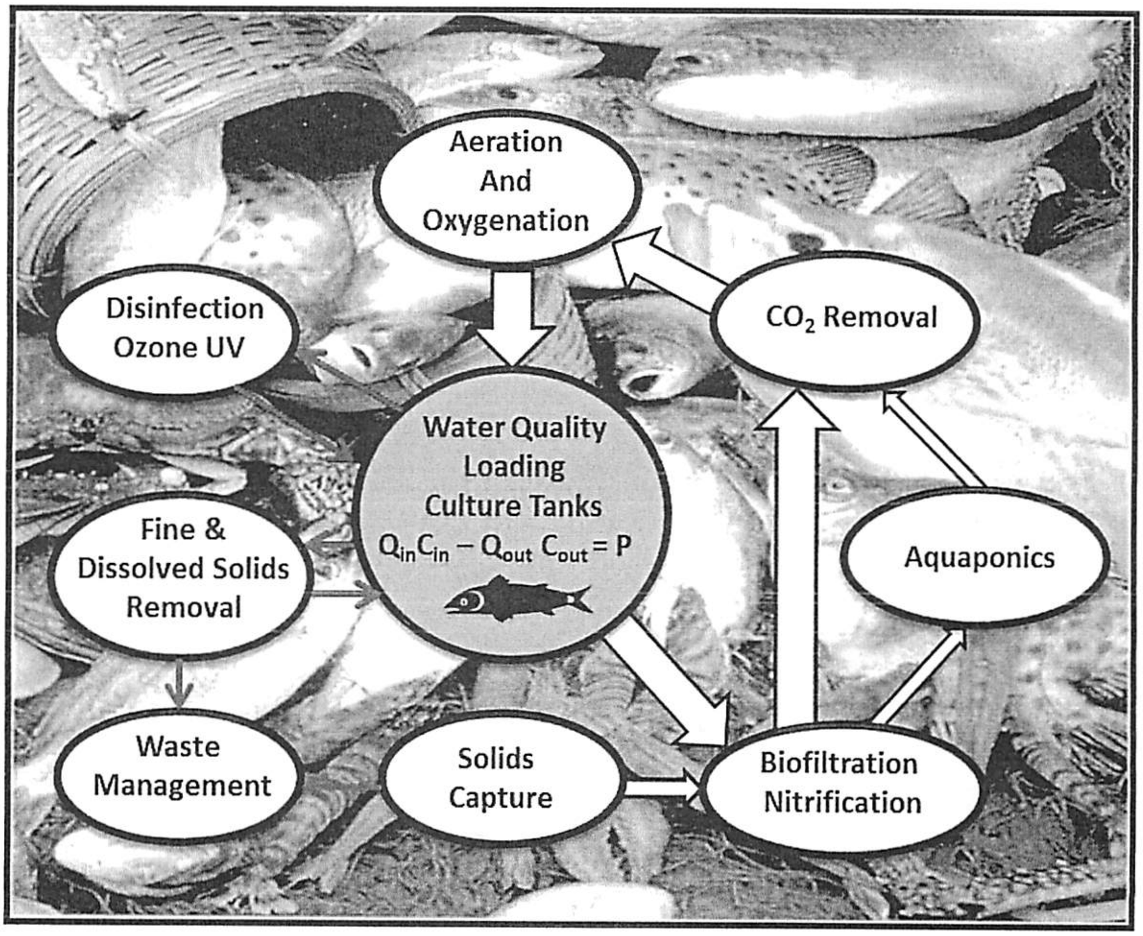
RECIRCULATING AQUACULTURE

Third Edition



Aquaculture CENTER

USDA

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CHAPTER 19

AQUAPONICS: INTEGRATING FISH AND PLANT CULTURE[1]

19.0 INTRODUCTION

Aquaponics, the combined culture of fish and plants in recirculating systems, has become increasingly popular. It is amazing the number of U-tube videos on design and construction of small scale backyard systems. Numerous short courses are taught on every possible level, from the simplest of home systems to commercial engineered systems. There are several text books and numerous popular press books on the subject. There are two national organizations and hundreds of local groups to promote the concept. Even in the small town of Tucson, AZ where one of the authors lives, there are over 350 members of the local Aquaponics group that meet monthly to share ideas and hear talks and lectures about all phases of fish and plant production. Hundreds of school districts are including aquaponics as a learning tool in their science curricula. The number of commercial aquaponic operations, though still small, is increasing.

Aquaponic systems are recirculating aquaculture systems that incorporate the production of plants without soil. Recirculating systems are designed to raise large quantities of fish in relatively small volumes of water by treating the water to remove toxic waste products and then reusing it. In the process of reusing the water many times, non-toxic nutrients and organic matter accumulate. These metabolic byproducts need not be wasted if they are channeled into secondary crops that have economic value or in some way benefit the primary fish production system. Systems that grow additional crops by utilizing by-products from the production of the primary species are referred to as integrated systems. If the secondary crops are aquatic or terrestrial plants grown in conjunction with fish, this integrated system is referred to as an aquaponic system.

Plants grow rapidly in response to dissolved nutrients that are excreted directly by fish or generated from the microbial breakdown of fish wastes. In closed recirculating systems with very little daily water exchange (less than 5%), dissolved

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nutrients accumulate and approach concentrations that are found in hydroponic nutrient solutions. Dissolved nitrogen, in particular, can occur at very high levels in recirculating systems. Fish excrete waste nitrogen directly into the water through their gills in the form of ammonia. Bacteria convert ammonia to nitrite and then to nitrate. Ammonia and nitrite are toxic to fish, but nitrate is relatively harmless and is the preferred form of nitrogen for growth of higher plants, such as fruiting vegetables. It is the symbiotic relationship between fish and plants that makes the consideration of an aquaponic system a reasonable system design criteria.

Aquaponic systems offer several advantages. In RAS's, the disposal of accumulated waste is always a major concern. Recirculating systems are promoted as a means of reducing the volume of waste discharge to the environment. Certainly the volume is reduced but the pollution load (organic matter, dissolved nutrients) per unit of discharge is correspondingly higher. This more concentrated discharge may pose a threat to the environment in some situations, or an additional expense if the wastewater is discharged to a municipal sewer system for further treatment. Effluent is discharged from the system to eliminate organic sediment and prevent nutrient buildup.

1) In aquaponic systems, the plants recover a substantial percentage of these nutrients, thereby reducing the need to discharge water to the environment and therefore extending water use, i.e., by removing dissolved nutrients through plant uptake, the water exchange rate can be reduced. 2) Minimizing water exchange reduces operating costs of aquaponic systems in arid climates and heated greenhouses where water or heated water represents a significant expense. Lennard (2006) demonstrated that nitrate accumulation in culture waters was reduced by up to 97% (Table 19.1) in the Aquaponic system when compared with the fish-only system.

Profitability is always a major concern when considering a recirculating system. Recirculating systems are expensive to construct and operate, and profitability often depends on serving niche markets for live fish such as tilapia, whole fresh fish on ice, or other high value products. 3) A secondary plant crop, which receives most of its required nutrients at no additional cost, improves system profit potential. The daily feeding of the fish provides a steady supply of nutrients to plants, which reduces or eliminates the need to discharge and replace depleted nutrient solutions or adjust nutrient solutions as is required in hydroponics. 4) The carbon dioxide vented from fish culture water can increase plant yields in enclosed environments. 5) The plants purify the culture water and can, in a properly sized and designed facility, eliminate the need for separate and expensive biofilters. Biofiltration represents a major capital expense and a minor operational expense. (*Not necessarily, the major capital costs are usually tanks and most importantly, solids capture device.*) In well-designed aquaponic systems, the hydroponic component can provide sufficient biofiltration for the fish, and therefore the cost of purchasing and operating a separate biofilter is avoided. *(Not necessarily recommended, both systems should have the ability to operate independent in case there is a system disruption in one or the other.)* These costs are charged to the hydroponic subsystem, which, in the case of lettuce, generates approximately two thirds of the system's income. *(Makes you wonder why you're growing the fish!)* The profitability of recirculating systems can thus be improved substantially with aquaponics, if there is a good market for the vegetable crop.

Table 19.1 Fish Growth, Lettuce Yield and Nitrate Removal for Fish-only Systems and Aquaponic Systems (Lennard, 2006)

Parameter	Fish-only	Aquaponic
Fish FCR	0.87 ± 0.01	0.88 ± 0.0
Lettuce yield (kg/m^2)	NA	5.77 ± 0.19
NO_3 accumulation (mg/l)	52.20 ± 5.28	1.43 ± 1.09
NO_3 removal (%)	0	97

(6) The expense of water quality monitoring is reduced in aquaponic systems as waste nutrients are generated daily at uniform levels and there is generally excess wastewater treatment capacity. 7) An aquaponics system also generates savings in several areas of construction and operation by sharing operational and infrastructural costs for pumps, blowers, reservoirs, heaters, and alarm systems. Initial capital investment is reduced in that an aquaponics system can be erected with a modest increase in acreage over that required for a hydroponic facility. Aquaponic systems do require high capital investment, moderate energy inputs, and skilled management *(in fish production as well as plant production!)*. The premium prices available in niche markets may be required for an aquaponic facility to be profitable.

Questionable Profitability

There are, of course, disadvantages to aquaponic systems. The most obvious of these is A) the large ratio of plant growing area in comparison to the fish rearing surface area. A large ratio of plant surface to fish surface is needed to achieve a balanced system where nutrient levels stay relatively constant. For example in the UVI raft system the ratio of plant growing area to fish surface area ratio is 7.3. Larger ratios are needed as solids removal efficiency decreases. In essence, aquaponic systems emphasize plant culture, which is an advantage if viewed by a horticulturist. *(RASponics on the other hand emphasis fish production, with the plants used for polishing the water of fine particles and to remove some of the nitrate.)* B) Most of the labor expended in the facility is devoted to seeding, transplanting, maintaining, harvesting, and packing plants. C) Additionally, a new set of skills is required for the plant component, so a commercial operation would do better with both an aquaculturist and horticulturist on staff. D) Another disadvantage is that the horticulturist must rely on biological control methods rather than pesticides to protect the plants from pests and diseases. However, this restriction can be viewed as an advantage in that the plant products can be niche marketed as "pesticide free".

Plants : Fish 7.3:1

19.1 SYSTEM DESIGN

The design of aquaponic systems closely mirrors that of recirculating systems in general with the addition of a hydroponic component and the possible elimination of a separate biofilter and devices (foam fractionators) for fine and dissolved solids removal. Fine solids and dissolved organic matter generally do not reach levels that require foam fractionation in aquaponic systems at the recommended design ratio. The essential elements of an aquaponic system consist of a fish rearing tank, a settleable and suspended solids removal component, a biofilter, a hydroponic component and a sump, Figure 19.1 (Rakocy and Hargreaves, 1993).

Effluent from the fish rearing tank is treated first to reduce organic matter concentration in the form of settleable and suspended solids. Next, the culture water is treated to remove ammonia and nitrite by fixed-film nitrification, which often occurs in the hydroponic component. As water flows through the hydroponic unit, some dissolved nutrients are recovered by plant uptake. Finally, water collects in a reservoir (sump) where it is returned to the rearing tank. The location of the sump may vary. For example, if elevated hydroponic troughs are used, the sump can be located after the biofilter and water would be pumped up to the troughs and returned by gravity to the fish rearing tank.

The system can be configured such that a portion of the flow is diverted to a particular treatment unit (Naegel, 1977; Wren, 1984). For example, a small side-stream flow may go to a hydroponic component after solids removal, while most of the water passes through a biofilter and returns to the rearing tank.

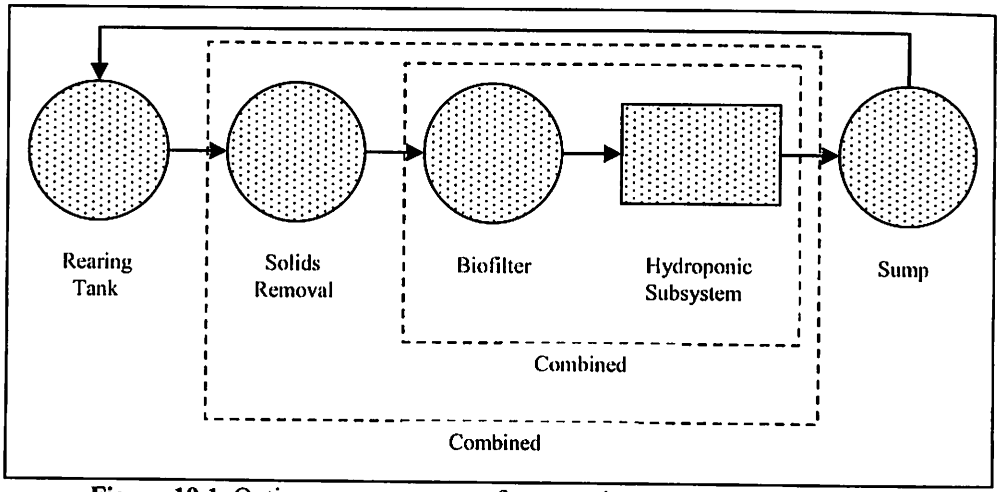


Figure 19.1 Optimum arrangement of aquaponic system components.

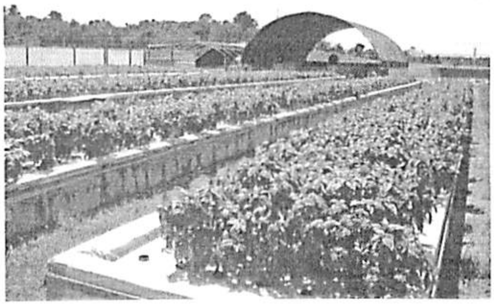
The biofiltration and hydroponic components can be combined by using a plant support media, such as gravel, (Lewis et al. 1978; Sutton and Lewis, 1982; Rakocy, 1984; Watten and Busch, 1984) or sand (McMurtry et al. 1990), which also functions as biofilter media. Raft hydroponics, which consists of floating sheets of polystyrene and net pots for plant support, can also provide sufficient biofiltration if the plant production area is sufficiently large (Rakocy, 1995). Combining biofiltration with hydroponics is a desirable goal because eliminating the expense of a separate biofilter is one of the main advantages of aquaponics. An alternative design combines solids removal, biofiltration, and hydroponics in one unit. The hydroponic support media (pea gravel) captures solids and provides surface area for fixed-film nitrification, although with this design it is important not to overload the unit with suspended solids. An overload of suspended solids is always a threat due to variations in fish

Avoid media-based systems

feeding activities and efficiency of the solid removal component. For these reasons, gravel or sand beds should be avoided for large commercial-scale operations.

AQUAPONICS RESEARCH AT THE UNIVERSITY OF THE VIRGIN ISLANDS (UVI)

Aquaponics research at the University of the Virgin Islands (UVI) has focused on the culture of tilapia in outdoor tanks equipped with raft hydroponics. As the UVI system developed, there were many design evolutions. Most of the experimental work was conducted in six replicated systems that consisted of a rearing tank (12.8 m^3), clarifier (1.9 m^3), two hydroponic tanks (13.8 m^2), and a sump (1.4 m^3), Fig. 19.2. The hydroponic tanks (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. Coarse gravel proved to be difficult to work with, so it was removed in favor of a raft system, consisting of floating sheets of polystyrene 1.22 m x 2.44 m x 3.8 cm (4 ft x 8 ft x 1.5 in). 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 fish rearing tank.



The fish rearing tank was situated under an opaque canopy and the clarifier and sump were covered with plywood. Shading inhibits algae growth, lowers daytime water temperature, and creates more natural light conditions for the fish. The rearing tank in this particular 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 tilapia at commercial densities (107 fish/m^3), the daily feed ration to the system was so high that 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). The optimum ratio between the fish feeding rate and plant growing area was determined, using Bibb lettuce as the baseline plant, to be 57 g of feed/day/m^2 of plant growing area, (Rakocy, 1989a). At this ratio, the nutrient accumulation rate decreased, and the hydroponic tanks were able to provide sufficient nitrification. This success enabled the RBCs to be removed when the fish stocking rates were reduced to levels that allowed feed to be administered near the optimum rate for good plant growth. The optimum ratio will vary depending on plant species and the production method, i.e., staggered vs. batch culture.

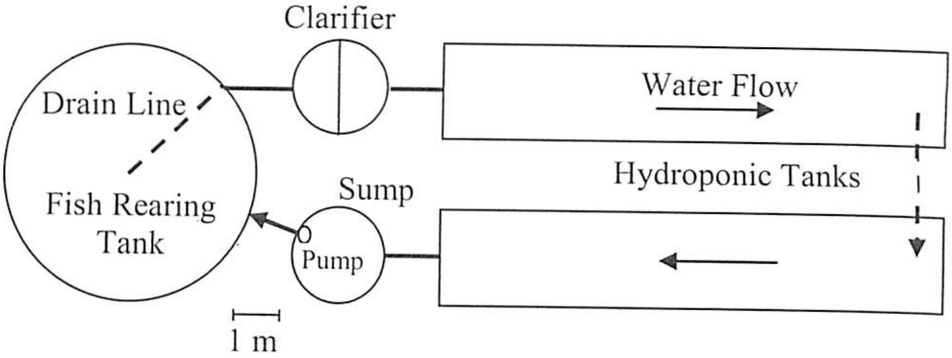
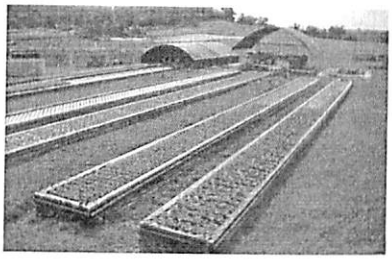


Figure 19.2 Design of UVI experimental aquaponic system.

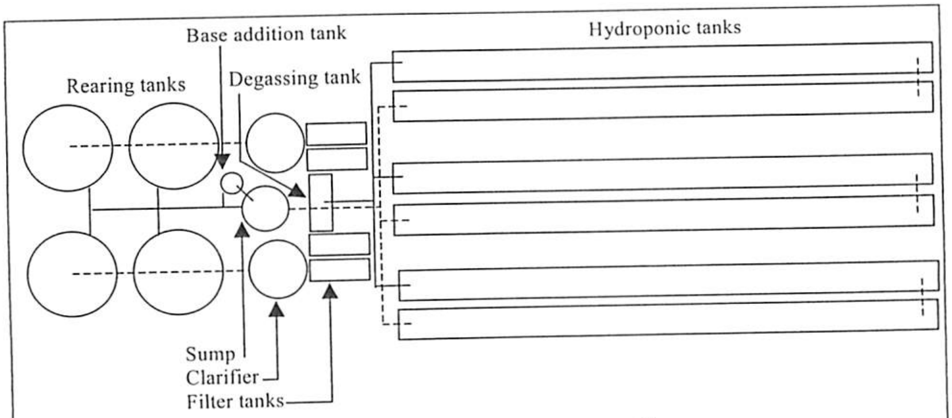
The experimental system was scaled up two times. In the first scale-up, the length of each hydroponic tank was increased from 6.1 m to 29.6 m. The optimum design ratio of 57g feed/day/m^2 of plant growing area allowed the rearing tank to be stocked with tilapia at commercial levels (for a diffused aeration system) without excessive nutrient accumulation.

"Rule of Thumb"

57 g of feed/day per square meter of plant growing
Area for staggered production of Bibb lettuce



In the second scale-up, the number of hydroponic tanks (29.6 m in length) was increased to six and the number of fish rearing tanks was increased to four, Fig. 19.3. This production unit design represents a realistic commercial scale, although there are many possible size options and tank configurations. For example, the number of hydroponic tanks could be reduced from six to two, as in the experimental unit, by increasing the width or length as long as the total area remained the same. Likewise, the rearing tanks (7.8 m^3) could be increased in size and/or number, provided there is a corresponding increase in the surface area of the hydroponic tanks. There is more flexibility in sizing and configuring outdoor systems, which are restricted to tropical or subtropical climates for year-round production of fish, than is available for indoor systems. In temperate indoor systems, the components must be configured tightly to conserve space, and the unit cannot exceed the width of a greenhouse bay, which ranges from 6.7 to 9.45 m. UVI's commercial-scale unit (second scale-up) could be configured to occupy as little as 0.05 ha of land.



TANK DIMENSIONS

Rearing tanks: Diameter: 10 ft, Height: 4 ft, Water volume: 2,060 gal each?
Clarifiers: Diameter: 6 ft, Height of cylinder: 4 ft, Depth of cone: 3.6 ft, Slope: 45°, Water volume: 1,000 gal
Filter and degassing tanks: Length: 6 ft, Width: 2.5 ft, Depth: 2 ft, Water volume: 185 gal
Hydroponic tanks: Length: 100 ft, Width: 4 ft, Depth: 16 in, Water volume: 3,000 gal, Growing area: 2,304 ft^2
Sump: Diameter: 4 ft, Height: 3 ft, Water volume: 160 gal
Base addition tank: Diameter: 2 ft, Height: 3 ft, Water volume: 50 gal
Total system water volume: 29,375 gal
Flow rate: 100 GPM,
Water pump: ½ hp
Blowers: 1½ hp (fish) and 1 hp (plants)
Total land area: 1/8 acre

PIPE SIZES

Pump to rearing tanks: 3 in
Rearing tanks to clarifier: 4 in
Clarifiers to filter tanks: 4 in
Between filter tanks: 6 in
Filter tank to degassing tank: 4 in
Degassing to hydroponic tanks: 6 in
Between hydroponic tanks: 6 in
Hydroponic tanks to sump: 6 in
Sump to pump: 3 in
Pipe to base addition tank: ¾ in
Base addition tank to sump: 1.25 in

Figure 19.3 Layout of UVI aquaponic system with tank dimensions and pipe sizes.

19.2 FISH PRODUCTION

Tilapia is the most common fish cultured in aquaponic systems. Although some aquaponic systems have used channel catfish, largemouth bass, crappies, rainbow trout, pacu, common carp, koi carp, goldfish, Asian sea bass (barramundi) and Murray cod, most commercial systems are used to raise tilapia. The majority of freshwater species, which can tolerate crowding, including ornamental fish, will do well in aquaponic systems. One species reported to perform poorly is hybrid striped bass because they cannot tolerate high levels of potassium, which is often supplemented to promote plant growth.

To recover the high capital cost and operating expenses of aquaponic systems and earn a profit, the fish rearing component and the hydroponic vegetable component must be operated near maximum production capacity on a continuous basis. Three fish stock management methods can be used to maintain fish biomass close to the systems maximum carrying capacity, the maximum amount of fish a system can support without restricting fish growth. Operating a system near its carrying capacity utilizes space efficiently, maximizes production, and reduces variation in the daily feed input to the system, an important factor in sizing the hydroponic component. The basic methods of fish management are sequential rearing, stock splitting and multiple rearing units. It is important to determine the best method for varying circumstances prior to designing a commercial system, as each method has different requirements. Changing rearing methodology in a production mode is costly and interruptive to steady fish production

SEQUENTIAL REARING

Sequential rearing involves the culture of several age groups (multiple cohorts) of fish in the same rearing tank. *(For example a mixed-cell raceway!)* When one age group reaches marketable size, it is selectively harvested with nets and a grading system, and an equal number of fingerlings are immediately restocked in the same tank. There are three problems with this system: 1) the periodic harvests stress the remaining fish and could trigger disease outbreaks; 2) stunted fish avoid capture and accumulate in the system, wasting space and feed; 3) it is difficult to maintain accurate stock records over time, which leads to a high degree of management uncertainty and unpredictable harvests. Nevertheless, sequential rearing has been used successfully on a commercial scale with tilapia, a very hardy species, despite its drawbacks. Sequential rearing may be risky for species less tolerant to the repeated stress of partial harvest.

STOCK SPLITTING

Stock splitting involves stocking very high densities of fingerlings and periodically splitting the population in half as the carrying capacity of the rearing tank is reached (Van Gorder, 1991). A typical stock splitting system would divide the initial population three times so that the fish would go from one tank to two tanks and then from two tanks to four tanks and finally from four tanks to eight tanks, from which marketable fish are harvested. Alternatively, single cohorts can be moved to successively larger a tank, which reduces stress on the fish and generally takes less time than trying to physically divide a single cohort into two equal populations, based on weight or number, to be placed in tanks of the original size.

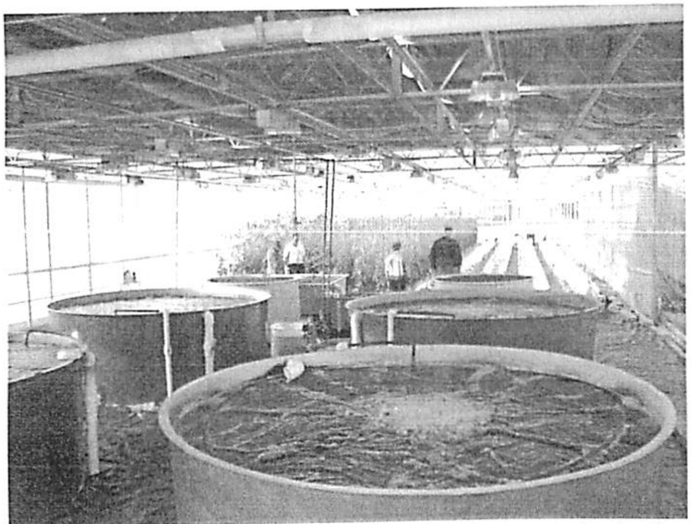
If the splitting cohort technique is chosen, a total of 15 rearing tanks are required to be able to harvest eight tanks at the end of each growth interval, a period of 5 or 6 weeks for tilapia. This method of fish management avoids the carryover problem of stunted fish and improves the accuracy of stock inventory assessment. However, the moves can be very stressful on the fish unless a swimway is installed, which connects all the rearing tanks to a narrow channel and the fish can be herded into it through a hatch in the wall of the rearing tanks and maneuvered into another rearing tank by movable screens. With swimways, the division of the populations in half involves some guesswork because the fish cannot be weighed or counted. An alternative method involves crowding the fish with screens and pumping them into a hauling tank or directly into another tank using a pescalator.

MULTIPLE REARING UNITS

With multiple rearing units, the entire population is moved to larger rearing tanks when the carrying capacity of the initial rearing tank is reached. The fish are either herded through a hatch between adjoining tanks or into "swimways" connecting distant tanks. Multiple rearing units usually come in modules of two to four tanks and are connected to a common filtration system. After the largest tank is harvested, all of the remaining groups of fish are moved to the next largest tank, and the smallest tank is restocked with fingerlings.

A variation of the multiple rearing unit concept is the division of a long raceway into compartments with movable screens. As the fish grow, their compartment is increased in size and moved closer to one end of the raceway where they will eventually be harvested. These should be cross-flow raceways or mixed-cell raceways (see Chapter 4) to ensure uniform water quality throughout the length of the tank. In a cross-flow raceway influent water enters the raceway through a series of ports down one side of the raceway while effluent water leaves the raceway through a series of drains down the other side. This system ensures that water is uniformly good throughout the length of the raceway. *(Although the idea seems very practical on paper, it is very hard to realize in practice, fish are incredibly good escape harvest and will quickly figure out how to move from cell to cell!)*

Another variation is the use of several tanks of the same size. Each rearing tank contains a different age group of fish, but they are not moved during the production cycle. This system does not utilize space efficiently in the early stages of growth, but the fish are never disturbed and the labor involved in moving the fish is eliminated.



A Portion of UVI's Aquaponic System Showing (counterclockwise from upper right): Clarifier, Two Filter Tanks, Degassing Tank with Internal Standpipe Well, and Return Sump.

UVI's current commercial-scale, aquaponic system uses multiple rearing tanks to simplify stock management, as the fish are not moved during their 24-week growout cycle. The system consists of four fish rearing tanks (7.8 m^3 each, water volume), two cylindro-conical clarifiers (3.8 m^3 each) with a 45° slope, four filter tanks (0.7 m^3 each), one degassing tank (0.7 m^3), six hydroponic tanks (11.3 m^3 each, 29.6 m x 1.2 m x 0.4 m), one sump (0.6 m^3) and one base addition tank (0.2 m^3). The total hydroponic surface area is 214 m^2, and the total system water volume is 110 m^3. Tilapia production is staggered in the four rearing tanks so that one rearing tank is harvested every 6 weeks. At harvest the rearing tank is drained and all of the fish are removed. The rearing tank is then refilled with the same water and immediately restocked with fingerlings for a 24-week production cycle

The system is used to culture Nile tilapia (*Oreochromis niloticus*) and red tilapia. Fry are sex-reversed with 17α-methyltestosterone according to the INAD (Investigations in New Animal Drugs) protocol to obtain a consistently high percentage (~99%) of male fingerlings. Nile tilapia fingerlings are stocked at a rate of 77 fish/m^3 to obtain a harvest size of 800–900 g. These large fish are processed for the fillet market. Red tilapia fingerlings are stocked at 154 fish/m^3 to achieve an average weight near 500 g for the whole fish West Indian market. Every six weeks approximately 500 to 600 kg of fish are harvested. Annual production has been 9,152 lbs. (4.16 mt) for Nile tilapia and 10,516 lbs (4.78 mt) for red tilapia (Table 19.2). However, production can be increased to 11,000 lbs (5 mt) with close observation of the *ad libitum* feeding response.

Tilapia grow well at high densities if good water quality is maintained. In the commercial-scale system, dissolved oxygen (DO) levels in the rearing tanks are maintained at 5–6 mg/L by high DO in the incoming water and by diffused aeration with air delivered through 22 air stones around the perimeter of the tank. A 1.5-hp (1.1 kW) blower provides air to the rearing and degassing tanks. Vigorous aeration vents carbon dioxide gas into the atmosphere and prevents its buildup. A high water exchange rate quickly removes suspended solids and toxic waste metabolites (ammonia and nitrite) from the rearing tank. A ½-hp in-line pump produces a flow of 380 Lpm (100 gpm) and an average retention time of 1.4 hours/rearing tank. However, flows to the individual rearing tanks are adjusted so that the tank with the highest biomass receives the highest flow rate, which exceeds 130 Lpm (35 gpm) for a retention time of less than 1 hour. The other rearing tanks receive proportionately lower flow rates relative to their biomass. Values of ammonia-nitrogen and nitrite-nitrogen in the rearing tanks are approximately 1–2 mg/L and <1 mg/L, respectively.

(This is contrary to what has been presented previously, with the shortest Hydraulic Retention Time going to the smaller fry and fingerlings to assure the maximum water quality. Rakocy employs an incredible number of air stones in his tanks, which provide a high re-aeration rate, but also maintains the solids in suspension. Thus the overall water quality is really not optimal compared to a dual-drain system where most of the solids are quickly removed from the center drains and directed to a solids capture device. For any other fish then Tilapia, these solids would cause gill fouling, off-flavor, slower growth rates and increased stress, which would result in higher disease potential. Tilapia have been both a blessing and a bane for aquaculture, allowing relatively poor water quality to be used in

production. As Michael always reminds me, 'even tilapia deserve good water quality to maximize growth, reduce stress and minimize disease potential!' This is why we have always recommended starting with a modest stocking density, 1/3 lb per gallon or less, to maximize the potential for successful growout. If for any reason the aeration were to fail on the above system, even tilapia would be dead or severally stressed within minutes!

Through careful attention to management of the water quality parameters of DO, ammonia-nitrogen and nitrite-nitrogen, it has been possible to grow tilapia at high densities. *(Assuming no equipment problems!)* Other water quality variables of importance to the system are water temperature, pH, and alkalinity. Water temperature ranges from a low of 23.0°C in the winter to a high of 29.0°C in the summer. The average water temperature has been 27.0°C, which is lower than the optimum temperature (30°C) for tilapia and higher than the optimum temperature (20–22°C) for many vegetables. The system water temperature is lower than that in nearby ponds because none of the system's surface area is exposed to direct sunlight. The pH is generally maintained at 7.0 by adding equal amounts calcium hydroxide and potassium hydroxide. Total alkalinity averages approximately 100 mg/L as calcium carbonate ($CaCO_3$).

Table 19.2 Average Production Values for Male Mono-sex Nile and Red Tilapia in the UVI Aquaponic System. Nile Tilapia Are Stocked at (77 fish/m^3 (0.29 fish/gallon) and Red Tilapia Are Stocked at (154 fish/m^3 (0.58 fish/gallon).

Tilapia	Harvest Weight per Tank (lbs)	Harvest Weight per Unit Volume (lb/gal)	Initial Weight (g/fish)	Final Weight (g/fish)	Growth Rate (g/day)	Survival (%)	FCR
Nile	1,056 (480 kg)	0.51 (61.5 kg/m^3)	79.2	813.8	4.4	98.3	1.7
Red	1,212 (551 kg)	0.59 (70.7 kg/m^3)	58.8	512.5	2.7	89.9	1.8

In general, it is recommended that the carrying capacity in aquaponic systems should not exceed 60 kg/m^3 (0.50 lb/gallon). This density will promote fast growth and efficient feed conversion and reduce crowding stress that may lead to disease outbreaks. Pure oxygen is generally not needed to maintain this density.

The logistics of working with both fish and plants are challenging. In the UVI system one rearing tank is stocked every 6 weeks. Therefore 18 weeks are required before a system is fully stocked. If multiple units are used, then fish may be stocked as frequently as once weekly and harvested and sold once weekly. Similarly, staggered crop production requires frequent seeding, transplanting, harvesting, and marketing. Therefore, the overarching goal in the design process is to reduce labor requirements wherever possible and make operations as simple as possible. For example, the purchase of four fish rearing tanks adds extra expense. One larger tank could be purchased instead and partially harvested and partially restocked every six weeks. However, this operation requires additional labor, which is a recurring cost, and makes management more complex. In the long run having smaller, multiple tanks, in which the fish are not disturbed until harvest (hence, less mortality and better growth) will be more cost effective. *(Or the fish could be harvested every two, three or even four weeks and kept in a purging tank for marketing. Tilapia will hold their weight for up to three weeks in a purging tank, requiring very little water treatment except for aeration.)*

19.3 SOLIDS

Fish generate fecal waste, most of which should be removed from the waste stream before it enters the hydroponic tanks. *(It is critical in NFT and raft systems that all the suspended and settleable solids be removed or else they will collect on the bottom, decompose and release toxic by-products or else collect on and smother the roots of the plants.)* Other sources of particulate waste are uneaten feed and organisms (e.g., bacteria, fungi, and algae) that grow in the system. If this organic matter accumulates in the system, it will depress dissolved oxygen (DO) levels as it decays and produce carbon dioxide and ammonia. If deep deposits of sludge form, they will decompose anaerobically (without oxygen) and produce methane and hydrogen sulfide, which is very toxic to fish.

Suspended solids have special significance in aquaponic systems. Suspended solids entering the hydroponic component may accumulate on plant roots and produce a deleterious effect by creating anaerobic zones and blocking the flow of water and nutrients to the plant. However, some accumulation of solids may be beneficial. As solids undergo decomposition by microorganisms, inorganic nutrients essential to plant growth are released to the water, a process known as mineralization. Mineralization supplies several essential nutrients. Without sufficient solids for mineralization, more nutrient supplementation is required, thereby increasing the operating expense and management complexity of the system. However, it may be possible to minimize or eliminate nutrient supplementation if fish stocking and feeding rates are increased relative to plants. Another benefit of solids is brought about by the action of decomposing microorganisms. Microbes associated with decomposing solids are antagonistic to plant root pathogens and help maintain healthy root growth. Therefore, it appears that a delicate balance must be reached between excessive accumulation of suspended solids and insufficient accumulation.

(Some small scale aquaponic systems are designed where the solids that are collected are mineralized outside of the system. A small tank is used to hold the solids for several days while air stones are used to heavily aerate and provide needed oxygen for the mineralization process. Then the aeration is stopped and the clear supernatant is decanted and added to the aquaponics nutrient flow or sump. Another method for larger systems would be to use a geotextile bag to collect the diluted waste stream, separate the solids from the nutrient rich supernatant, which can then be added to the aquaponics nutrient flow or sump.)

Chapter 5 Solids Capture describes some of the common devices used for removing solids from recirculating systems. These include settling basins, tube or plate separators, the combination particle trap and sludge separator, centrifugal separators, microscreen filters and bead filters. Sedimentation devices (e.g., settling basins, tube or plate separators) primarily remove settleable solids (>100 microns) while filtration devices (e.g., microscreen filters, bead filters) remove settleable and suspended solids. Solids removal devices vary in regards to efficiency, solids retention time, effluent characteristics (both solid waste and treated water) and water consumption rate. While many devices may be appropriate for aquaponic systems, there is no research on the relationship between techniques for solids removal and the performance of hydroponic vegetables.

Sand and gravel hydroponic substrates are sometimes used to remove solid waste from the water flow stream. The solids remain in the system to provide nutrients to the vegetables through mineralization. As solids accumulate in the media, there is an increase in the cation exchange capacity (CEC), i.e., the ability of the media to adsorb and retain cations, positively charged nutrients, which are available for plant growth. Since cation concentrations are often high in aquaponic systems, CEC is generally not an important factor to plant growth. The use of sand is becoming less common, but one popular aquaponic system uses small beds 2.4 m by 1.2 m (8 ft by 4 ft) containing pea gravel ranging from 3 to 6 mm (1/8 to 1/4 inch) in diameter. The hydroponic beds are flooded several times daily with system water and then allowed to drain completely, and the water returned to the rearing tank. During the draining phase, air is brought into the gravel. The high oxygen content of air (compared to water) speeds the decomposition of organic matter in the gravel. The beds are inoculated with worms (*Eisenia foetida)*, which improve bed aeration and assimilate organic matter.

The organic waste produced in aquaponic systems does not break down completely. The fraction of organic waste that resists microbial decomposition is referred to as being refractory. Particulate refractory compounds will slowly accumulate in substrates such as pea gravel or on the bottom or raft system troughs. Dissolved refractory compounds give the culture water a brown or tea color, which contains tannic acid, humic acid and other humic substances. These compounds have mild antibiotic characteristics and are beneficial to the system's fish and plants. Humic compounds form metalo-organic complexes with Fe, Zn, and Mn and thereby increase the availability of these micronutrients to plants.

SOLIDS REMOVAL

The most appropriate device for solids removal in a particular system may depend primarily on the organic loading rate (daily feed input and feces production) and secondarily on the plant growing area. For example, if large amounts of fish (high organic loading) are raised relative to the plant growing area, then a highly efficient solids removal device such as a microscreen drum filter is desirable. Microscreen drum filters capture fine organic particles, e.g., 60 micron and larger, which are retained by the screen for only a few minutes prior to backwashing and removal from the system. In this system, the dissolved nutrients excreted directly by the fish or produced by mineralization of very fine particles and dissolved organic matter may be sufficient for the size of the plant growing area. At the other extreme, if small amounts of fish (low organic loading) are raised relative to the plant growing area, then solids removal may be unnecessary, as more mineralization is needed to produce sufficient nutrients for the relatively large plant growing area. However, unstabilized solids, solids that have not undergone microbial decomposition, should not be allowed to accumulate on the tank bottom and form anaerobic zones. A reciprocating pea gravel filter (subject to flood and drain cycles), in which incoming water is spread evenly over the entire bed surface, may be the most appropriate device in this situation because solids are evenly distributed in the gravel and exposed to high oxygen levels (21% in air as compared to 0.0005-0.0007% in fish culture water) on the drain cycle, thereby enhancing microbial activity and increasing the mineralization rate.

UVI's commercial-scale aquaponic system relies on two cylindro-conical clarifiers to remove settleable solids (Rakocy, 1984). The fiberglass clarifiers each have a volume of 1.9 m^3 (500 gallons). The cylindrical portion of the clarifier is situated above ground and has a central baffle that is perpendicular to the incoming water flow (Figure 19.4). The lower conical portion has a 45° slope and is buried below ground. A drainpipe is connected to the apex of the cone. The drain pipe rises vertically out of the ground to the middle of the cylinder and is fitted with a ball valve. Rearing tank effluent enters the clarifier just below the water surface. The incoming water is deflected upward by a 45° pipe elbow to dissipate the current. As water flows under the baffle, turbulence diminishes and solids settle on the sides of the cone. The solids accumulate there and form a thick mat that eventually rises to the surface of the clarifier. To prevent this, approximately 30 male tilapia fingerlings are required to graze on the clarifier walls and consolidate solids at the base of the cone. Solids are removed from the clarifier three times daily. Hydrostatic pressure forces solids through the drain line when the ball valve is opened. A second, smaller baffle keeps floating solids from being discharged to the filter tanks.

The fingerlings serve another purpose. They swim into and through the drain lines and keep them clean. Without tilapia, the 10.2 cm (4 in) drain lines would require manually cleaning nearly every day due to bacterial growth in the drain lines, which constricts water flow. A cylindrical screen attached to the rearing tank drain prevents fingerings from entering the rearing tank.

In UVI's current commercial-scale system, the clarifier volumes have been increased to 3.8 m^3 (1000 gal) to achieve a 20-minute retention time, which resulted in much more effective removal of settleable solids. The clarifiers were constructed with standard fiberglass material. The slope of the conical portion was reduced to 45°. Although a 60° slope is more efficient for solids removal, installation of a heavy fiberglass tank with such a large cone is not feasible. Each clarifier is stocked with 40 male tilapia fingerlings to enhance clarifier performance, e.g., for grazing on surfaces and resuspending solids from upper reaches of the clarifier.

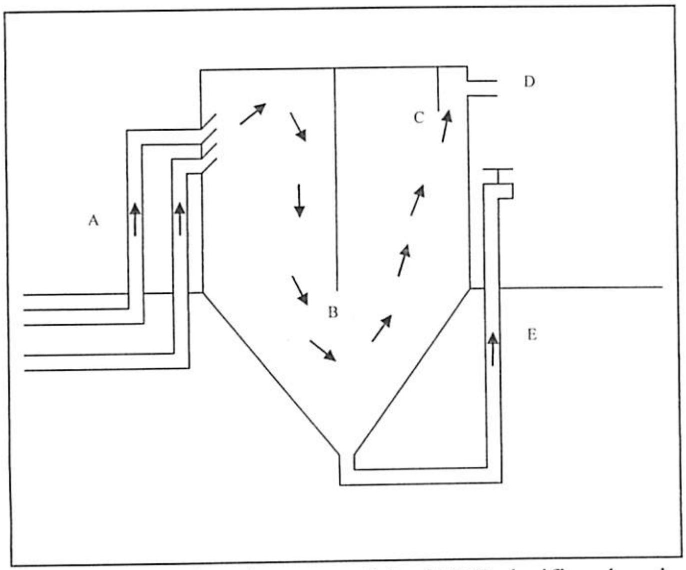


Figure 19.4 Cross sectional view (not to scale) of UVI clarifier showing drain lines from two fish rearing tanks (A), central baffle (B) and discharge baffle (C), outlet to filter tanks (D), sludge drain line (E) and direction of water flow (arrows).

Although the cylindro-conical clarifier can remove 21% of the dry weight of feed added to the system during a production cycle (Rakocy et al. 1991), large quantities of solids are not removed. Twarowska et al. (1996) determined that 35.3% of feed input to a tilapia culture system can be captured as settleable and non-settleable solids (based on volatile solids analysis) by using a particle trap and particle separator (17.6% removal) in combination with a microscreen drum filter (17.7% removal). These results indicate that the clarifier removes approximately 59% of the total removable solid waste. Although fingerlings are needed for effective clarifier performance, their grazing and swimming activities are also counterproductive in that they resuspend some solids which exit through the clarifier outlet. The fish in the clarifier grow rapidly and should be replaced with small (~50 g) fingerlings every 12 weeks.

With clarification as the sole method of solids removal, large quantities of solids were discharged into the hydroponic tanks where they settled out and formed sludge deposits more than 5-cm deep at the influent end. This was a very undesirable condition, adversely affecting the plant component, as the sludge would float to the surface, engulf the plant roots and either kill the plants or greatly reduce their growth. A series of experiments resulted in arriving at a design solution that incorporated another water treatment stage consisting of additional tanks filled with orchard netting for the removal of fine solids. Two rectangular filter tanks 0.7 m^3 (185 gal) were installed after each clarifier. Effluent from the clarifier

flows through these tanks in series. The netting is washed once or twice a week with a high-pressure water sprayer, and all the water in the filter tanks is discharged and the sludge is discharged to lined holding ponds. Prior to cleaning, a small sump pump is used to carefully return the filter tank water to the rearing tanks without dislodging the solids. This process conserves water and nutrients.

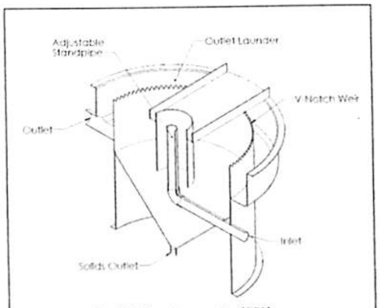
Effluent from the UVI rearing tanks is highly enriched with dissolved organic matter, which stimulates the growth of filamentous bacteria in the drain line, clarifier, and screen tank. The bacteria appear as translucent, gelatinous, light-tan filaments. Tilapia consume the bacteria and controls its growth in the drain line and clarifier, but bacteria does accumulate in the filter tanks. Without the filter tanks, the bacteria would overgrow plant roots. The bacteria do not appear to be pathogenic, but they do interfere with the uptake of dissolved oxygen, water, and nutrients, thereby affecting plant growth. The feeding rate to the system and the flow rate from the rearing tank determine the extent to which filamentous bacteria manifests itself, but it can be contained by providing a sufficient area of orchard netting, either by adjusting screen tank size or using multiple screen tanks. In systems with lower organic loading rates (i.e., feeding rates) or lower water temperature (hence, less biological activity), filamentous bacteria diminish and are not a problem.

The organic matter that accumulates on the orchard netting between cleanings forms a thick sludge. Anaerobic conditions develop in the sludge, which leads to formation of gases such as hydrogen sulfide, methane, and nitrogen. Therefore, a degassing tank is used in the UVI system to receive the effluent from the filter tanks. A number of air diffusers vent the gasses into the atmosphere before the culture water reaches the hydroponic plants. The degassing tank has an internal standpipe well that splits the water flow into three sets of hydroponic tanks.

In UVI's commercial-scale system, the combination clarifier and filter tanks have maintained very low levels of suspended solids. In one trial with leaf lettuce, suspended solids values averaged 4.2 mg/L in the filter tank effluent (Rakocy et al. 1997). The hydroponic tanks also contribute to suspended solids removal. There is no phytoplankton in the water, which is clear but darkly colored with humic substances

Solids that are discharged from aquaponic systems must be disposed in an environmentally acceptable manner (see Chapter 6 Waste Management and Utilization). There are several methods for effluent treatment and disposal. Effluent can be stored in aerated ponds and applied as relatively dilute sludge to land after organic matter has stabilized. This method is advantageous in dry areas where sludge can be used to irrigate and fertilize field crops. The solid fraction of the sludge can be separated from the water and used with other waste using geotextile membranes and polymers and used with other water products from the system (vegetable matter) to form compost. As an example, solids from the UVI commercial-scale aquaponic system are discharged through drain lines into two lined 16-m^3 ponds, which are continuously aerated with diffused air. As one pond is being filled over a 2 to 4-week period, water from the other pond is used to irrigate and fertilize field crops. Urban area facilities might have to discharge solid waste into sewer lines for disposal at the municipal sewage treatment plant.

(At this point it would be useful to look at both the design of the solids capture device and other devices that were not available at the time that Rakocy did his



Radial Flow Separator (RFS)

research or on his remote Caribbean island paradise!. One of the most important design changes to the clarifier used by Rakocy would be to modify it to reflect the design concept of a radial flow separator. Davidson et al. (2005) found the radial flow separator nearly twice as effective as a swirl separator at the same surface loading rates and same sized units and using a center cylinder more efficiently utilizes the cross-sectional area of the conical settling tank. Design 'Rule of Thumb' calls for a hydraulic loading rate of 120 to 200 Lpm/m^2 (3 to 5 gpm per ft^2) and a bottom discharge of from 5 to 15% of the flow or manual discharge of the stored solids in the conical bottom. Swirl separators are not inexpensive, and just as settling basins and drum filters, they are not effective at removing fine solids (diameter <50 μm). However, they can be quite effective in removing TSS: Davidson and Summerfelt (2005) report nearly 40% removal efficiency. In the same study, Davidson and Summerfelt (2005) determined that a radial-flow settler operated under the same hydraulic loading rate in the same system would remove almost 80% of the TSS, which doubled the removal efficiency produced by a swirl separator. For small systems, this might be adequate to maintain the solids concentrations low enough not to impact the plant production systems. These also loan themselves to the dual-drain system, where most of the solids exit through the center drains and this flow is only 10 to 20% of the total circulation. The sidewall discharge higher up in the water column is relative low in solids and could go directly into the plant production systems. Finally an entire 'family' of bead filters are now available covering a wide range of flow rates for small 'home systems' utilizing the bubble-washed bead filter line, to the large scale commercial facilities utilizing the propeller-washed line of filters.

19.4 BIOFILTRATION

A major concern in aquaponic systems is the removal of ammonia, a metabolic waste product excreted through the gills of fish. Ammonia will accumulate and reach toxic levels unless it is removed by the process of nitrification (referred to more generally as biofiltration), in which ammonia is oxidized first to nitrite, which is toxic. Then nitrite is oxidized to nitrate, which is relatively non-toxic. Two groups of naturally-occurring bacteria (*Nitrosomonas* and *Nitrobacter*) mediate this two-step process. Nitrifying bacteria grow as a film (referred to as biofilm) on the surface of inert material or they adhere to organic particles. Biofilters contain media with large surface areas for the growth of nitrifying bacteria. Aquaponic systems have used biofilters with sand, gravel, shells, or various plastic media as substrate (Rakocy and Hargreaves, 1993). Biofilters perform optimally at a temperature range of 25–30°C, a pH range of 6.0–9.0, saturated DO, low BODs < 20 mg/L, and total alkalinity of 100 mg/L or greater. Nitrification is an acid-producing process that destroys alkalinity. Therefore, an alkaline base must be added frequently depending on feeding rate to maintain relatively stable pH values. Some means of removing dead biofilm is necessary to prevent media clogging, short circuiting of water flow, decreasing DO values and declining biofilter performance. A discussion of nitrification principles and a description of various biofilter designs and operating procedures are given in Chapter 7 and 8.

Major biofilter options (rotating biological contactors, expandable media filters, fluidized bed filters, packed tower filters and moving bed bioreactors) are reviewed in Chapter 7 Biofiltration. If a separate biofilter is required or if a combined biofilter (biofiltration and hydroponic substrate) is used, the standard equations used to size biofilters may not apply to aquaponic systems as additional surface area is provided by plant roots and a considerable amount of ammonia removal is due to direct uptake by plants. However, the contribution of various hydroponic subsystem designs and plant species to water treatment in aquaponics systems has not been studied. Therefore, aquaponic system biofilters should be sized fairly close to the recommendations for recirculating systems.

Nitrification efficiency is affected by pH. The optimum pH range for nitrification is 7.0 to 9.0, although most studies indicate that nitrification efficiency is greater at the higher end of this range. Most hydroponic plants grow best at pH in the range of 5.8 to 6.2. The acceptable range for hydroponic systems is 5.5 to 6.5. The pH of a solution affects nutrient solubility, especially trace metals. Essential nutrients such as iron, manganese, copper, zinc, and boron are less available to plants at pH above 7.0 while the solubility of phosphorus, calcium, magnesium, and molybdenum sharply decreases at pH below 6.0. Compromise between nitrification and nutrient availability is reached in aquaponic systems by maintaining pH close to 7.0.

Nitrification is most efficient when water is saturated with DO. The UVI commercial-scale system maintains DO levels near 80% saturation (6 to 7 mg/L) by aerating the hydroponic tanks with numerous small air diffusers, one every 1.2 m (4 ft) distributed along the long axis of the tanks. Reciprocating (ebb and flow) gravel systems expose nitrifying bacteria to high atmospheric oxygen levels during the dewatering phase. The thin film of water that flows through NFT channels absorbs oxygen by diffusion, but dense plant roots and associated organic matter can block water flow and create anaerobic zones, which precludes the growth of nitrifying bacteria and further necessitates the installation of a separate biofilter.

Ideally, aquaponic systems should be designed so that the hydroponic subsystem also serves as the biofilter, which eliminates the capital cost and operational expense of a separate biofilter. Granular hydroponic media such as gravel, sand, and perlite provide sufficient substrate for nitrifying bacteria and generally serve as the sole biofilter in some aquaponic systems, although they have a tendency to clog, as stated earlier. If serious clogging occurs due to organic matter overloading, gravel and sand filters can actually produce ammonia as organic matter decays, rather than remove it. If this occurs, the gravel or sand must be washed, and the system must be redesigned by installing a solids removal device prior to the granular biofilter, or the organic loading rate must be decreased by reducing fish stocking and feeding rates. McMurtry et al. (1990) relied on sand for hydroponic substrate and biofiltration while the early work at UVI (Rakocy, 1984) utilized gravel media for both functions. In some aquaponic systems, nitrification in the hydroponic component has supplemented that in the biofilter. Lewis et al. (1978) used pea gravel for hydroponic

substrate in conjunction with an RBC for biofiltration. Watten and Busch (1984) used crushed-gravel hydroponic substrate and a trickling biofilter. When gravel was eliminated from UVI's experimental units, an RBC was installed for biofiltration. When the experimental units were scaled up the first time, two RBCs were installed.

A series of three stock management experiments were conducted in the scaled-up unit, in which the surface area of each RBC was 92.9 m^2 (1000 ft^2) and the total growing area for hydroponic lettuce was 71.4 m^2 (768 ft^2). In the first two experiments the feeding to the system ranged from 3 to 6 kg/day (6.6 to 13.2 lbs/day) and good water quality was maintained. A feeding rate of 4 kg/day (8.8 lbs/day) was nearly equivalent to the optimum design ratio (57 g of feed/day/m^2) for staggered lettuce production. In the third experiment the RBCs were eliminated to obtain a preliminary determination of the biofiltration capacity of the hydroponic component. The maximum feeding rate to the system was increased to 8 kg/day (17.6 lbs/day), and water quality continued to be good. Average levels of ammonia-nitrogen and nitrite-nitrogen in the rearing tank were 1.3 and 0.7 mg/L, respectively. This experiment showed that a combination of direct ammonia uptake by lettuce plants and nitrification on the hydroponic tank floor, walls, and the underside of the floating polystyrene sheets can provide sufficient nitrification to maintain good water quality at a feeding rate that is two times greater than the optimum design ratio. The total surface area in each hydroponic tank was 92.9 m^2 (1000 ft^2), not including the additional surface area provided by the plant roots. The same surface area as contained in an RBC.

Massive root development of tomato plants supported by a sheet of polystyrene in UVI's Aquaponic System.

An experiment was conducted in UVI's replicated systems, to determine the waste treatment capacity of raft hydroponics (Gloger et al. 1995). Three identical systems were stocked with large *Oreochromis niloticus* (480 g/fish) so that feed could be incremented weekly until the waste treatment capacity was reached. The fish were initially underfed. Romaine lettuce (Parris Island) at a density of 29.6 plants/m^2 was produced continuously on a 4-week, staggered cycle. The results were based on the hydroponic growing area, expressed as g/m^2/day. The mean values and ranges were as follows: feeding rate, 159 g/m^2/day (77 to 230); wet weight plant production, 338 g/m^2/day; dry weight plant production, 16.9 g/m^2/day; ammonia-nitrogen removal, 0.56 g/m^2/day (-1.23 to 2.29); nitrite-nitrogen removal, 0.62 g/m^2/day (-2.68 to 2.28); BOD removal, 4.78 g/m^2/day (0.0 to 4.92); COD removal, 30.29 g/m^2/day (-10.58 to 69.72); total nitrogen uptake by lettuce, 0.83 g/m^2/day; total phosphorus uptake by lettuce, 0.17 g/m^2/day. If the ammonia-nitrogen removal rate is divided by two to account for the surface area of the tank floor and the underside of the polystyrene sheet, the resultant value (0.28 g/m^2/day) falls within the range of removal rates reported for recirculating-system biofilters (Losordo, 1997). The maximum sustainable feeding rate was equivalent to 180 g/m^2/day, about three times greater than the optimum design ratio for the staggered production of Bibb lettuce in aquaponic systems.

Raft hydroponics not only provides adequate waste treatment for correctly-sized aquaponic systems and eliminates the need and expense of separate biofiltration units, but its excess treatment capacity ensures safe and stable water quality. After an initial acclimation period of about one month, experience with the UVI systems has shown that it is not necessary to monitor ammonia and nitrite values on a frequent basis, but weekly checks would be a prudent management practice.

Aquaponic systems using nutrient film technique (NFT) as the hydroponic component may require a separate biofilter. NFT consists of narrow plastic channels for plant support with a film of nutrient solution flowing through them. Compared to raft culture, the water volume and surface area of NFT are considerably smaller because there is just a thin film of water and no substantial side wall area and no raft underside surface area for colonization by nitrifying bacteria.

19.5 HYDROPONIC SUBSYSTEMS

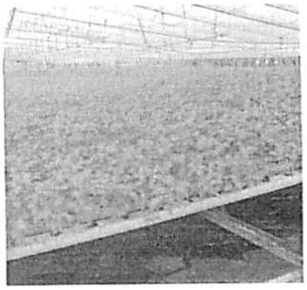
A number of hydroponic subsystems have been used in aquaponics (Rakocy and Hargreaves, 1993). Gravel hydroponic subsystems are common in small operations. To ensure adequate aeration of plant roots, gravel beds have been operated in a reciprocating (ebb and flow) mode, where the beds are alternately flooded and drained (Lewis et al. 1978; Lewis et al. 1980; Sutton and Lewis, 1982; Wren, 1984; Rakocy, 1984), or in a dewatered state, in which culture water is applied continuously to the base of the individual plants through small-diameter plastic tubing (Watten and Busch, 1984). Depending on its composition, gravel can provide some nutrients for plant growth, e.g., calcium is slowly released as the gravel reacts with acid produced during nitrification (Rakocy and Nair, 1987).

Gravel has several of negative aspects. The weight of gravel requires strong support structures. It is subject to clogging with suspended solids, microbial growth, and the roots that remain after harvest. The resulting reduction in water circulation together with decomposition of organic matter leads to the formation of anaerobic zones, which impairs or kills plant roots. The small plastic tubes used to irrigate gravel are also subject to clogging with biological growth. Moving and cleaning gravel substrate is difficult due to its weight. Planting in gravel is also difficult and plant stems can be damaged by abrasion in outdoor systems exposed to wind. Having high porosity, gravel retains very little water if drained. Disruption in flow will lead to the rapid onset of water stress (wilting). The sturdy infrastructure required supporting gravel and the potential of clogging imposes a size limitation on gravel beds.

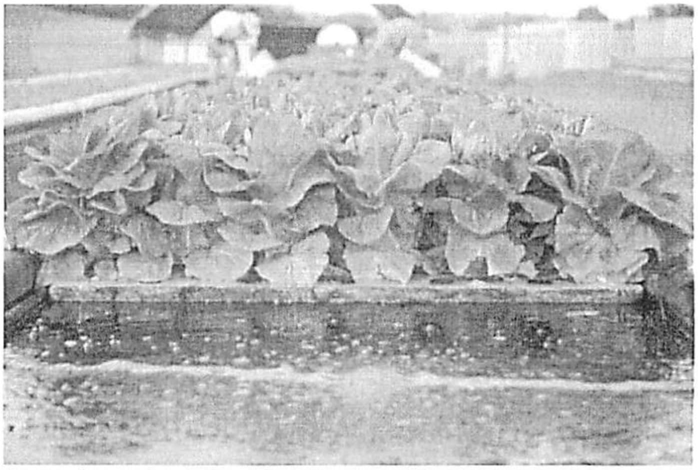
One popular gravel-based aquaponic system uses pea gravel in 1.2 m x 2.4 m (4 ft x 8 ft) beds that are irrigated through a distribution system of PVC pipes over the gravel surface. Numerous small holes in the pipes distribute culture water on the flood cycles. The beds are allowed to drain completely between flood cycles. Solids are not removed from the culture water and organic matter does accumulate, but the beds are tilled between planting cycles, allowing some organic matter to be dislodged and discharged.

Sand has been used as hydroponic media in aquaponic systems (Ferguson, 1982; McMurtry et al. 1990). Ferguson (1982) raised 28 types of vegetables in trays of sand that were stacked three tiers high in a commercial greenhouse. The greenhouse produced an average of 8,700 kg of vegetables during 10-week growth cycles in trays (0.6–0.9 m wide) with a total length of 1,155 m. The trays were made of parachute cloth so that water applied to the upper tray slowly percolated through it to irrigate the trays beneath it. McMurtry et al. (1990) constructed hydroponic sand beds (7.5 m x 1.5 m x 0.5 m) on sloped ground that was covered by polyethylene sheets. The beds were adjacent to in-ground rearing tanks with their floors sloping to one side. A pump in the deep end of the rearing tank was activated for 30 minutes five times daily to furrow irrigate the adjacent sand bed. The culture water percolated through the sand and returned to the rearing tank. The potential of sand substrates becoming clogged with solids can be reduced by regulating the solids loading rate. A coarse grade of sand is needed to reduce the potential for clogging over time and some solids should be removed prior to irrigation.

Perlite is another media that has been used in aquaponic systems. Perlite is placed in shallow aluminum trays 8 cm deep (3 inches) with a baked enamel finish. The trays vary from 20 cm to 1.2 m (8 inches to 4 ft) in width and can be fabricated to any length, but 6 m (20 ft) is the maximum recommended length. At intervals of 6 m (20 ft), adjoining trays should be separated by 8 cm (3 inches) or more in elevation so that effluent drops to the lower tray and becomes reaerated. A slope 1 to 144 (1 inch in 12 ft or 0.7%) is needed for water flow. A small trickle of water enters at the top of the tray, flows through the perlite, keeping it moist, and discharges into a trough at the lower end. Solids must be removed from the water before it enters the perlite tray. Full solids loading will clog the perlite, form short-circuiting channels, create anaerobic zones, and lead to non-uniform plant growth. Shallow perlite trays provide minimal area for root growth and are better for smaller plants such as lettuce and herbs.

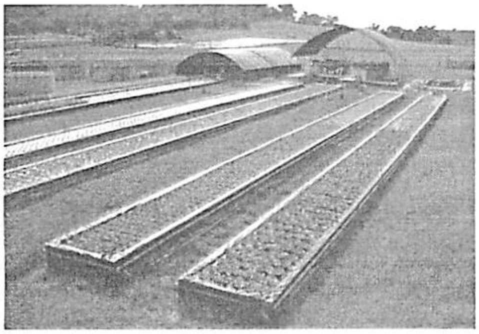


Nutrient film technique (NFT) has been successfully incorporated into a number of aquaponic systems (Head, 1984; Burgoon and Baum, 1984). NFT consists of many narrow plastic troughs 10 to15 cm wide (4 to 6 inches) in which plant roots are exposed to a thin film of water that flows down the troughs, delivering water, nutrients, and oxygen to the roots of the plants. The troughs are lightweight, inexpensive, and versatile. Troughs can be mounted over rearing tanks to efficiently utilize vertical greenhouse space. However, this practice is discouraged if it interferes with fish and plant operations such as harvesting. High plant density can be maintained by adjusting the distance between troughs to provide optimum plant spacing during the growing cycle. Aquaponic systems utilizing NFT require effective solids removal to prevent excess solids accumulation on roots, which can lead to root death and poor plant growth. With NFT, a disruption in water flow can lead quickly to wilting and death. Water is delivered at one end of the troughs by a PVC manifold with discharge holes above each trough and collected at the opposite, down-slope end in an open channel or large PVC pipe. The use of mirotubes, which are used in commercial hydroponics, is not recommended because they will clog. The holes should be as large as practical to reduce cleaning frequency.



Raft culture of romaine lettuce in an aerated hydroponic tank in UVI's Aquaponic System.

A floating or raft hydroponic subsystem is ideal for the cultivation of leafy green and other types of vegetables (Zweig, 1986; Rakocy et al. 1989b). Long channels with closed-cell polystyrene sheets support vegetables at the water surface with roots suspended in the culture water (Jensen and Collins, 1985). The system provides maximum exposure of roots to the culture water and avoids clogging, although suspended solids captured by the roots can cause root death if concentrations are high (Zweig, 1986). The sheets shield the water from direct sunlight and maintain lower than ambient water temperatures. A disruption in pumping does not affect the plant's water supply as in gravel, sand, and NFT subsystems. The sheets are easily moved along the channel to a harvesting point where they can be lifted out of the water and placed on supports at an elevation that is comfortable for the workers.



The UVI system uses three sets of two raft hydroponic tanks that are 30.5 m (100 ft) long by 1.22 m (4 ft) wide by 40.6 cm (16 inches) deep and contain 30.5 cm (12 inches) of water. The channels are lined with low density polyethylene liners (20 mils thick) and covered by expanded polystyrene sheets (rafts), which are 2.44 m (8 ft) long by 1.22 m (4 ft) wide by 3.8 cm (1.5 inches) thick. Net pots are placed in holes in the raft and just touch the water surface. Two inch net pots are generally used for leafy green plants while 7.62 cm (3-inch) net pots are used for larger plants such as tomatoes or okra. Holes of the same size are cut into the polystyrene sheet. A lip at the top of the net pot secures the net pot and keeps it from falling through the hole into the water. Seedlings are nursed in a greenhouse and then placed into net pots, and their roots grow into the culture water while their canopy grows above the raft surface.

A disadvantage of rafts in an aquaponic system is that roots are exposed to harmful organisms associated with aquaculture systems. For example, if tilapia fry gain access to the raft tanks, they consume plant roots and thereby severely stunt growth, although it is relatively easy to prevent the entry of tilapia by using a fine mesh screen. Similarly, blooms of zooplankton, especially ostracods, will consume root hairs and fine roots, retarding plant growth. Other pests are tadpoles, snails, and leeches that consume roots and nitrifying bacteria. These problems are surmounted by stocking some carnivorous fish that prey on pests in the hydroponic tanks. At UVI, snails are controlled with shellcracker sunfish (*Lepomis microlophus*), and zooplankton are controlled with black tetra (*Gymnocorymbus ternetzi*).

19.6 SUMP

Water flows by gravity from gravel, sand, and raft hydroponic subsystems to a sump, which is the lowest point in the system. The sump contains a pump or pump inlet which returns the treated culture water to the rearing tanks. If NFT troughs or perlite trays are located above the rearing tanks, the sump would be positioned in front of them so that water could be pumped up to the hydroponic component for gravity return to the rearing tanks. There should be only one pump to circulate water in an aquaponic system.

The sump should be the only tank in the system where the water level decreases as a result of overall water loss from evaporation, transpiration, sludge removal, and splashing. A mechanical valve is used for the automatic addition of replacement water from a storage reservoir or well. Municipal water should not be used unless it is de-chlorinated and surface water should not be used because it may contain disease organisms. A water meter should be used to record additions. Unusually high water consumption indicates a leak.

The sump is a good location for the addition of base to the system. Soluble base such as potassium hydroxide causes high and toxic pH levels in the sump. However, as water is pumped into the rearing tank, it is diluted and pH decreases to acceptable levels. The UVI system uses a separate base addition tank located next to the sump. As water is pumped from the sump to the fish rearing tanks, a small pipe, tapped into the main water distribution line, delivers a small flow of water to the base addition tank, which is well aerated with one large air diffuser. Base is added to this tank as needed to maintain a pH of 7.0 in the system. The base dissolves, gradually enters the sump and is pumped to the rearing tanks where it is quickly diluted in large volumes of turbulent water. Gradual addition of base avoids spikes in pH values, which are harmful to both fish and plants.

19.7 CONSTRUCTION MATERIALS

A wide range of materials are used to construct aquaponic systems. Budget limitations often play a major role in selecting inexpensive and questionable materials such as vinyl-lined, steel-walled swimming pools. Plasticizers used in vinyl manufacture are toxic to fish. The liners must be washed thoroughly or aged with water for several weeks before fish can be added safely to a tank of clean water. After a few growing periods, vinyl liners shrink upon drying, become brittle and crack, while the steel walls gradually rust. Nylon-reinforced, neoprene-rubber liners are not recommended either. Tilapia eat holes in rubber liners at the folds by grazing on microorganisms. Moreover, neoprene-rubber liners are not impervious to chemicals. If herbicides and soil sterilants are applied under or near rubber liners, these chemicals can diffuse into culture water, accumulate in fish tissue, and kill hydroponic vegetables.

Wood is not considered to be a good construction material for aquaponic systems because it prone to rotting in the high humidity environment. If wood is used, it must be untreated as treated lumber contains toxic compounds such as arsenic to inhibit bacterial growth. If these compounds leach into the water, they could affect the beneficial bacteria that the system depends on and contaminate the fish and vegetables. Untreated wood must be waterproofed with fiberglass matt and resin on the inside and epoxy paint on the outside. Wooden tanks must not be in contact with soil to prevent the entry of termites. In general, wooden tanks have a short life span.

Fiberglass is the best construction material for the rearing tanks, sump, and filter tanks. Fiberglass tanks are sturdy, durable, non-toxic, movable, and easy to plumb. An alternative to fiberglass is concrete, which is cheaper in many countries, although it lacks the flexibility of fiberglass construction. Commercially available NFT troughs, made from extruded polyethylene, are specifically designed to prevent puddling and water stagnation leading to root death and are preferable to makeshift structures (rain gutters, PVC pipes, etc.). Plastic troughs are commercially available for floating hydroponic subsystems, but they are expensive. A suitable alternative is to use of polyethylene liners and concrete-block or poured-concrete walls. Four types of liners have been tested in UVI's commercial-scale system. They are high-density polyethylene [1.5 mm (60 mil) and 0.5 mm (20 mil)], low-density polyethylene [0.5 mm (20 mil)], and a thick grade of nylon-reinforced vinyl with an under layer of high-density polyethylene. All of these liners are performing well after 5 to10 years, but it appears that 0.5-mm high-density polyethylene liners (HDPE) are best. They are easy to install, relatively inexpensive and durable, having an expected service life of 12 to 15 years. Initially, HDPE liners were black, but recently UV-resistant white liners have been introduced. White liners are preferable in that they reflect light and do not become as hot as black liners. This is an important characteristic in the tropics and during summers in temperate climates where the goal is to avoid high water temperatures.19.8

19.8 COMPONENT RATIOS

Aquaponic systems are generally designed to meet the size requirements for solids removal (for those systems requiring solids removal) and biofiltration (if a separate biofilter is used) for the amount of fish being raised. After the size requirements are calculated, it is prudent to add excess capacity as a safety margin. However, if a separate biofilter is used, the hydroponic component is the safety factor because a significant amount of ammonia uptake and nitrification will occur regardless of hydroponic technique.

Another key design criterion is the ratio between the fish rearing and hydroponic components. The key aspect of the criterion is the ratio of daily feed input to plant growing area. If the ratio of daily feeding rate to plant growing area is too high, nutrient salts will accumulate rapidly and may reach phytotoxic levels. Higher water exchange rates will be required to prevent excessive nutrient buildup. If the ratio of daily feeding rate to plants is too low, plants will develop nutrient deficiencies and more nutrient supplementation will be required. Fortunately, hydroponic plants grow well over a wide range of nutrient concentrations.

The optimum ratio of daily fish feed input to plant growing area will maximize plant production while maintaining relatively stable levels of dissolved nutrients. A volume ratio of 1 m^3 of fish rearing tank to 2 m^3 of pea gravel 3 to 6-cm (1/8 to 1/4 inch) in diameter as hydroponic media is recommended for reciprocating (flood and drain) gravel aquaponic systems. This ratio requires that tilapia are raised to a final density of 60 kg/m^3 (0.5 lb/gallon) and fed appropriately. With the recommended ratio no solids are removed from the system. The hydroponic beds should be cultivated (stirred up) between crops and inoculated with red worms to help break down and assimilate the organic matter. With this system nutrient supplementation may not be necessary.

"Rule of Thumb"

Pea Gravel Hydroponic Media
1 m^3 of fish tank volume to 2 m^3 of
hydroponic media

As a general guide for raft aquaponics, a ratio in the range of 60-100 g of fish feed/m^2 of plant growing area per day should be used. Ratios within this range have been used successfully in the UVI system for the production of tilapia, lettuce, basil and several other plants. In the UVI system all solids are removed, with a residence time of <1 day for settleable solids (>100 microns) removed by a clarifier, and 3 to 4 days for suspended solids removed by an orchard netting filter. The system uses rainwater, and supplementation is required for potassium, calcium, and iron.

"Rule of Thumb"

60-100 g of fish feed per day per square meter of plant growing area for the staggered production of leaf lettuce.

Another factor to consider in determining the optimum feeding rate ratio is the total water volume of the system, which affects nutrient concentrations. In raft hydroponics, approximately 75% of the system water volume is in the hydroponic component whereas gravel beds and NFT troughs contain minor amounts of system water. Theoretically in systems producing the same quantity of fish and plants, a daily feeding rate of 100 g/m^2 for example would produce total nutrient concentrations nearly four times higher in gravel and NFT systems (e.g., 1,600 mg/L) as compared to raft systems (e.g., 400 mg/L), but total nutrient mass would be equal among systems. Nutrient concentrations outside acceptable ranges affect plant growth. Therefore, the optimum design ratio varies depending on the type of hydroponic component. Gravel and NFT systems should have a feeding rate ratio that is approximately 25% of the recommended ratio for raft hydroponics.

Other factors involved in determining the optimum feeding rate ratio are the water exchange rate, nutrient levels in the source water, degree, and speed of solids removal and type of plant being raised. Lower rates of water exchange, higher source-water nutrient levels, incomplete or slow solids removal, resulting in the release of more dissolved nutrients through mineralization, and slower growing plants would allow a lower feeding rate ratio. Conversely, higher water exchange rates, low source-water nutrient levels, rapid and complete solids removal and fast growing plants would allow a higher feeding rate ratio.

The optimum feeding rate ratio is influenced by the plant culture method. With batch culture all plants in the system are planted and harvested at the same time. During their maximum growth phase, there is a large uptake of nutrients, which requires a higher feeding rate ratio during that period. In practice, however, a higher feeding rate ratio is used throughout the production cycle. With a staggered production system, plants are in different stages of growth, which levels out nutrient uptake rates and allows good production with slightly lower feeding rate ratios.

In properly designed aquaponic systems, the surface area of the hydroponic component is quite large compared to the surface area of the fish rearing tanks if it is stocked at commercial levels. The commercial-scale unit at UVI has a ratio of 7.3:1. The total plant growing area is 214 m^2 (2304 ft^2) compared to total fish rearing surface area of 29.2 m^2 (314 ft^2). With diffused aeration, final tilapia densities have reached a mean of 76 kg/m^3 (0.63 lbs/gal) With pure oxygen, final densities can be increased to 120 kg/m^3 (1.0 lb/gal) or greater. Therefore, smaller rearing tanks could be used to produce the same amount of fish and a ratio of 11.5:1 would be more appropriate.

"Rule of Thumb"

11.5 to 1 ratio of plant beds to fish tank surface area in high density fish systems (120 kg/m^3)

19.9 PLANT GROWTH REQUIREMENTS

Maximum plant growth in aquaponic systems requires 16 essential elements for proper nutrition. These nutrients are referred to below, in the order of their concentrations (mg/L) in plant tissue with carbon and oxygen being the highest. The essential elements are arbitrarily divided into macronutrients, those required in relatively large quantities, and micronutrients, those required in considerably smaller amounts. Three of the macronutrients, carbon (C), oxygen (O) and hydrogen (H), are supplied by water (H_2O) and carbon dioxide gas (CO_2). All of the remaining nutrients are absorbed from the culture water. Other macronutrients include nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), and sulfur (S). The seven micronutrients include chlorine (Cl), iron (Fe), manganese (Mn), boron (B), zinc (Zn), copper (Cu), and molybdenum (Mo). All of these nutrients must be in proper balance for optimum plant growth. High levels of one nutrient can influence the bioavailability of others. For example, excessive amounts of potassium may interfere with uptake of magnesium or calcium while excessive amounts of either of the latter nutrients may interfere with the uptake of the other two nutrients (Gerber, 1985).

An elevated CO_2 level in the atmospheric environment of unventilated hydroponic structures has given dramatic increases in crop yield in northern latitudes (Jensen and Collins, 1985). Kimball (1982) summarized the data on CO_2 enrichment from more than 360 observations on 24 crops in a series of 50 reports. The study showed that doubling atmospheric CO_2 increased agricultural yields by an average of 30%. The high cost of energy to generate CO_2 has discouraged its use in conventional hydroponic systems. However, an enclosed aquaponic system is ideal for generating CO_2 due to the huge amounts that are constantly vented from the culture water.

Luther (1990, 1991A, 1991B, 1991C, 1993) cites a growing body of evidence that healthy plant development relies on a wide range of organic compounds in the root environment. These compounds, generated by complex biological processes involving microbial decomposition of organic matter, include vitamins, auxins, gibberellins, antibiotics, enzymes, coenzymes, amino acids, organic acids, hormones, and other metabolites. These compounds are directly absorbed and assimilated by the plants and stimulate growth, enhance yields, increase vitamin, and mineral content, improve fruit flavor and hinder the development of pathogens. Various fractions of dissolved organic matter, e.g., humic acid, form organo-metalic complexes with Fe, Zn, and Mn, thereby increasing the availability of these micronutrients to plants (Chen and Solvitch, 1988). Luther states that although inorganic nutrients are necessary for plant survival, plants need organic metabolites from the environment to reach full hereditary potential.

Maintaining high DO levels in the culture water is extremely important for optimal plant growth, especially in aquaponic systems with their high organic loads. Hydroponic plants are subject to intense root respiration and they draw large amounts of oxygen from the surrounding water. If DO is deficient, root respiration decreases, resulting in reduced water absorption, decreased nutrient absorption, loss of cell tissue from roots and a reduction in plant growth (De Wit, 1978). Low DO levels correspond with high concentrations of carbon dioxide, conditions that promote the development of plant root pathogens. Chun and Takakura (1993) tested four nutrient-solution DO levels for hydroponic lettuce and found that root respiration, root growth, and transpiration were greatest at saturated DO levels.

Climatic factors also influence hydroponic vegetable production. Production is generally best in regions with maximum intensity and duration of light. Jensen and Collins (1985) reported that growth rates of lettuce plants in an Arizona greenhouse correlated positively with levels of available light up to the highest levels measured, although radiation levels in the Arizona desert are two to three times that of more temperate climates. When 30% shade cloth was used to cover lettuce plants in the UVI system, also in a region of intensive solar radiation, the plants elongated, the leaves twisted around the stem, and production declined. Growth slows substantially in temperate greenhouses during winter due to low solar radiation. Supplemental illumination can improve wintertime production, but it is not generally cost effective.

Water temperature is far more important than air temperature for hydroponic plant production. The best water temperature for most hydroponic crops is around is 20–22°C (68-75 °F). However, water temperature can go as low as the mid-60s for most common garden crops and slightly lower for winter crops such as cabbage, brussel sprouts and broccoli. Maintaining the best water temperature requires heating during the winter in temperate greenhouses and year-round cooling in tropical greenhouses. In addition to evaporative cooling of tropical greenhouses, chillers are often used to cool the nutrient solution. In tropical outdoor systems, complete shading of the fish rearing and filtration components lowers system water temperature. In raft hydroponics, the polystyrene sheets shield water from direct sunlight and maintain temperatures that are several degrees lower than those in open water bodies. Seasonal adjustment in selection of plant crop varieties may be necessary for both temperate and tropical aquaponic production. Plants cultured in outdoor aquaponic systems must be protected from strong winds, especially following transplanting when seedlings are fragile on most vulnerable to damage.

19.10 NUTRIENT DYNAMICS

Collectively dissolved nutrients are measured as total dissolved solids (TDS), expressed as mg/L, or as the capacity of the nutrient solution to conduct an electrical current (EC), expressed as millimhos/cm (mMho/cm). In a hydroponic solution the recommended range for TDS is 1,000 to 1,500 (1.5 to 3.5 mMho/cm). In an aquaponic system considerably lower levels of TDS (200 to 400 mg/L) or EC (0.3 to 0.6 mMho) will produce good results because nutrients are generated continuously. A concern with aquaponic systems is nutrient accumulation. High feeding rates, low water exchange, and insufficient plant growing areas can lead to the rapid buildup of dissolved nutrients to potentially phytotoxic levels. Phytotoxicity is encountered at TDS concentrations above 2,000 mg/L or EC above 3.5 mMho. Since aquaponic systems are characterized by variable environmental conditions such as daily feed input, solids retention, mineralization, water exchange, nutrient input from source water or supplementation, and variable nutrient uptake by different plant species, it is difficult to predict the exact level of TDS or EC and how it is changing. Therefore, the culturist should purchase an inexpensive conductivity meter and periodically measure TDS or EC. If dissolved nutrients are steadily increasing and approaching 2,000 mg/L as TDS or 3.5 mMho as EC, increasing the water exchange rate or reducing the fish stocking rate and feed input will quickly reduce nutrient accumulation. Since these methods either increase costs (i.e., more water consumed) or lower output (i.e., less fish produced), they are not good long-term solutions. Better but more costly solutions involve increased solids removal (i.e., upgrade the solids removal component) or enlarged plant growing areas.

Early work with UVI's experimental systems showed that conductivity measurements of TDS increased steadily as increasing quantities of feed were added to the system (Rakocy et al. 1993). Phytotoxic levels were reached after the addition of approximately 10 kg feed/m^3 of system volume. In an experiment to determine the optimum ratio of daily feed input to leaf lettuce growing area, the concentration of TDS increased by 147.5 g/kg of dry weight of feed at the optimum ratio of 57 g/day/m^2. However, during the first 8 months of operation of an early model of UVI's commercial-scale system, 26.9 kg of feed/m^3 of system volume was applied and the highest conductivity level was only 890 mg/L as TDS. The accumulation rate for TDS was 26 g/kg of dry weight of feed, Table 19.3. Three factors contributed to the lower nutrient-accumulation rate. The actual mean ratio of daily feed input to plant growing area (49.5 g/day/m^2) turned out to be less than the optimum design ratio. Lettuce productivity was greater in the commercial-scale system. Romaine and leaf lettuce plants grew to a size of 250–650 g in 4 weeks (8.9–23.2 g/day) in the commercial-scale system compared to an average Bibb lettuce size of 131 g in three weeks (6.2 g/day) in the experimental system. The average reduction of conductivity on passage through the hydroponic component during the first 8 months was 4.2 mg/L as TDS. Substantial amounts of solids were removed by the filter tanks and consequently less mineralization may have occurred than in the experimental systems.

Table 19.3 Nutrient Accumulation (g/kg Dry Weight Feed) of Conductivity and Major Cations and Anions from Two Experimental Aquaponic Systems and a Commercial-Scale Aquaponic System Using Raft Hydroponics for Lettuce Production

Nutrient	Exp. System 1[a]	Exp. System 2[b]	Commercial System[c]
Conductivity[d]	215.2	147.5	26.2
NO_3-N	35.6	14.9	3.7
PO_4-P	3.0	-	0.2
SO_4-S	1.9	1.8	0.6
K	66.0	-	4.2
Ca	-	7.3	2.3
Mg	1.2	1.8	0.4

[a] Supplementation with K but not Ca. Minor, one-time supplementation with P. From Rakocy et al. 1993

[b] Optimum feed to growing area ratio (57 g/day/m^2) from ratio study (Rakocy et al. 1993). K and Ca supplementation

[c] From the first 8 months of operation of an early model of the commercial-scale system. K and Ca supplementation

[d] As TDS

The major ions that contribute to increased conductivity are nitrate (NO_3^-), phosphate (PO_4^{-2}), sulfate (SO_4^{-2}), K^+, Ca^{+2} and Mg^{+2}. Levels of NO_3^-, PO_4^{-2} and SO_4^{-2} are usually sufficient for good plant growth while levels of K^+ and Ca^{+2} are generally insufficient for maximum plant growth. Potassium is added to the system in the form of potassium hydroxide (KOH) while Ca is added as calcium hydroxide [$Ca(OH)_2$]. In some systems Mg may be limiting. In the UVI commercial-scale system, KOH and $Ca(OH)_2$ are added in equal amounts usually in the range of 500-1,000 g in the UVI system. The bases are added alternately several times weekly to maintain pH near 7.0. Adding basic compounds of K and Ca serves the dual purpose of supplementing essential nutrients and neutralizing acid. Magnesium can be supplemented by using dolomite [$CaMg(CO_3)_2$] as the base to adjust pH. The addition of too much Ca can lead to the precipitation of phosphorous from culture water in the form of dicalcium phosphate [$CaHPO_4$]. All of the macronutrients with the exception of orthophosphate have a strong correlation with feed input (Rakocy et al. 1993).

The accumulation of nitrate ions is a concern with aquaponic systems. The discharge from one experimental system at UVI contained 180 mg/L as NO_3-N (Rakocy, 1994). The installation of the filter tanks in the UVI commercial-scale system provided a mechanism for controlling nitrate levels through the process of denitrification, the reduction of nitrate ions to nitrogen gas by anaerobic bacteria. Large quantities of organic matter accumulate on the orchard netting between cleanings. Denitrification occurs in anaerobic pockets that develop in the sludge. The entire water column moves through the accumulated sludge, which provides good contact between nitrate ions and denitrifying bacteria. The frequency of cleaning the netting regulates the degree of denitrification. When the netting is cleaned frequently, e.g., twice per week, sludge accumulation and denitrification is minimized, which leads to an increase in nitrate concentrations. When the netting is cleaned less frequently, e.g., once per week, sludge accumulation and denitrification are maximized, which leads to a decrease in nitrate levels. Nitrate-nitrogen levels can be regulated within a range of 1 to 100 mg/L or higher. High nitrate concentrations promote the growth of leafy green vegetables while low nitrate concentrations promote fruit development in vegetables such as tomatoes.

Denitrification recovers the alkalinity that is lost in the nitrification process. Sometimes an aquaponic system will go for long periods of time with no change in pH without any need to add bases such as calcium hydroxide or potassium hydroxide. Stable pH in an aquaponic system indicates that too much denitrification is occurring (somewhat counter intuitive). If there is no need to add base, the plants could develop calcium and potassium deficiencies. When pH is stable, the frequency of cleaning the filter tanks should be increased and any anaerobic zones that have been created due to the accumulation of solids in the system should be removed.

In a study using raft hydroponics for lettuce production, Seawright (1995) obtained similar results for macronutrient accumulation with two important exceptions: P accumulated in relation to feed input, but there was no significant relationship between feed input and N. Sodium bicarbonate ($NaHCO_3$) was added for pH control. The addition of Ca bases in the UVI system may have contributed to the precipitation of P from the culture water in the form of calcium phosphate [$Ca_3(PO_4)_2$]. Seawright removed solid waste from the system once per week and therefore denitrification may have been greater than in the UVI system where solid waste is removed at least twice per day from the clarifier and up to twice per week from the filter tanks. Although Seawright did not supplement with K, it accumulated with respect to feed input. However, plants require high levels of K and supplementation is needed in aquaponic systems. Seawright's finding that Ca is negatively correlated with feed input agrees with early work at UVI (Rakocy and Nair, 1987). Some investigators have found that Mg is limiting (Pierce, 1980; Head, 1984; Zweig, 1986). Magnesium can be supplemented by using dolomite [$CaMg(CO_3)_2$] as the base to adjust pH.

Sodium bicarbonate ($NaHCO_3$) should **never** be added to an aquaponic system for pH control. The accumulation of Na is a concern in aquaponic systems because high Na levels in the presence of chloride are toxic to plants (Resh, 1995). The maximum Na concentration in hydroponic nutrient solutions should not exceed 50 mg/L (Verwer and Wellman, 1980). Higher Na levels will interfere with the uptake of K and Ca (Douglas, 1985). In lettuce, reduced Ca uptake leads to tip burn, resulting in an unmarketable plant (Collier and Tibbitts, 1982). In UVI's systems, tip burn has occurred during the warmer months. Soluble salt (NaCl) levels in fish feed are relatively high. In the initial commercial-scale system, Na reached 51.0 mg/L in the 6th month and then declined to 37.8 mg/L in the 8th month, possibly due to rainfall dilution. The Na accumulation rate through the 6th month was 2.56 g/kg of dry weight feed. If Na exceeds 50 mg/L and the plants appear to be affected, a partial water exchange (dilution) may be necessary. Rainwater is used in UVI's systems because the groundwater of semiarid islands generally contains too much salt for aquaponics.

With the exception of Zn^{+2}, the micronutrients Fe^{+2}, Mn^{+2}, Cu^{+2}, B^{+3} and Mo^{+6} do not accumulate significantly in aquaponic systems with respect to cumulative feed input, Table 19.4 (Rakocy et al. 1993). The Fe^{+2} derived from fish feed is insufficient for hydroponic vegetable production and must be supplemented (Lewis et al. 1980; MacKay and Van Toever, 1981; Zweig, 1986). Chelated Fe^{+2} should be applied at a rate to achieve a Fe^{+2} concentration of 2.0 mg/L. Chelated Fe^{+2} has an organic compound attached to the metal ion to prevent it from precipitating out of solution and making it unavailable for plant nutrition. The best chelate is Fe-DTPA because it remains soluble at pH 7.0. Fe-EDTA is commonly used in the hydroponics industry, but it is less stable at pH 7.0 and needs to be replenished frequently. Fe^{+2} may also be applied in a foliar spray from which Fe^{+2} is absorbed directly through plant leaves. A comparison of Mn^{+2}, B^{+3} and Mo^{+6} levels with standard nutrient formulations for lettuce shows that their concentrations in aquaponic systems are several times lower than their initial levels in hydroponic formulations. Deficiency symptoms for Mn^{+2}, B^{+3} and Mo^{+6} are not detected in aquaponic systems, and so their concentrations appear to be adequate for normal plant growth. Concentrations of Cu^{+2} are similar in aquaponic systems and hydroponic formulations while Zn^{+2} accumulates in aquaponic systems to levels that are four to sixteen times higher than initial levels in hydroponic formulations. Nevertheless, Zn^{+2} concentrations usually remain within the upper limit for fish safety which is 1 mg/L in hydroponic solutions (Douglas, 1985).

Table 19.4 Mean Concentration (mg/L) of Micronutrients from Two Experimental Aquaponic Systems and a Commercial-Scale Aquaponic System Using Raft Hydroponics for Lettuce Production

	Micronutrient					
System	Fe	Mn	Cu	Zn	B	Mo
Exp. 1[a]	1.79	0.04	0.12	0.78	0.16	-
Exp. 2[b]	0.48	0.13	0.07	0.68	-	-
Commercial[c]	0.57	0.05	0.05	0.44	0.06	0.006
HNF[d]	5.0	0.5	0.03	0.05	0.5	0.02
HNF[e]	5.0	0.5	0.1	0.1	0.5	0.05

[a] From Rakocy et al. 1993.

[b] Optimum feed to growing area ratio (57 g/day/m^2) from ratio study (Rakocy et al. 1993).

[c] From the first 8 months of operation of a commercial-scale system.

[d] Hydroponic nutrient formulation for lettuce grown in the tropics (Resh, 1995).

[e] Hydroponic nutrient formulation for lettuce grown in Florida and California (Resh, 1995).

Seawright (1995) worked on the development of a "designer diet" for aquaponic systems that would generate nutrients in proportion to their requirements for hydroponic plant nutrition, thereby creating stable and balanced nutrient concentrations over prolonged periods. Data on the change in nutrient concentrations in relation to dietary nutrient input was collected for the co-culture of *O. niloticus* and romaine lettuce (Jericho). This data was used to develop a mass balance model theoretically capable of predicting the nutrient inclusion rates required in fish diets to maintain stable dissolved nutrient concentrations in aquaponic systems. The model was validated by applying a specially-formulated "designer diet" to an aquaponic system and maintaining near-equilibrium concentrations of Ca, K, Mg, N and P, suitable concentrations of Mn and Cu and acceptable accumulation rates of Na and Zn. The results showed that Cu, Fe, and Mn are not good candidates for dietary manipulation because of low bioavailability. Phosphorus is a good candidate at sub-neutral pH, but it precipitates from solution at basic pH. Sulfur, B and Mo were not tested. The fish grew well on the diet, but the development of bacterial diseases indicated that elevated nutrient levels may have lowered their disease resistance.

19.11 VEGETABLE SELECTION

Many types of vegetables have been grown in aquaponic systems, Tables 19.5-19.7. However, the goal is to select a vegetable for culture that will generate the highest level of income per unit area per unit time. Using this criterion, culinary herbs are the best choice. They grow very rapidly and command high market prices. The income from herbs such as basil, cilantro, chives, parsley, portulaca, and mint are many times higher than that from fruiting crops such as tomatoes, cucumbers, eggplant, and okra. For example, in experiments in UVI's commercial-scale system, basil production was 11,000 lbs annually at a value of $110,000 compared to annual production of 6,400 lbs of okra at a value of $6,400.

Table 19.5 Varieties and Yields of Cucumbers Evaluated in Aquaponic Systems[a]. Environmental Codes. TEMP=Temperate Zone, TROP=Tropical Zone, O=Outside, GH=Greenhouse

Variety	Yield (kg/plant)	Environment	Reference
Triumph	4.1	TEMP/O	Lewis et al. 1980
Patio Pik	1.6	TEMP/O	Lewis et al. 1980
Corona (Stokes)	28.6[b]	TEMP/GH	Burgoon and Baum, 1984
Bruinsma Vetomil	8.2[b]	TEMP/GH	Burgoon and Baum, 1984
Superator	4.1	TEMP/GH	Head, 1984
Sprint 4405	0.7	TEMP/GH	Wren, 1984
Burpee Hybrid II	7.3[b]	TEMP/GH	McMurtry, 1990

[a] From Rakocy and Hargreaves, 1993

[b] kg/m^2

Fruiting crops also require longer culture periods (90 days or more) and are subject to more pest problems and diseases. Lettuce is another good crop for aquaponic systems because it can be produced in a short period (3 to 4 weeks in the system), and, as a consequence, pest pressure is relatively low. Unlike fruiting crops, a high proportion of the harvested biomass is edible. Other suitable crops include Swiss chard, pak choi, Chinese cabbage, collard and watercress. The cultivation of flowers has potential in aquaponic systems. Good results have been obtained with marigold and zinnia in UVI's aquaponic system. Traditional medicinal plants and plants used for the extraction of modern pharmaceuticals have not been cultivated in aquaponic systems, but there may be potential in growing some of these plants.

Table 19.6 Varieties and Yields of Leafy Greens (Lettuce, Pak Choi, Chinese Cabbage, Spinach) Evaluated in Aquaponic Systems[a]. Environment Codes. TEMP=Temperate Zone, TROP=Tropical Zone, O=Outside, GH=Greenhouse

Variety	Yield (g/plant)	Environment	Reference
Ostinata	162	TEMP/GH	Baum, 1981
Reskia	236	TEMP/GH	Burgoon and Baum, 1984
All Year Round	236	TEMP/GH	Burgoon and Baum, 1984
Karma	98	TEMP/GH	Burgoon and Baum, 1984
Ravel	45–50	TEMP/GH	Burgoon and Baum, 1984
Salina	44	TEMP/GH	Burgoon and Baum, 1984
El Captain	43	TEMP/GH	Burgoon and Baum, 1984
Bruinsma Columbus	0	TEMP/GH	Burgoon and Baum, 1984
Salad Bowl	-	TEMP/GH	Head, 1984
Pak Choi	-	TEMP/GH	Head, 1984
Winter Bloomsdale (Spinach)	-	TEMP/GH	Head, 1984
Buttercrunch	-	TEMP/GH	Zweig, 1986
Buttercrunch	193	TROP/O	Rakocy, 1989B
Summer Bibb	180	TROP/O	Rakocy, 1989B
Le Choi	508	TROP/O	Rakocy, 1989B
Pak Choi	422	TROP/O	Rakocy, 1989B
50-Day Hybrid (Chinese Cabbage)	638	TROP/O	Rakocy, 1989B
Tropical Delight (Chinese Cabbage)	589	TROP/O	Rakocy, 1989B
Summer Bibb	107–116	TEMP/GH	Parker et al. 1990
Sierra	182–340	TROP/O	Rakocy et al. 1997
Nevada	149–360	TROP/O	Rakocy et al. 1997
Jerhico	267–344	TROP/O	Rakocy et al. 1997
Parris Island	181–446	TROP/O	Rakocy et al. 1997

[a] From Rakocy and Hargreaves (1993) and some more recent data.

Table 19.7 Varieties and Yields of Tomatoes Evaluated in Aquaponic Systems[a]. Environmental Codes: TEMP=Temperate Zone, TROP=Tropical Zone, O=Outside, GH=Greenhouse

Variety	Yield (kg/plant)	Environment	Reference
Tropic	0	TEMP/GH	Landesman, 1977
Floradel	5.4	TEMP/O	Lewis et al. 1978
Campbells 1327	4.6	TEMP/O	Lewis et al. 1978
San Marzano	4.6	TEMP/O	Lewis et al. 1978
Sweet 100	6.2	TEMP/O	Lewis et al. 1980
Better Boy	4.5	TEMP/O	Lewis et al. 1980
Rampo	3.9	TEMP/O	Lewis et al. 1980
Campbells 1327	2.3	TEMP/O	Lewis et al. 1980
Sweet 100	1.9	TEMP/GH	Baum, 1981
Spring Set	1.6	TEMP/GH	Baum, 1981
Sweet 100	0	TEMP/GH	MacKay et al. 1981
Jumbo	0	TEMP/GH	MacKay et al. 1981
Michigan Ohio Forcing	0	TEMP/GH	MacKay et al. 1981
Burpee Big Boy	0.2	TEMP/O	Markin, 1982
Floradel	8.9, 9.1	TEMP/O	Sutton and Lewis, 1982
Korala #127	6.8[b]	TEMP/GH	Burgoon and Baum, 1984
Vendor	4.1	TEMP/GH	Head, 1984
Tropic	0.5, 3.2	TROP/O	Watten and Busch, 1984
Homestead	2.7	TROP/O	Watten and Busch, 1984
Red Cherry	1.5	TROP/O	Watten and Busch, 1984
Prime Beefsteak	1.4	TROP/O	Watten and Busch, 1984
Vendor	0	TROP/O	Nair et al. 1985
Tropic	0	TROP/O	Nair et al. 1985
Jumbo	0	TROP/O	Nair et al. 1985
Perfecta	0	TROP/O	Nair et al. 1985
Laura	2.3–3.4	TEMP/GH	McMurtry, 1989
Kewalo	2.5–5.0	TEMP/GH	McMurtry, 1989
Sunny	10.1	TROP/O	Rakocy, 1989
Floradade	9.0	TROP/O	Rakocy, 1989
Vendor	3.7	TROP/O	Rakocy, 1989
Cherry Challenger	2.9	TROP/O	Rakocy, 1989
Champion	4.6[b]	TEMP/GH	McMurtry et al. 1990

[a] From Rakocy and Hargreaves, 1993

[b] kg/m^2

19.12 CROP PRODUCTION SYSTEMS

There are three strategies for producing vegetable crops in the hydroponic component. These are staggered cropping, batch cropping, and intercropping. A staggered crop production system is one in which groups of plants in different stages of growth are cultivated simultaneously in the hydroponic subsystem. This production system allows regular harvest of produce and relatively constant uptake of nutrients from the culture water. This system is most effectively implemented where crops can be grown continuously, as in the tropics, subtropics, or temperate greenhouses with environmental control (Zweig, 1986). At UVI, the production of leaf lettuce is staggered so that a crop can be harvested weekly on the same day, which facilitates marketing arrangements. Bibb lettuce reaches market size in three weeks from transplanting. Therefore, three growth stages of Bibb lettuce are cultivated simultaneously, and one third of the crop is harvested weekly. Red leaf lettuce and green leaf lettuce require four weeks to reach marketable size. The cultivation of four growth stages of these lettuce varieties allows one fourth of the crop to be harvested weekly. In three years of continuous operation of UVI's commercial-scale system, 148 crops of lettuce were harvested, which demonstrates the system's sustainability. Leafy green vegetables, herbs and other crops with short production periods are well suited for continuous, staggered production systems.

A batch cropping system is more appropriate for crops that are grown seasonally or have long growing periods (>3 months) such as tomatoes and cucumbers. Various intercropping systems can be used in conjunction with batch cropping. For example, if lettuce is intercropped with tomatoes and cucumbers, one crop of lettuce can be harvested before tomato plant canopy development limits light availability (Resh, 1995).

19.13 PEST AND DISEASE CONTROL

A number of plant pest and disease problems have been encountered in aquaponic systems. Pests observed on tomatoes include spider mite (Landesman, 1977; Nair et al. 1985), russet mite (Rakocy, unpublished data), hornworm (Lewis et al. 1978; Sutton and Lewis, 1982; Nair et al. 1985), western locust (Sutton and Lewis, 1982), fall armyworm, pinworm, aphid, and leaf minor (Nair et al. 1985). Diseases observed on tomatoes include blight (Lewis et al. 1980) and bacteria wilt (McMurtry et al. 1990). In UVI's systems, lettuce is affected by fall armyworm, corn earworm, and two species of pathogenic root fungus (*Pythium dissotocum* and *P. myriotylum*). The root diseases that plague conventional hydroponics may be a threat to aquaponics. Four viral, two bacterial and 20 fungal pathogens have been associated with root diseases in hydroponically grown vegetables (Stanghellini and Rasmussen, 1994). Most of the destructive root diseases in hydroponics have been attributed to the fungal genera *Pythium, Phytophthora, Plasmopara, Olpidium* and *Fusarium*.

Pesticides should not be used to control insects on aquaponic plant crops. Even pesticides that are registered would pose a threat to the fish and would not be permitted in a fish culture system. 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. Non-chemical methods of plant pest and disease control are required such as biological control (resistant cultivars, predators, antagonistic organisms, pathogens), physical barriers, traps, treatment of the nutrient solution (filtration, UV sterilization), manipulation of the physical environment and other specialized cultural practices. Opportunities for biological control methods are greater in enclosed greenhouse environments than exterior installations. McMurtry (1989) used *Encarsia formosa* and *Chrysopa carnea* to control greenhouse white fly (*Trialeurodes vaporariorum*) and *Hippodamia convergens* to control potato aphid (*Macrosiphum euphorbiac*). In UVI's systems, caterpillars are effectively controlled by twice-a-week spraying with *Bacillus thuringiensis*, a bacterial pathogen that is specific to caterpillars. The fungal root pathogens that are encountered in summer dissipate in winter in response to lower water temperature and manipulation of suspended solids levels. An outbreak of *Pythium* coincided with a period during which the efficiency of suspended solids removal was dramatically increased.

Prohibition on the use of pesticides makes crop production in aquaponic systems more difficult. However, this restriction assures that crops from aquaponic systems will be raised in an environmentally sound manner, free of pesticide residues. A major advantage of aquaponic systems 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, some of which may be antagonistic to plant root pathogens.

19.14 APPROACHES TO SYSTEM DESIGN

Several approaches can be used to design an aquaponic system. The simplest approach is to duplicate a standard system or scale a standard system down or up, keeping the components proportional. Changing aspects of a standard system is not recommended because changes often lead to unintended consequences. However, the design process often starts with a production goal for either fish or plants. In those cases there are some guidelines which can be followed.

USE A STANDARD SYSTEM THAT IS ALREADY DESIGNED.

The easiest approach is to use a standard system design that has been tested and is in common use with a good track record. It is early in the development of aquaponics, but standard designs will emerge. The UVI system has been well documented and is being studied or used commercially in several locations, but there are other systems with potential. Standard designs will include specifications for layout, tank sizes, pipe sizes, pipe placement, pumping rates, aeration rates, infrastructure needs, etc. There will be operation manuals and projected production levels and budgets for various crops. Using a standard design will reduce risk.

DESIGN FOR AVAILABLE SPACE.

If a limited amount of space is available such as in an existing greenhouse, then that space will define the size of the aquaponic system. The easiest approach is to take a standard design and scale it down. If a scaled-down tank or pipe size falls between commercially available sizes, it is best to select the larger size. However, the water flow rate should equal the scaled-down rate for best results. The desired flow rate can be obtained by buying a higher capacity pump and installing a bypass line and valve, which circulates a portion of the flow back to the sump and allows the desired flow rate to go from the pump to the next stage of the system. If more space is available than the standard design requires, then the system could be scaled up within limitations or more than one scaled-down system could be installed.

DESIGN FOR FISH PRODUCTION

If the primary objective is to produce a certain amount of fish annually, the first step in the design process will be to determine the number of systems required, the number of rearing tanks required per system and the optimum rearing tank size. The number of harvests will have to be calculated based on the length of the culture period. Assume that the final density is 60 kg/m^3 (0.5 lbs/gallon) for an aerated system. Take the annual production per system and multiply it by the estimated feed conversion ratio (the kilograms of feed required to produce one kilogram of fish). Convert the pounds of annual feed consumption to grams (454 g/lb) and divide by 365 days to obtain the average daily feeding rate. Divide the average daily feeding rate by the desired feeding rate ratio, which ranges from 60 to 100 g/m^2/day for raft culture, to determine the required plant production area. For other systems such as NFT, the feeding rate ratio should be decreased in proportion to the water volume reduction of the system as discussed in the component ratio section. Use a ratio near the low end of the range for small plants such as Bibb lettuce and a ratio near the high end of the range for larger plants such as Chinese cabbage or romaine lettuce. The solids removal component, water pump, and blowers should be sized accordingly

Sample problem:

This example illustrates only the main calculations, which are simplified (e.g., mortality is not considered) for the sake of clarity. Assume that you have a market for 227 kg (500 lbs) of live tilapia per week in your city and that you want to raise lettuce with the tilapia because there is a good market for green leaf lettuce in your area. The key questions are: How many UVI aquaponic systems do you need to harvest 227 kg (500 lbs) of tilapia weekly. How large should the rearing tanks be? What is the appropriate number and size of hydroponic tanks? What would the weekly lettuce harvest be?

1) Each UVI system contains four fish rearing tanks (Fig. 9.3). Fish production is staggered so that one fish tank is harvested every 6 weeks. The total growing period

per tank is 24 weeks. If 227 kg (500 lbs) of fish are required weekly, six production systems (24 fish rearing tanks) are needed.

2) Aquaponic systems are designed to achieve a final density of 60 kg/m^3 (0.5 lb/gallon). Therefore the water volume of the rearing tanks is 3.79 m^3 (1,000 gallons).

3) In 52 weeks, there will be 8.7 harvests (52/6 = 8.7) per system. Annual production for the system therefore is 2.0 mt (4,350 lbs) i.e. 227 kg per harvest x 8.7 harvests.

4) The usual feed conversion ratio is 1.7. Therefore annual feed input to the system is 3,360 kg (7,395 lbs) i.e. 2.0 mt x 1.7 = 3,360 kg.

5) The average daily feed input is 9.22 kg (20.3 lbs) i.e. 3,360 kg per year/365 days = 9.22 kg.

6) The average daily feed input converted to grams is 9,216 g i.e. 9.22 kg x 1000 g/kg = 9,216 g).

7) The optimum feeding rate ratio for raft aquaponics ranges from 60 – 100 g/m^2/day. Select 80 g/m^2/day as the design ratio. Therefore, the required lettuce growing area is 115.2 m^2 (9216 g/day divided by 80 g/m^2/day =115.2 m^2).

8) The growing area in square feet is 1,240 (115.2 m^2 x 10.76 ft^2/m^2 = 1,240 ft^2).

9) Select a hydroponic tank width of 1.22 m (4 ft). Therefore, the total length of the hydroponic tanks is 94.5 m (310 ft) i.e. 115.2 m^2 /1.22 m = 94.5 m).

10) Select four hydroponic tanks. They are 23.6 m (77.5 ft) long (94.5/4 = 23.6 m). They are rounded up to 24.4 m (80 ft) in length, which is a practical length for a standard greenhouse and allows the use of ten 2.36 m (8 ft) sheets of polystyrene per hydroponic tank.

11) Green leaf lettuce produces good results with plant spacing of 48 plants per sheet (16/m^2). The plants require a 4-week growth period. With staggered production, one hydroponic tank is harvested weekly. Each hydroponic tank with 10 polystyrene sheets produces 480 plants. With six aquaponic production systems 2,880 plants are harvested weekly.

In summary, weekly production of 227 kg (500 lbs) of tilapia results in the production of 2,880 green leaf lettuce plants (120 cases). Six aquaponic systems each with four 3.78 m^3 (1,000-gallon) rearing tanks (water volume) are required. Each system will have four raft hydroponic tanks that are 24.4 m long and 1.22 m wide (80 ft long by 4 ft wide).

DESIGN FOR PLANT PRODUCTION

If the primary objective is to produce a certain quantity of plant crops annually, the first step in the design process will be to determine the area required for plant production. The area needed will be based on plant spacing, length of the production cycle, number of crops per year or growing season, and the estimated yield per unit area and per crop cycle. Select the desired feeding rate ratio and multiple by the total area to obtain the average daily feeding rate that is required. Multiply the average daily feeding rate by 365 days to determine annual feed consumption. Estimate the feed conversion ratio (FCR) for the fish species that will be cultured. Convert FCR to feed conversion efficiency. For example, if FCR is 1.7:1, then the feed conversion efficiency is 1 divided by 1.7 or 0.59. Multiply the annual feed consumption by the feed conversion efficiency to determine net annual fish yield. Estimate the average fish weight at harvest and subtract the anticipated average fingerling weight at stocking. Divide this number into the net annual yield to determine the total number of fish produced annually. Multiply the total number of fish produced annually by the estimated harvest weight to determine total annual fish production. Divide total annual fish production by the number of production cycles per year. Take this number and divide by 60 kg/m^3 (0.5 lb/gallon) to determine the total volume that must be devoted to fish production. The required water volume can be partitioned among multiple systems and multiple tanks per system with the goal of creating a practical system size and tank array. Divide the desired individual fish weight at harvest by 60 kg/m^3 (0.5 lb/gallon) to determine the volume of water required per fish. Divide the volume of water required per fish into the water volume of the rearing tank to determine the fish stocking rate. Increase this number by 5 to 10% to allow for expected mortality during the production cycle.
The solids removal component, water pump, and blowers should be sized accordingly.

Sample problem:

Assume that there is a market for 1,000 Bibb lettuce plants weekly in your city. These plants will be sold individually in clear plastic clamshell containers. A portion of the root mass will be left intact to extend self life. Bibb lettuce transplants are cultured in a UVI raft system for 3 weeks at a density of 29.3 plants/m^2. Assume that tilapia will be grown in this system. The key questions are: How large should the plant growing area be? What will be the annual production of tilapia? How large should the fish rearing tanks be?

1) Bibb lettuce production will be staggered so that 1,000 plants can be harvested weekly. Therefore, with a 3-week growing period, the system must accommodate the culture of 3,000 plants.

2) At a density of 29.3 plants/m^2, the total plant growing area will be 102.3 m^2 (3000 plants divided 29.3/m^2 = 102.3 m^2). This area is equal to 1,100 square feet; i.e. 102.3 m^2 x 10.76 ft^2/m^2 = 1,100 ft^2.

3) Select a hydroponic tank width of 2.44 m (8 ft). Therefore, the total hydroponic tank length will be 41.9 m (137.5 ft); i.e.102.3 m^2 /2.44 m = 41.9 m.

4) Two raft hydroponic tanks are required for the UVI system. Therefore the minimum length of each hydroponic tank will be 20.95 m (68.75 ft) i.e. 41.9 m /2 = 20.95 m). Since polystyrene sheets come in 2.44 (8 ft) lengths, the total number of sheets per hydroponic tank will be 8.59 sheets (20.95 m divided by 2.44 m/sheet = 8.59 sheets). To avoid wasting material, round up to nine sheets. Therefore, the hydroponic tanks will be 21.94 m (72 ft) long; i.e.9 sheets x 2.44 m per sheet = 21.94 m).

5) The total plant growing area will then be 107 m^2 (1,152 ft^2); i.e. 21.94 m x 2.44 m per tank x 2 tanks = 107 m^2.

6) At planting density of 29.3 plants/m^2, a total of 3,135 plants will be cultured in the system. The extra plants will provide a safety margin against mortality and plants that do not meet marketing standards.

7) Assume that a feeding ràte ration of 60 g/m^2/day provides sufficient nutrients for good plant growth. Therefore, daily feed input to the system will be 6,420 g (14.1 lbs); i.e. 60 g/m^2/day x 107 m^2 = 6,420 g.

8) Annual feed input to the system will be 2,340 kg (5,146 lbs) i.e. 6.42 kg/day x 365 days = 2,340 kg)

9) Assume the feeding conversion ratio is 1.7. Therefore, the feed conversion efficiency is 0.59; i.e.1 kg of gain divided by 1.7 kg of feed = 0.59.

10) The total annual fish production gain will be 1,380 kg (3,036 lbs); i.e. 2,340 kg x 0.59 feed conversion efficiency = 1,380 kg.

11) Assume that the desired harvest weight of the fish will be 500 g (1.1 lbs) and that 50 g (0.11 lb) fingerlings will be stocked. Therefore, individual fish will gain 450 g (500 g harvest weight – 50 g stocking weight = 450 g). The weight gain per fish will be approximately 454 g (1 lb).

12) The total number of fish harvested will be 3,036; i.e. 1,380 kg of total gain divided by 0.454 kg of gain per fish = 3,036 fish.

13) Total annual production will be 1,518 kg (3,340 lbs) (3,036 fish x 0.50 kg/fish = 1,518 kg) when the initial stocking weight is considered.

14) If there are four fish rearing tanks and one tank is harvested every 6 weeks, there will be 8.7 harvests per year (52 weeks divided by 6 weeks = 8.7).

15) Each harvest will be 175 kg (384 lbs); i.e. 1,518 kg per year divided by 8.7 harvests per year = 175 kg/harvest).

16) Final harvest density should not exceed 60 kg/m^3 (0.5 lb/gallon). Therefore the water volume of each rearing tank should be 2.92 m^3 (768 gallons). The tank should be larger to provide a 2.4 cm (6 in) freeboard (space between the top edge of the tank and the water levels. A standard tank size of 3.8 m^3 (1,000 gallons) is recommended.

17) Assuming a mortality of 10% during the growth cycle, the tanks should be stocked with 385 juveniles each time ((175 kg / 0.5 kg/fish) x 1.1))

In summary, two hydroponic tanks each 21.94 m (72 ft) long by 2.44 m (8 ft) wide will be required to produce 1,000 Bibb lettuce plants per week. Four fish rearing tanks with a water volume of 3.8 m^3 (1,000 gallons) per tank will be required. Approximately 175 kg (384 lbs); of tilapia will be harvested every 6 weeks, and annual tilapia production will be 1,380 kg (3,036 lbs).

19.15 ECONOMICS

The economics of aquaponic systems depend on specific site conditions and markets. It would be inaccurate to make sweeping generalizations because material costs, construction costs, operating costs and market prices vary by location. For example, an outdoor tropical system would be less expensive to construct and operate than a controlled-environment greenhouse system in a cold temperate climate. Nevertheless the economic potential of aquaponic systems looks promising based on studies with the UVI system in the Virgin Islands and in Alberta, Canada.

The UVI system is capable of producing approximately 5,000 kg (11,000 lbs) of tilapia and 1,400 cases of lettuce or 5,000 kg (11,000 lbs) basil annually based on studies in the Virgin Islands. Enterprise budgets for tilapia production combined with either lettuce or basil have been developed. The U.S. Virgin Islands represent a small niche market with very high prices for fresh tilapia, lettuce, and basil as more than 95% of vegetables supplies and nearly 80% of fish supplies are imported. The budgets were prepared to show revenues, costs, and profits from six production units. A commercial enterprise consisting of six production units is recommended because one fish-rearing tank (out of 24) could be harvested weekly, thereby providing a continuous supply of fish for market development.

The enterprise budget for tilapia and lettuce show that the annual return to risk and management (profit) for six production units is US$185,248. The sale prices for fish $1.14/kg ($2.50/lb) and lettuce $20.00/case have been established through many years of market research at UVI. Most of the lettuce consumed in the Virgin Islands is imported from California. It is transported by truck across the United States to East Coast ports and then shipped by ocean freighters to Caribbean islands. Local production capitalizes on the high price that transportation adds to imported lettuce. Local production surpasses the quality of imported lettuce due to its freshness. Although this enterprise budget is unique to the U.S. Virgin Islands, it indicates that aquaponic systems can be profitable in certain niche markets.

The enterprise budget for tilapia and basil shows that the annual returns to risk and management for six production units are US\$693,726. Aquaponic systems are very productive in producing culinary herbs such as basil. A conservative sales price for fresh basil with stems in the U.S. Virgin Islands is \$4.55/kg (\$10.00/lb). However, this enterprise budget is not realistic in terms of market demand. The population (108,000 people) of the U.S. Virgin Islands cannot absorb 30,000 kg (66,000 lbs) of fresh basil annually, although there are opportunities for provisioning ships and export to neighboring islands. A more realistic approach for a six-unit operation is to devote a portion of the growing area to basil to meet local demand while growing other crops in the remainder of the system.

The breakeven price for the aquaponic production of tilapia in the Virgin Islands is \$0.67/kg (\$1.47/lb) compared to a sales price of \$1.14/kg (\$2.50/lb). The breakeven prices are \$6.15/case for lettuce (sales price = \$20.00/case) and \$0.34/kg (\$0.75/lb) for basil (sales price \$4.55/kg). The breakeven prices for tilapia and lettuce do not compare favorably to commodity prices. However, the cost of construction materials, electricity, water, labor, and land are very high in the U.S. Virgin Islands. Breakeven prices for tilapia and lettuce could be considerably lower in other locations. The breakeven price for basil compares favorably to commodity prices because fresh basil has a short shelf life and cannot be shipped great distances.

A UVI aquaponics system in an environmentally-controlled greenhouse at the Crops Diversification Center South in Alberta, Canada was evaluated for the production of tilapia and a number of plant crops. The crops were cultured for one production cycle and their yields were extrapolated to annual production levels. Based on prices at the Calgary wholesale market, annual gross revenue was determined for each crop per unit area and per system with a plant growing area of 250 m^2 (2,690 ft^2) (Table 19.8).

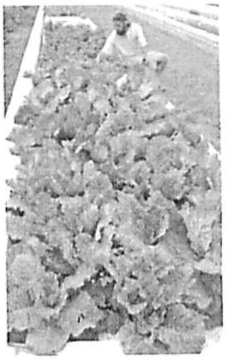
Annual production levels based on extrapolated data from short production cycles are subject to variation. Similarly, wholesale prices will fluctuate during the year based on supply and demand. Nevertheless the data indicates that culinary herbs in general can obtain a gross income more than 20 times greater than that of fruiting crops such as tomatoes and cucumbers. It appears that just one production unit could provide a livelihood for a small producer. However, this data does not show capital, operating, and marketing costs, which will be considerable. Furthermore, the quantity of herbs produced could flood the market and depress prices. Competition from current market suppliers will also lead to price reductions.

Table 19.8 Preliminary Production and Economic Data from the UVI Aquaponic System at the Crop Diversification Center South, Alberta, Canada.[1] (Data courtesy of Dr. Nick Savidov)

Crop	Annual Production		Wholesale Price		Total Value	
	lb/ft^2	tons/2690 ft^2	Unit	$	$/ft^2	$/2690 ft^2
Tomatoes	6.0	8.1	15 lb	17.28	6.90	18,542
Cucumbers	12.4	16.7	2.2 lb	1.58	8.90	23,946
Egg Plant	2.3	3.1	11 lb	25.78	5.33	14,362
Genovese Basil	6.2	8.2	3 oz	5.59	186.64	502,044
Lemon Basil	2.7	3.6	3 oz	6.31	90.79	244,222
Osmin Basil	1.4	1.9	3 oz	7.03	53.23	143,208
Cilantro	3.8	5.1	3 oz	7.74	158.35	425,959
Parsley	4.7	6.3	3 oz	8.46	213.81	575,162
Portulaca	3.5	4.7	3 oz	9.17	174.20	468,618

[1] Ecomonic data based on Calgary wholesale market prices for the week ending July 4, 2003.

19.16 PROSPECTS FOR THE FUTURE



Aquaponics is still in its infancy is becoming very popular in recent years and is being practiced mainly at the hobby and backyard levels. It is estimated that there are 1,500 aquaponic systems in the U.S. and many times this level in Australia. However, the number of commercial operations is still relatively small in the U.S. Hydroponic growers generally do not consider aquaculture as a nutrient source for their operations. Aquaculturists, on the other hand, frequently mention the possibility of incorporating hydroponics into their closed recirculating systems to mitigate waste discharge and earn extra income. Data from successful, large-scale trials is needed to attract investor capital and spur commercial development.

Although the design principles of aquaponic systems and the choice of hydroponic components and fish and plant combinations may seem challenging, aquaponic systems are quite simple to operate when fish are stocked at a rate that provides a good feeding rate ratio for plant production. Aquaponic systems are easier to operate than hydroponic systems or recirculating fish production systems because less monitoring is required and there is generally a wider safety margin for ensuring good water quality. Small aquaponic systems can provide an excellent hobby.

Systems can be as small as an aquarium with a tray of plants covering the aquarium top. Large commercial operations comprised of many production units and occupying several acres are certainly possible if markets can absorb the output. The educational potential of aquaponic systems is already being realized in hundreds of schools where students learn a wide range of subjects that are demonstrated through the construction and operation of aquaponic systems. Regardless of scale or purpose, the culture of fish and plants through aquaponics is a gratifying endeavor that provides food.

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