annually require 40.65 kg of $Ca(OH)_2$ and 38.85 kg of KOH. In addition to regulating pH, base addition supplements Ca and K, which are not generated in sufficient quantities from fish feed for good plant growth in aquaponic systems. During the same period, 18.17 kg of iron chelate (13%) was added to the system in eight doses. The annual projected iron requirement for the system would be 32.83 kg. All other required nutrients came from fish waste.

Daily make-up water averaged 2.61 m^3 or 2.4% of system volume. Water loss was attributed to sludge removal, net filter washing, splashing, evaporation and transpiration.

Okra production

During the 11.7-week okra trail, the plants grew luxuriously in the aquaponic system and began to produce fruit (pods) after 4.7 weeks (Figure 2). Although batch cultivation was used, there were no signs of nutrient deficiency during the production period. The *ad libitum* feeding method was monitored closely to avoid underfeeding. During the production trial, the ratio between daily feed input and plant growing area was 95.6 g/day/m^2. Okra production was consistently higher at the high density (4 plants/m^2), based on unit area (Table 4). However, production per plant was substantially greater at the low density (2.7 plants/m^2). The highest production (3.04 kg/m^2) was attained by the variety 'North South' at the high density.

Projected annual production of 'North South' is 13.37 kg/m^2 and 2,862 kg system (214 m^2). Okra can be sold for $2.20/kg in the U.S. Virgin Islands. Therefore, gross income from the sale of okra would be $29.42/$m^2$/year and $6,296/system/year. Rainfall was unusually heavy during the experimental period, and an outbreak of mildew may have lowered production.

Table 4. Okra production data.

Production	Variety	Low Density	High Density	Field
(kg/m^2)	Clemson	2.67	2.87	0.15
	Annie Oakley	2.37	2.76	-
	North South	2.58	3.04	-
	Mean	2.54	2.89	-
(g/plant)	Clemson	988	706	69
	Annie Oakley	878	677	-
	North South	955	747	-
	Mean	940	710	-

The field okra was slow to become established and started to produce fruit at 7.7 weeks. By the end of the experimental period, total production (0.15 kg/m^2) of field okra was only 5% of the production obtained in the aquaponic system. The management of field okra was more intensive than aquaponic okra and required the following additional procedures: soil preparation (plowing, rototilling and application of gypsum and inorganic fertilizer); weeding and mulching; pesticide application for ant control; periodic drip irrigation; and several foliar applications of trace elements.

Water quality – okra trial

Water quality parameters remained well within acceptable limits for tilapia production (Table 5). The difference in values between the filter tank effluent and the rearing tank influent represents the water treatment that occurred in the hydroponic component. Dissolved oxygen levels increased 33% while TAN and nitrite-nitrogen concentrations decreased 40%, 51%, respectively (Table 5 and Figures 3 and 4). DO levels increased due to the aeration of 144 air diffusers as filter tank effluent flowed through the hydroponic the tanks in 3 hours. TAN and nitrite-nitrogen concentrations decreased due to uptake by plants and nitrification. There were no substantial changes in the levels of TSS, turbidity and COD.

Table 5. Water quality during the okra production trial.

Parameter	Filter Tank Effluent	Rearing Tank Influent
Dissolved Oxygen (mg/L)	4.2 (3.7-4.6)	5.6 (3.9-6.3)
Water Temperature (°C)	27.9 (26.4-29.0)	-
pH	7.1 (6.8-7.4)	-
Total Alkalinity (mg/L as $CaCO_3$)	115.9 (96.7-155.6)	-
Total Ammonia-N (mg/L)	1.58 (0.49-2.42)	0.95 (0.20-1.82)
Nitrite-N (mg/L)	0.43 (0.09-0.94)	0.21 (0.01-0.66)
Total Suspended Solids (mg/L)	13 (4-28)	13 (4-32)
Turbidity (FTU)	50 (17-102)	51 (18-104)
Chemical Oxygen Demand (mg/L)	51.1 (14.6-74.3)	54.0 (14.6-132.1)

Water quality parameters of importance to plant culture are presented in Table 6. The electrical conductivity of a typical hydroponic nutrient solution ranges from 2.00-4.00 milliSiemen/cm (Resh, 1995). The average EC (0.5 mS/cm) during the okra trial was well below the standard range for hydroponic solutions. Similarly, the initial concentration of total dissolved solids in a hydroponic solution ranges from 1,000 to 2,600 mg/L, depending the type of plant being cultured. During the okra trial, the mean TDS level (236 mg/L) was well below the standard range of hydroponic nutrient concentrations. Aquaponics is fundamentally different than hydroponics in that nutrients are constantly generated in proportion to the feed being added to the system. The ratios of essential nutrients are suitable for good plant growth with the exception of calcium, potassium and iron, which have to be supplemented when the UVI system is supplied with rainwater. Hydroponic nutrient solutions rely on high initial concentrations to avoid nutrient depletion during the production cycle. Hydroponic nutrient solutions can be analyzed and replenished on a weekly basis to extend their use to a maximum of 3 months, at which time they must be discarded and replaced (Resh, 1995). Without weekly analysis and replenishment, hydroponic nutrient solutions must be discarded after 2 to 3 weeks. The UVI aquaponic system has been operated continuously for 4 years without a total water replacement event. Average daily water exchange rates range from 0.26 to 0.46% of system volume to replace water lost through sludge removal depending on whether the filter tanks are cleaned once weekly or twice weekly, respectively. Therefore, there is one complete water exchange every 385 days (once weekly) or 217 days (twice weekly).

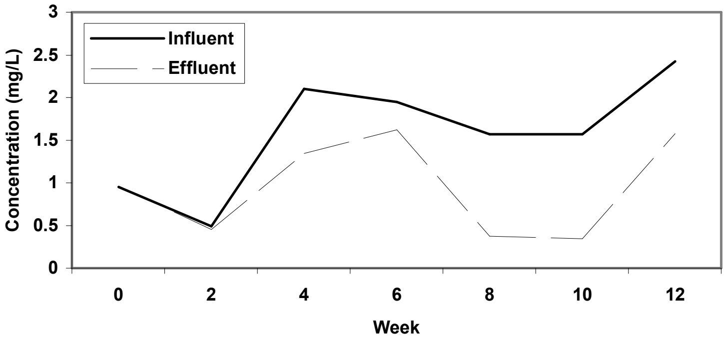


Figure 3. Total Ammonia Nitrogen concentrations in the hydroponic troughs, influent and effluent. Okra experiment, Fall 2003.

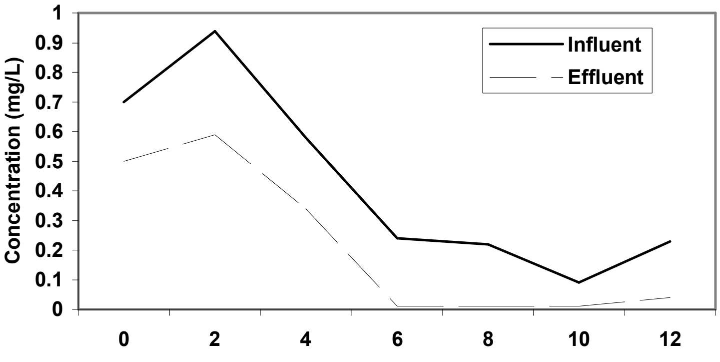


Figure 4. Total Nitrite Nitrogen concentrations in the hydroponic troughs, influent and effluent. Okra experiment, Fall 2003.

With the exception of zinc (Zn), copper (Cu) and iron (Fe), all other water quality parameters remained substantially lower during the okra trial than standard concentrations in a hydroponic nutrient solution (Table 6). The mean Zn concentration (0.34 mg/L) was about seven times higher than a standard hydroponic concentration (0.05 mg/L). The mean Cu concentration (0.03 mg/L) was comparable to a standard hydroponic concentration. Iron, which was added every 3 weeks at a standard hydroponic level (2 mg/L), averaged 1.3 mg/L.

Table 6. Water quality parameters during the okra production trial that affect plant growth.

Category	Parameter	Hydroponic Tank Influent	Hydroponic Tank Effluent
Total Nutrients	EC (mS/cm)	0.5 (0.3-0.6)	0.5 (0.3-0.6)
	TDS (mg/L)	236 (150-300)	236 (150-300)
Macronutrients (mg/L)	NO_3-N	26.3 (7.8-51.9)	27.5 (8.6-53.1)
	TP	16.4 (5.6-31.6)	15.9 (4.4-31.4)
	Orthophosphate	15.0 (4.5-36.5)	15.2 (4.4-37.8)
	K	63.5 (30.1-86.9)	64.6 (29.4-87.1)
	Ca	24.2 (14.7-31.6)	24.3 (14.6-32.1)
	Mg	6.0 (3.1-8.6)	6.0 (3.1-8.5)
	SO_4	18.3 (10.8-24.4)	18.8 (10.5-23.9)
Micronutrients (mg/L)	Cl	11.5 (6.5-14.9)	11.5 (6.6-14.8)
	Fe	1.3 (0.5-1.8)	1.3 (0.5-1.8)
	Mn	0.06 (0.02-0.09)	0.05 (0.01-0.09)
	Zn	0.34 (0.22-0.44)	0.34 (0.22-0.46)
	Cu	0.03 (0.01-0.03)	0.03 (0.02-0.04)
	B	0.09 (0.05-0.13)	0.09 (0.05-0.13)
	Mo	0.01 (0.00-0.02)	0.01 (0.00-0.01)
Other (mg/L)	Na	13.7 (9.9-19.8)	13.7 (9.9-19.7)

As effluent from the filter tanks flowed through the hydroponic tanks, there was virtually no change in most nutrient concentrations (Table 6). Although the retention time (3 hours) was relatively long, there was a large reservoir of nutrients due to the large water volume (68 m^3) in the hydroponic tanks. Therefore, uptake of nutrients on a single pass through the hydroponic tanks was generally undetectable. There was an average increase of 1.2 mg/L in the concentration of NO_3-N due to nitrification (Figure 5). The difference between total phosphorous and orthophosphate represents organic phosphorus. The concentration of organic phosphorus decreased by an average of 0.7 mg/L while the concentration of orthophosphate increased by an average of 0.2 mg/L, which indicates that mineralization was occurring in the hydroponic tanks and releasing phosphorus in a dissolved inorganic form.

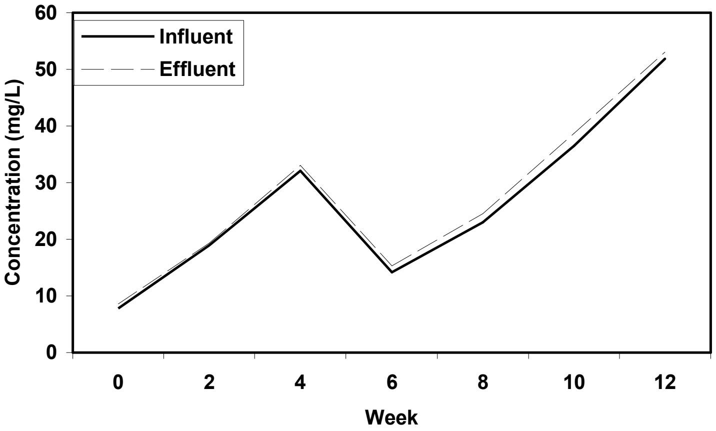


Figure 5. Total Nitrate Nitrogen concentrations in the hydroponic troughs, influent and effluent. Okra experiment, Fall 2003.

Conclusions

Nile and red tilapia performed well in the system, although red tilapia is a weaker fish as indicated by a lower survival rate (89.9%) compared to that (98.4%) of Nile tilapia. Annual production of Nile tilapia (4.16 mt) and red tilapia (4.78 mt) was lower than the target production of 5 mt. Closer attention to the *ad libitum* feeding method should increase annual production. For Nile tilapia, however, a slight increase in the current stocking rate (77 fish/m^3) and fingerling size (79.2 g) may be needed to reach annual production of 5 mt.

Batch and staggered production of basil produced comparable yields, but the growth of all plants in the same phase (i.e., batch culture) led to the depletion of nutrients in the culture water and the onset of nutritional deficiency disorders in the basil. During the batch production trial, the ratio of fish feed to plant growing area was 81.4 g/day/m^2, When four growth stages of basil were staggered, no deficiency symptoms appeared, although the feeding ratio (99.6 g/day/m^2) was higher due to elevated water temperatures and a better fish feeding response. With staggered production, the high nutrient demand by plants in the final growth stages was counterbalanced by lower nutrient demand by plants in the initial growth stages, thereby moderating the uptake of nutrients and avoiding nutrient depletion. Additional research could determine the optimum feeding ratio for staggered production of basil and whether or not batch culture of basil is feasible at a higher feeding ratio. Based on this experiment, it is recommended that a staggered production technique be used in aquaponic systems, especially for crops such as lettuce and basil with short production cycles.

Okra production in the aquaponic system was outstanding compared to field production. Production of Clemson at the low density (2.7 plants/m^3) was 18 times greater in the aquaponic system than in the field. However, the trial was relatively short (11.7 weeks), and it was affected by heavy rains and wet conditions, which stimulated the growth of mildew. Field okra may require a longer establishment period. A longer trial and drier conditions may reduce the difference in yields of okra produced in aquaponic systems and field plots. Moreover, the field plot soil was highly alkaline, which affects trace nutrient availability and growth.

Although okra grows rapidly in a raft aquaponic system and does well under warm conditions, it is not nearly as lucrative a crop as culinary herbs such as basil. It may be useful however for warm weather seasonal production in rotation with cool weather crops such as lettuce. Okra may also be a useful crop in operations that attempt to be the sole provider of a large variety of vegetables for farmer-operated restaurants.

The UVI aquaponic system has proven to be reliable, productive and robust. It is an ideal system for areas that have limited resources such as water or level land. It has also performed well in temperate climates in environmentally controlled greenhouses. Future research will determine the production capacity of a wide variety of vegetables, herbs and flowers, refine system operation, evaluate less expensive construction materials and methods and determine the economics of different plants crops.

References

Rakocy, J.E., D.S. Bailey, K.A. Shultz and W.M. Cole. 1997. Evaluation of a commercial-scale aquaponic unit for the production of tilapia and lettuce. pp. 357-372. *In:* K. Fitzsimmons (ed.). Tilapia Aquaculture: Proceedings of the Fourth International Symposium on Tilapia in Aquaculture, Orlando, Florida.

Rakocy, J.E., D.S. Bailey, J.M. Martin and R. C. Shultz. 2000. Tilapia production systems for the Lesser Antilles and other resource-limited, tropical areas. pp. 651-662. *In:* K. Fitzsimmons and J. Carvalho Filho (Eds.). Tilapia Aquaculture in the 21st Century: Proceedings from the Fifth International Symposium on Tilapia in Aquaculture, Rio de Janeiro, Brazil.

Rakocy, J.E., Shultz, R.C., Bailey, D.S. and Thoman, E.S. 2004. Aquaponic production of tilapia and basil: comparing a batch and staggered cropping system. Acta Horticulturae (ISHS) 648:63-69. (http://www.actahort.org/books/648/648_8.htm)

Resh, H.M. 1995. Hydroponic food production. Woodbridge Press Publishing Company, Santa Barbara, California.