Aquaponic Production of Tilapia and Basil: Comparing a Batch and Staggered Cropping System

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Abstract

Aquaponics is the combined culture of fish and hydroponic plants in recirculating systems. Aquaculture effluent provides most of the nutrients required by plants if the optimum ratio between daily feed input and plant growing area is maintained. An experiment was conducted in an outdoor, commercial-scale aquaponic system on 0.05 ha of land in the tropics. The objectives were to determine the production of tilapia and basil using batch and staggered cropping systems, compare aquaponics with field crop production and evaluate the ratio of feed input to plant growing area. The projected annual production of tilapia was 4.37 t. The mean yield of basil was 2.0, 1.8 and 0.6 kg/m^2 using batch, staggered and field cropping systems, respectively. Projected annual production of the system was 5.0 t of basil with staggered production. Nutrient deficiency symptoms appeared only in the batch-cultured basil. The feed input ratio was 81.4 g/day/m^2 for batch culture and 99.6 g/day/m^2 for staggered production. Staggered production moderated the uptake of nutrients. Basil production is sustainable in an aquaponic system with a feed input ratio of 99.6 g/day/m^2 and a staggered cropping system.

INTRODUCTION

Aquaponics is the combined culture of fish and plants in closed recirculating systems. Waste nutrients in the aquaculture effluent are used to produce plant crops. The effluent is treated (nutrient uptake, nitrification, etc.) in the plant component and returned to the fish rearing tanks. Aquaculture effluent typically supplies 10 of the 13 required plant nutrients in adequate amounts, with only Ca, K and Fe needing supplementation. Continuous generation of nutrients from fish waste prevents nutrient depletion while uptake of nutrients by the plants prevents nutrient accumulation, extends water use, and reduces discharge to the environment. Culture water can be used continuously for years. The balance between nutrient generation and removal also reduces the need for water quality monitoring. If production guidelines are followed, the only parameter that requires frequent monitoring is pH. pH decreases daily in response to the acid produced by the nitrification of ammonia, which is excreted by fish through their gills. Nutrient balance is achieved by maintaining an optimum ratio between daily fish feed input and plant growing area. Research on the staggered production of Bibb lettuce has shown that 57 g/day/m^2 is optimal (Rakocy, 1988). The optimum ratio depends on source-water nutrient levels, method of production (batch vs. staggered) and type of plant. The optimum ratio is not known for basil.

A commercial-scale aquaponic system has been developed at the University of the Virgin Islands (UVI) in St. Croix, U.S. Virgin Islands, which is located in the tropics (Rakocy, 2002). The system has been used to culture tilapia (*Oreochromis* spp.) and several types of lettuce (*Lactuca sativa*). The present study was conducted to determine the production of tilapia and basil (*Ocimum basilicum* ‘Genovese’) in this aquaponic system, using batch and staggered cropping systems, compare it to field crop production and evaluate the ratio of feed input to plant growing area.

MATERIALS AND METHODS

The UVI aquaponic system was situated outdoors and consisted of four fish rearing tanks (7.8 m^3 each), two cylindro-conical clarifiers (3.8 m^3 each), four filter tanks (0.7 m^3 each) containing orchard netting, one degassing tank (0.7 m^3), six raft hydroponic tanks (each of which was 11.4 m^3 and measured 30.5 m by 1.2 m by 30 cm: total hydroponic growing area was 214 m^2), one sump (0.6 m^3) and one base addition tank (0.2 m^3) (Fig. 1). Total system water volume was 110 m^3. The fish rearing and hydroponic tanks were each aerated by separate 1-hp blowers and air stones. A ½-hp water pump circulated water at a rate of 378 L/min. Average retention time was 1.4 hours in the fish rearing tanks and 3.0 hours in the hydroponic tanks. With the exception of the hydroponic tanks, all other tanks were situated under an opaque canopy. The production unit occupied 0.05 ha of land.

Prior to initiating the experiment the fish rearing tanks were in continuous operation for the production of Nile tilapia (*Oreochromis niloticus*) or red tilapia (*Oreochromis* sp.). Fish production cycles were 24 weeks. Production within the four rearing tanks was staggered so that one tank was harvested every 6 weeks. Nile tilapia fingerlings were stocked at 77 fish/m^3 while red tilapia fingerlings were stocked at 154 fish/m^3. Fingerlings averaged 70 g. The fish were fed three times daily *ad libitum* for 30 minutes with a complete diet of floating pellets containing 32% protein. Within 2 weeks of initiating the first basil trial using batch culture, the water pump was stopped for 16 days to upgrade the clarifiers. The fish were not fed during this period, but basil growth continued.

Using normal operating procedures, effluent from the fish rearing tanks flowed into the clarifiers, from which settleable solids were removed three times daily by opening the clarifier drain. Fine suspended solids were removed from the flow stream by adhering to orchard netting in the filter tanks. The filter tanks were drained twice a week, and the orchard netting was cleaned with a high-pressure water sprayer.

Effluent from the filter tanks flowed into a degassing tank where four air stones vented gases (carbon dioxide, nitrogen, methane and hydrogen sulfide) into the atmosphere, which were produced in the filter tanks. Fine-meshed screens under the inlets prevented tilapia fry from entering the degassing tank. Screens were cleaned daily. Internal standpipes in the degassing tank split the discharge into three waste streams.

Each waste stream from the degassing tank flowed through a set of two hydroponic tanks and discharged into a sump, from which the treated water was pumped back to the rearing tanks. A small side stream of sump water flowed through an aerated base addition tank back into the sump.

Water quality parameters were measured using standard methods (APHA, 1995), including pH (measured daily), dissolved oxygen (DO) and water temperature (measured intermittently) and total NH_3-N (TAN), NO_2-N, NO_3-N, TDS and EC (measured biweekly). The following parameters were measured March 5, April 5 and May 22: Ca, Mg, K, P, Fe, Mn, Cu, Zn, B and Mo.

pH was maintained in the range of 7.0-7.5 by alternately adding $Ca(OH)_2$ or KOH to the base addition tank. Iron chelate (13% EDTA Fe) was added at rate of 2 mg/L at 3-week intervals.

The system used rainwater, which was captured by a plastic liner (high density polyethylene) and stored in a covered tank. Make-up water was measured with a water meter.

Two basil production trials were conducted during the periods of January 28 - May 20 and June 18 - September 20, 2002. The 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 same 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 t/ha. The plants were irrigated as needed with well water. Each plot 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 a week with a commercial formulation of *Bacillus thuringiensis* to control caterpillars.

RESULTS AND DISCUSSION

There were six harvests of fish during the two basil trials (Table 1). Five of the harvests consisted of Nile tilapia and one consisted of red tilapia (harvest 1, staggered basil production trial). Total tilapia production was 2.89 t, and annual production was projected to be 4.18 t, based on the harvest data. However, the fish were not fed for 16 days near the outset of the experiment to upgrade the clarifiers. Assuming that feeding was not disrupted, adjusted annual production was projected to be 4.37 t. Total feed input was 1,673 kg in the batch trial and 1,642 kg in the staggered trial. Annual projected feed input to the system was 6.99 t. The selling price for whole tilapia is US$5.50/kg in the U.S. Virgin Islands. Based on the adjusted projection of annual production, gross income from fish sales would be US$24,035.

TAN and nitrite-N concentrations remained within safe limits for fish culture (Table 2). 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 7.4 (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.

Batch production of basil averaged 414.0 kg per harvest and 2.0 kg/m^2 (Table 3). There was some mortality after each harvest, and final survival was 84.7%. Cutting weakened the plants, whose 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 of the leaves. Initially there was a large reservoir of nutrients in the system as it had been operating for some time without plants, and no deficiencies appeared early in the trial when the fish were not fed during the clarifier upgrade. 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 $g/day/m^2$, which was higher than the optimum ratio of 57 $g/day/m^2$ for Bibb lettuce. 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.

Staggered production averaged 96.5 kg per harvest and 1.8 kg/m^2 (Table 4). Total production and yield were two times higher in the second harvest (131.0 kg and 2.4 kg/m^2) than in the first harvest (62.0 kg and 1.2 kg/m^2), respectively. 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 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 ratio and the even uptake of nutrients created a sustainable production system, although *Pythium* was more severe due to higher water temperatures. Increasing the ratio during the cool season would require the cultivation of more fish.

Yields per crop for batch (2.0 kg/m^2) and staggered (1.8 kg/m^2) production of basil were approximately one third of the yield (6.25 kg/m^2/crop) reported by Bradley and Marulanda (2001) in a hydroponic system. Annual yields for batch (25.0 kg/m^2) and staggered (23.4 kg/m^2) production were half as large the annual yield (56.2 kg/m^2) reported by Bradley and Marulanda because they produced fewer crops annually (nine crops compared to 13 crops in the present study). Bradley and Marulanda planted at a density (25 plants/m^2) that was three times higher than the density (8 plants/m^2) in the present study. Observations of the plants in the present study indicated that a higher density could be used in aquaponic raft culture.

Field production of basil resulted in much lower yields (0.6 kg/m^2) and average weight (104.4 g), but survival was 100%, as the plants did not have *Pythium* and could easily recover from cutting (Table 5). 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 were approximately three times more productive than field production (Table 6). Annual 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 would be 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/yr and US$110,210/system/yr compared to field production with gross income of US$172/m^2/yr and US$36,808/yr 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.

CONCLUSION

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.

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Tables

Table 1. Tilapia production from six harvests during the basil production trials.

Basil Production Method	Harvest	Total Fish Biomass (kg)	Feed Conversion Ratio	Survival (%)
Batch	1	632.3	1.80	98.8
Batch	2	429.3	1.78	100.0
Batch	3	416.9	1.75	99.2
Staggered	1	528.0	1.79	92.5
Staggered	2	417.7	1.71	99.5
Staggered	3	468.6	1.92	99.4
Overall Mean	-	482.1	1.79	-
Batch Mean	-	492.8	1.78	-
Staggered Mean	-	471.4	1.81	-

Table 2. Means values and ranges of water quality variables during basil production trials. Units are in mg/L unless otherwise noted.

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)
EC (mS/cm)	0.8 (0.7-0.8)	0.8 (0.7-0.8)
Calcium	11.9 (6.0-22.0)	-
Magnesium	6.5 (6.0-7.0)	-
Potassium	44.9 (37.1-56.9)	-
Phosphorus	8.2 (7.6-9.0)	-
Iron	2.5 (1.8-3.0)	-
Manganese	0.80 (0.05-0.10)	-
Copper	0.05 (0.04-0.07)	-
Zinc	0.44 (0.41-0.48)	-
Boron	0.19 (0.09-0.23)	-
Molybdenum	0.01 (0.00-0.02)	-

Table 3. Batch production of basil harvested four times.

Harvest	Total Production (kg)	Yield (kg/m^2)	Mean Weight Per Plant (g)	Survival (%)
1	441.0	2.1	-	-
2	423.1	2.0	-	-
3	372.3	1.7	-	-
4	419.4	2.0	286.5	84.7
Mean	414.0	2.0	-	-

Table 4. Staggered production of basil harvested two times.

Harvest[1]	Total Production (kg)	Yield (kg/m^2)	Mean Weight Per Plant (g)	Survival (%)
1a	66.8	1.2	174.8	88. 4
1b	114. 6	2.1	340.1	88.0
2a	57.7	1.1	207.6	64.4
2b	147.0	2.7	340.3	-
3a	59.9	1.1	138.6	-
3b	93.4	1.7	216.1	-
4a	63.7	1.2	147.4	-
4b	168.9	3.2	412.0	-
Overall Mean	96.5	1.8	247.1	-
Mean a	62.0	1.2	167.1	-
Mean b	131.0	2.4	327.1	-

[1] a and b represent the first and second harvests of a section, respectively.

Table 5. Field production of basil harvested two times.

Harvest[1]	Yield (kg/m^2)	Mean Weight Per Plant (g)	Survival (%)
1a	0.4	57.1	100
1b	0.9	151.9	100
2a	0.2	28.6	100
2b	1.0	169.4	100
3a	0.4	57.1	100
3b	1.0	168.1	100
4a	0.3	56.3	100
4b	0.9	147.0	100
Overall Mean	0.6	104.4	100
Mean a	0.3	49.8	100
Mean b	1.0	159.1	100

[1] a and b represent the first and second harvests of a section, respectively.

Table 6. Comparison of basil yield, mean plant weight, survival and gross income with three production methods.

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

Figures

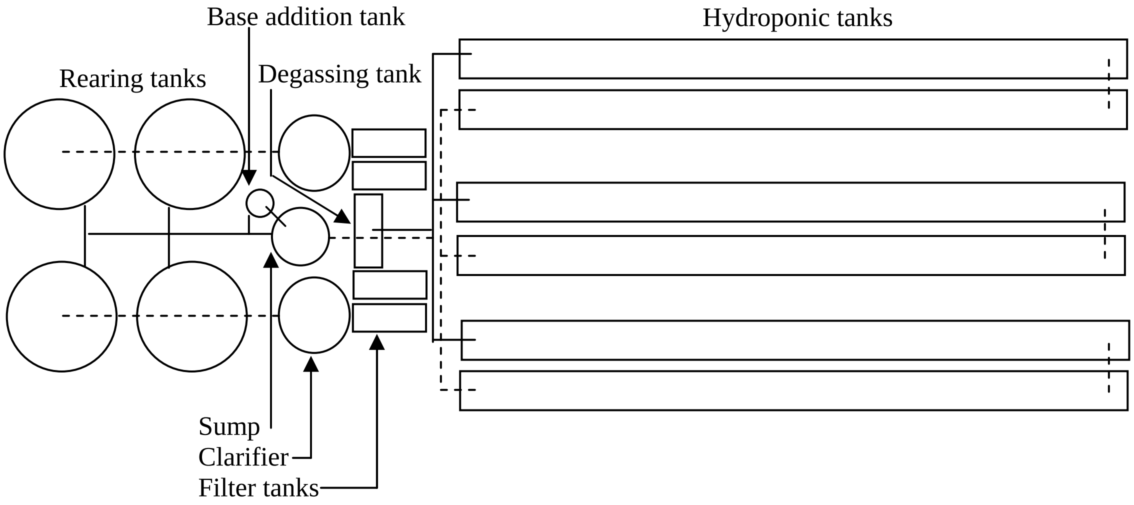

Fig. 1. Diagram of aquaponic system not drawn to scale. In the water distribution system, influent water is shown as solid lines and effluent water is shown as dashed lines.