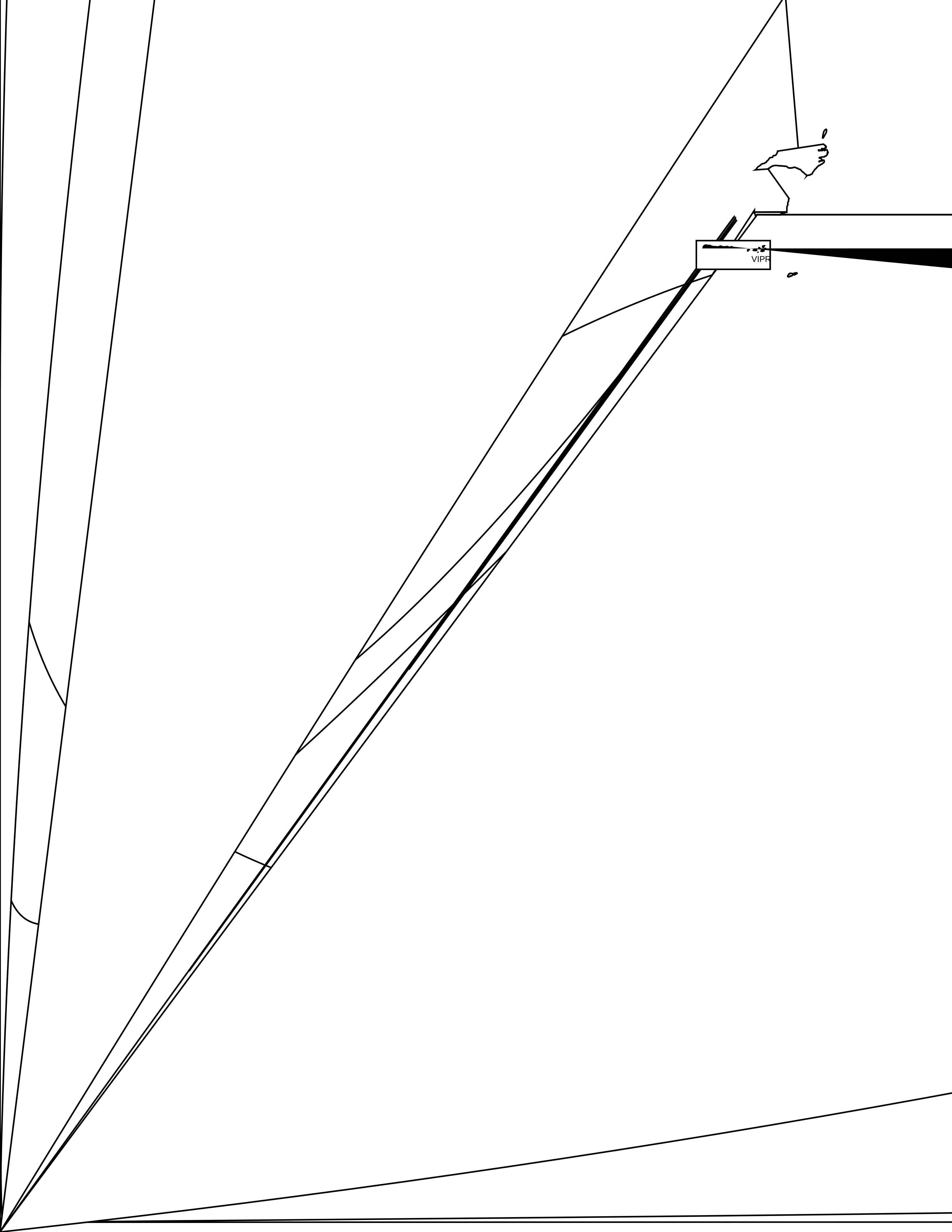
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nutrients at no cost improves a systemÕs profit potential. The daily application of fish feed provides a steady supply of nutrients to plants and thereby eliminates the need to discharge and replace depleted nutrient solutions or adjust nutrient solutions as in hydroponics. 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 recirculating 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.

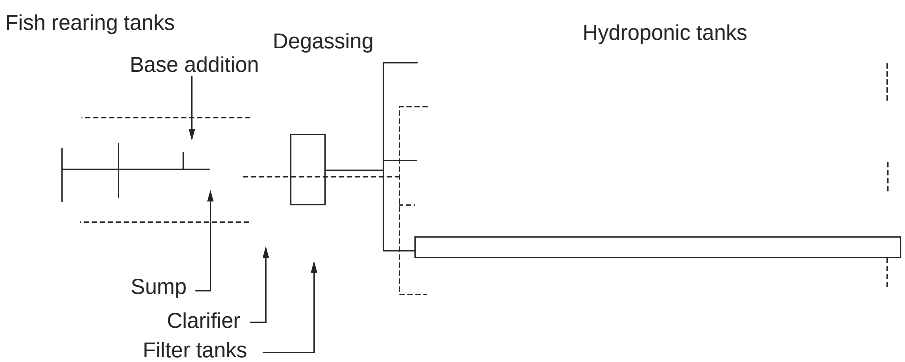
System design

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 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. 2).

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 so that a portion of the flow is diverted to a particular treatment unit. For example, 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 aquaponics. 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 fixed-film nitrification, although with this design it is important not to overload the unit with suspended solids.



to maintain accurate stock records over time, which leads to a high degree of management uncertainty and unpredictable harvests.

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 ÒswimwayÓ 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 maneuvered 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.

Multiple rearing units

With multiple rearing units, the entire population is moved to larger rearing tanks when the critical standing crop of the initial rearing tank is reached. The fish are either herded through a hatch between adjoining tanks or into ÒswimwaysÓ 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, 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 labor 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 (Figs. 3 and 5). 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 2,060 gallons and is heavily aerated with 22 air diffusers. The flow rate to all four tanks is 100 gallons/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.

pared to water) speeds the decomposition of organic matter in the gravel. The beds are inoculated with red worms (Eisenia foetida

Figure 7. Components of the UVI aquaponic system at the New Jersey EcoComplex at Rutgers University.

the rearing tank determine the extent to which filamentous bacteria grow, but they 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 the 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 (Fig. 7). 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.

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 (Nitrosomonasand 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. Biofilters perform optimally at a temperature range of 77 to 86 ¡F, 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. A discussion of nitrification principles and a description of various biofilter designs and operating procedures are given in SRAC Publication Nos. 451, 452 and 453.

Four major biofilter options (rotating biological contactors, expandable media filters, fluidized bed filters and packed tower filters) are discussed in SRAC Publication No. 453. 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 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 (high 8s). Most hydroponic plants grow best at a pH of 5.8 to 6.2. The acceptable range for hydroponic systems is 5.5 to 6.5. 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.

be fabricated to any length, with 20 feet the maximum recommended length. At intervals of 20 feet, adjoining trays should be separated by 3 inches or more in elevation so that water drops to the lower tray and becomes re-aerated. A slope of 1 inch in 12 feet 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.

Nutrient film technique (NFT) has been successfully incorporated into a number of aquaponic systems. NFT consists of many narrow, plastic troughs (4 to 6 inches wide) 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 use 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. In aquaponic systems that use NFT, solids must be removed so they do not accumulate and kill roots. 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; it is collected at the opposite, down-slope end in an open channel or large PVC pipe. The use of microtubes, 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.

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 100 feet long by 4 feet wide by 16 inches deep and contain 12 inches of water. The channels are lined with low-density polyethylene liners (20 mil thick) and covered by expanded polystyrene sheets (rafts) that are 8 feet long by 4 feet wide by 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 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 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 plantÕs 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 (Fig. 9).

A disadvantage of rafts in an aquaponic system is that roots are exposed to harmful organisms associated with aquaculture systems. If tilapia fry gain access to the hydroponic tanks, they consume plant roots and severely stunt plant growth, although it is relatively easy to keep fish from entering by placing a fine mesh screen at the entry point of water into the degassing tank. Similarly, blooms of zooplankton, especially ostracods, will consume root hairs and fine roots, retarding plant growth. Other pests are tadpoles and snails, which consume roots and nitrifying bacteria. These problems can be surmounted by increasing water agitation to prevent root colonization by zooplankton and by stocking some carnivorous fish such as red ear sunfish (shellcrackers) in hydroponic tanks to prey on tadpoles and snails.

Sump

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Other factors 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 grown. 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 slow-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 large compared to the surface area of the fish-rearing tank (stocked at commercially relevant densities). The commercial-scale unit at UVI has a ratio of 7.3:1. The total plant growing area is 2,304 ft^2 and the total fish-rearing surface area is 314 ft^2.

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 macronutrientsÑcarbon (C), oxygen (O) and hydrogen (H)Ñare 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 sulfur (S). The seven micronutrients include chlorine (Cl), iron (Fe), manganese (Mn), 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.

Enriching the air in an unventilated greenhouse with CO_2 has dramatically increased crop yields in northern latitudes. Doubling atmospheric CO_2 increases agricultural yields by an average of 30 percent. However, the high cost of energy to generate CO_2 has discouraged its use. An aquaponic system in a tightly enclosed greenhouse is ideal because CO_2 is constantly vented from the culture water.

There is 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. Directly absorbed and assimilated by plants, these compounds 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-metallic complexes with Fe, Mn and Zn, thereby increasing the availability of these micronutrients to plants. Although inorganic nutrients give plants an avenue to survival, plants not only use organic metabolites from the environment, but also need these metabolites to reach their full growth potential.

Maintaining high DO levels in the culture water is extremely important for optimal plant growth, especially in aquaponic systems with their [illegible]

Crop varieties may need to be adjusted seasonally for both temperate and tropical aquaponic production. Plants cultured in outdoor aquaponic systems must be protected from strong winds, especially after transplanting when seedlings are fragile and most vulnerable to damage.

Nutrient dynamics

Dissolved nutrients are measured collectively as total dissolved solids (TDS), expressed as ppm, 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 ppm (1.5 to 3.5 mmho/cm). In an aquaponic system, considerably lower levels of TDS (200 to 400 ppm) or EC (0.3 to 0.6 mmho/cm) 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 occurs at TDS concentrations above 2,000 ppm or EC above 3.5 mmho/cm. Because aquaponic systems have 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 approach 2,000 ppm as TDS or 3.5 mmho/cm as EC, increasing the water exchange rate or reducing the fish stocking rate and feed input will quickly reduce nutrient accumulation. However, because 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 removing more solids (i.e., upgrade the solids removal component) or enlarging the plant-growing areas.

The major ions that increase conductivity are nitrate (NO_3^-), phosphate

(mmho/cm). nien0.0sola296 TGb2333 TD (-)Tj 125 0.68 0 87.2129 735.2027 Tc 0.0296e gf

ictnutho/c(8.6adda.282669. A.ndT)]That nupartz295.282669Tm -0.02lo8.dTJ T*j 134e 0[(] [(w

els in hydroponic formulations. Deficiency symptoms for Mn $^{+2}$, B^{+3} and Mo^{+6} are not detected in aquaponic systems, 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 limit that is safe for fish.

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 mark cr8.8hT* prce. The

Figure 10. Healthy roots of Italian parsley cultured on rafts in a UVI aquaponic system at the Crop Diversification Center South in Alberta, Canada.

of the standard design 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 that can be followed.

Use an aquaponic system that is already designed. The easiest approach is to use a 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, as in an existing greenhouse, then that space will define the size of the aquaponic system. A standard design can be scaled down to fit the space. 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 0.5 pound/gallon for an aerated system. Take the annual production per system and multiply it by the estimated feed conversion ratio (the pounds of feed required to produce 1 pound 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 500 pounds 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 500 pounds 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. 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 500 pounds 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 0.5 pound/gallon. Therefore, the water volume of the rearing tanks is 1,000 gallons.
3. In 52 weeks, there will be 8.7 harvests (52 Ö 6 = 8.7) per system. Annual production for the system, therefore, is 4,350 pounds (500 pounds per harvest × 8.7 harvests).
4. The usual feed conversion ratio is 1.7. Therefore, annual feed input to the system is 7,395 pounds (4,350 lb × 1.7 = 7,395 lb).
5. The average daily feed input is 20.3 pounds (7,395 lb/year Ö 365 days = 20.3 lb).
6. The average daily feed input converted to grams is 9,216 g (20.3 lb × 454 g/lb = 9216 g).
7. The optimum feeding rate ratio for raft aquaponics ranges from 60 to 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 (9,216 g/day Ö 80 g/m^2/day =115.2 m^2).
8. The growing area in square feet is 1,240 (115.2 m^2 × 10.76 ft^2/m^2 = 1,240 ft^2).
9. Select a hydroponic tank width of 4 feet. The total length of the hydroponic tanks is 310 feet (1,240 ft^2 Ö 4 ft = 310 ft).
10. Select four hydroponic tanks. They are 77.5 feet long (310 ft Ö 4 = 77.5 ft). They are rounded up to 80 feet in length, which is a practical length for a standard greenhouse and allows the use of ten 8-foot 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 ten polystyrene sheets produces 480 plants. With six aquaponic production systems 2,880 plants are harvested weekly.

In summary, the weekly production of 500 pounds of tilapia results in the production of 2,880 green leaf lettuce plants (120 cases). Six aquaponic systems, each with four 1,000-gallon rearing tanks (water volume), are required. Each system will have four raft hydroponic tanks that are 80 feet long by 4 feet 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 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 0.5 pound/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 0.5 pound/gallon to determine the volume of water (in gallons) required per fish. Divide the number of gallons required per fish by the water volume of the rearing tank to determine the fish stocking rate. Increase this number by 5 to 10 percent 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 (3,000 plants Ö 29.3/m^2 = 102.3 m^2). This area is equal to 1,100 square feet (102.3 m^2 × 10.76 ft^2/m^2 = 1,100 ft^2).
3. Select a hydroponic tank width of 8 feet. The total hydroponic tank length will be 137.5 feet (1,100 ft^2/8 ft = 137.5 ft).
4. Multiples of two raft hydroponic tanks are required for the UVI system. In this case only two hydroponic tanks are required. Therefore, the minimum length of each hydroponic tank will be 68.75 feet (137.5 ft Ö 2 = 68.75 ft). Since polystyrene sheets come in 8-foot lengths, the total number of sheets per hydroponic tank will be 8.59 sheets (68.75 ft Ö 8 ft/sheet = 8.59 sheets). To avoid wasting material, round up to nine sheets. Therefore, the hydroponic tanks will be 72 feet long (9 sheets × 8 ft per sheet = 72 ft).
5. The total plant growing area will then be 1,152 ft^2 (72 ft × 8 ft per tank × 2 tanks = 1,152 ft^2). This is equal to 107 m^2 (1,152 ft^2 Ö 10.76 ft^2/m^2).
6. At a 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 rate 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 (60 g/m^2/day × 107 m^2 = 6,420 g). This is equal to 14.1 pounds of feed (6,420 g Ö 454 g/lb = 14.1 lb).

3,340 pounds (3,036 fish × 1.1 lb/fish = 3,340 lb) 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 Ö 6 weeks = 8.7).
15. Each harvest will be 384 pounds (3,340 lb per year Ö 8.7 harvests per year = 384 lb/harvest).
16. Final harvest density should not exceed 0.5 pound/gallon. Therefore, the water volume of each rearing tank should be 768 gallons (384 lb Ö 0.5 lb/gal = 768 gal). The tank should be larger to provide a 6-inch freeboard (space between the top edge of the tank and the water levels).
17. Each fish requires 2.2 gallons of water (1.1 lb Ö 0.5 lb of fish/gal = 2.2 gal per fish).
18. The stocking rate is 349 fish per tank (768 gal Ö 2.2 gal/fish = 349 fish).
19. To account for calculated mortality, the stocking rate (349 fish per tank) should be increased by 35 fish (349 fish × 0.10 = 34.9) to attain an actual stocking of 384 fish per tank.

In summary, two hydroponic tanks (each 72 feet long by 8 feet wide) will be required to produce 1,000 Bibb lettuce plants per week. Four fish-rearing tanks with a water volume of 768 gallons per tank will be required. The stocking rate will be 384 fish per tank. Approximately 384 pounds of tilapia will be harvested every 6 weeks, and annual tilapia production will be 3,340 pounds.

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. For example, an outdoor tropical system would be less expensive to construct and operate than a controlled-environment greenhouse system in a 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 11,000 pounds of tilapia and 1,400 cases of lettuce or 11,000 pounds 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.

The enterprise budget for tilapia and lettuce shows that the annual return to risk and management (profit) for six production units is US$185,248. The sale prices for fish ($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 of imports caused by transportation costs. Locally produced lettuce is also fresher than imported lettuce. 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 return to risk and management for six production units is US$693,726. Aquaponic systems are very efficient in producing culinary herbs such as basil (Fig. 11) and a conservative sale price for fresh basil with stems in the U.S. Virgin Islands is $10.00/pound. 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 66,000 pounds of fresh basil annually, although there are opportunities for provisioning ships and exporting to neighboring islands. A more realistic approach for a six-unit operation is to devote a portion of the growing area to basil to meab-
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Table 2. 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)

	Annual production		Wholesale price		Total value	
Crop	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
Eggplant	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.