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# AQUAPONICS: THE INTEGRATION OF FISH AND VEGETABLE CULTURE IN RECIRCULATING SYSTEMS

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## ABSTRACT

A commercial-scale, aquaponic system for the intensive production of tilapia and hydroponic vegetables has been developed at the Virgin Islands Agricultural Experiment Station. The system is well suited for Caribbean islands and other tropical regions where fresh water is scarce or level farm land is limited. It consists of a fish rearing tank, a clarifier, two hydroponic tanks and a reservoir, and is reliable, productive and easy to operate. Water continuously circulates between the fish and hydroponic components. The fish grow rapidly on a pelleted diet that is high in protein. Waste from the fish provides most of the nutrients required by vegetables. The vegetables recover these nutrients as a valuable by-product and purify the water. The presence of both fish and plants creates a very stable growing environment, while high nutrient levels and unlimited water promote rapid vegetable growth. This system is economical because nutrient costs are reduced, the need for expensive filtration devices is eliminated, component operating and infrastructural costs are shared, land requirements are small, water is conserved, and environmental impacts are minimized.

## INTRODUCTION

Field crop production and aquaculture potential on many Caribbean islands are hindered by rugged topography or insufficient water resources. As a consequence, large quantities of food must be purchased abroad with considerable impact on fragile island economies. For example, the Lesser Antilles imported 16,500 mt of fish and fish products in 1987 at a cost of U.S. $56 million (FAO, 1987). Alternative production systems are needed to boost local food supplies and retain foreign exchange.

The University of the Virgin Islands (UVI) Agricultural Experiment Station has taken a new approach to growing more food by integrating vegetable hydroponics with fish culture in recirculating systems, a technology that is being called aquaponics. These diverse agricultural enterprises are being combined to increase production while minimizing nutrient inputs and the consumption of water.

In fish culture, only a minor proportion (25-30%) of nutrients applied in the form of feed are retained by fish as weight gain. The remaining nutrients are excreted in solid and dissolved forms. Dissolved nutrients accumulate in recirculating systems with low water exchange and high feeding rates to levels which approximate hydroponic nutrient solutions (Nair et al., 1985).

Vegetable hydroponics is incorporated into recirculating systems to recover nutrients that would otherwise accumulate or be discharged into the environment. Vegetables are a valuable by-product of fish production that enhance system profit potential. Although nutrients are not a major expense in commercial hydroponics, most essential plant nutrients derived from feed accumulate in recirculating systems at no additional expense, and in a broader sense the use of these nutrients saves the energy that would have gone into making inorganic fertilizers.

Integrating fish culture and vegetable hydroponics can offer additional savings through shared infrastructure (e.g., pumps, reservoirs, monitoring and control systems) and shared overhead (e.g, security systems, administrative support). Nutrient removal by plants improves effluent quality and enhances fish production. Plant roots and hydroponic structures improve water quality by capturing solids and providing surface area for biofiltration (the oxidation of fish waste products by bacteria).

Aquaponic systems use water more efficiently through the interaction of fish and plants (Rakocy, 1989). Water exchange rates can be minimized because plants extract nutrients that inhibit fish growth. Applications of fish feed forestall the need to discharge and replace depleted nutrient solutions. Minimizing water exchange reduces operating costs of aquaponic systems in arid climates.

Aquaponic systems are capital intensive and require moderate amounts of electrical energy from an uninterrupted source. Backup electrical generation is essential.

## SYSTEM DESIGN

Although there is wide variability in the design of aquaponic systems, the optimum arrangement of system components consists of a fish rearing tank, as solids removal unit, a biofilter, a vegetable production unit, and a reservoir (Rakocy and Hargreaves, 1993). Biofilter and hydroponic components may be combined if the hydroponic tank and its plant support media provide sufficient surface area for biofiltration.

Figure 1 illustrates an experimental, aquaponic system at UVI in which biofiltration and hydroponic vegetable production are combined. This system consists of a 12.3-$m^3$ fish rearing tank, a 1.9-$m^3$ clarifier for solids removal, two 2.1-$m^3$ hydroponic tanks (6.10 m L x 1.22 m W x 0.28 m D) and a 1.4-$m^3$ reservoir (sump). Floating polystyrene sheets contain 12.8 $m^2$ of plant growing area. Total water volume during operation is 17.3 $m^3$.

Based on this design, a commercial-scale system was developed that contained a larger reservoir (6.8 $m^3$) for rainwater storage and larger hydroponic tanks (29.59 m L x 1.27 m W x 0.41 m D) with a total growing area of 71.4 $m^2$ and minimum water volume of 37.1 $m^3$. Construction of an even larger system is in the planning stages. The experimental and commercial systems are located outdoors and are not covered, with the exception of the rearing tank, which is shaded from sunlight with an opaque canopy.

Most aquaponic system components are constructed from fiberglass, which is sturdy, durable, non-toxic, movable, and easy to plumb. The hydroponic tanks are constructed from cement blocks lined with a high-density polyethylene liner. Poured concrete walls with a polyethylene liner provide a suitable, but more expensive alternative.

## COMPONENT RATIOS

Aquaponic systems are designed to meet size requirements for solids removal and biofiltration at the desired level of fish production. The solids removal unit and biofilter are built to a size that provides adequate waste treatment at the maximum fish density and feeding rate. The commercial-scale system at UVI has sustained 400 kg of tilapia and a daily feeding ration of 8 kg.

Another important ratio is the size of the hydroponic component in relation to fish production capacity. The critical determinant in sizing the hydroponic component is the daily feed (nutrient) input to the system. The optimum ratio between lettuce and tilapia was determined by evaluating six plant-to-fish ratios ranging from 1.2 to 7.5 (Rakocy, 1989). Maximum lettuce production (3.1 kg/$m^2$/crop) occurred at the ratio of 1.9 plants to 1 fish, which was equivalent to a daily feeding rate of 2.4 g/plant. This ratio was used as a guide in designing

UVI's commercial-scale system for lettuce production. A daily feeding ration of 4 to 6 kg is maintained for the staggered production of 2,112 heads of bibb lettuce (density = 29.6 heads/ $m^2$) or a smaller number of loose leaf and romaine lettuce. The plant growing area is seven times larger than the fish rearing area.

## HYDROPONIC SUBSYSTEM

Aquaponic systems employ a wide range of hydroponic subsystems (sand, gravel, nutrient film technique, rafts), but fine media such as sand and gravel is subject to clogging by suspended solids not previously removed from the water flow and by the growth of microorganisms within the media. UVI's commercial-scale system uses a floating (raft) hydroponic subsystem that consists of two long aerated channels, each of which contains 12 polystyrene sheets (2.43 m L x 1.22 m W x 3.8 cm thick). Circular holes (5 cm) are cut through the polystyrene sheets at the desired plant spacing. Transplants are placed into plastic net pots which have been inserted into the holes. Some male tilapia fingerlings are placed into the channels and restricted to the bottom section by a rigid screen to prevent access to the plant roots, which they would consume. The swimming action of the fish prevents the accumulation of solids on the tank floor.

## PLANT GROWTH REQUIREMENTS

Maximum plant growth in aquaponic systems requires proper nutrition consisting of six macronutrients (N,P,K,Ca,Mg, and S) and seven micronutrients (Cl,Fe,Mn,Zn,Cu,Mo, and B). A high dissolved oxygen concentration (>5mg/liter) in the water surrounding the plant roots is required for healthy growth. Excessive solids or stagnant water in the root zone leading to oxygen depletion will cause root dieback and water stress within the plant which leads to wilting and blossom-end rot of fruit in crops such as tomatoes. Effective solids removal and aeration of the root zone are major design and operational considerations of the hydroponic subsystem.

Other important factors for hydroponic vegetable production are climatic. Production is generally best with maximum intensity and duration of sunlight. Maintaining an optimum temperature range for hydroponic vegetables may require siting aquaponic systems at higher, cooler elevations in the tropics. Outdoor aquaponic systems require protection from strong winds, especially following transplanting when seedlings are most vulnerable to damage.

## WATER QUALITY MANAGEMENT

Dissolved oxygen concentrations of >5 mg/L are required in the fish rearing tank for maximum growth. Numerous aeration systems are available. The UVI system uses a combination of diffused aeration from air stones around the perimeter of the tank and a vertical-lift pump in the center of the tank which sprays water onto the air. A blower provides air to the air stones in the rearing tank and the hydroponic tanks.

Ammonia and feces, the major waste products from fish, require removal from the culture water. Fish excrete waste nitrogen from their gills in the form of ammonia. Dissolved inorganic nutrients are produced by direct excretion from the fish and mineralization of organic matter.

After water is discharged from the rearing tank, feces and suspended solids are removed by a cylindro-conical clarifier with a 60 degree bottom slope, which provides good removal of settleable suspended solids if it is stocked with 20 to 30 male tilapia fingerlings. These fish dislodge solids that adhere to the slope and concentrate them at the base of the cone. Sludge is removed several times daily by opening a drain valve. The clarifier has not been effective at removing fine, colloidal material. A second solids removal unit is being designed to capture fine solids with a filtration mechanism.

Effective removal of solids is necessary for optimum system performance. As solids decompose, they exert a high biochemical oxygen demand (BOD), which lowers system oxygen levels or requires additional aeration. Microbial decay of organic matter interferes with biofiltration and produces ammonia. Some promising new technologies for removal of solids include bead filters (Malone and Coffin, 1991) and various screen filters (Tetzlaff, 1991).

Additional treatment of sludge and nutrient-enriched effluent is required prior to discharge to mitigate environmental impact. Options for stabilization of sludge and effluent include aerated and anaerobic lagoons, aerobic and anaerobic digestion, and composting (Chen et al., 1991). Effluent may be applied to land as irrigation water. Stabilized sludge can also be disposed of by land application as a soil amendment.

Following the clarifier, culture water passes to a biofilter designed primarily for the oxidation of ammonia and nitrite through the growth of nitrifying bacteria. Ammonia is oxidized to nitrite by Nitrosomonas bacteria and nitrite is oxidized to nitrate by Nitrobacter bacteria. Ammonia gas and nitrite are toxic to fish at low concentrations (<1 mg/L) while fish tolerate very high nitrate levels (>100 mg/L). Nitrifying bacteria occur naturally in water and require one month to colonize biofilter surfaces. The feeding rate is reduced during the biofilter acclimation period.

Aquaponic-system biofilters employ sand, gravel, shells, or various plastic media as substrate for microbial attachment. One of the leading biofilter designs is the rotating biological contactor (RBC), which consists of many fiberglass disks mounted on an floating axis. Continuous rotation of the axis alternately exposes the disks to culture water and air, creating an ideal growing environment for nitrifying bacteria.

The UVI system initially contained two 93-$m^2$ RBCs located after the clarifier. Each hydroponic tank provides 126 $m^2$ of additional surface area. Midway through a production trial, the RBCs were removed to determine if the hydroponic tanks could provide adequate nitrification at the design feeding rate of 4 to 6 kg/day. Low ammonia and nitrite levels were maintained, thereby demonstrating that raft hydroponics eliminates the need for a separate biofiltration unit at the optimum plant-to-fish ratio.

Hydroponic vegetables contribute to water quality improvement by direct uptake of dissolved nutrients, including ammonium ions. Loose leaf and romaine lettuce are estimated to remove about 32% of total dissolved nitrogen from UVI's commercial-scale system.

The oxidation of ammonia and nitrite is a process that produces acid, thereby lowering pH. If pH values decrease to less than 7.0, nitrification becomes less efficient and ammonia and nitrite levels rise. It is necessary to monitor pH on a daily basis and to add small amounts of base to maintain pH values near 7.0. However, too much base will reduce the availability of many micronutrients to plants.

Common bases for aquaponic systems include calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), caustic potash (KOH), quick lime (CaO), and hydrated lime ($Ca(OH)_2$). Baking soda ($NaHCO_3$) is not a suitable base because $Na^+$ can accumulate to levels that are toxic to plants. Caustic potash and quick lime are used at UVI.

## NUTRIENT ACCUMULATION

Nutrients accumulate in recirculating systems as a consequence of low water exchange and high feeding rates. Nutrient accumulation is one of the critical design and management considerations of aquaponic systems. The accumulation rate is a function of feeding rate, food composition, nutrient supplementation, solids removal efficiency, plant uptake (number and growth stage), and water exchange rate. Once the desired nutrient concentration is obtained in the culture water, some of these variables (e.g., water exchange rate) may be manipulated in an effort to maintain steady-state conditions.

Nutrient accumulation increases the conductivity of culture water. In an aquaponic system with a low rate of water exchange (<1% system volume/day), conductivity increases at approximately 200 g as TDS (total dissolved solids)/kg of dry weight of feed applied (Rakocy et al., 1993). Critical conductivity is obtained at approximately 2000 mg/L as TDS (3125 micromhos/cm), or after the addition of 10 to 20 kg of feed/$m^3$ of system volume depending on the quantity of plant growth. Higher conductivity can be detrimental to plant growth. The relative accumulation of different nutrients approximately reflects feed composition for macronutrients (N>Ca>K>P>Mg) and micronutrients (Fe>Zn>Mn>B>Cu).

The ability to control the nutrient composition of fish culture water is limited. Nutrients in fish culture water do not reach levels (2000 mg/L as TDS) normally utilized in commercial vegetable hydroponics without the addition of large amounts of feed. However, aquaponic-system water is suitable for plant culture after the addition of relatively small amounts of feed and at TDS levels $<500$ mg/L. When an aquaponic system is put into operation, the fish are added a few weeks before the first planting to allow time for nutrients to accumulate to the minimal levels required for good plant growth.

The water source for UVI's aquaponic systems is rainwater, which is collected on catchments and stored in large, covered tanks. The low TDS levels ($<100$ mg/L) of rainwater extend water usage. The ground water of semiarid islands such as St. Croix generally has high TDS levels and large amounts of sodium ions. The surface water and groundwater of wet, mountainous, Caribbean islands have lower TDS levels and may be suitable for aquaponic systems.

## NUTRIENT SUPPLEMENTATION

Although nutrient salts accumulate in aquaponic systems, not all of the essential nutrients are present in sufficient quantities. Nutrients that require supplementation in the UVI system are potassium (as $KOH$), calcium (as $CaO$ or $Ca(OH)_2$), and iron (as iron chelate containing 10% iron by weight). Approximately equal weights of $KOH$ and $CaO$ are alternately added to the sump to maintain pH at 7.0. Frequent, small additions prevent wide swings in pH which are harmful to both fish and plants. Iron is supplemented every 3 weeks by adding 2/mg/L. Iron may be applied as a dilute foliar spray (0.1% Fe-EDTA) in combination with a surfactant. Nutrient deficiencies may vary depending on the water source (chemistry), fish feed and hydroponic substrate used.

## SUITABLE SPECIES

Several species of fish have been cultured in aquaponic systems, but the most appropriate species for the Caribbean is tilapia, a hardy, freshwater species that is native to Africa and the Middle East. Tilapia tolerates crowded conditions and handling. It is resistant to diseases, grows quickly, converts feed efficiently, and tastes delicious. Red tilapia hybrids resemble colorful ocean fish and are readily accepted by West Indians. Florida red tilapia and Nile tilapia (Oreochromis niloticus) are being cultured at UVI.

A wide range of vegetables have been grown in aquaponic systems, including high-value cash crops such as tomatoes, lettuce, and cucumbers. Lettuce is particularly suitable for aquaponic-system culture. A crop of lettuce can be produced in a short time period from transplanting, and, as a consequence, pest pressure in relatively low. Lettuce has been the main crop used in the development of aquaponic systems at UVI. Other crops with potential include pak choi, Chinese cabbage, peppers, herbs such as sweet basil and chives, bush beans, and celery.

## FISH STOCK MANAGEMENT

A continuous mode of fish rearing is required in aquaponic systems for maximal utilization of production capacity. Aquaponic systems are less efficient if they are operated in a batch mode, whereby a fixed number of fingerlings are stocked and raised to marketable size over several months as the daily feeding ration is gradually increased up to the maximum allowable feeding rate for maintenance of acceptable water quality. With continuous rearing, the system is operated at a level of fish biomass and daily feed application that is near the carrying capacity at all times. Operation of the system near the carrying capacity will assure a constant supply of dissolved nutrients for hydroponic plant production.

The UVI system has been operated in a continuous production mode by using a stock splitting method (Van Gorder, 1991). The rearing tank is stocked with a large number (1,000) of fingerlings so that the initial feeding rate will permit maximum plant growth. As the fish grow and require more feed, a portion (250) of the stock is removed every 6 weeks. In a commercial operation, these fish would be placed in other production units that are also operated near the carrying capacity. With stock splitting, the feeding rate remains relatively constant throughout the entire 24-week production cycle. The fish are allowed unrestricted access to feed from demand feeders. Using a complete diet (floating pellets, 32% protein), UVI's commercial- scale system is capable of producing 1280 kg of tilapia annually.

Stock splitting is stressful to fish and requires considerable labor. In large operations, the logistics of moving fish is difficult. A system of multiple rearing units, all of which are connected to one hydroponic subsystem, may be more efficient. Each rearing tank would contain a different size group of fish to allow continuous production. Although feeding rations to the individual rearing units would vary according to fish biomass, the overall feeding rate to the system would be relatively constant. This method will be tested in a new, commercial-scale system that is being built at UVI.

Fish grown in intensive production systems are subject to acquiring off-flavors in their flesh by absorbing odorous compounds through their gills. The compounds are produced by natural biological processes in the culture system. Tilapia are always tested for flavor before they are sold and routinely placed in clean water for a week to purge any off-flavors that are detected.

## CROP PRODUCTION SYSTEMS

A staggered crop production system is one in which plant groups in different stages of growth are cultivated simultaneously in the hydroponic subsystem. This production system allows regular harvest of produce and relatively constant nutrient uptake from culture water. Leafy green vegetables, herbs and other crops with short production cycles are well-suited for continuous production systems. The UVI system uses a 3 or 4-week staggered production schedule for leaf lettuce. From 12 to 29 cases of lettuce (288 to 704 plants) are harvested every week depending on lettuce type. The harvest takes place in the morning and is immediately followed by transplanting with 3-week-old, greenhouse plants. Planting density varies from 16.2 to 29.6 plants/m$^2$.

A batch cropping system is more appropriate for vegetables with extended growing periods such as tomatoes and cucumbers. Various intercropping systems are also used. Lettuce is often intercropped with tomatoes or cucumbers. One crop of lettuce is harvested before the tomato or cucumber canopy develops.

## PEST AND DISEASE CONTROL

A number a plant pests have been encountered in UVI's aquaponic systems. Pests observed on tomatoes include spider mite, russet mite, hornworm, fall army worm, pinworm, aphid, and leaf minor. Lettuce has been affected by fall army worm and cabbage looper. Pak choi and Chinese cabbage have been attacked by aphids. Most pesticides cannot be used in aquaponic systems to control insect outbreaks on vegetables because of their toxicity to fish or because they have not been approved for use in fish culture. Similarly, most therapeutants for treating fish parasites and diseases should not be used either. Vegetables may absorb and concentrate them. Even the common practice of adding salt to treat fish diseases or reduce nitrite toxicity would be deadly to vegetables.

Insect control techniques for vegetables in aquaponic systems are limited to the use of biological control, traps, resistant varieties, screening, and specialized cultural practices. For example, screening or weekly spraying with Bacillus thuringensis (Thuracide), a biological control agent, are very effective in the control of fall army worms and cabbage loopers on lettuce.

Limitation on the use of pesticides is a disadvantage to crop production in aquaponic systems. However, this restriction assures that crops from aquaponic systems will be raised in an environmentally-sound manner and will be free from pesticide residues. A major advantage of the UVI system is that crops are less susceptible to attack from soil-borne diseases. It also appears that aquaponic systems may be more resistant to diseases that affect standard hydroponics. This resistance may be due to the presence of some organic matter in the culture water which creates a stable, ecologically-balanced, growing environment with a wide diversity of microorganisms.

VEGETABLE YIELDS

Crop yields from UVI's aquaponic systems have been greater than yields from local field crops and comparable to average yields of soilless culture. The tomato varieties Sunny and Floradade yielded 10.1 and 9.0 kg/plant (18.4 and 16.3 kg/$m^2$) of ripe fruit over a 16-week production period. Chinese cabbage (50-Day Hybrid) and pak choi (Le Choi) attained average weights of 638 g (11.3 kg/$m^2$/crop) and 508 g (8.7 kg/$m^2$/crop) over a 4-week production cycle from transplant stage. Lettuce yields of 786 g/plant (12.7 kg/$m^2$) have been attained for Montello (a crisphead variety) in a 5-week growing period, 660 g/plant (10.7 kg/$m^2$) for Parris Island (a romaine) in 4 weeks, and 522 g/plant (8.4 kg/$m^2$) for Sierra (a red loose leaf variety) in 4 weeks.

OUTLOOK AND POTENTIAL

A partial economic analysis of UVI's commercial-scale system indicates that the system has profit potential in St. Croix (Bailey et al., 1994). This study concentrated on capital costs, operating costs and revenue of one production unit but did not consider overall infrastructural or administrative costs for a full-scale operation. A comprehensive economic evaluation will be undertaken after the present commercial system is scaled up in size by a factor of three. This evaluation will determine economies of scale, based on number of production units, and develop enterprise budgets. However, results of economic studies in St. Croix will have limited application to other Caribbean locations. Each operation will require a site-specific analysis of cost, revenue and potential profits.

A marketing study of aquaponic-system products has been conducted for more than a year with very encouraging results. Lettuce has been sold to 42 outlets in St. Croix, ranging from wholesalers to tourist restaurants, while tilapia has been sold to 21 outlets, primarily West Indian restaurants. The most attractive features of these products have been their freshness and high quality. The continuous production schedules of commercial aquaponic systems would meet another strong consumer demand: consistency of supply. Local production from aquaponic systems offers an attractive alternative to expensive food imports that are often poor in quality.

Attempts to increase fish and vegetable supplies in the Caribbean have been hindered by insufficient knowledge of appropriate production techniques or resource limitations. These barriers may be overcome through the intensive production of fish and vegetables under controlled conditions in aquaponic systems, which conserve land, water and nutrients. Although more complex than traditional production methods, aquaponic systems are reliable and easy to operate after the basic principles are learned. Being on the threshold of commercial development, aquaponic system technology holds promise for the future of Caribbean agriculture.

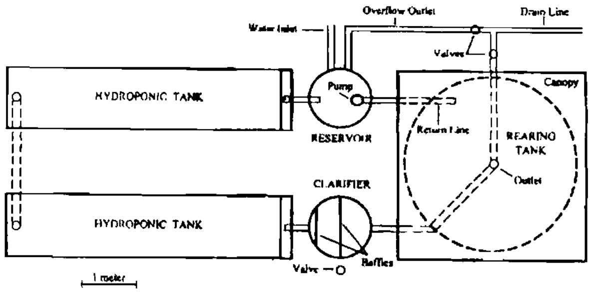


Figure 1. A closed recirculating system for integrating vegetable hydroponics with fish culture.

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