An Overview of Aquaponic Systems: Aquaculture Components

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Introduction

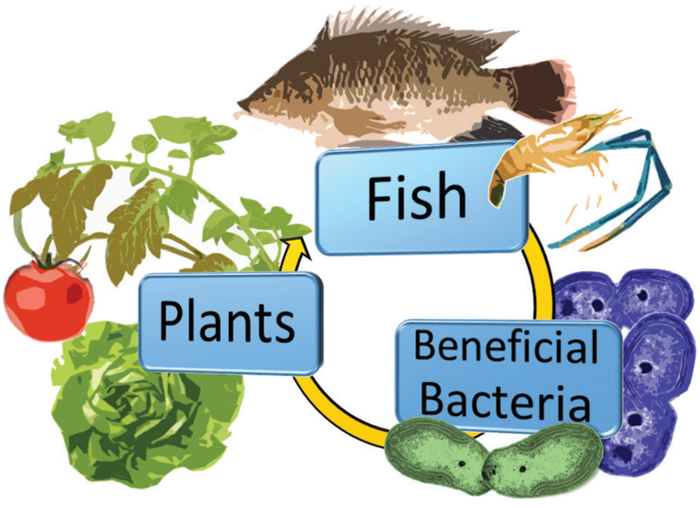
Aquaponics is an integrated production operation that encompasses recirculating aquaculture systems and hydroponics to produce fish and plants in a closed-loop system that mimics the ecology of nature. Simply said, the fish produce nutrient-rich effluent that fertilizes the plants, and the plants filter the water for the fish. Fish waste from the aquaculture portion of the system is broken down by bacteria into dissolved nutrients that plants then utilize to grow in the hydroponic component. This nutrient removal not only improves water quality for the fish but also decreases overall water consumption by limiting the amount released as effluent. The synergistic relationship of the fish and plants has created a popular perception of sustainability around aquaponics by the general public. Additionally, aquaponics can be scaled from a bench-top hobby unit to multi-acre commercial production facilities.

Advantages of this closed-loop system over conventional crop production methods include:

- reduced land area requirements,
- reduced water consumption,
- accelerated plant growth rates,
- year-round production in controlled environments,
- operational efficiency with shared equipment,
- reduced or eliminated effluents, and
- multiple crops produced simultaneously.

High-value herbs, vegetables, and leafy greens, as well as fish, crayfish, worms, and a number of other products can all be produced, which the producer can use to meet a highly diversified market. Because aquaponics is a closed-loop system, nutrient effluence is virtually non-existent, allowing agriculture to take a large step toward environmental sustainability. Moreover, fish, plant, and waste solids can all be captured and converted into fertilizer products for additional sale. These benefits make aquaponics a viable option for gardeners and producers who have limited space or reside in cities, giving more people access to locally-produced, healthy foods.

Hydroponics and recirculating aquaculture evolved as separate disciplines for decades before aquaponics was discovered, meaning there is very little specialized equipment for aquaponics. For information on system design for aquaponics, please refer to the North Central Region Aquaculture Center publication "An Overview of Aquaponic Systems: Hydroponic Components" (NCRAC TBS 0123) https://store.extension.iastate.edu/Product/15111.



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Aquaculture System Components

There are several basic components required for an aquaponics system to run effectively. Recirculating aquaculture systems (RAS) are self-contained growing environments for producing aquatic organisms. Price, components, functionality, and production capabilities can all vary greatly in RAS, but all systems must have a place for solids removal, biological filtration, water flow, and for the culture animals to live. Examples of recirculating aquaculture system components are illustrated in "Intensive Aquaculture Systems – Managing Iowa Fisheries" (PM 1352F) https://store.extension.iastate.edu/Product/4761. The aquaponic system designed and used at Iowa State University can be seen in Figure 1. A general overview of RAS components (not fully inclusive) is presented in the following text.

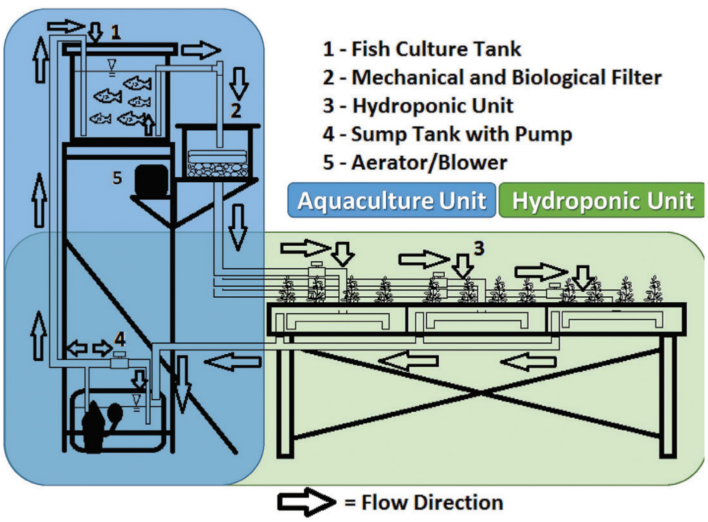

Figure 1. Schematic representation of the aquaponic units used at Iowa State University.

Culture Tanks – The culture tank is where the fish live during their growth to the desirable market size. In aquaculture, there are three main stages of fish production: Phase 1–Hatchery, Phase 2–Nursery, and Phase 3–Growout. As the fish grow their requirements for space, food, water quality, lighting, flow, and other factors will change. It is important to maintain good water quality, adequate oxygen levels, ideal flow rates, and waste removal in this area. Water quality is related to chemical components in the water such as ammonia and nitrite, as well as elements needed for respiration, namely oxygen. For information regarding water quality, see "Water Quality – Managing Iowa Fisheries" (PM 1352A) https://store.extension.iastate.edu/Product/4756, "Water Quality Management for Recirculating Aquaculture" (FA 0003A) https://store.extension.iastate.edu/Product/14271, and "Standard Operating Procedures – Water Quality Management for Recirculating Aquaculture" (FA 0003B) https://store.extension.iastate.edu/Product/14272.

Generally, there is a direct relationship between fish size and tank size (i.e., small fish should be grown in small tanks). Also, the volume of water available to the fish directly affects the dilution of potential toxins in the water as well as the stability of water temperature and other water quality parameters; typically, the more water available to the fish the better. The shape and materials used for the culture tanks may be different depending on fish species, space limitations in the building, flow regime requirements, grading, sorting, and harvesting needs, and other factors (Table 1). The cost of these tanks depends on source materials (Table 2).

Table 1. Culture tank shape.

Type	Quality Grade	Pros	Cons	Cost
Round	Depends on materials and design	Aids waste removal Promotes swimming fish	Space inefficient Difficult to grade and harvest	Depends on materials
Square/ Rectangular	Depends on materials and design	Space efficient Easy to grade and harvest	Some fish cannot adapt to tank corners Flat surfaces cause injuries to swimming fish Solids tend to collect in corners of tanks causing water quality issues (i.e. dead zones)	Depends on materials
Elliptical	Depends on materials and design	Compromise between square and round tanks More space efficient than round tanks Promotes swimming fish Easy to grade and harvest	Moderate solids removal ability	Depends on materials

Table 2. Culture tank materials.

Material	Grade	Pros	Cons	Cost
Plastic/ HDPE (High Density Polyethylene)	Moderate	Light weight Widely available/pre-manufactured Non-corrosive HDPE is food safe UV resistant Cleanable	Size limited by material strength Rectangular tanks can deform due to water weight	Moderate
Fiberglass	High	High strength Can be used for any tank shape Can be purchased as modules for easy shipping Modular design allows for variable tank size Non-corrosive with gel coating Cleanable	Can degrade when exposed to UV light Non-gel coated fiberglass will cause skin irritation for workers	Moderate/ High
Stainless Steel	High	Durable Food safe Cleanable	Expensive Will corrode when exposed to salt water	Very High
Lined Structures	Low	Relatively inexpensive Adaptable to culture needs Good for do-it-yourself systems Generally non-corrosive	Non-food grade materials may leach chemicals into the culture water Structure construction and materials affect durability Difficult to clean	Low/ Moderate

Aeration – The process of aeration agitates the water, creating a large surface area for contact between air and water, thus enhancing gas exchange. The smaller the bubbles, the greater gas exchange that can occur. Aeration should be provided in the culture tank to aid the removal of carbon dioxide (CO_2) and increase the dissolved oxygen (DO) concentration. Aeration is typically supplied with a blower that pushes air through a porous sand or ceramic block called an air stone. Air bubbles can make some fish species feel hidden and more comfortable, while improving feeding behavior.

It is also necessary to provide a cover to prevent fish from jumping out of the tanks; some fish, like tilapia, are powerful jumpers and given the opportunity will escape to their demise. Using a heavy lid made of waterproof material that covers the tank completely is ideal. However, gas exchange is important for fish respiration, thus leaving small gaps to retain the fish while allowing air to get in and out is necessary. This can be done with plywood, foam insulation, or by attaching plastic mesh to a polyvinyl chloride (PVC) frame (Figure 2) to cover the tank. A mesh covering allows easy access for feeding and gas exchange, while an opaque cover will reduce sunlight penetration into the tanks decreasing stress on fish, reducing algae growth, and reducing temperature fluctuations due to solar inputs. A combination of lid types may be preferable.

Figure 2. Culture tank with a mesh covering.

Waste Management – Solid waste removal is critical for maintaining high water quality for the fish to live and grow. There are many solids removal techniques that include the dual drain method, bottom drain, side drain, and solids lifting outflow. The Iowa State aquaponics system (Figure 1) is only one of many designs that may be used to successfully raise fish and plants. See the reference section for more information of alternative aquaponic system designs.

A solids lifting outflow (SLO) design is used in the system shown in Figure 3, which consists of a PVC pipe that extends from the desired water depth down to approximately 0.5-1 inch (15-25 mm) from the bottom of the tank. This will allow settled solids to be removed without letting the fish escape. Outside the culture tank it is critical that a PVC tee be installed with the open end pointed up, and a PVC pipe pointed down toward the filter tank. Some systems put the tee on the inside of the tank to help with clogging issues, but care should be taken to prevent fish from escaping through the top opening. The open tee will prevent a siphon from forming, which could, inadvertently, completely empty the fish tank and kill the fish.

Figure 3. Soilds lifting ouflow.

A larger piece of PVC pipe can be slipped over the outflow, resting on the mechanical filter pad to prevent excessive splashing and unnecessary evaporation. An added benefit of this splash cover is that it gives the effect of a protein skimmer, reducing the waste load of the water and allowing for heavier feeding rates if desired.

A protein skimmer, or foam fractionator, is a device that uses the sticky nature of protein to create bubbles in the culture water. As the bubbles rise, they climb up between two closely-spaced surfaces by capillary rise, allowing the protein to escape the water. The protein removed from the water can be seen as a brown film collecting on the PVC pipes in Figure 4.

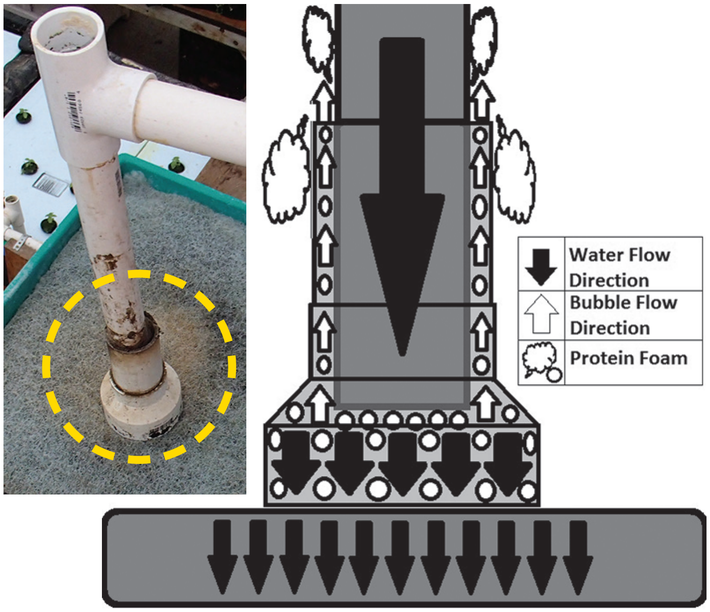

Figure 4. Protein skimmer (foam fractionator) above the solids filter pad.

An emergency overflow (Figure 5) should be installed at a slightly higher elevation than the primary outflow; the water directed back to the sump to prevent water loss should the outflow become clogged or if the pump flow rate is too great. The overflow is pictured as the gray, upward pointing elbow piece in Figure 5. This outflow may require a screen

Figure 5. Culture tank plumbing including an emergency water overflow.

cover with a mesh to prevent feed and fish from flowing back into the sump. A .125 to .25 inch (3-6 mm) mesh is recommended to retain feed while still allowing water to flow freely.

Solids Filtration – In RAS, it is necessary to use a complete feed with adequate protein and lipid levels to promote fast growth rates. Unfortunately, fish are not able to fully utilize the feed; approximately 25-50 percent of the feed will become waste that must be removed from the system quickly to prevent degradation in water quality. These waste solids range in size from less than 10 microns (dissolved solids) to 30-100 microns (suspended solids) to over 100 microns (settleable solids). Each of these particle sizes vary in their removal methods, some of which are described in Table 3. If solids are not removed, bacteria will break down the feed causing an oxygen deficit that can kill the fish and beneficial bacteria in the biofilter. It can also cause a release of ammonia, which is directly toxic to the fish. To remove these solids, filters have been developed that can serve both to remove the actual solids as well as perform the services of a biofilter, enhancing operational efficiency of the RAS.

Table 3. Solids filtration systems used in recirculating aquaculture systems.

Type	Quality Grade	Pros	Cons	Cost
Suspended solids filtration				
Bead/sand filter	Moderate/ High	Excellent filtration Doubles with biofiltration	Frequent back-flushing/ maintenance	Moderate/ High
Filter pads	Low/ Moderate	Inexpensive	Frequent maintenance Moderate effectiveness	Low
Microscreen rotating drum filters	High	Handles large water volumes Very effective Self-cleaning	Expensive	Very High
Radial flow settlers	Moderate/ High	Simple design Very effective	Availability	Moderate
Swirl separators	Moderate	Simple design	Moderate effectiveness	Moderate
Quiescent zone settlers	Low/ Moderate	Simple design	Space requirements Cleaning required	Low
Dissolved solids filtration				
Foam fractionators/ protein skimmers	Moderate/ High	Relatively simple design Low maintenance	Expensive Not very effective in fresh water	Moderate/ High
Cartridge filters	Moderate	Simple	Maintenance	Moderate
Ozonation	High	Extremely effective Oxygenates water Kills pathogens	Potential biological hazard Corrosive Expensive	High

There are many types of mechanical filters: inexpensive filter pads that must be cleaned by hand, passive water clarifiers, fluidized sand and bead filters that combine solids and biological filtration, and high-volume and high-cost-self-cleaning-micro-screen drum filters. Each of these systems have their advantages for filtering capacity, maintenance, and cost. Filter pads such as those used in industrial air handling units (Figure 6) are a cost effective solution, but require daily cleaning. At higher fish capacities and feeding rates solids must be cleared from the filter more frequently and automated filters may become necessary to reduce labor costs.

Figure 6. Solids filter pad material.

Biological Filtration – A biological filter takes advantage of bacterial processes to convert toxic byproducts of fish feeding into non-toxic forms that can be used by plants. The biofilter consists of a substrate where beneficial bacteria (e.g. Nitrosomonas spp., Nitrobacter spp. and others) can grow in high densities with high exposure to water and air for the conversion of toxic ammonia and nitrite to nitrate. This biological breakdown process is limited by surface area for bacterial attachment, temperature, dissolved oxygen, alkalinity, pH, availability of ammonia and nitrite, and other factors. Most biological filters use a high surface area medium that is resistant to breakdown and allows space for water flow and gas transfer to maximize toxin conversion. Some biological filters can serve dual purpose as either solids filtration or degassing chambers in addition to toxin conversion, which enhances operational efficiency.

There are many choices for biofilter design and substrate material, with some mechanical filters also functioning as the biofilter. The best choice is usually the least expensive and lightest weight product that will allow for water and air to pass through without clogging. An effective biofilter solution can be PVC ribbon, which is cheap and light weight with high surface area.

Table 4. Types of biological filtration used in recirculating aquaculture systems.

Type	Quality Grade	Pros	Cons	Cost
Bead/Sand filters	Moderate/ High	Operational efficiency with solids filtration	Frequent backwashing	Moderate/ High
Fluidized bed biofilter	High	Extremely effective	Can go anoxic if aeration or water flow fails	Moderate/ High
Trickling bed biofilter	Moderate	Effective Simple	Can go anoxic if aeration or water flow fails	Moderate
Rotating contact biofilter	Moderate/ Low	Effective	More likely to break down	Moderate

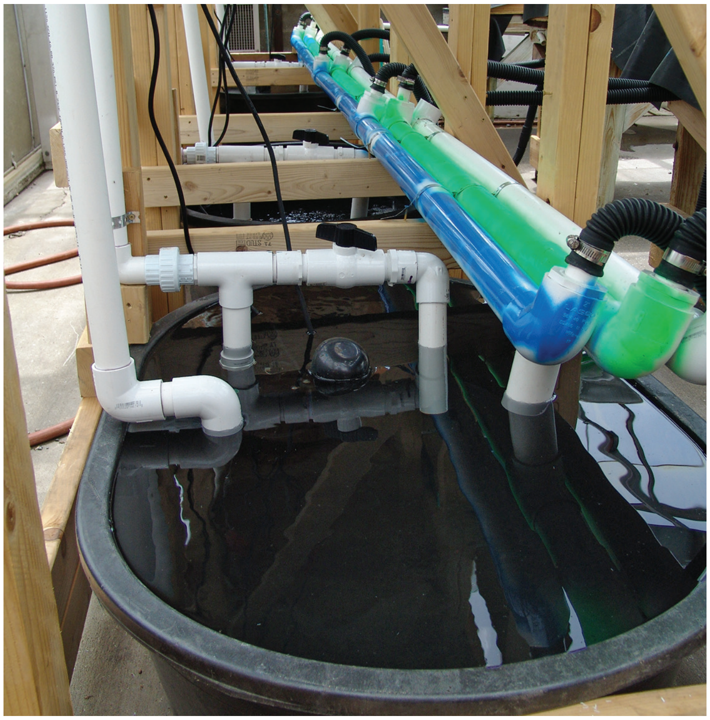

Figure 7. Sump tank with pump.

Sump Tank – The sump tank is the ultimate collection area for water that flows by gravity and is located at the lowest elevation in the entire system. The sump tank (Figure 7) is also a reservoir that generally contains no plants or fish and is a good addition point for mixing chemical and nutrient additives that must dissolve before entering the system. Additional biofilter substrate or cleaner fish like mosquito fish, redear sunfish, or juvenile tilapia can be added into the sump tank if needed, but should be guarded from the pump intake. In the Iowa State system the sump tank contains the pump, which is the starting point for moving water among the various system components. There are many options for pumps, but two of the main types used in aquaponics are impeller pumps and airlift pumps.

Pumps – Pumps are used for moving water among the various system components. There are many methods for moving water and many engineering considerations that should be incorporated into system design in order to maximize efficiency. The flow dynamics of water should be considered in conjunction with sizing a pump. For example, the water flow velocity is important to keeping pipes clean on the inside, and the height of water movement (head pressure) will affect the total flow rate that a pump can yield.

Table 5. Pumps used in recirculating aquaculture systems.

Type	Quality Grade	Pros	Cons	Cost
Submersible impeller	Moderate	No need to cut holes in tanks	Lower live expectancy Risk of water contamination if pump seals fail	Moderate
Inline impeller	High	Efficient at moving water Longer life expectancy	Requires more plumbing	High
Airlift	Low	Simple No moving parts Operational efficiency with aeration	Less effective at moving water Major height limitations	Low

Figure 8. Submersible impeller pump with waterfall aeration.

Impeller pumps use the centrifugal force of an impeller within a chamber with a single inflow and single outflow to create water flow. Generally, impeller pumps are run by electricity but there are models that run off fuel combustion if electricity is unavailable. Because these pumps run on electricity it is imperative that the electrical components are waterproof. Impeller pumps come in submersible and in-line models, but run on the same principle. The electrical components of submersible pumps (Figure 8) are sealed inside either a plastic or insulated metal housing. A benefit of submersible pumps is that they will never lose access to the water they pump unless the sump tank runs dry. In-line pumps (Figure 9) tend to have a longer running life and offer more options for volume and pressure ratings than submersible pumps. However, in-line pumps must be primed before moving water, and depending on how it is installed, loss of prime, especially during electrical outages, may be a major issue

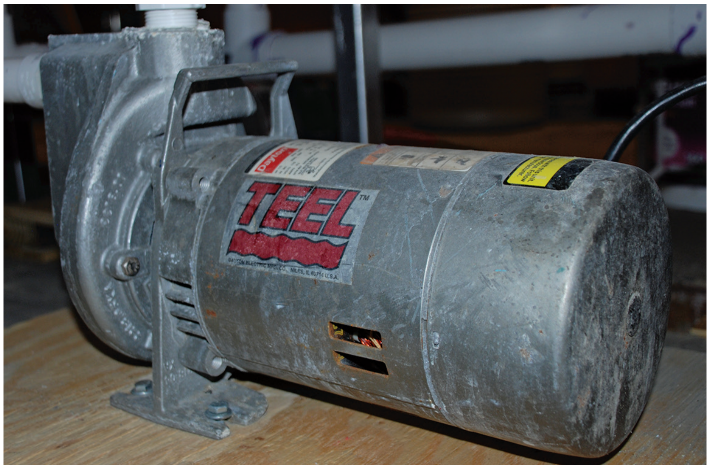

Figure 9. In-line impeller pump.

Airlift pumps (Figure 10) move water through the use of air bubbles. A simple airlift pump will inject air into a pipe that is submerged in the water, and the rising bubbles force water through the pipe. Airlift pumps are efficient because of the dual action of aeration and water movement. Another advantage to using an airlift system is the air supplied by the blower can be used to supply aeration to the deep-water culture unit. Airlift pumps work well for creating directional flow, but are generally limited in pumping height (<2 ft or 60 cm), and may not be useful for some applications. However, there have been advancements in airlift technology that may allow them to move water vertically up to 20 feet (6 meters) in elevation.

Figure 10. Airlift pump.

Plumbing – Plumbing is used to transfer water among the system components, and can be a range of sizes and materials depending on the purpose (Table 6). PVC is extremely common in recirculating aquaculture systems because it is rigid, light weight, relatively inexpensive, easy to work with, and widely available. Vinyl tubing may be used in small applications that are not under high pressure. Steel is the strongest pipe material and may be appropriate for some applications, however steel is extremely susceptible to rust and corrosion when exposed to salt water. Copper is commonly used in home applications because of its innate anti-microbial properties, and ability to handle very high water temperatures. Copper is expensive, requires skill to plumb together, and can cause toxicity issues to invertebrates like crayfish, shrimp, and prawns.

The pipe diameter should be sized appropriately for the volume, pressure, temperature, and head loss of the water that will be experienced in the different areas of the system. Pressurized water pipes should always be glued together, and are typical of the inflow section to the culture tank and some solids filters. Non-pressurized drain lines should be sized larger than the pressurized lines to ensure they can handle the flow rate needed without clogging and causing overflows. The diameter of the pipes should be designed to eliminate biofouling, while still creating the desired flow rates to the tanks.

Table 6. Plumbing systems used in recirculation aquaculture systems.

Material	Quality Grade	Pros	Cons	Cost
PVC	Moderate/ High	Widely available Relatively inexpensive Low skill requirement Durable	Biofouling possible Not UV resistant. Will break down in sunlight.	Moderate
Vinyl	Low	Widely available Relatively inexpensive Convenient	Low durability Not rated for high pressure	Low
Steel	High	Durable Handles high heat High heat exchange	Easily corroded	High
Copper	High	Antimicrobial/non-biofouling Heat tolerant Durable	Biohazard to invertebrates Requires skilled plumber Expensive	High

Gas Exchange, Aeration, and Oxygenation

Gas exchange is the process of adding or removing chemical components that are dissolved in the water, and is critical in recirculating aquaculture. Oxygen is critical to the biological processes in recirculating aquaculture, both in fish and beneficial bacteria. High dissolved oxygen levels promote nitrogen processing and nutrient uptake in the plant roots. Air is typically injected as small bubbles via airstones (Figure 11) in the fish tank and hydroponic unit. Free aeration should be taken advantage of whenever possible; this includes waterfall action from a pipe into a reservoir (Figure 8), trickling water over filter pads, and biofilter substrate. Additionally, the removal of potentially toxic gasses like carbon dioxide (CO_2), nitrogen gas (N_2), hydrogen sulfide (H_2S), and others can be done through gas exchange. Aeration is the process of creating high amounts of air to water contact. This is typically done through injecting air into the water through a diffuser (porous media) or by dropping water through the air. The more surface area exposed between the air and the water in this process, the more gas exchange. Keep in mind the water will become more like the air that it is exposed to, so if oxygen is high in the air, then it will be high in the water, but the same is true with carbon dioxide, which will tend to build up in buildings that do not have good ventilation. Carbon dioxide is a heavy gas that will tend to settle near the floor. Extra caution should be taken to vent out carbon dioxide from a recirculating aquaculture system.

Air injection into the water can be done many ways (Table 7). For high volume, low pressure applications, a blower is recommended. Blowers are limited by depth of water and function best in less than three feet (0.9 m) of water. Compressors overcome the depth limitation by creating high pressure air, but are limited by volume. Compressor systems are generally used in ponds for vertical mixing of the water rather than gas exchange at depths greater than eight feet. A venturi is an air injection system that takes advantage of vacuum suction created by pressurized water movement. Essentially, a venturi nozzle sucks air into the water flow stream creating tiny bubbles and efficient gas exchange. One concern with venturi systems is the potential for supersaturation of a gas under high pressure in the water that can come out of suspension in the fish’s blood, leading to gas bubble disease.

Conversely, water can be sprayed or dripped into the air for gas exchange. A propeller or agitator style unit forces a disruption at the air-water interface to promote gas exchange. Fish must be excluded from this area as they can be damaged by the blades of the unit. A degassing tower uses a controlled waterfall effect over a rigid and porous substrate to create tiny water droplets. These are very effective and relatively inexpensive. These methods do cause a good amount of evaporation and humidity in the air, which can cause issues with corrosion and breakdown of equipment or structures as well as potential for mold.

Oxygenation is a process of increasing the dissolved oxygen of the water by injecting pure oxygen into it. This allows the water to stay clear and calm while providing high oxygen levels, which can aid in solids removal. A major concern with pure oxygen injection is the potential for supersaturation and formation of gas bubble disease in fish. Additionally, pure oxygen can be quite expensive.

Ozonation is a process of running an electric current in contact with pure oxygen to create the ozone molecule. Ozonation has the three-fold benefit of destroying dissolved organic molecules from the water as well as microbial pathogens, and providing high dissolved oxygen levels in the water as it breaks down from O_3 to O_2. However, because of ozone's strong oxidative power it poses a risk to fish, beneficial bacteria, humans, and to the equipment itself. It is critical to work with an engineer to develop an ozonation process that will have a high level of safety for the system.

Table 7. Aeration and oxygenation types used in recirculation aquaculture systems.

Component	Type	Quality Grade	Pros	Cons	Cost
Aeration	Blower	High	Energy efficient Heat produced can be redirected to warmwater fish	Expensive Uses electricity Depth limited Loud	High
	Compressor	High	Allows for larger and deeper tanks	Expensive Uses electricity Air volume limited Loud	High
	Venturi	Moderate	Operational efficiency when used with multi-use pump	Potential for supersaturation and fish disease	Moderate
	Agitator/ Propeller	Moderate/ High	Efficient in O_2 introduction and CO_2 removal Typically emergency use only	Evaporation Degrades in humidity Expensive Uses electricity Hazard to fish	Moderate/ High
	Degassing Tower	Low/ Moderate	Safe Efficient No/little extra energy usage Relatively inexpensive	Evaporation Humidity	Low/ Moderate
Oxygenation	Liquid Oxygen	High/ Moderate	Very effective Widely available	Expensive Potential for supersaturation and fish disease	High/ Moderate
	Ozonation	High	Very effective Operational efficiency gained	Expensive Potential biohazard	High

Air can be added to the water through an aerator (low volume, low pressure), blower (high volume, low pressure) or compressor (high pressure, low volume). Aerators are relatively inexpensive, but volume limited. Blowers are more efficient, but they do not produce enough pressure to push air more than three feet (0.9 m) down into a water column. A compressor is needed to force air deeper than three feet, but it is more expensive to operate and doesn't provide as much air volume.

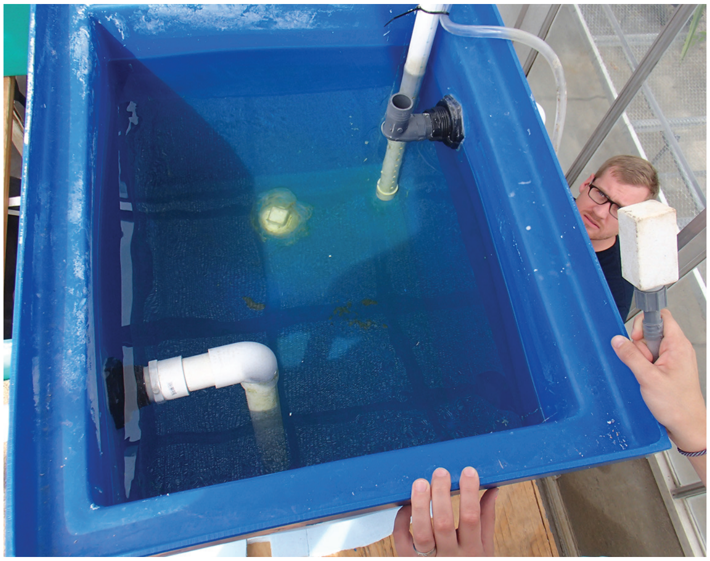

Figure 11. Airstone for the culture tank.

Water Management

Source Water – Source water is an important consideration in any aquaculture system. The water source utilized (e.g., groundwater, surface runoff, rainwater collected, or municipal source) will determine the management practices appropriate for treating the water prior to entering the system. For more detailed information about water quality see ISU Extension and Outreach publications "Water Quality Management for Recirculating Aquaculture" (FA 0003A) https://store.extension.iastate.edu/Product/14271, and "Standard Operating Procedures – Water Quality Management for Recirculating Aquaculture" (FA 0003B) https://store.extension.iastate.edu/Product/14272.

Municipal (city and rural) water may be relatively cold with a high pH and chlorine including chloramines. A head tank (Figure 12) provides a staging area where the municipally-sourced water is allowed to warm to the ambient air temperature and the water is dechlorinated. There are two main types of chlorination that many water treatment facilities use—chlorine and chloramine. Chlorine gas is odorous and unstable in water, and can be aerated out of the water overnight. Chloramine is an odorless molecule that is very stable in water and must be broken down into its components of chlorine and ammonia by compounds such as sodium sulfite or sodium thiosulfate. Both chlorine and ammonia are toxic to the fish and must be processed prior to being introduced into the system. Concerns specific to the use of sodium sulfite or thiosulfate includes lowered DO and pH levels, and release of ammonia from the dechlorination process; therefore water quality must be measured prior to introduction into the aquaponic system.

Figure 12. Head tank with covering to prevent algae.

Some municipalities may artificially alter water pH. An incoming water pH of 9.0 will make many nutrients in the water unavailable for plant uptake. Therefore, food grade phosphoric acid, which can provide a plant macronutrient, may be added to the head tank to adjust the water pH to the optimal range of 6.5-7.2. Ammonia toxicity is affected by pH also, with higher pH (>7.0) causing more ammonia to remain in the toxic NH_3 form rather than the relatively non-toxic NH_4^+ form. Some fish, particularly Barramundi, are sensitive to changes in pH, so extreme caution should be used when altering pH. Gradual changes over several days will help prevent stress and disease.

Sunlight, warm temperatures, and nutrients in the water can cause algal growth that can steal nutrients from the plants of interest or cause biofouling and water quality issues. Therefore, it is beneficial to use an opaque container with a lid to prevent light penetration and algae growth in the head tank.

Water Temperature Control

Fish growth and beneficial bacterial efficiency are directly related to temperature. Each species has a range of temperatures that can be tolerated, with an optimal temperature that should be achieved consistently for maximum growth rates. Heating and cooling of the water may be necessary to achieve this optimal temperature. It is important to be mindful of the energy costs associated with raising or lowering water temperatures, especially in regard to the surrounding environment. Temperature is much easier to control in a well-insulated building that does not receive solar inputs. Seasonal variation in temperature can make the difference of profitability for a business, especially in temperate climates. The fish species should be matched with the prevailing temperatures to achieve maximum efficiency.

Heaters and chillers work by surface-to-water contact to exchange heat. Modifying the air temperature to match the desired water temperature will make temperature regulation much faster and more efficient. Consider the source of heat and its cost relative to other options at different times of day and throughout the year to reduce costs associated with heating and cooling. Additionally, renewable energy sources like geothermal, solar, and wind may be more sustainable in the long-term, but can have high installation and operational costs that can be offset by some government programs.

Boiler systems use a counter current exchanger to transfer heat between one source and another. The heating source could be from woody biomass or other waste products to enhance sustainability. As an ecologically friendly method of temperature regulation, geothermal heating helps stabilize the water and air temperature relatively close to that of ground water, 54-58°F (12-15°C), thus reducing heating costs for winter.

Many plants, especially lettuce, produce leaves best at temperatures of 60-65°F (15-18°C). These temperatures are quickly exceeded during summer months in a greenhouse, causing the plant to go to seed at 70-80°F (21-27°C), rendering the crop unmarketable. Cooling the water can be important in a greenhouse setting or in other hot growing conditions. Chilling is done either through evaporation, compression, or heat exchange. Refrigerator units cool the water through contact between cool surfaces; inline or drop-in units are available. Some greenhouses use misters or evaporative coolers to reduce temperatures and regulate humidity. Geothermal cooling works the same as heating by stabilizing the water and air temperature relatively close to that of ground water, 54-58°F (12-15°C), reducing cooling costs for summer.

Table 8. Water temperature control systems used in recirculating aquaculture systems.

Type	Quality Grade	Pros	Cons	Cost
Water heating				
Boiler with heat exchanger	High	Self-contained system Adaptable heating sources	Requires external heat source	Moderate/High
In-tank heating element	Moderate/High	Effective	Localized effectiveness (needs flow)	Moderate
Ambient air heater	Moderate	Effective Adds efficiency to other heating programs	No direct heat to water Questionable sustainability	Moderate
Solar water heater	Moderate	Renewable energy	New technology Influenced by seasonal changes	Moderate/High
Geothermal	Moderate/Low	Requires little to no energy Unlikely to break down	Limited temperature change Expensive to install	High
Water cooling				
Inline chiller	High	Self-contained system	Prone to freezing up	Moderate/High
In-tank chiller	Moderate	Less freezing hazard	Localized effectiveness (needs flow) Less efficient	Moderate
Geothermal	Moderate	Requires little to no energy Unlikely to break down	Limited temperature change Expensive to install	High

Water Sterilization

Pathogens are a concern for plant, fish, and human welfare. Because fish waste comes in direct contact with the plant roots, there is potential for cross contamination of the product. Good agricultural practices (GAPs) can help reduce the contamination risk. Clean water that is free of pathogens is ideal for growing fish at their optimal rate. Because of the continuous reuse of water and close quarters of the fish produced in recirculation systems, diseases can spread quickly. Because sick fish do not eat there is high potential for water quality degradation as well, especially in highly automated systems. Ultraviolet irradiation and ozonation have been used in aquaculture operations (Table 9).

Ultraviolet irradiation is an effective method of killing single-celled microorganisms that are present in the water column (Figure 13). An ultraviolet light (UV) sterilizer is a tool that is used to reduce pathogen loads in the water. In RAS systems UV sterilizers are commonly used in combination with ozone to kill pathogens. UV requires a certain amount of exposure time to microbes to be effective, thus flow rate is very important. UV is not very effective for larger organisms or when the water becomes turbid. Additionally, UV bulbs degrade over time and should be replaced on a regular schedule.

Ozonation is a process of running an electric current in contact with pure oxygen to create the ozone molecule. Ozone is a highly reactive and corrosive oxidizing gas that destroys organic matter, including bacterial and viral pathogens. Ozone has the three-fold benefit of destroying dissolved organic molecules from the water as well as microbial pathogens, and providing high dissolved oxygen levels in the water as it breaks down from O_3 to O_2. However, because of ozone's strong oxidative power it poses a risk to fish, beneficial bacteria, humans, and the equipment itself. Ozone proves to be particularly dangerous when used in saltwater systems because it reacts with bromide in the water, which may create toxins. It is critical to work with an engineer to develop an ozonation process that will have a high level of safety. Additionally, ozone production requires expensive specialized equipment. It is recommended that UV is used in conjunction with ozone after it is injected because the UV breaks down O_3 to O_2. Careful calculations of ozone are demanded, and monitoring ozone concentrations will help reduce risk. ISU Extension and Outreach publication "On-farm Food Safety: Guide to Good Agricultural Practices" (PM 1974A) https://store.extension.iastate.edu/Product/6539 covers some considerations for on-farm food safety GAPs.

Figure 13. Ultraviolet light sterilizer.

Table 9. Water sterilization systems used in recirculating aquaculture operations.

Type	Quality Grade	Pros	Cons	Cost
Ultraviolet Irradiation	Moderate	Less expensive Deactivates ozone	Many factors affecting effectiveness	Moderate
Ozonation	High	Very effective	Expensive	High

Environmental Systems Monitors and Controls

Environmental monitoring is critical to success in recirculating aquaculture. This may be done manually by facility managers or remotely though monitors. The ability to know the status of a system in terms of electricity, temperature, water quality, humidity, and security may be considered a luxury for small operations, but is a necessary exercise in risk management for larger facilities. Not only do these meters provide peace of mind to a facility manager, they also can reduce long-term labor costs associated with continuous monitoring of the water. Many automated monitoring systems provide an alarm system to alert facility managers to potential hazards, and some give managers the ability to alter the growing environment from their smart phone or computer (Table 10). Additionally, a backup generator that automatically engages in the event of a power outage will save fish, but an additional failsafe of automatic oxygen diffusion into the tanks during an outage should be worked into the contingency plan.

Table 10. System monitors and controls.

Type	Quality Grade	Pros	Cons	Cost
Hand-Held Meter	Moderate	Convenient Promotes frequent tank inspection	Requires manual use	Moderate
Fixed Position Meter	High	Convenient	May discourage worker attendance	Moderate/ High
Remote Sensing Meter	High	Convenient	May discourage worker attendance	High
Alarm System	Moderate/ High	Risk Management	May discourage worker attendance	Moderate/ High
Data Logging Sensor	High	Long-term data available	May discourage worker attendance	Moderate/ High

Water Quality Analysis

It is critical to monitor and manage water quality on a continuous basis when growing fish at high densities. Unlike other forms of livestock production, it is difficult for humans to sense when environmental conditions are out of their desired range before it is too late. Dissolved oxygen, pH, temperature, ammonia, and nitrite are measured at least once daily, or even more if an issue is suspected. As fish feed, oxygen, and pH levels fall, carbon dioxide and ammonia levels increase. Intensive management of water quality to mitigate these changes is necessary to ensure fish survival.

There is a variety of testing equipment on the market for a variety of price points (Table 11). Generally, the higher the cost of the unit, the more accurate it will be, but the accuracy of the test is only as good as the skill of the person performing the test. Although accuracy is desired, one should not sacrifice consistency for accuracy. Trends in water quality can help a fish farmer predict upcoming issues and react to them before they put the fish's lives in danger.

Table 11. Water quality testing options.

Type	Quality Grade	Pros	Cons	Cost
Manual Chemical Analysis	Moderate	Fairly accurate	Fairly expensive Time consuming	Moderate/ High
Spectrophotometry Chemical Analysis	High	Accurate Convenience available at a cost	Expensive Can be time consuming	High
Test Strips	Low	Easy Fast Convenient Inexpensive	Inaccurate	Moderate/ Low

Water Testing Equipment

Key water quality parameters like dissolved oxygen, pH, and temperature should be tested daily. There are less expensive, low-tech methods for testing: test strips, chemical analysis, and thermometers; as well as high-cost, high-tech probe meters (Figure 14) that collect data quickly and accurately. The quality and efficiency of each of these testing techniques are generally correlated with price, therefore they should be selected based on system size, materials, and labor budgets.

Figure 14. Measuring dissolved oxygen, pH and temperature with a water quality probe.

Critical chemical components such as ammonia, nitrite, nitrate, and alkalinity should be measured twice a week. Other components like CO_2, chloride, and iron should be tested every one to two weeks. Some chemical reagents used for water chemistry analysis are toxic and should not be consumed or poured down the drain, but rather disposed of properly. Contact a waste management service or wastewater treatment facility for details. As with other water testing equipment, there is a range of time and expense for each method and they should be selected based on system size, materials, and labor budgets. For more details on water chemistry management, see ISU Extension and Outreach publications “Water Quality Management for Recirculating Aquaculture” (FA 0003A) https://store.extension.iastate.edu/Product/14271 and “Standard Operating Procedures – Water Quality Management for Recirculating Aquaculture” (FA 0003B) https://store.extension.iastate.edu/Product/14272.

Culture Species Selection

When choosing a specific species one should consider the organism’s needs for temperature, salinity, and protein as these affect costs associated with growing, as well as their potential for incorporation into integrated systems such as aquaponics. Be mindful that regulatory complexities may exist for any given species (especially exotics), and that appropriate regulatory authorities should be contacted to ensure that all the proper permits are in place before importing products. Additionally, in terms of a startup facility and risk management, one should consider the ease (or difficulty) of culturing that organism. Some species are far too sensitive to variation in water quality to be considered viable for culture. Value of the product and markets must be considered in addition to all of the other aforementioned factors when formulating a business model around an individual species. Generally, as the ease of culture increases from low to high, the less system complexity that is necessary for successful production of a given species.

Aquaponic System Types

In general, there are two main types of aquaponics systems—coupled and de-coupled. Coupled, or balanced systems, work on the premise that the incoming feed to the fish provide the exact nutrient requirements for the plants being grown. In theory, each time the water passes through the plant culture unit the nutrients, namely nitrate, are scrubbed from the water, and feed additions are necessary to provide for additional plant needs. Variability in feeding time, feed volume, fish and plant size, temperature, pH, and water chemistry all play a role in the rate of nutrient uptake.

Coupled/Balanced Aquaponics

Coupled aquaponics systems (Figure 15) typically have a unidirectional flow of water starting in the fish culture unit, passing through a solids filter, biological filter, hydroponic unit, and sump tank before being pumped back to the fish, completing the cycle. The consistency of incoming feed, solids and biological filtration, and plant nutrient uptake are all critical to the continued and predictable production of products to market.

Fish feed generally contains 10 out of the 13 macro and micronutrients needed for plant growth, which is a huge benefit to producers. The three that are generally lacking include calcium, iron, and potassium, which may need to be supplemented. Because feed contains some ionic nutrients like phosphorus, a mineralization or digestion step is required to break it down and liberate all of the nutrients available. Often when a producer experiences yellowing of the produce it is due to nutrient deficiencies either from iron or other elements that are not fully broken down. Iron itself will precipitate out of solution as iron oxide unless it is chelated by a non-ionic binder like Ethylenediaminetetraacetic acid (EDTA). Generally, iron is added at 2 mg/L every two weeks in a balanced system.

Unfortunately, when dealing with biological systems, the theoretical process rarely holds true to observations. Because of the intimate balance of fish, bacteria, and plants

Figure 15. Overview of an aquaponic system. Photo by R. Charlie Shultz.

it is nearly impossible to treat any one of these components without affecting the others. For example, the use of salt for treating fish disease is a common and safe practice in RAS, but in aquaponics the influx of salt, particularly chloride, is a major disruptor of plant growth. Conversely, organic certified insecticides like neem oil can kill fish at high enough concentrations.

De-Coupled Aquaponics

De-coupled aquaponics systems provide separation between the fish and plant portions of the overall aquaponics cycle, providing contingencies for treatment of disease or catastrophic loss in one portion of the system without complete failure of the overall operation. A typical de-coupled system has a stand-alone RAS system whose effluent water drains into a collection area for use in the independent hydroponic system. With multiple water sources, the hydroponic unit can function with inputs from the RAS effluent or from a municipal source should issues with salt or other fish therapeutants arise. A de-coupled system helps eliminate the compromises in pH, temperature, and other water quality parameters that make a coupled system difficult to deal with. For example, the nitrifying bacteria that process ammonia into nitrate prefer a slightly alkaline pH of 7.0-8.5, whereas plants are optimized to absorb nutrients best at pH 5.0-6.5. In a de-coupled aquaponics system pH can be manipulated to optimize nitrification as well as plant growth. Additionally, the culture temperature of the fish no longer forces the producer to grow a particular species for that temperature range. If local market conditions dictate that a cold water fish species like trout is ideal, yet the plant market desires warm weather herbs like basil, both species can be optimized simultaneously without adversely affecting one another. Finally, if additional nutrients are required for a particular plant species, facility managers can manipulate the water as needed.

Conclusions

Aquaponic systems present a unique opportunity for year-round production of plants and fish. Out-of-season production of leafy greens, herbs, and vegetables can be a major source of income for aquaponic producers, as they can take advantage of much higher seasonal prices. The high quality and freshness of aquaponic produce is highly desired by chefs in metropolitan areas. If aquaponic producers can fill the seasonal gaps with fresh produce, buyers are more likely to keep them as a vendor, allowing producers to capture a larger market share. Additionally, the local foods movement and consumer willingness to pay more for a superior product is a major advantage to aquaponic producers.

Aquaponics can be done on a wide range of scales; from a bench-top aquarium for the hobbyist to a multi-acre commercial facility capable of producing substantial amounts of fish and plants per year. As in other agriculture operations, profitability in the aquaponics business model is related to scale and efficiency of production. Research conducted at Iowa State suggests that it may be possible to generate a profit when producing tilapia and basil in a greenhouse facility in Iowa. This system model demonstrates that the value of the fish (tilapia) produced has very little effect on profitability, but rather the price and amount of plants (basil) produced often determines economic viability.

Aquaponics may be an attractive opportunity for individuals wanting to change their lifestyle to a slower pace with a modest income. In a well-designed and efficiently run aquaponics facility, the ability to profit is greater as the plant growing area increases because of increased product output, efficient use of resources, stability of the system, and regularity of production. However, a larger facility does not necessarily mean more profit. One should consider supply and demand principles and wholesale versus retail pricing to determine the actual returns to the farmer. It is critical, therefore, for potential aquaponic farmers to do their due diligence in business planning and market research as well as hands-on education prior to investing in an aquaponics business to ensure success.

Written by D. Allen Pattillo, fisheries and aquaculture specialist with Iowa State University Extension and Outreach.

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Resources

Agricultural Marketing Resource Center http://www.agmrc.org

Aquaponics Association http://aquaponicsassociation.org

Aquaponics Journal http://aquaponicsjournal.com

ATTRA National Center for Appropriate Technology https://attra.ncat.org

Fisheries, Aquaculture and Aquaponics YouTube Playlist https://www.youtube.com/watch?v=xAudq28n8l0&list=PLyDHx-rmZpCljgr4za05H2eHKwmMhJYI1

ISU Extension and Outreach UKNOW How-to Videos https://www.youtube.com/playlist?list=PLpkEiJv9k6M28Ho_AyCky6AWzuC7ksaMM

ISU Extension Store http://store.extension.iastate.edu

Iowa State University Fisheries Extension http://www.nrem.iastate.edu/fisheries

North Central Regional Aquaculture Center http://www.ncrac.org

Southern Regional Aquaculture Center – Aquaponics Publication Series https://srac-aquaponics.tamu.edu

Sustainable Agriculture Research and Education Program http://www.sare.org

USDA – National Agricultural Library https://www.nal.usda.gov/afsic/aquaponics

University of Minnesota Aquaponics http://www.aquaponics.umn.edu/aquaponics-resources

Texas A&M Aquaponics http://fisheries.tamu.edu/aquaponics

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USDA United States Department of Agriculture

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