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How to Build and Operate a Simple Small-to-Large Scale Aquaponics System

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INTRODUCTION

Aquaponics is the symbiotic production of vegetables and fish. Fish eat food and release metabolites into the water derived from the food. These metabolites are further metabolized by bacteria, and the products of this metabolism are pumped into a plant grow bed where they are taken up by plants for nourishment. Aquaponics is suitable for environments with limited land and water because it produces about three to six times the vegetables (Resh 2004) and uses about 1% of the freshwater used by traditional aquaculture (Rakocy 1989).

Sneed et al. (1975) published the first description of an aquaponic system, which diverted aquaculture effluent through plant growing troughs. The concept was that the nutrients in aquaculture effluent could be put to good use to nourish and grow plants; meanwhile, potentially polluted fish water would be cleaned up before being released into the environment. Plants showed signs of nutrient deficiencies within a month, likely due to a couple of factors. In hindsight, fertilizer nitrate nitrogen was 150 times lower than it is today. Furthermore, the culture water was exposed to sunlight, which allowed microalgae to grow and further reduced the available nutrients. At around the same time, Dr. John Todd and Nancy Jack Todd led similar work at the New Alchemy Institute, which resulted in a natural wastewater treatment system marketed as a 'living machine.'

In 1978, Lewis et al. sought to address the dilute nutrient issue. They worked with the first recirculating aquaponic system, which was developed to operate with a high fish stocking density. While the idea was good, nitrate concentrations were too low at 6–10 mg/L, and producers were required to add a complete nutrient solution to support tomato growth. As a general rule of thumb, nitrate levels should be around 46 mg/L. The low nitrate levels coupled with high amounts of fish feed suggested that massive denitrification, or conversion of fertilizer nitrate to nitrogen gas, was occurring and the nitrogen was being released into the atmosphere.

In 1986, Zweig developed a simple and productive aquaponic system by matching the feeding rate and biomass of the fish to the estimated nitrogen needs of the plants. Iron deficiency was addressed by replacing 20% of the fish feed with rabbit feed. While this work was an important step in the development of the technology, it went largely unnoticed.

In 1985, Nair et al. (1985) developed a recirculating aquaponics system at the University of the Virgin Islands (UVI). Similar to the system of Lewis et al. (1978), it used complex components and engineering that kept operating costs high at $3.18/kg of tilapia produced (1985 prices). Tomato plants grew poorly despite an estimate that nitrogen production by fish should have exceeded plant requirements by ten fold. Unfortunately, the understanding and prevention of denitrification was not well understood at the time. Salts that inhibit the growth of some plant species (Jones 2005) accumulated in the system. Iron averaged 0.1 mg/L, which is less than the minimum of 1–2 mg/L suggested for hydroponic plant culture (Jones 2005). Researchers Mark McMurtry, Douglas Nelson, and Paul Nelson of North Carolina State University also developed a recirculating aquaponics system. They placed their plants in a gravel bed creating an *in situ* biofilter.

In 1993, Rakocy and Hargreaves reviewed aquaponics research and concluded that estimates of nutrient uptake and a deeper understanding of culture water nutrient dynamics are a necessity in the development of criteria for designing aquaponics systems. Rakocy et al. (1993) attempted to track plant nutrient uptake in the UVI aquaponic systems operated with and without plants. Unfortunately, nutrients accumulated at equal rates in all systems and uptake by plants was not demonstrated. A follow up experiment was conducted to determine the optimal fish-number-to-plant-growing-area ratio. In hindsight, we now believe that the nutrients produced by fish should have exceeded plant needs in all treatments. Lettuce head weights were about the same in all treatments irrespective of the range of fish stocking densities tested. The plants grown in the aquaponics system were smaller than those produced hydroponically (172–248 g; Kratky 2005), suggesting malnutrition. After refinement, the system produced lettuce heads of a comparable size (181–344 g; Rakocy et al. 1997). A number of years later, it was demonstrated that the UVI system could be operated productively and continuously (Rakocy et al. 2004). The final system consisted of four fish tanks, six plant troughs, a clarifier tank, screen filter tanks, degassing tanks, a sump tank, a base addition tank, a water pump, two air blowers, and over 200 air stones. A technically trained staff was used to operate it. Rakocy was effectively the first person to develop a fully-functional aquaponics system and thus, is often referred to as the 'grandfather of aquaponics.'

Generally, plants were grown in water on floating polystyrene sheets called rafts (Rakocy 1989). Rafts require substantial aeration of the water to provide oxygen to plant roots and to support nitrification. Kratky (2005) used a system in which plant roots were held out of the water and exposed to moist air; this could be called a nutrient film technique. Lennard and Leonard (2006) tested three kinds of systems, some of which have been subsequently used by others. They tested the following designs: gravel systems flooded with water, systems using the nutrient film technique in which plant roots were exposed to air and roots were bathed with a thin layer of fish water, and raft systems. They found that the gravel systems flooded with water were the best. Ako (2013) tested trickling water under gravel, gravel ebb and flow, rafts with air gaps, and standard rafts. He found the first two to be best, but the former to be more maintenance free.

It has been more than 20 years since Rakocy modified the technology, yet there are no known successful commercial systems based on his design. One purpose of the work highlighted in this publication is to remedy this. However, we can now see in hindsight that aquaponics is economically challenging. It cannot tolerate low prices for vegetables, low system biological performance, high capital expenses, or high operational expenses and remain profitable (Tokunaga et al.) In some Pacific Islands, vegetables are very expensive because they must be imported by airplane. Aquaponics has the advantage of producing vegetables that taste uniquely good and are grown organically, as fish and pesticides are incompatible. In particular, our objectives were to develop systems that require less capital investment and to develop operating instructions that are based on basic biology and chemistry. Systems should have clear chemical specifications, and remedies for chemical imbalances should be provided.

BUILDING A SYSTEM

The present systems were modeled after Kratky's (2005) extremely inexpensive hydroponics systems. Kratky used simple wooden boxes. Grow-bed units are shallow wooden boxes with a piece of plywood for a bottom (3/4" x 4' x 8'), two 2" x 4" side pieces (8' long), and two 2" x 4' end pieces (4' long) (Fig. 1). These grow-beds are quick and inexpensive to construct (about $84 each). Each bed produces 48 heads of leafy greens, such as lettuce; some vegetables, such as mustard cabbage (kai choy or *Brassica juncea*), require 5 weeks to grow to a pound.

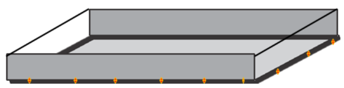

Figure 1. Grow tray

To construct the box, screws are placed through the bottom once every approx. 41 cm (16").
2x8 stainless steel screws (5.1 cm long and 0.44 cm in diameter) or 3x10 stainless steel screws (5.1 cm long and 0.52 cm in diameter) are used, as shown in Fig 2. A photo of the bottom and sides of a tray ready for attachment (Fig. 3.) Boxes are constructed upside down.

Figure 2. Steel screws used to attach the walls of the grow-beds.

Figure 3. Bottom of tray ready to be screwed to sides.

The plastic liner is then attached (Fig. 4). Growers can find their own plastic; one available source is www.reefindustries.com.

Figure 4. Attaching liner to the tray.

In practice, many trays are attached to each other. Figure 5 shows a typical setup for commercial production. Usually 8 pieces of plywood form a raceway. The number 8 is used because rolls of plastic are usually about 100 feet long. The greatest challenge is to ensure that all of the trays are level. They need to be level or fish water will puddle somewhere in the tray. Raceways are supported by double hollow tiles (as seen in Figure 5).

Figure 5. Typical raceways consisting of 8 pieces of plywood connected end to end.

Trays at the first commercial farm built with the Ako and Baker (2009) system design are about 5 years old and show no signs of wearing. This is because the wood never gets wet.

Tray covers. Plants sit in 2” (5.1 cm) net pots supported by the white polystyrene covers, or rafts, shown below (Fig. 6). Grow-beds are filled with enough water to reach the bottom of the net pots, and lettuce plant roots grow down into the water to take up nutrients. It is noted that this leaves about 5 cm (or 2 inches) of air space between the raft and the surface of the water, approximating well-aerated tilled soil.

Figure 6. Young lettuce plant in a net pot on a polystyrene sheet.

Recently we have found superior and more consistent performance growing plants in about 5 cm of volcanic cinder flushed with about 1.5 cm of fish water. We call this a trickle (i.e., trickle filter) gravel system. Ebb and flow systems using bell siphons are just as good but we prefer trickle gravel systems because worms can live and eat fecal material from fish in these systems. The raceway below is an ebb and flow raceway (Fig. 7).

Figure 7. Gravel filled raceway with plants growing in the gravel.

Water is pumped from the fishtanks into the raceway, and returns to the fish tank via a standpipe and bulkhead.

As the project evolved, nursery sheets were developed. These are similar to the polystyrene tray covers, but are drilled much more densely to support the growth of 98 small plants per tray cover (when the plants are very small). The polystyrene sheets rest on the wall of the tray, and three 4” plastic flower pots may be placed in each tray to prevent sheets from sagging. Most farmers use seed-starting trays, which are closely-spaced sheets of cups that may be filled with potting soil. However, potting soil adds organic matter to the system. The seed-starting trays are kept moist for about three weeks, after which time plants are large enough to plant in growout trays. Most plants require about three more weeks before they are harvested and sold.

Most farmers automate seeding. Putting one seed in each cup is very tedious and time consuming. Aquaponics is very labor intensive (Tokunaga et al. 2014) and automation is welcomed.

Lettuce plants require partial shading to grow well in tropical climates such as Hawaii or the Pacific Islands (Wolff and Coltman 1990). At UHM, lettuce was found to grow well under 50% shade cover from a shadecloth. Figure 5 shows raceways with shadecloth.

Initial work has been done with the red sails variety of leaf lettuce. It was found to grow well in this system. Other varieties of lettuce such as Manoa lettuce or romaine lettuce were also found to grow well; kai choi and bok choy (*Brassica juncea*) and basil (*Ocimum basilicum*) have also done well. Other farmers grow beets, cucumber, tomatoes, blueberries, strawberries, and watercress.

Mosquitoes are a frequent problem in raft aquaponics systems, as stagnant water can accumulate in grow beds. They may be easily controlled by stocking about 3 male guppies in each grow tray to eat mosquito larvae. Stocking of multiple genders may lead to breeding, and if populations get too high the guppies will eat the plant roots.

The following ratios work well for aquaponics. We suggest using the nutrient-flux hypothesis, which matches the feed fed (42 g/day of Silver Cup trout chow with 42% protein) to the amount of metabolites that must be remediated and detoxified by either a gravel grow bed or a 4.2 gallon (16 L) submerged biofilter in a 321 L tank (Fig. 8). To make this biofilter, a cylinder measuring 10” by 13” (25 x 32 cm) is made from extruded plastic netting and filled with PVC biofilter media. A 25 W air pump and three 6-inch airstones are optimal to aerate such a tank. The tank should be filled with about 200 L of water. The initial stocking density of fish should be 2.5 kg. The fish tanks must be shaded to prevent microalgae from growing.

Figure 8. Plastic fish tanks with biofilter.
A 15 cm ruler is shown for size reference.

Fish feeding should start out slowly and increase over two weeks to the level of about 6.5 tablespoons of feed (42 g) per day. This is a rough estimate, as the fish determine how much they want to eat. The slow increase should allow for the growth of bacteria, which are recruited from the environment to detoxify the water. Fish are fed twice daily; once in the mid-morning when water temperatures begin to rise and once in the evening. The best way to determine feeding amounts is to feed fish the predetermined amount, and then ten minutes after feeding, count the number of particles remaining. If 5-10% of the feed remains after 10 minutes, the meal size should be kept the same; if more than 10% is left over, the meal size should be decreased; if less than 5% is left over, the meal size should be increased. Iron chelate (1/8 teaspoon) must be added weekly to each raceway.

Water quality should be tested twice a week so that toxicants such as ammonia and nitrite could be monitored to ensure they are declining as biofilter bacteria grow. We use a YSI 55 DO meter to test our water; it is expensive but DO is very important in aquaponics. Dissolved oxygen must be kept above 5 mg/L in the fish tanks for the fish to feed vigorously, and above 2 mg/L anywhere in the system to prevent denitrification from occurring. We use a portable pH meter (Pinpoint; American Marine Inc, Ridgefield, CT, USA) in the field and generally aim to keep the pH above 6.0. If it falls below, we add potassium carbonate to the water at a level of 1 teaspoon for every 80 teaspoons of feed fed to remediate pH. We have found that feeding slows or stops if pH is too low. Total ammonia and nitrite may be measured using inexpensive API or Tetra kits, though Hach and LaMotte kits are more accurate and should be considered the gold standard. Total ammonia may be converted to unionized ammonia by using the Henderson-Hasselbach equation:

$$pH = pK_a + \log(\text{unionized ammonia}/\text{total ammonia})$$

pH is measured and pK_a is 9.25 for ammonia. Total ammonia or TAN (total ammonia nitrogen) is measured using the kit. Once the unionized ammonia value is calculated, it must be kept in mind that 1.46 mg/L is lethal for tilapia (Evans et al. 2006). Nitrite values must be multiplied by 0.31 to get nitrite-nitrogen. A level of about 16 mg/L is lethal for tilapia (Lewis et al. 1986). Nitrate-nitrogen may be determined using Salifert kits, though Lamotte kits (LaMotte Company, Chestertown, MD, USA) are more accurate but unstable. Good levels in the fish tank are about 47 mg/L but when the water is flowed, it becomes diluted; we have had successful aquaponics trials with nitrate-nitrogen at 15 mg/L. Bioremediating bacteria and nutrient levels should stabilize after about a month. Levels of toxins should be low.

If you experience any issues, use the checklist on the following page to ensure your system is functioning properly.

<u>AQUAPONICS 'BEST MANAGEMENT PRACTICES' CHECKLIST</u>

1. **Are your plants in the sun?** *Plants grow by photosynthesis, which requires light of at least 30,000 Lux. We use a light meter on farms where plants are not in direct sunlight, and don't bother with light determinations where plants are in the sun.*

2. **Are your fish tanks shaded?** *If not, algae can grow and use up the nutrients.*

3. **Are your fish feeding to satiety?** *We normally ask the farmer how much food the fish eat, and then conduct our 10 min satiety test. In all cases we have found that the fish were being underfed. This leads to fertilizer nitrate levels that are too low.*

4. **What is your nitrate nitrogen level?** *When these are low (<15 mg/L) there is probably some denitrification occurring; when this occurs, we use the DO meter to find low DO spots, which must be corrected.*

5. **Have you considered switching to a trickle gravel system?** *Our research has found these are more efficient systems that are easier to maintain.*

6. **How is your organic certification going?** *Organically certified vegetables sell for between $3 and $4 per pound. Prices are the largest determinant of profitability according to Tokunaga et al (2014).*

7. **Are your fish dying?** *If so, unionized ammonia or nitrite may be too high in the system, and biofiltration needs to be boosted.*

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