Aquaponic (Integrating Fish and Plant Culture) Systems

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Abstract: Aquaponic is the combined culture of fish and plants in recirculation systems, has become increasingly popular. Nutrients, which are excreted directly by the fish or generated by the microbial breakdown of organic wastes, are absorbed by plants cultured hydroponically (without soil). Fish feed provides most of the nutrients required for plant growth. As the aquaculture effluent flows through the hydroponic component of the recirculation system, fish waste metabolites are removed by nitrification and direct uptake by the plants, thereby treating the water, which flows back to the fish-rearing component for reuse. Aquaponic has several advantages over other recirculation aquaculture systems and hydroponic systems that use inorganic nutrient solutions. The hydroponic component serves as a biofilter, and therefore a separate biofilter is not needed as in other recirculating systems. Aquaponic systems have the only biofilter that generates income, which is obtained from the sale of hydroponic produce such as vegetables, herbs and flowers. In the UVI system, which employs raft hydroponics, only calcium, potassium and iron are supplemented. The nutrients provided by the fish would normally be discharged and could contribute to pollution. Removal of nutrients by plants prolongs water use and minimizes discharge. Aquaponic systems require less water quality monitoring than individual recirculation systems for fish or hydroponic plant production. Aquaponic increases profit potential due to free nutrients for plants, lower water requirements, elimination of a separate biofilter, less water quality monitoring and shared costs for operation and infrastructure.

Keywords: Aquaponic, Aquaculture, Agriculture

1. Introduction

Aquaponic, also known as the integration of hydroponics with aquaculture, is gaining increased attention as a bio-integrated food production system. In aquaponics, nutrient-rich effluent from fish tanks is used to fertigate hydroponic production beds. This is good for the fish because plant roots and rhizobacteria remove nutrients from the water. These nutrients generated from fish manure, algae, and decomposing fish feed are contaminants that would otherwise build up to toxic levels in the fish tanks, but instead serve as liquid fertilizer to hydroponically grown plants. In turn, the hydroponic beds function as a biofilter stripping off ammonia, nitrates, nitrites, and phosphorus so the freshly cleansed water can then be recirculated back into the fish tanks. The nitrifying bacteria living in the gravel and plant roots play a critical role in nutrient cycling.

In hydroponics applications, the nutrient solution needs to be prepared measured, mixed, and then added to the reservoir. In aquaponic, there's no mixing fertilizer involved, making it a great way for beginners to cultivate plants. Only the fish needs to be fed. In closed recirculation systems with very little daily water exchange (less than 2%); dissolved nutrients accumulate in concentrations similar to those in hydroponic nutrient solutions. Dissolved nitrogen, in particular, can occur at very high levels in recirculation systems. Fish excrete waste nitrogen, in the form of ammonia, directly into the water through their gills. 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 growing higher plants such as fruiting vegetables.

Aquaponic systems offer several benefits. Dissolved waste nutrients are recovered by the plants, reducing discharge to the environment and extending water. Minimizing water exchange reduces the costs of operating aquaponic systems in arid climates and heated greenhouses where water or heated water is a significant expense. Having a secondary plant crop that receives most of its required nutrients at no cost improves a system’s profit potential. The plants remove nutrients from the culture water and eliminate the need for separate and expensive biofilters. Aquaponic systems require substantially less water quality monitoring than separate hydroponic or recirculation aquaculture systems. Savings are also realized by sharing operational and infrastructural costs such as pumps, reservoirs, heaters and alarm systems. In addition, the intensive, integrated production of fish and plants requires less land than ponds and gardens. Aquaponic systems do require a large capital investment, moderate energy inputs and skilled management. Niche markets may be required for profitability. A number of universities globally are currently exploring the science of aquaponics to advance this extreme cultivation technique (Dunning et al. 1998, Edwards, 2003, Diver 2006, Rakocy et al. 2004, 2006).

2. Aquaponic Systems

2.1. System Design

The design of aquaponic systems closely mirrors that of recirculation systems in general, with the addition of a hydroponic component and the possible elimination of a separate biofilter and devices (foam fractionators) for removing fine and dissolved solids. Fine solids and dissolved organic matter generally do not reach levels that require foam fractionation if aquaponic systems have the recommended design ratio. The essential elements of an aquaponic system are the fish-rearing tank, a settleable and suspended solids removal component, a biofilter, a hydroponic component, and a sump (Fig. 1).

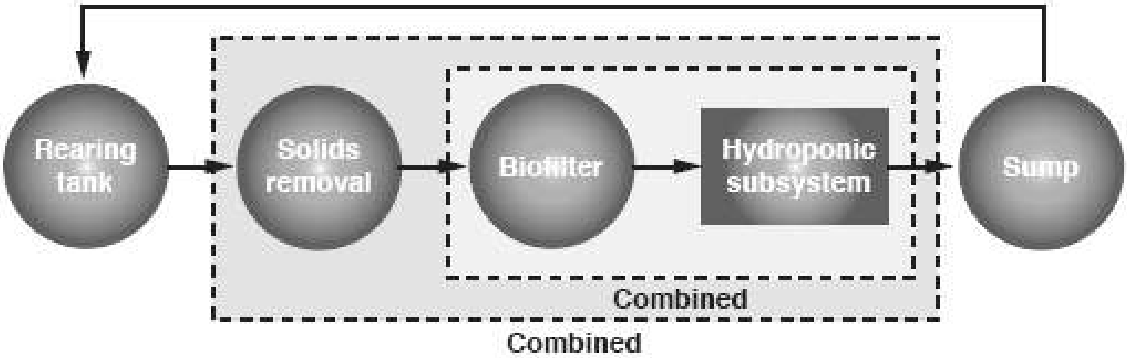

Figure 1: Optimum Arrangement of Aquaponic System Components (Rakocy et al. 2006).

Effluent from the fish-rearing tank is treated first to reduce organic matter in the form of settleable and suspended solids. Next, the culture water is treated to remove ammonia and nitrate in a biofilter. Then, water flows through the hydroponic unit where some dissolved nutrients are taken up by plants and additional ammonia and nitrite are removed by bacteria growing on the sides of the tank and the underside of the polystyrene sheets (i.e., fixed-film nitrification). Finally, water collects in a reservoir (sump) and is returned to the rearing tank. The location of the sump may vary. 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 that a small side-stream flow may go to a hydroponic component after solids are removed, while most of the water passes through a biofilter and returns to the rearing tank.

The biofilter and hydroponic components can be combined by using plant support media such as gravel or sand that 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 large enough. Combining biofiltration with hydroponics is a desirable goal because eliminating the expense of a separate biofilter is one of the main advantages of aquaponic. An alternative design combines solids removal, biofiltration and hydroponics in one unit. The hydroponic support media (pea gravel or coarse sand) captures solids and provides surface area for fixedfilm nitrification, although with this design it is important not to overload the unit with suspended solids. As an example, Fig. 2 shows the commercial-scale aquaponic system that has been developed at the University of the Virgin Islands (UVI). It employs raft hydroponics (Rakocy et al. 2004, 2006).

2.2. Fish Production

Tilapia is the fish species most commonly cultured in aquaponic systems. Although some aquaponic systems have used channel catfish, *Clarias* spp., largemouth bass, crappies, rainbow trout, sturgeon pacu, common carp, koi carp, silver carp, grass carp, goldfish, Asian sea bass (barramundi) and Murray cod, most commercial systems are used to raise tilapia. Most freshwater species, which can tolerate crowding, will do well in aquaponic systems (including ornamental fish). One species reported to perform poorly is hybrid striped bass. 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, both the fish rearing and the hydroponic vegetable components must be operated continuously near maximum production capacity. The maximum biomass of fish a system can support without restricting fish growth is called the critical standing crop. Operating a system near its critical standing crop uses space efficiently, maximizes production and reduces variation in the daily feed input to the system, an important factor in sizing the hydroponic component. There are three stocking methods that can maintain fish biomass near the critical standing crop: sequential rearing, stock splitting and multiple rearing units (Szyper 1989, Rakocy et al. 2006, Lorena et al. 2008).

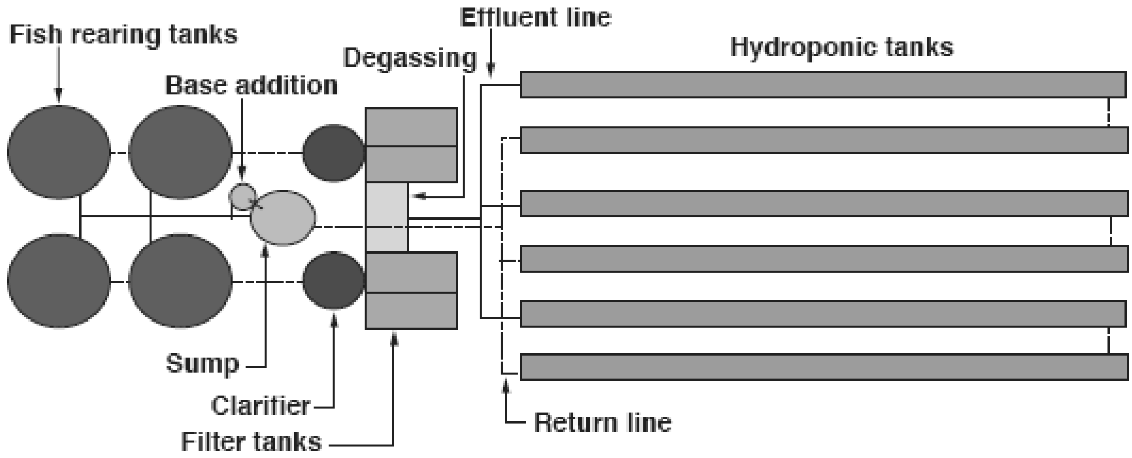

Figure 2. Layout of UVI Aquaponic System (Rakocy et al. 2006).

2.2.1. ***Sequential Rearing***

Sequential rearing involves the culture of several age groups (multiple cohorts) of fish in the same rearing tank. 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; and 3) it is difficult to maintain accurate stock records over time, which leads to a high degree of management uncertainty and unpredictable harvests.

2.2.2. ***Stock Splitting***

Stock splitting involves stocking very high densities of fingerlings and periodically splitting the population in half as the critical standing crop of the rearing tank is reached. This method avoids the carryover problem of stunted fish and improves stock inventory. However, the moves can be very stressful on the fish unless some sort of "swimway" is installed to connect all the rearing tanks. The fish can be herded into the swimway through a hatch in the wall of a rearing tank and manoeuvred into another rearing tank by movable screens. With swimways, dividing the populations in half involves some guesswork because the fish cannot be weighed or counted. An alternative method is to crowd the fish with screens and pump them to another tank with a fish pump.

2.2.3. ***Multiple Rearing Units***

With multiple rearing units, the entire population is moved to larger rearing tanks when the critical stand-ing crop 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 concepts 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, with influent water entering the raceway through a series of ports down one side of the raceway and effluent water leaving the raceway through a series of drains down the other side. This system ensures that water is uniformly high quality throughout the length of the raceway. 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 use space efficiently in the early stages of growth, but the fish are never disturbed and the labour involved in moving the fish is eliminated. A system of four multiple rearing tanks has been used successfully with tilapia in the UVI commercial scale aquaponic system (Fig 2). Production is staggered so one of the rearing tanks 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. Each circular rearing tank has a water volume of 7,800 litters and is heavily aerated with 22 air diffusers. The flow rate to all four tanks is 375 litters/minute, but the flow rate to individual tanks is apportioned so that tanks receive a higher flow rate as the fish grow. The average rearing tank retention time is 82 minutes. Nile tilapia are stocked at 77 fish/m3 and red tilapia are stocked at 154 fish/m3. Annual production has been 4.16 mt. for Nile tilapia and 4.78 mt for red tilapia (Tab. 1). However, production can be increased to 5 mt. with close observation of the *ad libitum* feeding response (Rakocy et al. 2006).

Tilapia	Harvest weight per tank (kg)	Harvest weight per unit volume (kg/m^3)	Initial Weight (g/fish)	Final Weight (g/fish)	Growth Rate (g/day)	Survival (%)	FCR
Nile	480	61.5	79.2	813.8	4.4	98.3	1.7
Red	551	70.7	58.8	512.5	2.7	89.9	1.8

Table 1: Average Production Values for Male Mono-Sex Nile and Red Tilapia in the UVI Aquaponic System.

The logistics of working with both fish and plants can be challenging. In the UVI system, one rearing tank is stocked every 6 weeks. Therefore, it takes 18 weeks to fully stock the system. If multiple units are used, fish may be stocked and harvested as frequently as once a week. Similarly, staggered crop production requires frequent seeding, transplanting, harvesting and marketing. Therefore, the goal of the design process is to reduce labour wherever possible and make operations as simple as possible. For example, purchasing four fish-rearing tanks adds extra expense. One larger tank could be purchased instead and partially harvested and partially restocked every 6 weeks. However, this operation requires additional labour, which is a recurring cost and makes management more complex. In the long run, having several smaller tanks in which the fish are not disturbed until harvest (hence, less mortality and better growth) will be more cost effective (Racoky et al. 2004, 2006).

2.3. Solids

Most of the fecal waste fish generate should be removed from the waste stream before it enters the hydroponic tanks. 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 sulphide, which are very toxic to fish. Suspended solids have special significance in aquaponic systems. Suspended solids entering the hydroponic component may accumulate on plant roots and create anaerobic zones that prevent nutrient uptake by active transport, a process that requires oxygen. However, some accumulation of solids may be beneficial. As solids are decomposed 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, which increases the operating expense and management complexity of the system. However, it may be possible to minimize or eliminate the need for nutrient supplementation if fish stocking and feeding rates are increased relative to plants. Another benefit of solids is that the microorganisms that decompose them are antagonistic to plant root pathogens and help maintain healthy root growth. Sand and gravel hydroponic substrates can remove solid waste from system water. Solids remain in the system to provide nutrients to plants through mineralization. With the high potential of sand and gravel media to clog, bed tillage or periodic media replacement may be required. The use of sand is becoming less common, but one popular aquaponic system uses small beds (250 cm by 125 cm) containing pea gravel ranging from 0.31 to 0.63 cm 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 (com- pared to water) speeds the decomposition of organic matter in the gravel. The beds are inoculated with red worms (*Eisenia foetida*), which improve bed aeration and assimilate organic matter (Hutchinson et al. 2004, Racoky et al. 2004, 2006).

2.3.1. *Solids Removal*

The most appropriate device for solids removal in a particular system depends primarily on the organic loading rate (daily feed input and feces production) and secondarily on the plant growing area. For example, if large numbers of fish (high organic loading) are raised relative to the plant growing area, a highly efficient solids removal device, such as a microscreen drum filter, is desirable. Microscreen drum filters capture fine organic particles, which are retained by the screen for only a few minutes before backwashing removes them 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. 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 plants. However, un-stabilized 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 percent in air as compared to 0.0005 to 0.0007 percent in fish culture water) on the drain cycle. This enhances microbial activity and increases the mineralization rate. With clarification as the sole method of solids removal, large quantities of solids would be discharged to the hydroponic component. Therefore, another treatment stage is needed to remove re-suspended and fine solids. In the UVI system, two rectangular tanks, each with a volume of 700 litres, are filled with orchard/bird netting and installed after each of the two clarifiers (Fig. 2). Effluent from each clarifier flows through a set of two filter tanks in series. Orchard netting is effective in removing fine solids. The filter tanks remove the remaining 50 percent of total particulate solids. The orchard netting is cleaned once or twice each week. Before 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. The netting is cleaned with a high-pressure water spray and the sludge is discharged to line holding ponds. The organic matter that accumulates on the orchard netting between cleanings forms a thick sludge.

Anaerobic conditions develop in the sludge, which leads to the formation of gases such as hydrogen sulphide, methane and nitrogen. Therefore, a degassing tank is used in the UVI system to receive the effluent from the filter tanks (Fig. 2). 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. Solids discharged from aquaponic systems must be disposed of appropriately. 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 the organic matter in it has stabilized. This method is advantageous in dry areas where sludge can be used to irrigate and fertilize field crops. The solid fraction of sludge can be separated from water and used with other waste products from the system (vegetable matter) to form compost. Urban facilities might have to discharge solid waste into sewer lines for treatment and disposal at the municipal wastewater treatment plant (Hutchinson et al. 2004, Racoky et al. 2004, 2006).

2.4. 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, and then to nitrate, which is relatively non-toxic. Two groups of naturally occurring bacteria (*Nitrosomonas* and *Nitrobacter*) mediate this two-step process (Fig 3) (Cacchione 2007). 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. Biofilters perform optimally at a temperature range of 25 to 30 °C, a pH range of 7.0 to 9.0, saturated DO, low BOD (<20 mg/liter) and total alkalinity of 100 mg/liter or more. Nitrification is an acid-producing process. Therefore, an alkaline base must be added frequently, depending on feeding rate, to maintain relatively stable pH values. Some method of removing dead biofilm is necessary to prevent media clogging, short circuiting of water flow, decreasing DO values and declining biofilter performance (Hutchinson et al. 2004).

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 is taken up by plants. However, the contribution of various hydroponic subsystem designs and plant species to water treatment in aquaponic systems has not been studied. Therefore, aquaponic system biofilters should be sized fairly close to the recommendations for recirculation 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 (high 8s). Recommended pH ranges for hydroponic systems are between 5.5 and 6.5 and for aquaculture systems are between 6.5 and 8.5 (Tyson et al. 2004). The pH of a solution affects the solubility of nutrients, especially trace metals. Essential nutrients such as iron, manganese, copper, zinc and boron are less available to plants at a pH higher than 7.0, while the solubility of phosphorus, calcium, magnesium and molybdenum sharply decreases at a pH lower than 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 percent saturation (6 to 7 mg/L) by aerating the hydroponic tanks with numerous small air diffusers (one every 4 feet) 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 (nutrient film technique) 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 the media has a tendency to clog. If serious clogging occurs from 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 design must be modified by installing a solids removal device before the media, or else the organic loading rate must be decreased by stocking fewer fish and reducing feeding rates.

Raft hydroponics, which consists of channels (with 30 cm of water depth) covered by floating sheets of polystyrene for plant support, also provides sufficient nitrification if solids are removed from the flow before it reaches the hydroponic component. The waste treatment capacity of raft hydroponics is equivalent to a feeding ratio of 180 g of fish feed/m2 of plant growing area/day. This is equivalent to about 4.5 kg of feed for each 250 cm x 125 cm sheet of polystyrene foam. After an initial acclimation period of 1 month, it is not necessary to monitor ammonia and nitrite values in the UVI raft system A significant amount of nitrification occurs on the undersides of the polystyrene sheets, especially in the areas exposed to strong currents above air diffusers where the biofilm is noticeably thicker (Hutchinson et al. 2004, Racoky et al. 2004, 2006).

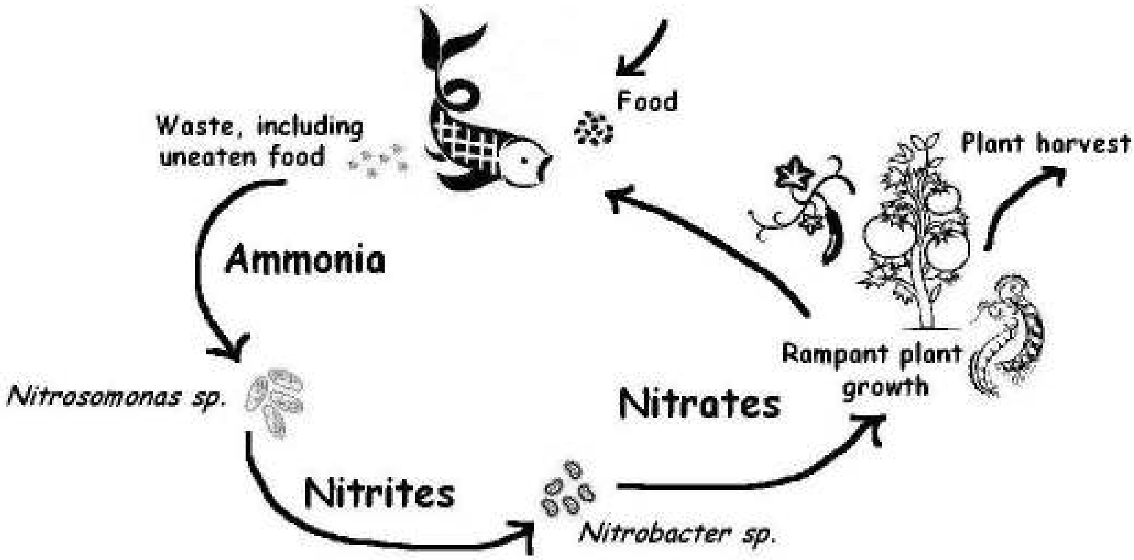

Figure 3: The Nitrogen Cycle in Aquaponic Systems (Cacchione 2007).

2.5. Hydroponic Subsystems

A number of hydroponic subsystems have been used in aquaponic. 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, or in a non flooded state, where culture water is applied continuously to the base of the individual plants through small diameter plastic tubing. 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). One popular gravel-based aquaponic system uses pea gravel in small 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 cycle. The beds are allowed to drain completely between flood cycles. Solids are not removed from the culture water and organic matter accumulates, but the beds are tilled between planting cycles so that some organic matter can be dislodged and discharged. Sand has been used as hydroponic media in aquaponic systems and is an excellent substrate for plant growth. In an experimental system, sand beds (7.5 m long by 1.5 m wide by 15 cm deep) were constructed on slightly sloped ground covered by polyethylene sheets adjacent to in-ground rearing tanks, with the tank 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. A coarse grade of sand is needed to reduce the potential for clogging over time and some solids should be removed before irrigation. Perlite is another media that has been used in aquaponic systems. Perlite is placed in shallow aluminium trays (7.5 cm deep) with a baked enamel finish. The trays vary from 20 cm to 10 cm wide and can be fabricated to any length; with 50 cm the maximum recommended length. At intervals of 50 cm, adjoining trays should be separated by 7.5 cm or more in elevation so that water drops to the lower tray and becomes re-aerated. A slope of 2.5 cm in 30 cm is needed for water flow. A small trickle of water enters at the top of the tray, flows through the perlite and keeps 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.

A floating or raft hydroponic subsystem is ideal for the cultivation of leafy green and other types of vegetables. The UVI system uses three sets of two raft hydroponic tanks that are 30 m long by 125 cm wide by 4 m deep and contain 3 m of water. The channels are lined with low-density polyethylene liners (20 mil thick) and covered by expanded polystyrene sheets (rafts) that are 250 cm long by 125 cm wide by 3.8 cm 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 7.5 cm 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 it and keeps it from falling through the hole into the water. Seedlings are nursed in a greenhouse and then placed into net pots. Their roots grow into the culture water while their canopy grows above the raft surface. The system provides maximum exposure of roots to the culture water and avoids clogging. The sheets shield the water from direct sunlight and maintain lower than ambient water temperature, which is a beneficial feature in tropical systems. 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 workers (Alka et al. 2000, Racoky et al. 2006).

2.6. 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 that returns the treated culture water 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. 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 (Hutchinson et al. 2004, Racoky et al. 2006).

2.7. Construction Materials

Many materials can be used to construct aquaponic systems. Budget limitations often lead to the selection of inexpensive and questionable materials such as vinyl-lined, steel walled swimming pools. Fibreglass is the best construction material for rearing tanks, sumps and filter tanks. Fibreglass tanks are sturdy, durable, non-toxic, movable and easy to plumb. Polyethylene tanks are also very popular for fish rearing and gravel hydroponics because of their low cost. NFT troughs made from extruded polyethylene are specifically designed to prevent the pudding and water stagnation that lead to root death and are preferable to makeshift structures such as PVC pipes. Plastic troughs are commercially available for floating hydroponic subsystems, but they are expensive. A good alternative is the 20-mil polyethylene liners that are placed inside concrete block or poured-concrete side walls. They are easy to install, relatively inexpensive and durable, with an expected life of 12 to 15 years. A soil floor covered with fine sand will prevent sharp objects from puncturing the liners. Lined hydroponic tanks can be constructed to very large sizes hundreds of feet long and up to 9 m wide (Racoky et al. 2004, 2006).

2.8. 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 quantity 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.

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 30 litter of fish-rearing tank to 220 litter of pea gravel hydroponic media (0.31 cm to 0.63 cm in diameter) is recommended for reciprocating (flood and drain) gravel aquaponic systems. This ratio requires that tilapia be raised to a final density of 250 g/4 l 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.

As a general guide for raft aquaponics, a ratio in the range of 60 to 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 micrometers) removed by a clarifier, and 3 to 7 days for suspended solids removed by an orchard netting filter. The system uses rainwater and requires supplementation for potassium, calcium and iron (Racoky et al. 2004, 2006).

2.9. Plant Growth Requirements

For maximum growth, plants in aquaponic systems require 16 essential nutrients. These are listed below in the order of their concentrations 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). The remaining nutrients are absorbed from the culture water. Other macronutrients include nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P) and sulphur (S). The seven micronutrients include chlorine (Cl), iron (Fe), manganese (Mn), and boron (B), zinc (Zn), copper (Cu) and molybdenum (Mo). These nutrients must be balanced for optimum plant growth. High levels of one nutrient can influence the bioavailability of others. For example, excessive amounts of potassium may interfere with the uptake of magnesium or calcium, while excessive amounts of either of the latter nutrients may interfere with the uptake of the other two nutrients. Water temperature is far more important than air temperature for hydroponic plant production. The best water temperature for most hydroponic crops is about 24 °C. 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 (Alka et al. 2000, Racoky et al. 2004, 2006).

2.10. Vegetable Selection

Many types of vegetables have been grown in aquaponic systems. However, the goal is to culture a vegetable that will generate the highest level of income per unit area per unit time. With 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 is much 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 5,000 kg annually at a value of $110,000, compared to okra production of 2,900 kg annually at a value of $ 6,400. Fruiting crops also require longer culture periods (90 days or more) and have 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, has relatively few pest problems. Unlike fruiting crops, a large portion of the harvested biomass is edible. Other suitable crops are 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 for growing some of these plants. All plant production has to be coupled to the producer's ability to market the final product (Rakocy et al. 2006). In Canada, greenhouse tomato and cucumber production in aquaponic system in 2004/2005 reached 20.7 kg/plant/year and 33.4 kg/plant/year respectively exceeding average yields of these crops in greenhouse sector in Alberta for the first time. The average yield of basil increased in from 8.7 kg/m^2 of greenhouse area to 11.9 kg/m^2 in 2005 compared to 2005 (Savidow 2005).

2.11. Pest and Disease Control

Pesticides should not be used to control insects on aquaponic plant crops. Even pesticides that are registered would pose a threat to fish and would not be permitted in a fish culture system. Similarly, therapeutants for treating fish parasites and diseases should not be used because vegetables may absorb and concentrate them. The common practice of adding salt to treat fish diseases or reduce nitrite toxicity is detrimental to plant crops. Nonchemical methods of integrated pest management must be used. These include biological control (resistant cultivars, predators, pathogens, antagonistic organisms), physical barriers, traps, and manipulation of the physical environment. There are more opportunities to use biological control methods in enclosed greenhouse environments than in exterior installations. Parasitic wasps and ladybugs can be used to control white flies and aphids. In UVI's systems, caterpillars are effectively controlled by twice weekly spraying with *Bacillus thuringiensis*, a bacterial pathogen that is specific to caterpillars. Fungal root pathogens (*Pythium*), which are encountered in summer at UVI and reduce production, dissipate in winter in response to lower water temperature. The prohibition on the use of pesticides makes crop production in aquaponic systems more difficult. However, this restriction ensures that crops from aquaponic systems will be raised in an environmentally sound manner and be free of pesticide residues. A major advantage of aquaponic systems is that crops are less susceptible to attack from soil borne diseases. Plants grown in aquaponic systems may be more resistant to diseases that affect plants grown in standard hydroponics. This resistance may be due to the presence of some organic matter in the culture water that creates a stable growing environment with a wide diversity of microorganisms, some of which may be antagonistic to plant root pathogens (Racoky et 2006).

2.12. Economics

The economics of aquaponic systems depends 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. The UVI system is capable of producing approximately 5,000 kg of tilapia and 630 cases of lettuce or 5,000 kg of 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 percent of vegetable supplies and nearly 80 percent 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 (Rakocy et al. 2006). In Canada, water use efficiency in mixed basil/tilapia operation was 394.3 liters per $100 of output, which is for 65.7% more efficient than in the best hydroponics system (600 liters per $100 of output) (Savidow, 2005).

3. Conclusion

Aquaponic systems retain water for long periods of time, require less monitoring, and provide free nutrients. Aquaponic system encounters fewer pest and disease problems than traditional hydroponic systems due to the amount of organic material in the water. In contrast to the sought after sterile environment of hydroponics, the aquaponic system thrives on a diversity of bacteria – bacteria that can be antagonistic to pathogens and bacteria that boost plants' immune systems. In fact, the aquaponic system has operated for several years without changing the water. Unlike traditional hydroponic solutions that require a complete nutrient mix, the UVI system's tilapia provides adequate amounts of 10 of the 13 nutrients essential to plants. Only potassium, calcium and iron must be supplemented. And to maintain the proper pH level the operators add either calcium hydroxide or potassium hydroxide, which provide the missing potassium and calcium nutrients. Iron is added separately Normal recirculation aquaculture systems discharge an estimated five to ten percent of system water daily due to excess nitrate accumulation. UVI's system uses nitrates and other nutrients for plant growth, so it discharges less than one percent of system water daily, alleviating the potential for pollution related to water discharge. Aquaponic is the only system in the world that has a biofilter that makes money (Sherrill 2008). New technologies take time to be accepted and implemented. However, global water shortages have created a more urgent interest in aquaponic, one of the most water-efficient systems in the world.

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