A Commercial-Scale Aquaponic System
Developed at the University of the Virgin Islands

James E. Rakocy*, Donald S Bailey, R. Charlie Shultz, and Jason J. Danaher

Agricultural Experiment Station
University of the Virgin Islands
RR 1, Box 10,000, Kingshill, VI 00850 U.S.
jrakocy@uvi.edu

Abstract

Aquaponics is the combined culture of fish and plants in recirculating systems. Nutrients generated by the fish, either by direct excretion or microbial breakdown of organic wastes, are absorbed by plants cultured hydroponically. Fish provide most of the nutrients required for plant nutrition. As the aquaculture effluent flows through the hydroponic component of the recirculating system, fish waste metabolites are removed by nitrification and direct uptake by plants, thereby treating the water, which flows back to the fish rearing component for reuse.

The University of the Virgin Islands Aquaculture Program has developed a commercial-scale aquaponic system. The system consists of four fish rearing tanks (7.8 m^3 each, water volume), two cylindro-conical clarifiers (3.8 m^3 each), four filter tanks (0.7 m^3 each), one degassing tank (0.7 m^3), six hydroponic tanks (11.3 m^3 each, 214 m^2 of plant growing area), one sump (0.6 m^3), and one base addition tank (0.2 m^3). The system contains 110 m^3 of water and occupies a land area of 0.05 ha. Major inputs are fish feed, water (1.5% of system volume daily on average), electricity (2.21 kW), base [$Ca(OH)_2$ and KOH] and supplemental nutrients (Ca, K, Fe). The system can produce nearly 5 mt of tilapia along with 1400 cases (24-30 heads per case) of leaf lettuce or 5 mt of basil or a variety of other crops.

The UVI system represents an appropriate or intermediate technology that can be applied outdoors under suitable growing conditions or in an environmentally controlled greenhouse. The system conserves and reuses water, recycles nutrients and requires very little land. The system can be used on a subsistence level or commercial scale. Production is continuous and sustainable. The system is simple, reliable and robust. The UVI aquaponic system does require a relatively high capital investment, moderate energy inputs and skilled management, though management is easy if production guidelines are followed.

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.

Design Evolution and Operation

Aquaponic research at UVI began with six replicated systems that consisted of a rearing tank (12.8 m^3), a cylindro-conical clarifier (1.9 m^3), two hydroponic tanks (13.8 m^2) and a sump (1.4 m^3) (Rakocy 1997). The hydroponic tanks (6.1 m long by 1.22 m wide by 28 cm deep) were initially filled with gravel supported by wire mesh above a false bottom (7.6 cm). The gravel bed, which served as a biofilter, was alternately flooded with culture water and drained. Due to the difficulty of working with gravel, the gravel was removed and a raft system, consisting of floating sheets (2.44 m long x 1.22 m wide x 3.8 cm thick) of polystyrene, was installed. A rotating biological contactor (RBC) was then used for nitrification. Effluent from the clarifier was split into two flows, one going to the hydroponic tanks and the other to the RBC. These flows merged in the sump, from which the treated water was pumped back to the rearing tank.

The rearing tank in this design proved to be too large relative to the plant growing surface area of the hydroponic tanks, or, conversely, the hydroponic tanks were too small relative to the size of the rearing tank. When the rearing tank was stocked with Nile tilapia (*Oreochromis niloticus*) at commercial rates, nutrients rapidly accumulated to levels that exceeded the recommended upper limits for hydroponic nutrient solutions [2,000 mg/L as total dissolved solids (TDS)] (Rakocy et al. 1993). Using Bibb lettuce, the optimum ratio between the fish feeding rate and plant growing area was determined (Rakocy 1989). At this ratio (57 g of feed/m^2 of plant growing area/day) the nutrient accumulation rate decreased and the hydroponic tanks were capable of providing sufficient nitrification. Therefore, the RBCs were removed and the fish stocking rates were reduced to levels that allowed feed to be administered near the optimum rate for good plant growth.

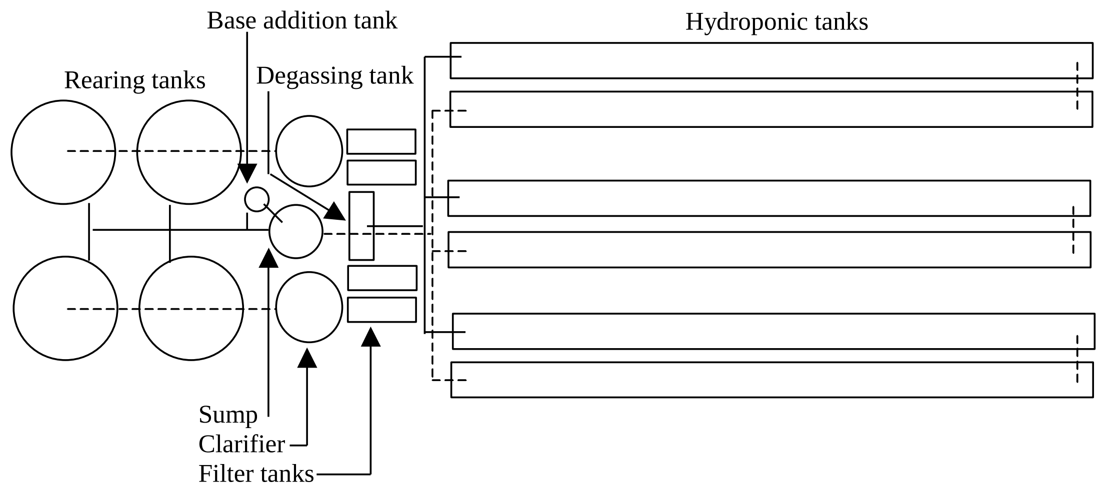
The experimental system has been scaled up three times. In the first scale-up, the length of each hydroponic tank was increased from 6.1 m to 29.6 m. The optimum design ratio was used to allow the rearing tank to be stocked with tilapia at commercial levels (for a diffused aeration system) without excessive nutrient accumulation. In the second scale-up, the number of hydroponic tanks (29.6 m in length) was increased to six; the number of fish rearing tanks was increased to four (each with a water volume of 4.4 m^3); the number of clarifiers was increased to two; four filter tanks (0.7 m^3 each) were added and the sump was reduced to 0.6 m^3. This production unit, commercial aquaponics 1 (CA1), represented a realistic commercial scale, although there are many possible size options and tank configurations. The final scale-up, commercial aquaponics 2 (CA2), involved the enlargement of the four fish rearing tanks (each with a water volume of 7.8 m^3) and the two clarifiers (each with a water volume of 3.8 m^3) and the addition of a 0.7-m^3 degassing tank (Figure 1). The commercial-scale units could be configured to occupy as little as 0.05 ha of land.

The rearing tanks and water treatment tanks were situated under an opaque canopy, which inhibited algae growth, lowered water temperature, which is beneficial for hydroponic plant production, and created more natural lighting conditions for the fish.

The system used multiple fish rearing tanks to simplify stock management. Tilapia production was staggered in four rearing tanks so that one rearing tank was harvested every 6 weeks. The fish were not moved during their 24-week growout cycle. In a 2.5-year production trial in CA 1 using sex-reversed Red tilapia, annual production was 3,096 kg, based on the last 11 harvests out of 19 harvests (Rakocy et al. 1997). Fingerlings, stocked at 182 fish/m^3, grew at an average rate of 2.85 g/day to a size of 487 g. The final biomass averaged 81.1 kg/m^3. This was equivalent to annual production of 175.7 kg/m^3 of rearing tank space. The average feed conversion and survival were 1.76 and 91.6%

The stocking density appeared to be too high for maximum growth and efficient feed conversion. Midway through each production cycle, *ad libitum* feeding leveled off at approximately 5 kg per rearing tank. As the fish grew in the last half of the production cycle, feed consumption did not increase. Therefore more of the feed was used for maintenance and less was used for growth, leading to a relatively high feed conversion ratio for 487-g fish. In CA2 the stocking rate for red tilapia has been lowered by 15% to 154 fish/ m^3. The growth of Nile tilapia was evaluated at a stocking rate of 77 fish/m^3. With larger rearing tanks and higher growth rates, it was anticipated that CA2 could produce 5 mt of tilapia annually.

Based on the results of 20 harvests (four for Red tilapia and 16 for Nile tilapia) with the CA2 system, Red tilapia grew to an average of 512.5 g (Rakocy et al. 2004a). The West Indian market 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 averaged 813.8 g, a preferable size 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). Projected annual production was 4.16 mt for Nile tilapia and 4.78 mt for Red tilapia.



Tank Dimensions	Pipe Sizes
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 L/min, Pump: 0.37 kW Blowers: 1.1 kW (fish) and 0.74 kW (plants) Total land area: 0.05 ha.	Pump to rearing tanks: 7.6 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. Current design of the UVI commercial aquaponic system (CA2).

To achieve 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.

Production trials with the CA1 system employed two methods of *ad libitum* feeding. A demand feeder, used initially, was replaced by belt feeders, utilizing variable quantities of feed adjusted to meet the demand. Neither method proved to be entirely satisfactory. With demand feeders, high winds would shake the feeder, which then dispensed too much feed, or clumps of feed would block the funnel opening of the demand feeder, which then delivered too little feed. The belt feeders periodically failed, not delivering any of the daily feed ration. Both devices were expensive and required support structures. In CA2 the fish were fed *ad libitum* by manual feeding three times daily, which proved to be much more satisfactory.

In a CA1 production trial, DO levels were maintained at a mean of 6.2 mg/L by high DO in the incoming water and by diffused aeration with air delivered through 10 air stones (22.9 cm x 3.8 cm x 3.8 cm) around the perimeter of the tank. In the last 12 weeks of the growout period, a 40-watt vertical lift pump was placed in the center of the tank for additional aeration. The pump pushed the floating feed to the perimeter of the tank and some feed pellets were splashed out of the tank during initial feeding frenzies. Vigorous aeration vented carbon dioxide gas into the atmosphere and prevented its buildup. A high water exchange rate quickly removed suspended solids and toxic waste metabolites (ammonia and nitrite) from the rearing tank. A 0.74-kW in-line pump moved water at an average rate of 378 L/min from the sump to the rearing tanks (mean retention time, 0.8 h). Values of ammonia-nitrogen and nitrite-nitrogen in the rearing tanks averaged 1.47 and 0.52 mg/L, respectively. A pH of 7.2 was maintained by frequently adding equal amounts of calcium hydroxide and potassium hydroxide. Total alkalinity averaged 56.5 mg/L as calcium carbonate.

In CA2 the vertical lift pump was eliminated, and the number of air stones around the rearing tank perimeter was increased to 22 (15.2 cm x 3.8 cm x 3.8 cm). The air stones pushed feed to the center of the tank and no feed was lost due to feeding frenzy splashing. With larger water volumes, the retention time increased to an average of 1.37 hours. A 1.1 kW blower provided sufficient aeration for the fish rearing tanks while a 0.74 kW blower was used for the hydroponic tanks.

Effluent from the fish rearing tanks flowed into two 1.9-m^3 clarifiers in the CA1 production trial. Separate drains from two of the rearing tanks were connected to each clarifier [see Rakocy (1997) for a detailed description]. The clarifiers removed settleable solids, but the amount of solids collected was not as great with the 9.5-minute retention time in the production trial as it had been in previous trials with longer retention times (>20 minutes). Therefore, in CA2 the clarifiers were increased in size to 3.8 m^3 and the retention time increased to 19 minutes. The bottom slope of the new clarifiers was 45º as compared to 60º slopes in the 1.9-m^3 clarifiers. Sludge was removed from the clarifiers three times daily.

Settleable solids in the clarifiers adhered to the sides of the cones and did not slide to the bottom where they could be removed by opening the drain line. It was necessary to stock about 20 male tilapia in the each clarifier. They were not fed. As these fish fed on organisms growing on the clarifier walls, solids rolled to the cone bottom and were easily removed by opening the drain line. The tilapia also swam into the rearing tank drain lines and kept them free of biofouling organisms. Tilapia in the clarifiers grew rapidly and needed to be replaced every 12 weeks with smaller (~ 50 g) fingerlings. If they became too large, their swimming activity stirred up the settled solids, which was counterproductive to clarification.

Suspended solids levels, which decline slightly on passage through the clarifier, were reduced further before the effluent entered the hydroponic tanks. Excessive solids were detrimental to plant growth. Solids adhered to plant roots, created anaerobic conditions and blocked nutrient uptake. Two filter tanks in series, each with a volume of 0.7 m^3 and filled with orchard netting (1.9 cm mesh), received effluent from the clarifier and removed considerable amounts of suspended solids, which adhered to the orchard netting. In the CA1 production trial, total suspended solids averaged 9.0 mg/L in the rearing tanks, 8.2 mg/L in the effluent from the clarifiers (a 9% reduction) and 4.5 mg/L in the effluent from the filter tanks (a 45% reduction). The filter tanks were drained and the orchard netting was washed with a high-pressure sprayer once or twice per week. Solids from the filter tanks and clarifiers were discharged through drain lines into two 16-m^3, lined ponds, which were continuously aerated using air stones. As one pond was being filled over a 2 to 4-week period, water from the other pond was used to irrigate and fertilize field crops.

A separate study showed that of the total amount of solids removed from the system the clarifiers removed approximately 50% (primarily settleable solids) while the filter tanks removed the remaining 50% (primarily suspended solids).

The relatively slow removal of solids from the system (three times daily from the clarifiers and 1-2 times weekly from the filter tanks) was an important design feature. While solids remained in the system, they were mineralized. The generation of dissolved inorganic nutrients promoted vigorous plant growth. In addition, filter-tank solids created anaerobic zones where denitrification occurred. As water flowed through the accumulated organic matter on the orchard netting, nitrate ions were reduced to nitrogen gas. Nitrate was the predominant nutrient in the aquaponic systems. High nitrate levels promoted vegetative growth but inhibited fruiting. With fruiting plants such as tomatoes, low nitrate concentrations maximized fruit production. Nitrate levels were controlled by regulating the cleaning frequency of the filter tanks. If the filter tanks were cleaned twice per week, there was less solids accumulation, less denitrification and higher nitrate levels. If the filter tanks were cleaned once per week, there was more solids accumulation, more denitrification and lower nitrate levels.

Alkalinity is produced during denitrification and by plants which excrete alkaline ions though their roots. There were periods when the pH did not decline for weeks at a time, which was detrimental to plant growth since calcium and potassium could not be supplemented through the addition of base. To prevent periods of stable pH, the filter tanks were cleaned more frequently (twice per week) and any accumulation of solids on the bottom of the hydroponic tanks, which could be anaerobic, were removed.

Organic decomposition in the filter tanks produced carbon dioxide, methane, hydrogen sulfide, nitrogen and other gases. If filter-tank effluent entered the hydroponic tanks directly, it retarded the growth of plants near the inlet. Therefore, a 0.7-m^3 degassing tank was added to the CA2 system. Filter-tank effluent entered the degassing tank and was vigorously aerated, venting potentially harmful gasses into the atmosphere. Degassing-tank effluent was split into three equal portions, each of which passed through a set of two hydroponic tanks. In each set of tanks, water flowed 59.2 m before returning to the sump and being pumped back to the fish rearing tanks.

The hydroponic tanks retained the fish culture water for an average of three hours before it returned to the fish rearing tanks. Each set of hydroponic tanks contained 48 air stones (7.6 cm x 2.5 cm x 2.5 cm), located 1.22 m apart along the central axis of the tank, which re-aerated and mixed the water, exposing it to a film of nitrifying bacteria that grew on the tank surface areas, especially the underside of the polystyrene sheets. In the CA1 production trial, DO increased from 4.0 to 6.9 mg/L on passage through the hydroponic tanks (Rakocy et al. 1997). Through direct nutrient uptake by plants or bacterial oxidation, Gloger et al. (1995) found that the UVI raft hydroponic tanks removed an average of 0.56 g of total ammonia-nitrogen, 0.62 g of nitrite-nitrogen, 30.29 g of chemical oxygen demand, 0.83 g of total nitrogen and 0.17 g of total phosphorous per m^2 of plant growing area per day using romaine lettuce. The maximum sustainable wastewater treatment capacity of raft hydroponics was found to be equivalent to a feeding rate of 180 g/m^2 of plant growing area/day. Therefore raft hydroponics exhibited excess treatment capacity.

The optimum feeding rate ratio of 57 g of feed/m^2 of plant growing area/day, needed to reduce nutrient accumulation, was determined using the initial small-scale systems. Nutrient levels increased but at a lower rate, and there was no filter tank. As the system design evolved to the final commercial size (CA2), up to 5,600 L of water were dumped weekly (5% of the system water volume) during the filter tank cleaning process, which resulted in nutrient concentrations remaining in a steady state at feeding rate ratios of 60 to 100 g/m^2/day. This range of feeding rate ratios was well within the wastewater treatment capacity of 180 g/m^2/day. Therefore, after an initial acclimation period of one month, it was not necessary to monitor ammonia or nitrite values in the commercial-scale system provided that the film on nitrifying bacteria on the underside of the rafts remained intact.

Several materials were used to construct the hydroponic tanks. The best construction materials consisted of poured concrete walls (40 cm high and 10 cm wide) and a 23-mil high-density polyethylene tank liner. The black liners used for CA1 absorbed considerable heat along the top of the tank walls. For CA2 the portion of the liners above the water level was painted white to reflect heat. Subsequently UV-resistant, white liners were used. The polystyrene sheets were painted white with a potable grade latex paint to reflect heat and prevent the deterioration that results if it is exposed to direct sunlight.

There were several advantages to raft culture. There was no limitation on tank size. Rafts provided maximum exposure of the roots to the culture water and avoided clogging. The sheets shielded the water from direct sunlight and maintained lower than ambient water temperatures, which was beneficial to plant growth. A disruption in pumping did not affect the plant's water supply. The sheets were easily moved along the channel to a harvesting point, where they were lifted out of the water and placed on supports at an elevation that was comfortable for workers.

A disadvantage of raft culture was that the plant roots were vulnerable to damage caused by zooplankton, snails, leeches and other aquatic organisms. Biological methods have been successful in controlling these invasive organisms. Ornamental fish, particularly tetras (G*ymnocorymbus ternetzi*), were effective in controlling zooplankton, and red ear sunfish (shellcrackers, *Lepomis microlophus*) were effective in controlling snails. Shellcrackers also prey on leeches.

During the 2.5-year production trial for tilapia and lettuce in CA1, total annual lettuce production averaged 1,404 cases (Rakocy et al 1997). Lettuce production cycles from transplanting seedlings to harvest were 4 weeks. In 112 lettuce harvests, marketable production averaged 27 cases per week and ranged from 13-38 cases (24-30 heads/case). Average harvest weight was 269 g for Sierra (red leaf), 327 g for Parris Island (romaine), 314 g for Jericho (romaine) and 265 g for Nevada (green leaf). The plants were weighed after the lower leaves were trimmed. Production was always greater during the cooler winter months when water temperature averaged 25.1ºC than in the summer months when water temperature averaged 27.5ºC.

Fish feed provided adequate levels of 10 of the 13 nutrients required for plant growth. The nutrients requiring supplementation were K, Ca and Fe. During the production trial, 168.5 kg of KOH, 34.5 kg of CaO, 142.9 kg of $Ca(OH)_2$ and 62.7 kg of iron chelate (10%) were added to the system, which was equivalent to the addition of 16.1, 3.3, 13.7 and 6.0 g, respectively, for every kilogram of feed added to the system. The amount of Ca and K added was the result of the quantity of base required to maintain pH at 7.2. The optimum pH value for the UVI aquaponic system has been revised to 7.0. Rainwater was used in all the aquaponic systems at UVI because the NaCl content of groundwater in the Virgin Islands was too high.

Two species of pathogenic root fungi (*Pythium myriotylum* and *P. dissoticum*) caused production to decline during the warmer months. *Pythium myriotylum* caused root death while *P. dissoticum* caused general retardation in the maturation rate of the plant. CA2 was designed to lower water temperature, through shading, reflective paint and heat dissipation manifolds (attached to the blowers), in an effort to minimize the effects of *Pythium*. A plant potting media containing coconut fibers (coir) was used to produce transplants for CA2 instead of the peat-based potting media used for CA1 because some peat products contain *Pythium* spores. The use of resistant varieties and antagonistic organisms also offer potential for *Pythium* control in aquaponic systems.

The only significant insect problem with lettuce was caused by caterpillars of the fall armyworm and corn earworm. These caterpillars were controlled by twice weekly sprays with *Bacillus thuringiensis*, a bacterial pathogen that is specific to caterpillars.

Using the final design of system CA2 for production of basil was evaluated (Rakocy et al. 2004b). Annual production was projected to be 5.0 mt (Figure 2).

Figure 2. Basil production in the UVI aquaponic system (CA2).

Economics

The economics of the UVI aquaponic system is very site specific. The cost of construction materials, labor and inputs such as feed, chemicals and electricity vary widely from one country to another. In the Virgin Islands the current sales price for live tilapia is US$6.60 per kg. Assuming that a commercial scale system can produce 5 mt of tilapia annually, total annual income from fish sales will be $33,000.

The income from crop production depends on the production level and commercial value of the crop. A number of crop production trials have been conducted. Each crop requires a different planting density and length of production cycle. The greatest annual income for the commercial-scale UVI system is obtained by herbs such as chives and basil (Table 1). These production levels exceed the market size on small islands. Intermediate income levels are obtained from lettuce while fruiting crops such as cantaloupe and okra produce very low income (Table 1).

It is recommended that a commercial operation consists of six production units (systems). With a total of 24 fish rearing tanks, one fish rearing tank can be harvested weekly, yielding 574 kg of fish. A consistent amount of fish on a weekly basis facilitates market development. Based on experience, this amount of tilapia can be sold weekly on a small island.

The best marketing strategy is direct sales to customers either by delivering fish to restaurants and stores or by establishing a sales outlet at the production site. With the latter strategy it is important to select a location that is highly visible and convenient to customers. Selling fish as a commodity will substantially reduce the sales price.

Table 1. Production parameters and income levels for vegetables grown in the commercial-scale UVI aquaponic system.

Vegetable	Planting Density (#/m^2)	Production Cycle Length (weeks)	Sales Price (US$)	Annual Income (US$/$m^2$)	Annual System Income (US$)
Leaf lettuce	20	4	1.50 each	292	62,595
Romaine lettuce	16	4	1.50 each	234	50,076
Basil	16	4	26.40/kg	515	110,210
Okra	3.7	12	1.10/kg	15	3,210
Cantaloupe	0.67	13	2.99/kg	46	9,844
Chives	80.7	6	1.00/bunch	700	149,800

Conclusion

The UVI aquaponic system represents an appropriate or intermediate technology that can be applied outdoors under suitable growing conditions or in an environmentally controlled greenhouse. It is ideal for areas that have limited resources such as water or level land. The system is highly productive and intense but operates well within the limits of risk. It conserves and reuses water, recycles nutrients and requires very little land. With its small land requirement it is economically feasible to locate systems close to urban markets, thereby reducing transportation costs. The system can be used on a subsistence level or a commercial scale. The system is simple, reliable and robust. Production is continuous and sustainable as demonstrated by nearly 10 years of continuous operation in its current configuration. The UVI aquaponic system does require a relatively high capital investment, moderate energy inputs and skilled management, though management is easy if production guidelines are followed.

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