KENTUCKY STATE UNIVERSITY

AQUAPONICS
Production Manual

A Practical Handbook for Growers

Kentucky State University
Land Grant Program

JANELLE HAGER • LEIGH ANNE BRIGHT • JOSH DUSCI • JAMES TIDWELL

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About the Authors

Janelle Hager has nine years of experience working in aquaponics and six years of experience in AP research. She developed the first fully online aquaponics curriculum for both undergraduate and graduate students at KSU (AQU 452/552). Her research focuses on finding practical solutions to improve aquaponic practices for small or limited resources farmers. She is currently working towards her PhD in Plant and Soil Science at the University of Kentucky focusing on food safety in aquaponics.

Leigh Anne Bright received her BS in Biology from KSU in 1997 and her MS in Aquaculture and Aquatic Sciences from KSU in 2002. Her primary focus area has been Production and Practical Diets in warmwater species. She has 27 peer reviewed publications. She has worked extensively with aquaculture diet manufacturing, making trial diets and test ingredients on-site at KSU. She has travelled both in the US and internationally, working with researchers to manufacture fish diets in on-site projects.

Joshua Dusci is a recent graduate of KSU holding a master's degree in Aquaculture/Aquatic Sciences. His research focused on evaluating freshwater prawn, *Macrobrachium rosenbergii*, as a biological solids control within the hydroponic troughs of raft aquaponic systems. Josh is currently developing his passion for aquaponics at his consulting company, Reel Aquaponics LLC, located in Tulsa, OK. He continues to pursue opportunities in the private sector, with his primarily client being Symbiotic Aquaponic LLC.

Dr. Jim Tidwell is Professor and Chair of the School of Aquaculture and Aquatic Sciences at KSU. He received his BS in Biology from the Univ. of Alabama in Birmingham, his MS in biology from Samford Univ., and his PhD in Aquaculture from Mississippi State Univ. He was named a KSU Distinguished Professor in 2014. He has authored or co-authored over 130 articles in refereed scientific journals as well as eleven book chapters and served as editor on three books. He has served as President of both the US Aquaculture Society and the World Aquaculture Society. In 2019 he received the Distinguished Lifetime Achievement Award from the United States Aquaculture Society.

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3a	Somerville *et al.* 2014
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5a	EcoFilms Australia
5b	Aquaculture Systems Technology
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Table Credits

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1, 2, 3, 4, 5, 8, 9	Janelle Hager
6, 10	Somerville *et al.* 2014
7	Masser *et al. 1999*
11	Amy Storey

Bessin, R. 2003. Beet armyworm in Kentucky. University of Kentucky Cooperative Extension Service, Lexington, Kentucky, USA. ENTFACT-308: 2p.

Crouse, D. 2017. Soils and plant nutrients. North Carolina Extension Gardener Handbook. NC State Extension, Raleigh, NC.–URL:https://content.ces.ncsu.edu/extension-gardener-handbook/1-soils-and-plant-nutrients#section_heading_7276 [accessed 2020-09-22].

Food and Agriculture Organization of the United Nations (2016). FAO/INFOODS Global Food Composition Database for Fish and Shellfish Version 1.0-uFiSh1.0. Rome, Italy.

Worley, J. 2015. Hobby Greenhouses. University of Georgia Extension Bulletin 910.

Forward

The Big Picture

The world population is an estimated 7.7 billion and is expected to reach 10 billion by 2050. To feed this expanding global populace, food production must increase by 30-50%. This increase would require that land used to raise crops expand by almost 1.5 billion acres; that is about ¾ the size of the continental United States.

In 2020, agriculture utilized almost 50% of the world's vegetated land. The ongoing increase in atmospheric CO_2 levels, leading to increased global warming, would be exacerbated by the large-scale conversion of forested lands to crop land necessary for food production. In addition, current agriculture production accounts for 90% of all water used by humankind. This growth and consumption of resources is not sustainable. Alternative ways to increase food production are required; we simply cannot just do more of what we are doing now.

The World Resources Institute (WRI) recently published a report titled "Creating a Sustainable Food Future" (Searchinger *et al*. 2014). The authors propose five "courses" or ways to produce more food without increasing environmental impacts. Aquaponics is a concept that addresses several of these initiatives.

One of the WRI courses is to increase food production without expanding agricultural land. To accomplish this, they state that "increased efficiency of natural resource use is the single most important step toward meeting both food production and environmental goals." As opposed to most recommendations, they propose increasing production intensity as a pathway to sustainability. Aquaponics is one of the more efficient and intensive food producing systems available. It is efficient in terms of the amount of food produced per unit area, unit of water, and unit of nutrients added to the system, especially in tropical or sub-tropical climates where heating costs are minimized.

Another solution proposed in the report is to increase fish supply. There is an indication that fish consumption is predicted to rise 58% by 2050 (Searchinger *et al*. 2014). However, the WRI study assumes that production from capture fisheries will actually decrease 10% during the same period. To meet consumption demand, aquaculture will need to at least double output. However, that would add to land use issues through the construction of 50 million acres of new production ponds. The authors pose that aquaculture must also become more land-efficient and that water recirculation technologies could help intensify production, reduce land use, and provide better pollution control.

Aquaponic production is a promising model for resource reuse and efficiency; this along with other regenerative agricultural techniques can have local impacts on many of these pressing problems and serve as a model for future technologies and developments.

I. Overview

The aquaponic system design channels nutrient-rich water from the fish culture system through plant beds in direct contact with the roots to effectively feed the plants. In turn, nitrogenous waste is removed through uptake by the plants for growth. Thus, the water is effectively cleaned and ready for reuse in fish culture.

Definition

Aquaponics (AP) is a self-supporting food production system that combines recirculating aquaculture with plant culture in the absence of soil (hydroponics). High-volume fish production results in nutrient-rich water that can be used to provide nutrients for plant cultivation.

Context

Development of aquaponic systems resulted from the need to reduce costs associated with high-nutrient effluent discharged from recirculating aquaculture systems (RAS). Known for intensive aquaculture, RAS can produce large quantities of fish in a small volume of water. Some water is discharged and replaced in the system over time, as solid waste and toxic nitrogen by-products (ammonia (NH_3-N), nitrite (NO_2-N), and nitrate (NO_3-N)) build up. Concentrated discharge from intensive aquaculture is a barrier to positive consumer perception of aquaculture. However, these accumulated nutrients can be similar in composition and concentration to hydroponic nutrient solutions and often exist in the form preferred by plants (Rackocy *et al.* 2006). Combining these two production technologies provides an efficient and sustainable method of growing fish and produce.

Importance

Hydroponics and intensive RAS each have ecological and economical drawbacks when considered individually. Hydroponic crops rely on chemical fertilizers that are expensive, hard to source, and in some cases are derived from rapidly disappearing natural resources. In intensive fish production, concentrated wastes are generated (i.e. effluent) that require expensive treatment methods, leading to poor consumer perception regarding environmental impacts. The high initial investment may be prohibitive to potential producers, as well. Aquaponics provides the opportunity to utilize aquaculture effluent while growing plants with a sustainable, cost-effective, and non-chemical nutrient source.

The integration of fish culture and plant production can provide several opportunities for farmers or producers, including sustainable agriculture, marketing versatility, and generation of multiple income streams. Environmentally, plant growth and yield in aquaponics can meet, or in some cases surpass, output values of either hydroponics or soil-based agriculture (Pantanella *et al.* 2011, Savidov *et al.* 2005). The shared core concepts of efficient water and land use, the ability to intensify crop production year round, and use in geographic areas not suitable for traditional agriculture has driven a recent increase in the popularity of aquaponics (Somerville *et al.* 2014).

While production values have been shown to be similar to both hydroponics and RAS (Pantanella 2013, Savidov *et al.* 2005), the integration of these systems can make it more difficult to manage. Many groups interested in aquaponic production are deterred by the high start-up cost and lack of proven models for success. Understanding that aquaponics is a complete ecosystem is essential to provide correct conditions for fish, plants, and bacteria, which are the three major groups of organisms that drive AP systems.

System Types

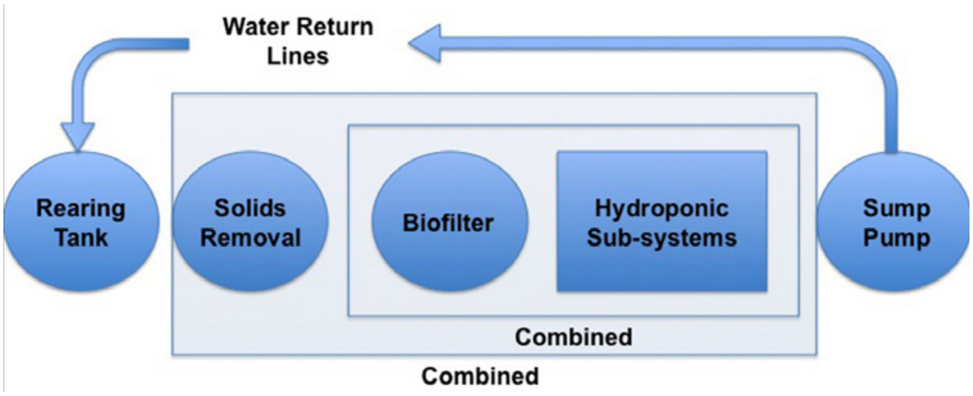
There are two main types of AP systems, coupled and decoupled. The coupled approach is widely used and is based on feeding the system known nutrient-input amounts/values. The support for plant growth and bacterial consumption (in the biofilter) typically come from commercial fish food and must be factored into system input requirements. These ratios are used to ensure that toxic waste products from fish effluent do not build up (due to an insufficient biofilter), excess nitrates do not occur (from not enough plants), and nitrate deficiencies do not develop (from an excess of plants). Recommended operating ratios for aquaponic systems will be covered in the Structure and Design section.

Given the wide range of growing conditions among fish, plants, and bacteria, coupled systems do not operate at the optimum values for either fish or plants. The ideal nutrient environment for fish would usually be nutritionally inadequate for most plants, and an ideal nutrient level for plants would be toxic to most fish. For this reason, decoupled systems are being explored, though their use is not widespread. In a decoupled aquaponic system, the RAS and hydroponic components are joined but operate as separate systems that can be controlled independently (Goddek *et al.* 2016, Pantanella 2013). Typically, water that feeds the hydroponic system does not enter back into the fish culture tanks after being filtered by the plants. Instead, water lost though transpiration and evaporation in the hydroponic unit is replaced with water from the RAS, which in turn is replaced with new water (Kloas *et al.* 2015). This setup offers greater control over the individual system and allows each to be operated at their optimal range. Disease treatment and nutrient deficiencies (or toxicities) are more easily managed, as well. Decoupled systems are not as well researched as coupled systems and require producers to have a higher level of expertise in hydroponics, plant nutrient management, and aquaculture system design.

II. Structure and Design

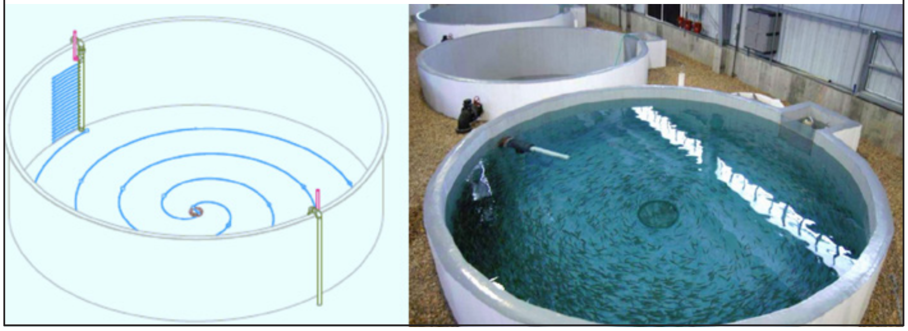
The majority of aquaponic systems follow the same basic design or "order of operations" (Figure 1). The main components of aquaponic systems are a fish culture tank, solids filtration, biological filtration, hydroponic component, and sump. The solids and biological filtration can either be combined (ex. media-based system) or separated into different units (ex. deep water culture).

FIGURE 1
Order of Operations for aquaponic systems



Fish Culture

FIGURE 2
Use of tangential or circular flow



Fish tanks for aquaponics come in a wide range of shapes, sizes, and materials, with selection being largely based on culture species. The majority of large systems use round tanks that either have a flat- or cone-bottom. Use of tangential flow will prevent dead zones when used in round tanks (Figure 2). Cone-bottom tanks allow solids to concentrate at the bottom (in the cone) and be easily flushed from the system. Flat-bottom tanks are more widely available, but solids removal requires additional steps to ensure proper removal of organic material dispersed across the bottom of the tank. Square tanks may also require additional cleaning as solids or debris can settle in corners (Somerville *et al.* 2014). Sizing for fish culture tanks follow RAS principles, with a 3:1 width to height ratio being ideal for proper water movement and flow. Fish tanks are generally the highest point of the system and water flows via gravity to the solids filtration component.

Commercial-grade tanks are commonly made from strong, UV-stable materials like high-density polyethylene (HDPE) plastic or fiberglass. On a smaller scale or in areas with limited resources, intermediate bulk containers (IBC) or lined cement troughs may be utilized. Food-grade and UV resistant materials are necessary as many repurposed tanks may have held chemicals or hazardous materials, making them unsuitable fish intended for consumption.

Solids Filtration

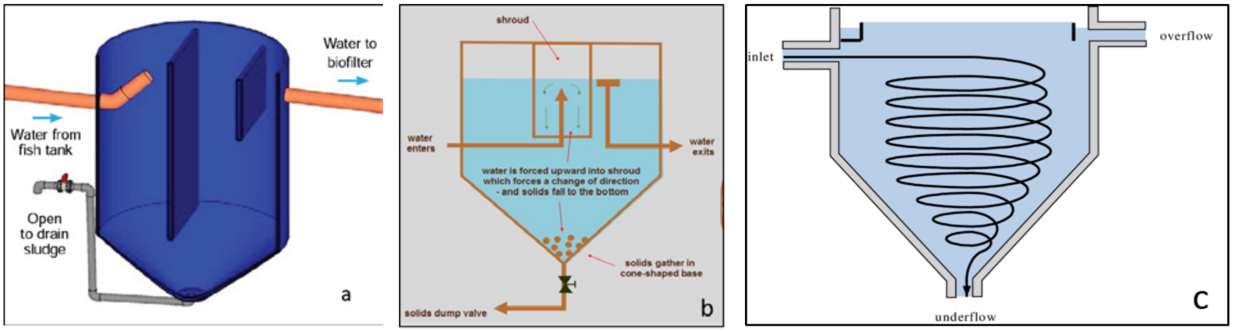
Effective solids filtration is a key component to a well-functioning system and potentially the most important aspect as it influences the efficiency of all other processes. Solids are mostly produced from uneaten feed, fish waste, and bacteria biofilms (classified as suspended solids) (Timmons and Ebeling 2013). If waste is not removed, it can settle on plant roots (preventing uptake of nutrients), collect in areas of low water flow (resulting in poor water quality), cause the build-up of noxious gas, and clog pipes (preventing sufficient water flow) (Somerville *et al.* 2014).

The solids filtration utilized depends on the quality and quantity of feed entering the system, with all designs coming directly from RAS technology. The two main categories of solids filtration are sedimentation and mechanical filtration (Lennard 2012).

Sedimentation: Sedimentation refers to solids settling from the water column via gravity, which occurs in the clarifier. Clarifier, or (solids removal) designs include baffles, radial flow filters, and swirl separators (Figure 3a, b, c). Radial flow separators are most commonly used and have been shown to be more effective at removing settleable solids than a swirl filter in RAS (Davidson and Summerfelt 2005). Baffle and swirl clarifiers are similar in solids removal efficiency (Danaher *et al.* 2013). Recommendations for construction material follow that of fish tanks mentioned above.

FIGURES 3a, b, c

Clarifier designs for capturing settleable solids: a) baffles, b) radial flow filters, c) swirl separator



Proper sizing of clarifiers and appropriate water flow rate are essential for effective solids removal. If relying solely on a clarifier to remove settleable solids, a 30-minute retention time is required. This simply means that most solids that can settle via gravity will do so within 30 minutes. A water flow rate of 5 gallons per minute for small tanks and 25 gallons per minute for large tanks should be used to calculate the size of the filtration tank needed. Filtration that is under-sized (or a flow rate that is too fast) will not be adequate to remove fish solids, resulting in accumulation further down in the system. Likewise, oversizing the component is not ideal as it increases the upfront cost, requires a larger footprint in the facility, and results in a greater amount of water use through inefficient discharge.

Clarifiers will only remove the large solid particles in the water, leaving solids that are too small to settle out of the water (Summerfelt *et al*. 2001). These suspended solids must be removed. A practice made popular by the University of the Virgin Islands is directing water from the clarifier through tanks filled with orchard netting (Figure 4). Netting material traps fine solids, allowing clean water to be skimmed from the surface. Other options for removing suspended solids are fine mesh bags, women's stockings, filter pads, and others. These items may quickly become clogged if settleable solids are not effectively removed in the clarifiers.

Mechanical Separation: Mechanical separation is the active removal of solids via a screen or media (Lennard 2012). These filters are extremely efficient, removing solids larger than 50 microns, resulting in less time spent on cleaning and maintenance due to their convenient automatic backwash feature. Examples of these filters include drum filter (Figure 5a) and a pressurized bead filter (Figure 5b).

FIGURE 4

Fine solids filter

FIGURE 5a

Rotating drum filter

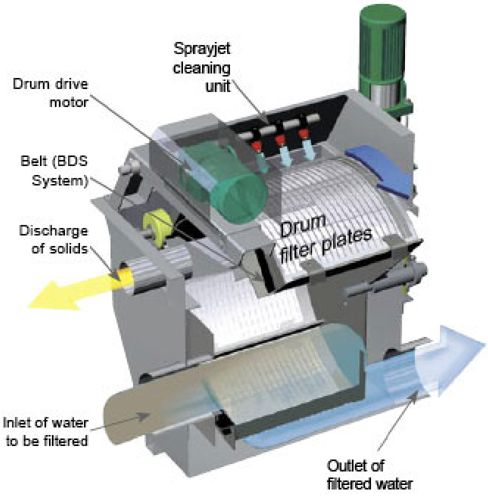
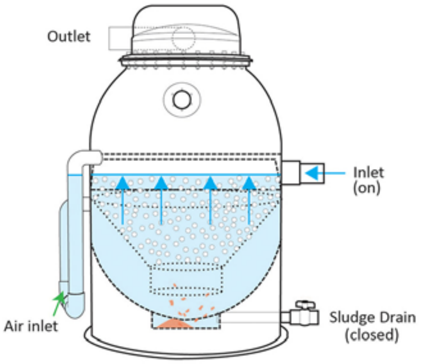


FIGURE 5b
Bead filter



Mechanical filters have a high price tag, often making them prohibitive for small-scale practitioners. In addition, they require more advanced knowledge to operate and are difficult to obtain in developing countries. This type of filtration would be appropriate for a large, decoupled aquaponic system or those that focus the majority of their operation on fish production.

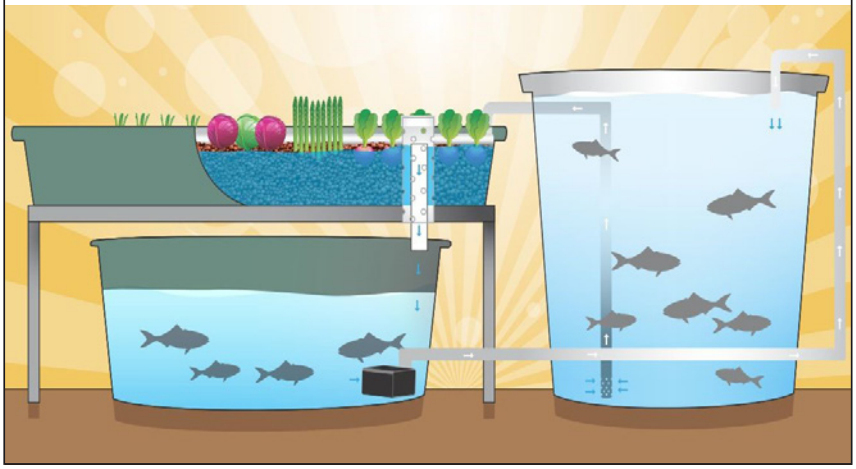
Biological Filtration

Biological filtration refers to the breakdown of ammonia (NH_3 and NH_4^+) into nitrite (NO_2) and then further into nitrate (NO_3) by naturally occurring, nitrifying bacteria. These bacteria live on the surface area of media contained in a tank— collectively called the biofilter. The process of converting ammonia to nitrate will be detailed in the section on water quality.

In RAS, the biofilter is designed to operate at low pressure. There is a dedicated tank filled with substrate like Kaldnes media, granular media, plastic balls, or other inert materials that have a large specific surface area or surface area of the media per unit volume. The higher the specific surface area, the more bacteria can grow on the media, translating to a higher ammonia removal capacity. Typical biofilter designs for RAS include trickle towers, submerged media, fluidized beds, sand filters, and static bed filter. In aquaponics, the biofilter can either be a separate unit or part of the system. In deep water culture (DWC), the plant trough walls, raft bottoms, and plant roots provide a significant surface area for nitrifying bacteria to colonize. Unlike RAS, the AP system itself typically provides ample surface area for bacteria to colonize, particularly for coupled systems that are appropriately sized. The nutrient film technique (NFT) system (see section below) is an exception, as only a thin layer of water is applied to the plants. If the biofilter is a separate unit, it should be located after the solids removal unit.

Plant Culture or Hydroponic Subsystem

FIGURE 6
Flood and drain system



The hydroponic portion of the system encompasses the majority of the facility footprint. Three primary designs are used: media beds, deep water culture (DWC), and NFT.

Media-based systems: The design of media-based systems, sometimes called flood-and-drain, is fairly straight forward. A container filled with substrate is periodically flooded with water from the fish tank. Water then drains back to the sump (or fish tank) drawing oxygen into the substrate for plant roots and nitrifying bacteria. The media bed supports the plant as it grows and serves as a solids and biological filter (Figure 6). Due to relatively few components and ease of construction and operation, these systems are popular for hobbyists and in developing regions. However, it is uncommon to find commercial production using only media beds as they are less productive than other types discussed below. Rule of Thumb for media systems are detailed in Table 1.

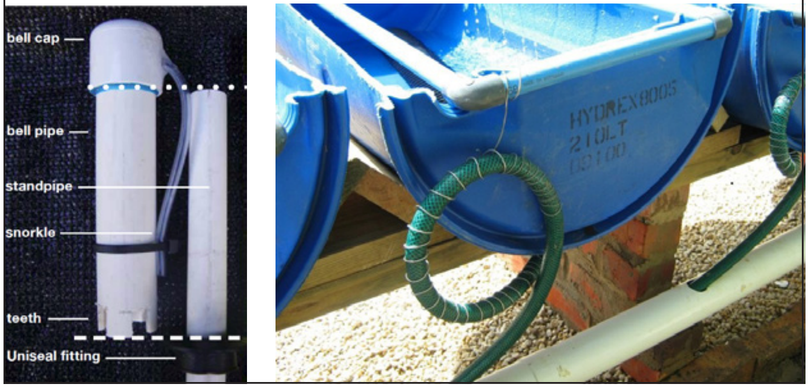
Table 1: Rules of thumb for media-based aquaponic systems.

Rules of Thumb for Media-Based Aquaponic Systems	
Substrate Characteristics	• Porous to increase oxygen and water retention • Provide adequate drainage • Easy to handle • Light-weight • Cost effective
System Design	• Plant beds should be at least 12 inches (30 cm) deep • Water should remain 2 inches below the surface of the media to prevent algae from growing in the surface of the media • Media displaces 60% of the volume of the plant bed. Fish tanks or sumps should be sized so the pump does not run dry and tank does not overflow during the flood and drain cycle. • 1:1 ratio of fish tank volume to plant bed volume for simple design involving solely a fish tank and plant bed. • 2:1 or 3:1 ratio can be achieved by addition of the sump (Figure 5)
Carrying Capacity	• Low fish stocking density • Separate solids filtration needed for increase fish density • Feeding rate is 25-40% less than values reported for deep water culture
Water Flow Management	• Fish tank volume should be circulated through the plant bed every hour • Water flow
Maintenance	• Cleaning required at regular intervals to remove solids • Red worms can be added to move solids trapped in beds

A variety of materials can be used as substrate, including pea gravel, lava rock, expanded clay pebbles, or other inert media; practitioners may be limited by what is locally available. Water flow in the system is controlled by either a timer or siphon. Using the timer method, water is pumped for a set amount of time, allowing the bed to fill. When the timer shuts off, water drains until the timer engages the pump again. The siphon method is often implemented using an automatic bell siphon (Figure 7a) or loop siphon (Figure 7b). In both siphon methods, the pump runs continuously, controlling how fast the bed fills and drains. Fox *et al.* (2010) gives comprehensive, step-by-step instructions for building, operating, and troubleshooting an automatic bell siphon.

FIGURE 7a, 7b

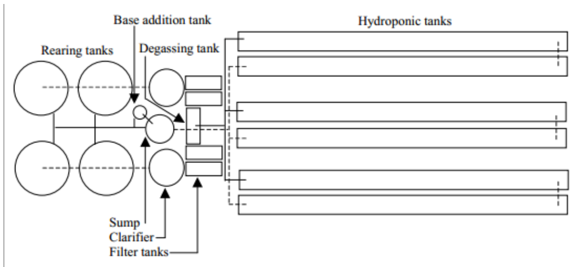
Bell siphon (a) or loop siphon (b)



Constant-flow media systems offer an alternative to the flood-and-drain method. Heavily aerated water flows into the media bed. Instead of a flood-and-drain cycle, the water level stays constant by using a standpipe. This drastically reduces the size of the sump needed for this type of growing system.

FIGURE 8

UVI deep water culture system



Tank Dimensions

Rearing tanks: Diameter: 3 m, Height: 1.2 m, Water volume: 7,800 L
Clarifiers: Diameter: 1.8, Height of cylinder: 1.2 m, Depth of cone: 1.1 m, Slope: 45º, Water volume: 3,785 L
Filter and degassing tanks: Length: 1.8 m, Width: 0.76 m, Depth: 0.61 m, Water volume: 700 L
Hydroponic tanks: Length: 30.5 m, Width: 1.2 m, Depth: 41 cm, Water volume: 11,356 L
Sump: Diameter: 1.2 m, Height: 0.9 m, Water volume: 606 L
Base addition tank: Diameter: 0.6 m, Height: 0.9 m, Water volume: 189 L
Total system water volume: 111,196 L
Flow rate: 378 Lpm, Pump: ½ hp, Blowers: 1½ hp (fish) and 1 hp (plants)
Total land area: 0.05 ha.

Pipe Sizes

Pump to rearing tanks: 10 cm
Rearing tanks to clarifier: 10 cm
Clarifiers to filter tanks: 10 cm
Between filter tanks: 15 cm
Filter tank to degassing tank: 10 cm
Degassing to hydroponic tanks: 15 cm
Between hydroponic tanks: 15 cm
Hydroponic tanks to sump: 15 cm
Sump to pump: 7.6 cm
Pipe to base addition tank: 1.9 cm
Base addition tank to sump: 3.2 cm

Deep Water Culture: This growing method involves suspending plants in a floating raft, allowing the roots to hang down into the water (Figure 8). Plant roots are in constant contact with nutrient-rich water from the fish tank. Effective solids filtration is a requirement in these systems to prevent solids from entering the plant bed and clogging plant roots. Aeration must also be provided in the plant troughs to maintain adequate oxygen levels for plant roots and beneficial bacteria. Along with their large water holding capacity that keeps water quality parameters more stable, the underside of the rafts and lining of the troughs provide adequate space for nitrifying bacteria to colonize. The design itself also provides a cushion against power outages, as roots stay submerged in water despite loss of water or air flow.

Table 2: Rules of thumb for DWC in aquaponics.

Rules of Thumb for Deep Water Culture in Aquaponics	
Substrate Characteristics	• Rafts are commonly made from HDPE plastic or polystyrene boards • Beds should be insulated to prevent temperature fluctuations in the system
System Design	• Beds should be a 12 inches (30 cm) deep • Width of bed may vary but typically are 4 feet wide • Efficient solids filtration is needed to prevent solids from accumulating in the plant beds • Aeration is needed in fish tanks and plant troughs • Water flow rate of 5-10 gallons per minute
Carrying Capacity	• High fish stocking density achieved with solids and biological filtration • Fish stocking density not to exceed 60kg/m³ (0.5 lb/gallon) • Fish consume 1-3% of the body weight in feed per day* • Feed input for leafy greens is 40-60g of food/m²/day feeding 32% protein diet • Feed input for fruiting crops is 60-100g of food/m²/day feeding 32% protein diet • Leafy greens stocked at 20-25 plants/m² • Fruiting crops stocked at 4 plants/m²
Water Flow Management	• 1-4 hour water retention time in plant troughs • Long, narrow beds help water move through the system
Maintenance	• Fine solids may accumulate in the troughs and will need to be removed • Clarifier drained daily • Fine solids capture cleaned weekly

*Exception is in early life stages where fish can consume 5-10% of their body weight in food per day.

Deep water culture (DWC) is more productive (kg of produce/m² growing space) than media-based systems; however, it can be more difficult to manage on a smaller scale. These systems are well researched by the hydroponics and aquaponics industry and are commonly implemented in commercial settings. Leafy greens and herbs, such as basil, do well in this production system. Fruiting crops like tomatoes, cucumbers, and peppers can be successful with appropriate nutrient densities and structural support. The DWC technique may not be suitable for areas where access to supplies or equipment is limited. Rules of thumb for DWC in aquaponics are listed in Table 2.

Nutrient Film Technique: Nutrient Film Technique (NFT) technology comes directly from the hydroponics industry. In this method, plants are inserted into the top of shallow horizontal channels. A small film of water is pumped through the channel, coming into contact with plant roots that utilize those nutrients for growth (Figure 9). NFT systems, like DWC, require sufficient solids filtration to prevent contamination of plant roots. In contrast to DWC, NFT systems need a separate biological filter, as the channel alone does not provide enough surface area for sufficient growth of nitrifying bacteria.

These systems are more complex to design, build, and manage than media-based systems. If channels are not sized correctly, plant roots can disrupt water flow by clogging the pipes. This design assumes a degree of risk, as pump failure can result in large crop loss if water flow does not resume quickly. However, NFT can be a great system for urban areas or rooftops as they are lightweight, use very little water, and can be made from easily sourced materials. Rules of thumb for NFT in aquaponics are listed in Table 3.

FIGURE 9
NFT system

Table 3: Rules of thumb for NFT in aquaponics

Rules of Thumb for Nutrient Film Technique in Aquaponics	
Substrate Characteristics	• Channels can be made from pre-fabricated plastic, rain gutter material, or PVC pipe • White pipes should be used as they reflect sunlight keeping the inner channel cool
System Design	• Square or rounds channels are suitable • Channel diameter should be appropriate for the crop's root size • Leafy greens - 7.5 cm pipe diameter • Fruiting crops – 11 cm pipe diameter • Channels should not exceed 12 m to avoid nutrient deficiencies in plants at the end of the pipe • Slope of channel need to be 1 cm/m to ensure an adequate flow • Efficient solids filtration required as solids can clog tubes • Heavy aeration required
Carrying Capacity	• High fish stocking density of 60kg/m^3 (0.5 lb/gallon) can be achieved with appropriate solids and biological filtration • Plant need a minimum of 21 cm between
Water Flow Management	• 1-4 hour water retention time in plant troughs • Long, narrow beds help water move through the system
Maintenance	• Channels needs to be cleaned between harvest • Back up pumps and generators are needed as plants are very vulnerable during outages

*Exception is in early life stages where fish can consume 5-10% of their body weight in food per day.

Sump

The sump is the lowest point of the system and where water collects to be distributed as needed throughout the system. Water quality samples can be taken here and amendments can be made without overwhelming the fish or hydroponic components. While not a requirement, the addition of a sump prevents the water level from changing in either the fish tank or hydroponic component. In other cases where safeguards are put in place, the fish tank or hydroponic component can be used as the sump.

III. System Technology

Water Sources

Sourcing water is an important consideration, as it directly impacts system management and performance. Typically, 1-3% of total system water is replaced per day depending on climate, time of year, and crops being produced (Somerville *et al.* 2014). Water is lost in the system through evaporation, transpiration into the plant, and through normal processes of splashing, cleaning, and harvesting.

Water with a salinity above 0.8 parts per thousand (ppt) are typically not suitable for aquaponic production as the majority of cultured plants do not tolerate even a small degree of salt (Shannon and Grieve 1998). Common aquaponic crops with a salinity tolerance include lettuce (0.83 – 2.8 ppt), kale (up to 7.4 ppt), Swiss chard (1.5 – 3.5 ppt), and tomatoes (up to 5.8 ppt) (Maggio *et al.* 2007, Shannon and Grieve 1998, Shannon *et al.* 2000). Even though some crops do show an ability to tolerate salt, growth is compromised at some point during production..

The majority of aquaponic producers utilize rainwater, well water, municipal water or a combination for their systems.

Rainwater: Rainwater typically has a neutral or slightly acidic pH, slight calcium and magnesium hardness, and no salinity (Somerville *et al.* 2014). In large systems, rainwater is generally best utilized in conjunction with other sources to reduce overhead cost and improve sustainability.

Rainwater run-off can easily be captured from roofs or gutters and stored for later use. Water collected from roofs should be treated prior to use, as they may contain bacteria and pathogens from bird or rodent droppings. Considerations include areas that may receive acid rain, laws that prohibit collection, and roof material and age. Some research has suggested that new and aging roofs are not suitable for collection (Clark *et al.* 2008), as materials such as shingles, cedar, and uncoated galvanized aluminum can contaminate water with chemicals, heavy metals, and pollutants.

Well water: Well water is a viable option for some producers. Considerations include potential contaminants and bedrock composition. Chemicals that are particularly harmful include heavy metals, iron, and sulfur. Aquifers with bedrock composed of limestone have high water hardness and alkalinity concentrations. Alkalinity (bases in the water like carbonates, bicarbonates, and hydroxides) prevents swings in pH, which is naturally lowered in aquaponics from nitrification. Alternately, producers with very low fish production may require water treatment to decrease hardness and/or alkalinity before use (Somerville *et al.* 2014). Lack of fish and subsequent feed input can cause pH to remain too high, making certain nutrients inaccessible to the plant. Pumping rate of the aquifer will also need to be determined if it will be the only source of water for an aquaponic system. This is particularly important in systems that will require large water additions or replacement.

Municipal water: Municipal water is ideal for use in aquaponic systems. Chlorine in tap water eliminates bacteria, pathogens, and algae, making it a safe and reliable source of water. Chlorine and chloramines, however, must be removed before use as it is toxic to fish and will kill off the nitrifying bacteria. Chloramine is basically a very stable molecule of chlorine bound to ammonia. Unlike chlorine alone, chloramines cannot evaporate out of the water. This provides rural households with a safe supply of drinking water but makes its use tricky for aquaponic producers. Free chlorine in the water can be gassed off in 48-72 hours with aeration. Chloramines require chemical dissipation (ex. sodium thiosulfate) or charcoal filtration. Given the small volume of water exchange, chloramines typically do not negatively impact an aquaponic system. Typically, you can replace around 10% of the system water volume without treating or testing for chlorine/chloramines.

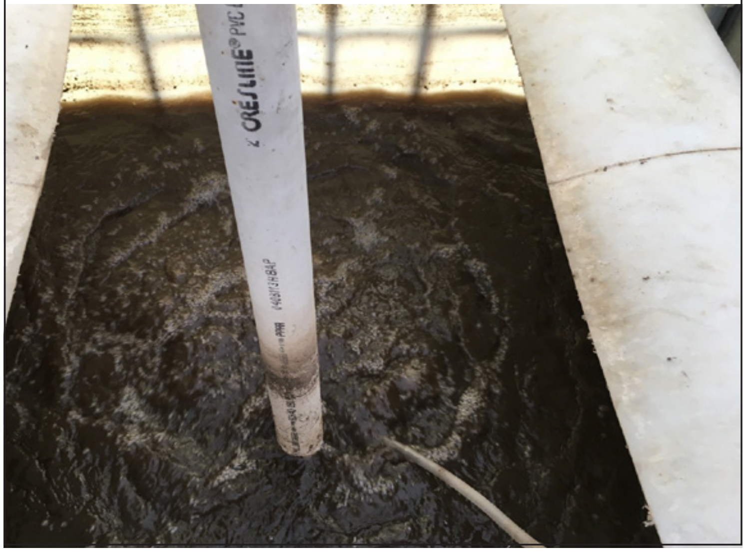
Surface water: Surface water includes ponds, lakes, rivers, and streams. Surface water can introduce pathogens, algae, snails, and other organisms. In addition, many surface waters are contaminated with pollutants or agricultural run-off that pose a food safety threat to the organisms in the system and to consumers.

Disposal of Waste

Recovery and digestion of fish effluent is more important in aquaponics than waste disposal. A large portion of feed is excreted as solid waste. Nutrients essential for plant growth are trapped within this concentrated slurry and should be recovered to reduce production costs and limit the need for nutrient supplementation. Recovery of these nutrients moves aquaponic production towards a zero-discharge system. Nutrients can be recovered through aerobic or anaerobic digestion of solids. Direct application of nutrients to crop land or composting sludge may be appropriate.

Mineralization: Approximately 20% of the N and 50% of the P from the feed is utilized by the fish for their growth (Timmons *et al*. 2018). The remainder of the N and P (70% and 30%, respectively) is excreted as a waste product by the gills and as particulate waste (10% and 20% for N and P, respectively). Particulate waste also contains macro- and micronutrients not absorbed by the fish. Recovery of these nutrients can improve plant growth and limit the need for supplemental nutrients.

FIGURE 10
Mineralization



Mineralization of fish effluent functions similarly to the processes that occur in soil. In AP, concentrated fish effluent is discharged into an offline holding tank. Microbes aerobically (or anaerobically) degrade organic solid materials, releasing soluble inorganic nutrients into the water, which are then available for plants to use (Delaide *et al*. 2018, Goddek *et al*. 2018). Only in an inorganic form are nutrients available to plants. Under aerobic conditions, heavy aeration is applied to concentrated solids (Figure 10). After 8-10 days, aeration is turned off, solids are allowed to settle, and clarified water is released into the system (Pattillo 2017). Under anaerobic conditions, bacteria decompose organic matter in environments with little to no oxygen. Anaerobic digestion produces methane gas (CH_4) that can be utilized as biofuel (Dana 2010) and concentrated digestant that can be applied to greenhouse crops (Pickens 2015) or used for seedling production (Danaher *et al*. 2009, Pantanella *et al*. 2011). Anaerobic digestion of fish solids is more complex to manage than aerobic digestion and may be cost prohibitive due to the large digester volume needed (Chen *et al*. 1997).

Limited information exists on microbial contribution or environmental processes that underlay effective aerobic mineralization of fish effluent; however, studies suggest that nutrient recovery from fish solids can be significant (Cerozi and Fitzsimmons 2017, Cerozi and Fitzsimmons 2016, Goddek *et al.* 2018, Rakocy *et al.* 2016, Tyson *et al.* 2011, Yogev *et al.* 2016, Khiari *et al.* 2019, Graber and Junge 2009). Preliminary results from on-site AP research systems at Kentucky State University (KSU) show that aerobic mineralization of fish effluent for 14 days resulted in a 143% increase (7.61 to 18.5 mg/L) in phosphate (PO_4), a 47% increase in nitrate (NO_3-N; 28.5 to 41.7 mg/L), and ≥ 20% increase in Ca (57.97 to 74.23 mg/L) and K (27.38 to 32.7 mg/L) compared to system water (unpublished). However, even if nutrients are recovered from effluent and provided in the right form and quantity, interactions with other nutrients and water chemistry can sometimes make them unavailable to plants (Bryson and Mills 2014).

Direct application: Waste can also be applied directly as a soil amendment, composted through traditional heat-treatment methods, or via vermicompost (worm composting). Direct application should be used as a low-grade fertilizer or if the slurry is less than one percent solids. Heat-based composting of dewatered fish solids requires additional expertise and labor cost but can add an important additional income stream. Vermicomposting uses similar methods to traditional composting but does not rely on heat to process waste. Worms consume organic matter, fragment and aerate the solid material, and can potentially provide a supplemental live feed for fish (Yeo and Binkowski 2010). Compost can include vegetable waste or other compostable materials from production. It is not uncommon for mineralized effluent to be bottled and sold directly to home gardeners or small greenhouse operations; however, some restrictions may apply depending on your local regulations.

IV. Grow Out Management

Proper management of fish and plants is a critical element that should be detailed in a production plan. Whether large or small scale, producers must implement strategies for best operation practices. This part of the plan should include, at minimum, fish and plant stocking densities, dates for planting and harvest, and their location or movement within the system (Bregnballe 2010). Additional components should include identification of a steady supply of fish year-round, maximization of space and resources, and a tailored or modified plan based on culture species and individual objectives.

Suitable Species of Fish for Culture

Unfortunately, not all fish species adapt well to tank culture, just as not all animal species adapt to being farm animals. Since fish are cold blooded, almost everything about their growth and health is influenced by temperature (see Tables 4 and 6 for details). The temperature of the culture water will partially dictate what species can or should be raised in your system. Other important factors will be how densely you intend to raise them and for what purpose or market. The rule of thumb for stocking density is 0.5 pound of fish weight per 1 gallon of water in grow out RAS. The following are considerations about what to grow for specific markets.

- What is selling in your current stores or restaurants?
- Can you address niche markets such as farmer's markets or are there minority groups in your area that have specific preferences?
- What seasonal markets do you want to address?
- What product forms will you be willing to address?
- What is your ambient temperature for your growing period? What energy implications does that have? What is the cost?

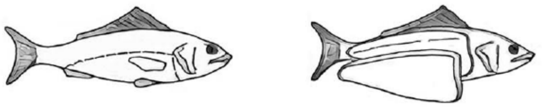
For some producers, fish are not an important part of the overall economics of the system and are primarily "nutrient generators" for the plants. For others, selling food fish is an important profit center for the aquaponics system. Aquaponic producers may have the benefit of providing a one-stop-shop for both fish and vegetables. If that is the case, the aquaponics producer should plan ahead on what their final fish product will be. Will the fish be sold live, whole on ice, or processed? For product forms, see Figure 11. Once you are selling processed fish, there are many more issues to be considered in terms of product form and processing regulations, such as:

- Do you have access to a certified processing facility?
- Do you have current HACCP regulations for the species you intend to process?
- What does the packaging cost?
- How will processing and packaging affect your budget?

FIGURE 11
Fish processing forms

(a) **Whole or round:** completely intact, as caught.

(d) **Steaks:** cross-section slices, each containing a section of backbone.



(b) **Drawn:** viscera removed.

(e) **Fillet:** boneless sides of fish, with skin on or off.

(c) **Dressed:** viscera, scales, head, tail and fins removed.

(g) **Sticks:** cross section of fillets

Several fish species have been successfully cultured in aquaponic systems. Overall growth parameters of these are given in Table 4. Important factors when deciding on the proper species also include availability of quality brood-stock or fingerlings, growth rate to market size, and feed cost and supply. Freshwater species are preferred, as most of the plant crops produced in aquaponics have very low tolerance of salinity. Also, hybrid striped bass (*Morone chrysops x M. saxatilis*), which can be raised in aquaculture recycle systems, are reported to do poorly in aquaponics due to intolerance of the high potassium levels supplemented to support plant growth (Rackocy *et al.* 2006), though they have been grown successfully (Diessner 2013).

Table 4: Summary of fish species suitable for aquaponics.

Species	Temperature (C)		Total ammonia nitrogen (mg/L)	Nitrite (mg/L)	Dissolved oxygen (mg/L)	Crude protein in feed (%)	Growth rate	Year-round supply of fingerlings (US)	Market value ($US/lb live)	Consumer Acceptance
	Vital	Optimal								
Nile tilapia *Oreochromis niloticus*	4-34	25-30	< 2	< 1	> 4	28-32	600g in 6–8 months	Yes	$3.00	Good
Common carp *Cyprinus carpio*	14-36	27-30	< 1	< 1	> 4	30-38	600g in 9–11 months	Yes	NA	Poor
Channel catfish *Ictalurus punctatus*	5-34	24-30	< 1	< 1	< 3	25-36	400g in 9–10 months	Yes	$2.00	Good
Largemouth bass *Micropterus salmoides*	5-34	24-30	< 1	< 2	> 4	45-48	600g in 14-16 months	Seasonal	$4.00-5.00	Moderate
Rainbow trout *Oncorhynchus mykiss*	10-18	14-16	< 0.5	< 0.3	> 6	42	1,000g in 14-16 months	Seasonal	$3.00	Good
Barramundi *Lates calcarifer*	18-34	26-29	< 1	< 1	> 4	38-45	400g in 9–10 months	No	$8.00-9.00	Good

Species Overviews

Tilapia: Tilapia (usually *Oreochromis niloticus* or the Nile tilapia) are the most cultured fish in aquaponic systems. They are tolerant of both crowding and relatively poor water quality conditions. They do best at water temperatures of 25-30°C. At temperatures < 24°C, their growth slows substantially, and they become susceptible to disease. They breed readily and abundantly. In fact, if using mixed sex fish, unintended spawning in the system can be a problem particularly in DWC beds where tilapia will consume all available plant roots. Monosex fish (all male) are available and preferred. Tilapia are widely accepted in the marketplace. If available, ethnic markets, which accept live or whole fish, should be considered. The tilapia is most efficient when grown to ¾-1 lb. in final weight. For processed products, such as fillets, tilapia must be raised to large sizes since they have low fillet yields (33% of body weight) compared to other species. Producers who choose to culture tilapia can be in competition with imported frozen product or with large domestic recycle systems, which drives down market price.

Common carp or Koi: The common carp and the Koi are the same species (*Cyprinus carpio*). The Koi is just a colorful genetic strain. Although widely consumed in other parts of the world, there is no food fish market for carp in the U.S. Carp are very hardy, have a wide temperature tolerance, and tolerate crowding and poor water quality. Fingerlings for stocking are usually readily available. They can be marketed as ornamentals, fetching high prices per fish. For systems that primarily use the fish as a source of organic nutrients, Koi can be a good choice because of their hardiness.

Channel catfish: The channel catfish (*Ictalurus punctatus*) is a major aquaculture production species in the southern U.S. It is widely accepted in the marketplace but brings a relatively low sale price, resulting in low profit potential. Ethnic consumers may pay higher prices for whole, quality catfish. Although a good pond culture species, the channel catfish is not as hardy as some people assume. In tanks they can be aggressive, and injury during feeding may occur from barbs located on the head of the fish. At water temperatures between 20-28°C, catfish are susceptible to a bacterial disease known as ESC (Enteric Septicemia of Catfish).

Largemouth bass: Largemouth bass (LMB, *Micropterus salmoides*) have become a relatively popular culture species. They bring high selling prices, as they have markets as both food fish and recreational stocking. Bass will not readily accept artificial feeds as small fingerlings so producers must buy fish that have been feed trained. So far, LMB growth in tanks is much slower than for fish grown in ponds (Watts *et al*. 2016). Lack of domestication and confinement to the high-density environment of tanks contributes to additional time to harvest for tank-cultured LMB. LMB fingerlings are available most of the year from sportfish suppliers but the price differential is large. For example, in April or May, the price for a 2-3 inch fingerling is >$1.25 USD per fish, but in June they are $0.30-0.40 USD per fish. Two-inch feed-trained fingerlings are generally available in early June from suppliers in Arkansas and Alabama and 6-8” fingerlings are available in the late fall (usually November).

Rainbow trout: The rainbow trout has the longest history of culture of all the fish considered here. While the others are warm water species, the trout is a cold-water species with optimal temperatures of 14-16°C. Because they evolved in cold-water environments, they need high levels of dissolved oxygen and have little tolerance for poor water quality. Trout fingerlings are available in certain areas of the U.S. (Idaho and North Carolina) but are not always available in small numbers. If conditions are properly maintained, trout grow rapidly and are well received by consumers. Trout require a high protein feed, with a minimum of 45% for juveniles and adults. Trout production for small-scale producers is challenging due to the high cost of feed and competition with commercial markets.

Barramundi: The barramundi is a native of Southeast Asia and into Australia. Like the tilapia, it has been successfully raised in different production systems. It is often sold in restaurants and markets as Asian Sea Bass. It grows rapidly and produces a product that is well received. However, at present, there is no source of fingerlings in the U.S.

Fingerling Production and Supply

Fingerlings for fish culture can either be obtained from a supplier or produced in-house. Availability, price, number of fingerlings needed, and level of expertise are the main factors that determine the method of choice. Type of species cultured, season, and location can also heavily influence the methods.

Supply: The best option for small-scale producers is to buy from a supplier. Suppliers should maintain detailed breeding records, use high-quality broodstock, and implement Best Aquaculture Practices (BAPs). In the case of fish fingerlings, cheaper is not always better.

Knowing when fingerlings are available for purchase will help ensure quality fingerlings. Certain species such as bass, bluegill, and yellow perch fingerlings are considered seasonal and are easiest to find during the summer months after they have been feed-trained. Small fish that are available off-season will likely be stunted and would not achieve optimal growth rates. Species such as tilapia and koi can be bought consistently year-round.

Regardless of the supplier, anytime fish are purchased they should be handled properly, acclimated, and added into a quarantine system for 1-2 weeks to help prevent any disease/parasitic outbreaks within the main production system. If the fish are healthy at the end of the quarantine period, then they should be size graded and distributed into the main system. Addition of salt to the water during transportation and holding can prevent disease issues by reducing stress on the fish and result in a higher survival rate. Information on salting for transport and holding can be found in SRAC Publication No. 390 (Wynne and Wurts 2011).

Production: If producing fingerlings in-house, the producer will need to determine the amount of fish needed to meet production demands. Typically, oversizing fingerling production is done to maintain maximum production capacity. Fingerling production will need to be done in a separate system to limit the spread of disease and to ensure optimal conditions for growth. The producer will also need additional tanks for broodstock, which should be of known lineage, age, and proper size (Egna and Boyd 1997). Spawning can be natural or artificial but is typically natural in a commercial setting (Egna and Boyd 1997). The benefits of producing fingerlings in-house include cutting out the fingerling supplier, ensuring quality fingerlings, getting a quick supply of fingerlings, and potentially earning additional revenue from fingerling sales. Some downsides include the need for more space, need for quality broodstock, need for fingerling production expertise, and a higher initial investment.

Fish Stocking

Fish culture should be well planned, as mismanagement of densities within the system can lead to issues with nutrient build-up/deficiencies, solids accumulation, water quality concerns, and poor fish health. Consider that aquaponic systems typically do not operate with a fish density exceeding 0.5 pounds/gallon. Three of the most common fish production plans are sequential rearing, stock splitting, and multiple rearing units.

Sequential Rearing: Sequential rearing involves one tank, containing multiple age-groups of fish (Rackocy *et al.* 2006), where the market-sized population is selectively harvested, and fingerlings are restocked in equal number. While this seems manageable, the continuous grading required can be stressful on remaining stock, leading to increased risk of disease and death. In addition, stunted fish remain in the system, consuming feed that will not yield any return for operation costs. Carnivorous fish are not well suited for this management strategy, as younger fish are susceptible to predation.

Stock Splitting: Stock splitting requires accession of fingerlings at a high rate, followed by halving the population when tank biomass capacity is reached (Rackocy *et al.* 2006). Benefits include the ability to remove stunted fish and better control over inventory. However, moving the fish increases the risk of disease and fish loss. Swim ways, a permanent or temporary channel connecting tanks, have been successfully installed to limit stress on fish but accurate counts and weights of the fish are hard to ascertain.

Multiple Rearing Units: Operating multiple rearing units is the most popular method of fish stocking and management. This method utilizes several tanks connected by a common filtration system (Rackocy *et al.* 2006). When maximum biomass in one tank is achieved, the entire population is moved to a larger tank, typically connected via a hatch or swim way.

The University of the Virgin Islands (UVI) in St. Croix uses a variation on the multiple rearing unit system. They operate four fish tanks of the same size, with same-age fish in each, stocked in time increments. Fish grow from fingerling to market size in one tank, with no movement until harvest. In this scenario, there is always a tank that is either ready for or nearing harvest. While tank volume is not utilized efficiently, fish stress and labor costs are decreased, while knowledge of stock inventory is increased (Rackocy *et al.* 2006).

Plants

Stocking and harvesting strategies can also be implemented in the hydroponic portion of the system. The three most common strategies are staggered cropping, batch cropping, and intercropping (Rackocy *et al.* 2006). Their implementation and success depend on geographic location (tropical or temperate regions), crop variety (leafy vs. fruiting crops), and market demand.

Aquaponic producers typically grow leafy green crops, which have a lower value per unit value and high yield. Lettuce, Swiss chard, kale, basil, and other herbs are typically ready for harvest between 3-5 weeks from transplanting (6-8 weeks from seed), resulting in a steady income stream. Fruiting plants like tomatoes, cucumbers, and peppers take 10-16 weeks to harvest, resulting in longer growing periods and lower yields, but they have a higher individual value. Producers often grow a variety of crops to diversify their markets and reach a number of consumer groups.

It is critical to invest time in a production strategy that realistically evaluates inputs and product output. Market demands vary among countries, regions, and even among neighboring cities. Producers should calculate the real-estate value of their system, often in price per square foot. To illustrate this, a comparison between two types of lettuce can be used. Figure 12 shows two different types of lettuce grown at the University of Virgin Islands in St. Croix. Although Parris Island romaine has a higher individual value ($/head) than Boston bibb, when the planting density and growth period are considered, Boston bibb brings a higher value per square meter of growing area per week than the Parris Island romaine. The main takeaway here is that high density and frequent harvests may an increased value, even when individual value of the crop is low. Information presented here is just an example and calculations should be tailored to a specific crops, farm, market, and regional costs for production.

FIGURE 12
Value of crops

Variety	Density (plants/m^2)	Growth Period (weeks)	Value ($/head)	Value ($/$m^2$)	Value ($/$m^2$/week)
Parris Island romaine	16	4	2.00	32.00	8.00
Boston bibb	30	3	1.00	30.00	10.00

To understand if the crop is profitable, the cost of labor from seed to harvest, price of seed, propagation supplies, and retail packaging will need to be subtracted from the price/m^2/week. If the selling price is below that of its "real-estate value," the hydroponic portion may be operating at a loss. In addition, producers may have multiple harvests from the same crop. Kale and Swiss chard are crops that can sustain multiple harvests without a decrease in quality of the produce, therefore increasing the value of that real estate. The strategies included here are not a comprehensive list but can be developed and adapted for individual plants.

Staggered Crops: Staggered cropping is growing multiple stages of crops in the same system and typically allows a consistent and regular harvest to be maintained (Somerville *et al.* 2014) (Figure 13). For example, if a head of lettuce takes three weeks to reach maturity, three stages are cultivated at the same time, resulting in a weekly harvest. This method is used with crops that are ready for harvest in a short time, usually leafy greens or herbs. This method maintains a constant nutrient uptake by the plants, resulting in better control of the system and water quality parameters, making system management and outputs more predictable.

Batch Crops: Batch cropping is commonly used when a longer growing period is required, such as with tomatoes and cucumbers. Produce is collected in batches as it ripens or becomes available.

Intercropping: Some producers will intercrop their plants, meaning crops with a short time to harvest are planted along with larger, fruiting ones (Figure 14). For example, if a producer is growing lettuce and tomatoes together, the lettuce crop can be harvested before the canopy of the tomatoes grows tall enough to shade it out.

FIGURE 13
Staggered cropping

FIGURE 14
Intercropping

V. Feed

Fish feed is the driving force behind the aquaponic system. Fish feed is primarily made up of protein, carbohydrate, and fat, with other ingredients like fiber, vitamins, minerals, and binders in smaller quantities. The nutrient components of these ingredients, whether pre-digested by the fish or simply broken down in the water, become the nutrient source for the plants in the system. However, for better or worse, these are the only nutrients available for plant crop growth, so fish feed input requires careful management. Table 5 outlines the feeding rate for fish based on body weight. To calculate the amount of feed needed to support plant and fish growth, Feed Conversion Ratio (FCR) must be calculated. The FCR is a ratio of fish diet fed in relation to fish flesh gained. The ideal FCR is 1, or 1 pound of diet fed to 1 pound of fish growth, but a more realistic number is closer to 1.4-1.8. FCR is calculated using the following formula:

$$FCR = \text{total feed input (g)} \div \text{total weight gain (g)}$$

Protein is the limiting factor in fish growth but is also the most expensive dietary component. For these reasons, it is important to choose the appropriate diet for fish. Inadequate protein will reduce growth and too much protein is cost prohibitive and can lead to water quality issues. Figure 15 details protein requirements for commonly cultured fish species.

Before feed is purchased for production, practical considerations include fish age, feed size, protein/carbohydrate content, floating vs. sinking pellets, length of time in storage, and feed storage area. The rule of thumb when choosing pellet size is that the pellet should be as big as the fish's mouth. As fish grow, so should the size of the pellet. Pellets are classified as float, slow sink, or sink, and the right choice depends on the species being fed. Feed manufacturers are able to give directions on the right type of feed for each production stage. Storing feed is actually a big consideration, as nutrient quality begins to decay after production. Feed storage in a dark, chilled or frozen environment is preferable, as it delays nutrient quality degradation but can introduce moisture resulting in moldy pellets. Molded feed must be thrown out, or composted into a garden, but must never be fed to fish, as it may contain toxins produced by the mold. Only enough feed should be purchased that can be fed in six months of straight production. When not used, feed should be kept in a cold, dry place with low relative humidity.

Table 5: Recommended feed chart for tank culture of Tilapia.

Length (cm)	Average Weight (g)	Standard Feed Size	Range of Feeding Rate (% biomass/day)	Feeding Frequency
< 2.5	< 0.5	#00, #0, #1 Crumble	20 – 15	4x per day
2.5 - 6.4	0.5 – 5	#2 Crumble	15 – 10	4x per day
6.4 - 10.2	5 – 18	#3 Crumble	10 – 5	4x per day
10.2 – 15.2	18 – 75	1 mm	5 – 3	3x per day
15.2 – 20.3	75 – 150	1/8 inch (3 mm)	3 – 1.5	3x per day
20.3 – 33	150 – 450	3/16 inch (4 mm)	3 – 1.5	2x per day
33+	> 450	3/16 inch (4 mm)	1	1-2x per day

*Reproduced and adapted from DeLong *et al.* (2009) and Sawyer, J.D. (2019).

Formulated

Formulated feeds are nutritionally complete pellets that are formulated for specific fish and life stage (Figure 15). Unlike other animal crops in agriculture, the nutritional needs of fish vary greatly among species for protein, fat, and carbohydrate inclusions. A carnivorous fish who eats at the top of its food chain, like a largemouth bass, requires a diet with high protein and low carbohydrates. On the other hand, omnivorous or herbivorous fish, like catfish or tilapia, require less protein and can tolerate higher levels of carbohydrate in their diets. This is important in aquaponics because the nutrient composition of the feed pellet drives the nutrient load available to the plants. As the fish feed is consumed and excreted by the fish, nutrients are released into the water as dissolved or solid particulates, which get circulated and used for plant growth. For example, feeds with a higher protein content will deliver a higher amount of total ammonia nitrogen (TAN) to the system, as nitrogen is primarily derived from the protein in the feed. The amount of TAN produced from a particular feed per day can be calculated using the following formula from Timmons and Ebeling (2013):

PTAN = Feed input (g) x Protein content (%) x *0.092 ÷ time

*0.92 represents = 0.16 x 0.80 x 0.80 x 0.90
- 16% (protein is 16% N)
- 80% N is assimilated
- 80% assimilated N is excreted
- 90% of N excreted as TAN + 10% as urea

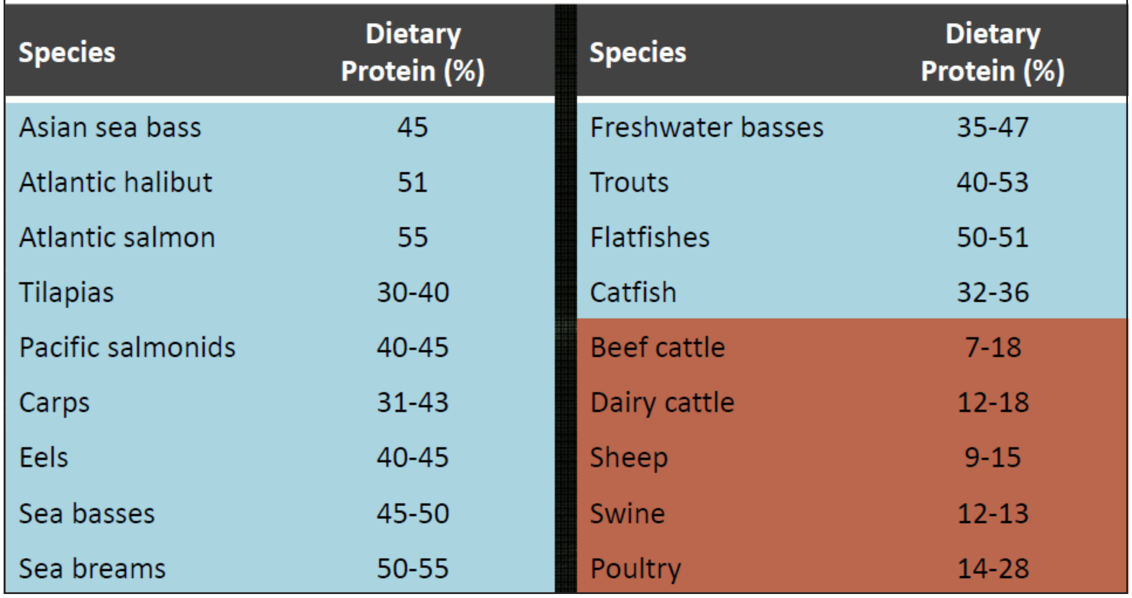
Example calculation for 2,000 g feed per day at 32% protein:

PTAN = 2,000 g x 0.32 x 0.092 ÷ 1 day

PTAN = 58.9 g

This rate is equivalent to approximately 3% of the feed rate per day.

FIGURE 15
Protein requirement for commonly produced fish species



Species	Dietary Protein (%)	Species	Dietary Protein (%)
Asian sea bass	45	Freshwater basses	35-47
Atlantic halibut	51	Trouts	40-53
Atlantic salmon	55	Flatfishes	50-51
Tilapias	30-40	Catfish	32-36
Pacific salmonids	40-45	Beef cattle	7-18
Carps	31-43	Dairy cattle	12-18
Eels	40-45	Sheep	9-15
Sea basses	45-50	Swine	12-13
Sea breams	50-55	Poultry	14-28

Commercial aquaculture feeds are extruded so that they maintain their integrity in the water (i.e. they hold together and do not break apart easily when in contact with the water). Feed that is steam extruded will float, where feed that is pressure/temperature extruded will sink. Feeds can also be slow sink, which results from a combination of ingredient ratio (% inclusion of carbohydrate) and type of extrusion. The type of feed required will depend on the biology and feeding nature of the culture fish.

Supplemental

A common question among small-scale and hobby aquaponic growers is if they can feed vegetable scraps, insects, or loose grains to their fish. These are known as supplemental diets and only meet part of the nutrient requirement of the fish. This is sometimes seen in traditional aquaculture practices in which fish are contained in large bodies of water where they can scavenge additional foods from the environment. Because aquaponics is a completely closed system, a complete diet must be fed. In addition, if fish must expend energy to scavenge for loose food or scraps, they are not growing at their full potential. Providing all their required nutrition in one, appropriately sized pellet allows the fish to convert more of that energy into growth, rather than using it to find food.

Alternative Diets

Alternative diets are a great option to utilize bulk products that are a byproduct of another production system, non-traditional ingredients, or even agriculture scraps. These diets would be prepared on-site and would still be combined in a ratio to meet both the nutrient requirements of the fish and the plant crop. One area where this is seen is in the brewing of craft beer or spirits. The spent grains from the fermentation process (brewer's grains) typically have a protein content high enough to be used in combination with another protein component, again dependent on the crops to be grown. Also utilized are refuse from animal processing plants, scraps from crop harvest, or even earthworm or other insect sources. One newer insect meal being used is black soldier fly larvae (BSFL). This is an especially good protein source because the larvae can be "gut-loaded," or fed whatever precursor food would most benefit the fish consuming it, like foods high in Omega-3 fatty acids.

VI. Water Quality Parameters

Understanding water chemistry in aquaponics is essential to providing optimal growth conditions for the fish, plants, and bacteria. By culturing fish in a recirculating system, all the essential elements for survival— such as temperature, oxygen, pH, and water clarity— need to be provided. Like all organisms, those cultured in aquaponic systems have optimum ranges for growth and survival. While there is overlap between optimum water quality ranges for each organism, a compromise must be made in many aspects of production (Table 6).

Table 6: Recommended water quality parameters for aquaponics*.

Organism	Temperature (°C)	pH	Ammonia (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	DO (mg/L)
Warm water fish	22 – 32	6 – 8.5	< 3	< 1	< 400	4 – 6
Cold water fish	10 – 18	6 – 8.5	< 1	< 0.1	< 400	6 – 8
Plants	16 – 30	5.5 – 7.5	< 30	< 1	< 250	> 3
Bacteria	14 – 34	6 – 8.5	< 3	< 1	-	4 – 8
Compromise for Aquaponics	18 – 30	6 – 7	< 1	< 1	< 150	5 – 8

*Reproduced and adapted from FAO small-scale aquaponic food production (Somerville *et al.* 2014).

The five most important water chemistry parameters to consider for aquaponics are dissolved oxygen, temperature, pH, total ammonia nitrogen, and alkalinity.

Dissolved Oxygen

Oxygen is required at high levels by fish, plants, and bacteria. Oxygen content is quantified by the dissolved oxygen (DO) in water and is expressed as milligrams per liter (mg/L) (Somerville *et al.* 2014). The intensive nature of aquaponic systems requires oxygen supplementation. Oxygen can enter the system by agitation at the surface or by diffusers in the water column. Fish stocking density, number and type of plants, amount of organic solids, biological oxygen demand, and temperature are all factors that determine how much DO is needed (Rackocy *et al.* 2006, Wurts and Durborow 1992). DO and temperature have an important relationship. Oxygen is more soluble in cold water than it is in warm water, meaning that cold water can retain higher levels of dissolved oxygen than warm water. This is particularly important for producers raising warm water fish or operating in areas that experience high year-round or seasonal temperatures. It is recommended that dissolved oxygen be maintained between 5-8 mg/L. DO is difficult to measure, as meters can be expensive or hard to find. In this case, producers can purchase DO aquarium test kits or contact local Extension or universities for assistance.

Temperature

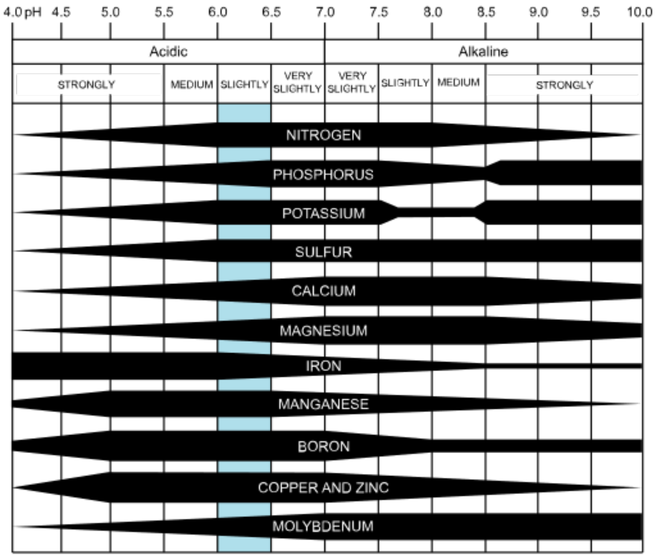
Water temperature is more important in aquaponics than air temperature. Many water chemistry factors are affected by temperature, such as the amount of toxic ammonia (un-ionized) present and the solubility of oxygen. It also directly impacts the health and survival of both fish and plants. Fish are poikilothermic, or cold-blooded. This means that their body temperature is dependent on water temperature. At extreme temperature, fish will stop eating, becoming lethargic and susceptible to disease. In plants, high temperature can reduce the uptake of essential plant nutrients, such as calcium, force early flowering in cool weather crops, and increase potential for plant roots pathogens like *Pythium* spp. For this reason, it is important to prevent wide swings in daily temperature. Shading or covering water surfaces, insulating fish tanks and plant beds, and utilizing passive or solar heating in greenhouses are strategies many producers employ. In temperate areas where temperature changes drastically from season to season, producers can alternate fish and plant crops seasonally to reduce heating or cooling costs.

pH

The pH is a measure of the acidity or basicity of a solution. It is determined by the presence or absence of free hydrogen ions (H^+), where the more H^+ present, the more acidic a solution is. An acidic solution has a low pH. The pH is measured on a scale from 1-14, with 7 being neutral. A pH value below 7 indicates a solution is acidic and above 7 indicates a solution is basic. The pH is recorded on a logarithmic scale and thus is not intuitive for many practitioners. For example, if the pH of an aquaponic system measures 7, then after two weeks measures 5, the pH has not dropped by a degree of 2, but rather 100 times. Understanding the pH scale is critical for water management and correction.

Fish, plants, and bacteria have specific tolerance ranges for pH. While they can tolerate parameters outside their optimal range, sub-par conditions can greatly affect growth and survival. Fish can tolerate a wide range of pH, from 6.0-8.5, but they need to be acclimated slowly to changes. The pH is particularly important for plants and bacteria. All micro- and macro-nutrients are available to plants at a pH between 6.0-6.5 (Figure 16). Above or below this range, certain nutrients are not available to the plants. When pH exceeds 7.5, plants quickly become deficient in essential nutrients like iron, phosphorous, and manganese (Somerville *et al.* 2014). Conversely, low pH can have negative impacts on nitrifying bacteria. Below 6.0, the ability to convert ammonia to nitrate is greatly reduced.

FIGURE 16
Soil pH and nutrients



There are many factors that influence pH. Nitrification (discussed in the following section) and fish stocking density drive pH down by producing H^+ and CO_2, respectively. Amendments are needed to bring pH up to suitable culture levels. Managing pH begins with consistent monitoring and recording. If pH is low, chemicals that increase total alkalinity, like calcium hydroxide (hydrated lime; $Ca(OH)_2$), agricultural lime (calcium carbonate ($CaCO_3$)), calcium potassium hydroxide (KOH), or potassium carbonate (K_2CO_3), can be used. The addition of calcium and potassium bases are alternated to provide essential nutrients not contained in fish food. Due to their high pH (10-11), these bases must be added with caution and in small doses, as to not raise the pH too quickly. Nitrification constantly drives pH down by depleting the water's total alkalinity and release of H^+ ions, so consistent monitoring is important. The need to lower pH is typically not an issue for aquaponic producers, due to nitrification. Producers may need to amend their water source, however, by adding hard water or chemicals to increase alkalinity, which stabilizes or increases pH. If the pH of the system is constantly high, even after cycling, the first step is to make sure solids are not accumulating in the system. Solids that accumulate form anaerobic (low or no oxygen) zones. When anaerobic conditions develop, a process called denitrification, where nitrate is converted back into ammonia, occurs. Alkalinity is released during this transformation, which stabilizes the pH.

Total Ammonia-Nitrogen

Nitrogen enters the aquaponic system as crude protein in the fish feed. Approximately 30% of protein in the fish food is retained by the fish. Seventy percent is digested and released as solid waste or excreted as ammonia via the gills or as urea (Timmons and Ebeling 2013). Total ammonia nitrogen (TAN) is comprised of two forms that exist in a ratio of un-ionized ammonia (NH_3, which is toxic to fish) to ionized ammonia (NH_4^+ which in non-toxic). The presence of one form over the other is dependent on pH and temperature. At high pH (basic) and temperature, there is a higher proportion of toxic ammonia. At low pH (acidic) and temperature, ammonia binds to excess H^+ ions and becomes the less toxic form, ammonium. Generally, water quality tests will give the TAN value, which encompasses both NH_3 and NH_4^+. The exact value of toxic ammonia can be determined by taking the number that intersects the recorded temperature and pH (Table 7) and multiplying it by the present TAN value (Masser *et al.* 1999).

Table 7: Fraction of total ammonia in the toxic (un-ionized) form at different pH values and temperatures.

	Temperature (°C)												
pH	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**
7.0	.0013	.0016	.0018	.0022	.0025	.0029	.0034	.0039	.0046	.0062	.0060	.0069	.0080
7.2	.0021	.0025	.0029	.0034	.0040	.0046	.0054	.0062	.0072	.0083	.0096	.0110	.0126
7.4	.0034	.0040	.0046	.0054	.0063	.0073	.0085	.0098	.0114	.0131	.0150	.0173	.0198
7.6	.0053	.0063	.0073	.0086	.0100	.0116	.0134	.0155	.0179	.0206	.0236	.0271	.0310
7.8	.0084	.0099	.0116	.0135	.0157	.0182	.0211	.0244	.0281	.0322	.0370	.0423	.0482
8.0	.0133	.0156	.0182	.0212	.0247	.0286	.0330	.0381	.0438	.0502	.0574	.0654	.0743
8.2	.0210	.0245	.0286	.0332	.0385	.0445	.0514	.0590	.0676	.0772	.0880	.0998	.1129
8.4	.0328	.0383	.0445	.0517	.0597	.0688	.0790	.0904	.1031	.1171	.1326	.1495	.1678
8.6	.0510	.0593	.0688	.0795	.09114	.1048	.1197	.1361	.1541	.1737	.1950	.2178	.2422
8.8	.0785	.0909	.1048	.1204	.1376	.1566	.1773	.1998	.2241	.2500	.2774	.3062	.3362
9.0	.1190	.1368	.1565	.1782	.2018	.2273	.2546	.2836	.3140	.3456	.3783	.4116	.4453
9.2	.1763	.2008	.2273	.2558	.2861	.3180	.5312	.3855	.4204	.4557	.4909	.5258	.5599
9.4	.2533	.2847	.3180	.3526	.3884	.4249	.4618	.4985	.5348	.5702	.6045	.6373	.6685
9.6	.3496	.3868	.4249	.4633	.5016	.5394	.5762	.6117	.6456	.6777	.7078	.7358	.7617
9.8	.4600	.5000	.5394	.5778	.6147	.6499	.6831	.7140	.7428	.7692	.7933	.8153	.8351
10.0	.5745	.6131	.6498	.6844	.7166	.7463	.7735	.7983	.8207	.8408	.8588	.8749	.8892
10.2	.6815	.7152	.7463	.7746	.8003	.8234	.8441	.8625	.8788	.8933	.9060	.9173	.9271

Source: (Masser et al. 1999)

Through the process of nitrification, bacteria convert ammonia-nitrogen (NH_3) to nitrite (NO_2^-) and then to nitrate (NO_3^-). Ammonia and nitrite are 100 times more toxic to fish than nitrate (Somerville *et al.* 2014). Plants primarily utilize nitrogen in the form of ammonium (NH_4^+), NO_3^- and amino acids such as L-glycine (Rentsch *et al.* 2007, Sanchez and Doerge 1999). In a fully functioning aquaponic system, ammonia and nitrite values should be close to zero and nitrate should be below 150mg/L. While fish can tolerate much higher levels, upward to 400 mg/L (Timmons and Ebeling 2013), values exceeding 250 mg/L can have negative impacts on plants (Rackocy *et al.* 2006). From a management perspective, it is important to know the tolerance range of fish and plant species to optimize growth conditions. At excessive levels, these toxic compounds can damage fish gills and stunt their growth.

Alkalinity

Alkalinity is an often-overlooked aspect of water quality but is essential in maintaining a stable system. Alkalinity is a measure of water's ability to buffer, or resist, changes in pH (Wurts and Durborow 1992). The most common forms of alkalinity are carbonates (CO_3^-) and bicarbonates (HCO_3^-). These carbonates bind to free H^+ ions, a result of nitrification, preventing a drop in pH. Water with low alkalinity and a steady rate of nitrification experience wide swings in pH, which can be detrimental to the health of fish, plants, and bacteria. It is recommended to maintain alkalinity between 60-140 mg/L.

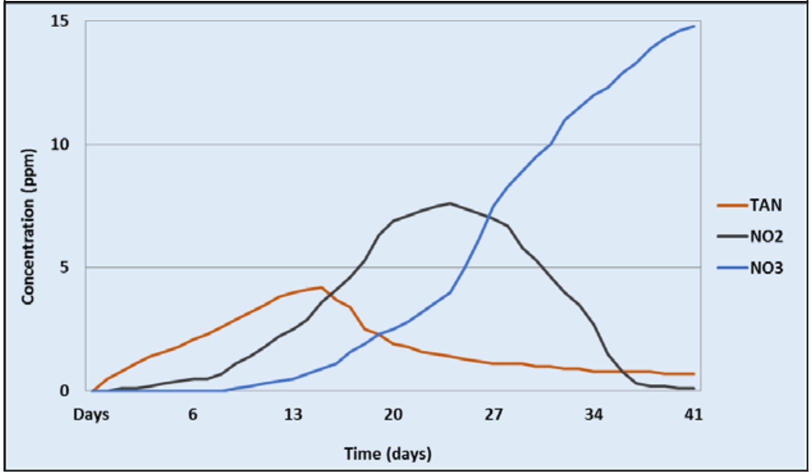
Alkalinity is often confused with water hardness. Hardness is determined by the quantity of positive ions, namely calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, present in the source water. Water from limestone bedrock has a high hardness (120-180 mg/L), while soft water has a low hardness (0-60 mg/L). Soft water is associated with rainwater or groundwater from volcanic bedrock. Water lacking appropriate hardness needs to receive amendments as Ca^{2+} and Mg^{2+} ions, which are essential for both plants and fish.

Alkalinity is not normally tested on a regular basis in aquaponics but is maintained through the addition of bases to raise pH. In addition to those listed above, non-chemical measures to increase alkalinity and pH include addition of finely crushed seashells, coarse limestone grit, and crushed chalk (Somerville *et al.* 2014). Placed in a mesh bag, they can be added to the sump until pH or alkalinity raises to the appropriate level. The size of your system will dictate how long these amendments will be effective and how often they will need to be replaced. Care must be taken to wash these items thoroughly to prevent contaminates from entering the system.

Cycling the System

Cycling refers to the process of establishing the biological filter. This can take between six to eight weeks (Figure 17). Nitrifying bacteria are found naturally in the environment, so the process begins by adding a source of ammonia. This can be accomplished through adding fish, fish food, or water from a well-established system, or a combination of these. One of the most common mistakes when using fish to cycle a system is adding too many fish initially. This

FIGURE 17
Cycling the system



causes ammonia levels to spike, often resulting in fish death. Starting with 20% of the total fish capacity is a good rule of thumb. This allows the appropriate, system-specific biological organisms to colonize. If using a fish-less cycling strategy, household ammonia can be used. It is important to source surfactant-free ammonia, as it lacks detergents commonly added to these products that are unsuitable for the system.

Corrective Measures

- **Low dissolved oxygen (below 5 mg/L)**: increase aeration, reduce feeding until corrected
- **Low pH (below 6.0)**: add base (calcium hydroxide, calcium carbonate, potassium hydroxide or potassium carbonate), reduce feeding until corrected
- **High ammonia (above 1 mg/L TAN)**: reduce feeding until corrected, perform 20% water exchange, check for accumulated solids, increase biological filtration
- **High nitrite (above 0.5 mg/L)**: reduce feeding until corrected, perform 20% water exchange, increase biological filtration
- **Consistently high nitrate**: reduce fish biomass or feeding rate, add more plant biomass
- **Nitrate consistently at zero**: increase fish feed or fish biomass
- **Low alkalinity**: add carbonate bases ex. (calcium carbonate, potassium carbonate)

***Note**: Adding any base to the system must be done with care. Small additions of these chemicals result in a large increase in pH. Base additions should be calculated before addition. Always err on the side of caution.

VII. Plant Nutrient Dynamics

Most plants can be described by five main structures: roots, stem, leaves, flowers, and fruits. Dissolved nutrients and water enter the plant via the roots through passive and active (requiring energy) transport. The xylem, located in the stem, is a one-way transport channel that moves water and minerals from the roots' hairs into the main body of the plant through capillary action. The stem is typically the primary support structure for leaves, buds, and other organs. The leaves are the powerhouse of the plant and use solar energy to convert carbon dioxide (CO_2) and water into glucose (energy) and oxygen (the photosynthetic process). Glucose is transported to other parts of the plant via the phloem. Flowers and fruits are the reproductive organs of the plant. Flowers require fertilization to develop into fruits. This can be accomplished by wind, insects, birds, mammals, etc. In a greenhouse, flowers can be pollinated by fans' gently shaking the plant, causing it to release pollen grains, or manually using a Q-tip or soft paintbrush.

Like in soil, plants grown in aquaponics derive their nutrients and energy for growth and reproduction from photosynthesis, dissolved inorganic salts, and metabolites produced by bacteria and fungi. In aquaponics, the nutrients are derived from feeding fish. Plants have some ability to select the rate at which they absorb various ions. Just because the nutrient is provided in adequate quantities does not mean that the plant is absorbing it. Plants have 16 essential nutrients required for optimal health and growth (Table 8). Essential nutrients are those that cannot be synthesized by the organism and are classified by structural, macro-, and micro-, delineating how much is required by the plant. Nutrients can also be categorized by their mobility. Mobile nutrients are elements that can be transported throughout the plant (usually to new growth) as needed. Once immobile nutrients are deposited in the leaves (typically older or primary leaves), they are fixed and unable to be transported to other parts of the plant. This can benefit producers when signs of a nutrient deficiency are apparent by narrowing down the causative ions. Mobile nutrient deficiencies occur in older leaves whereas immobile nutrients occur in new growth of the plant. Three nutrients are not provided in adequate quantities in fish feed to support plant growth. These nutrients are calcium (Ca), potassium (K), and iron (Fe). As discussed above, $CaCO_3$ and K_2CO_3 are used to both amend pH and provide essential nutrients. Iron is supplemented in the chelated form, which keeps it soluble in the water and prevents it from oxidizing in the system. Fe-DTPA is recommended because it is more stable at the pH suitable for aquaponics (6.0-7.5) and more cost effective than other forms.

Table 8: Sixteen essential nutrients required by plants for optimal health and growth. Circled elements represent limiting nutrients in aquaponics. Mobile nutrients are represented by (m) and immobile nutrients by (i).

Essential Elements for Plant Growth		
Structural	Macro	Micronutrients
Carbon (C)	Nitrogen (N)^{M}	Iron (Fe)^{i}
Hydrogen (H)	Phosphorous (P)^{M}	Manganese (Mn) ^{i}
Oxygen (O)	Potassium (K)^{M}	Boron (B)^{i}
	Calcium (Ca)^{i}	Molybdenum (Mo)^{M}
	Magnesium (Mg)^{M}	Copper (Cu)^{i}
	Sulfur (S)^{i}	Zinc (Zn)^{i}
		Chlorine (Cl)^{M}

Providing and Measuring Plant Nutrients

Nutrients enter the aquaponic system in the fish feed. The amount of nitrogen that is available to the plant is directly related to the protein content of the feed. The higher the protein content, the more nitrogen is available for plant growth. Unfortunately, high protein feeds are very expensive, so feeding a higher protein feed than your culture species requires is cost prohibitive. Nitrogen comes from the breakdown of proteins, whose structural components are made up of nitrogen-rich amino acids. Approximately 20% of the nitrogen and 50% of the phosphorous from the feed is utilized by the fish for growth. Much of the N and P (70% and 30%, respectively) is excreted as a waste product by the gills, and the remainder (10% and 20% for N and P, respectively) is excreted as particulate waste. Particulate waste, what we refer to in aquaponics as "solid," also contains macro- and micro-nutrients not absorbed by the fish. Utilizing this waste product can be accomplished through mineralization.

Table 9: Nutrient analysis of mineralized aquaponic system effluent after 14 days.

Category	Day 0	Day 14	% change
pH	6.54	6.48	-1%
EC	0.6	0.76	27%
MAJOR CATIONS (PPM)			
Calcium(Ca)	57.97	74.23	28%
Magnesium(Mg)	13.31	17.54	32%
Potassium(K)	27.38	32.65	19%
Sodium(NA)	33.89	43.68	29%
Ammonium(NH4-N)	0.79	0	-79%
MAJOR ANIONS (PPM)			
Nitrate(NO3-N)	28.47	41.74	47%
Chloride(Cl)	46.76	62.61	34%
Fluoride(F)	0	0	0%
Sulfate(SO4)	53.29	58.92	11%
Phosphate(PO4)	7.61	18.5	143%
Carbonates(CO3)	0	0	0%
Bicarbonates(HCO3)	19.81	22.21	12%
Alkalinity(mg)	16.25	18.21	12%
TRACE (PPM)			
Aluminum(AL)	0.01	0.05	400%
Iron(Fe)	1.95	1.95	0%
Manganese(Mn)	0.001	0.03	290%
zinc(Zn)	0.37	0.42	14%
Copper(Cu)	0.02	0.08	300%
Boron(B)	0.06	0.08	33%
Molybdenum(Mo)	0	0	0%

Mineralization of fish effluent functions similarly to processes in soil. In aquaponics, concentrated fish effluent is discharged into an offline holding tank. Microbes aerobically (or anaerobically) degrade organic solid materials, releasing soluble inorganic nutrients into the water, which are then available for plants to use (Delaide *et al.* 2018, Goddek *et al.* 2018). Nutrient-rich water can be accessed via the settling of particulate matter and siphoning water from the top.

Limited information exists on ideal environmental conditions necessary to achieve effective aerobic mineralization of fish effluent. Preliminary results from on-site aquaponic research systems at KSU show that mineralizing fish effluent for 14 days resulted in a 143% increase in phosphate (PO4), a 47% increase in nitrate (NO3^{-}N), and ≥ 20% increase in calcium (Ca), magnesium (Mg), and potassium (K) compared to system water (Table 9). The particulate solids have an NPK ratio of 4:5:1, as well as notable levels of Ca and Mg.

Plant nutrients are quantified through laboratory testing of water and plant tissue. Testing can be rather expensive for farmers (typically between $20-$75 USD per sample) and results are not immediate. Some universities may provide free testing that can expedite the process and cut down on costs. Measuring the electrical conductivity (EC) of the water is helpful in determining the concentration of nutrient salts but does not quantify what nutrients are available to plants. The acceptable EC range for aquaponics is between 0.5-2.0 µS/cm.

Common Nutrient Deficiencies

A skill that is beneficial for aquaponics producers to keep in their toolbox is the ability to visually diagnose nutrient deficiencies. Once a plant exhibits symptom of a deficiency, severe stress is already occurring. Early detection and diagnosis are important.

Process of elimination can help growers successfully identify a nutrient deficiency. Key factors include recognizing where it occurs in the plant (mobile or immobile nutrient); taking note of the general appearance, such as color pattern or overall appearance; and eliminating other factors that may be causing the issue, such as light or heat damage. Below are common nutrient deficiencies that occur in aquaponics.

Nitrogen: Although not very common in aquaponic systems, nitrogen deficiencies most commonly occur when the fish culture units are undersized for the amount of plants in the system. Complete chlorosis (yellowing) of older leaves is the first sign and can spread to the whole plant if left untreated (Figure 18a). Other signs are slow or stunted growth and plants that look stretched. Nitrogen deficiency is typically not an issue in appropriately designed, well-cycled aquaponics systems.

Phosphorous: Phosphorous deficiency in plants is characterized by dark green and/or purple coloration in older leaves (Figure 18b). It may also manifest at the tips and edges of the leaves, giving them a burnt look. Availability of P to plant is greatly reduced when pH is outside the range of 6.0-7.5 and when temperatures are ≤ 10°C (Islam *et al.* 2019). Symptoms are more noticeable in young plants, which have a greater relative demand for P than mature plants.

Potassium: Potassium deficiency does not immediately result in visible symptoms. Leaf margins will appear tanned, scorched, and/or have small black spots that later aggregate into necrotic region (Figure 18c). Margins of the leaves will cup downward, and growth will be restricted. Potassium is a key nutrient for proper flower and fruit development. Inadequate supply of K will result in flowers' dropping off the plant. High K concentrations can reduce the uptake of Ca by the plant. K is a limiting nutrient in aquaponics and must be supplemented to maintain levels required for plant growth.

FIGURE 18a
Nitrogen deficiency

FIGURE 18b
Phosphorous deficiency

FIGURE 18c
Potassium deficiency

Calcium: Calcium is a limiting nutrient in aquaponics. Deficiencies will appear on new plant growth, as it is a mobile nutrient. Signs are small, deformed leaves that may exhibit scorched margins (tip burn) (Figure 18d). End blossom rot on tomato fruits is a characteristic sign of a Ca deficiency (Figure 18e). Even when adequate Ca is present, it is restricted from entering the plant in humid conditions and has antagonistic relationships with potassium (Somerville *et al.* 2014). In addition to CaCO3, crushed coral can be used to maintain Ca levels and increase alkalinity in aquaponic systems. Using crushed coral is anecdotal but has been effective in small and medium sized system. Using a source that is sanitized is critical as to not introduce foreign organisms or disease into the system

Iron: Iron is one of the more easily recognized deficiencies. Fe deficiency is characterized by chlorosis (yellowing) between the veins of the leaf (Figure 18f). The veins themselves will remain green. As Fe is an immobile nutrient, symptoms will appear on new leaves. Signs appear similar to a Mg deficiency but are easily differentiated, as Mg symptoms appear on older leaves (Mg is a mobile nutrient). Chelated Fe is added to the system to maintain Fe levels at 2 mg/L.

FIGURE 18d
Calcium deficiency in lettuce

FIGURE 18e
Calcium deficiency

FIGURE 18f
Iron deficiency

VIII. Integrated Pest Management

Eliminating insect pests in aquaponic systems is more difficult than in traditional soil-based or hydroponic growing methods. Common insecticides are typically toxic to aquatic vertebrates at very low concentrations. Many practitioners implement an ecosystem-based approach to pest prevention and reduction, known as integrated pest management (IPM). This strategy may implement a pronged approach of physical, environmental, biological, and/or microbial controls.

Physical Controls

Preventing insects from entering the greenhouse is the best pest management strategy for aquaponics. Prevention is accomplished through consistent monitoring and physical controls. The use of adhesive, pheromone, or light traps can be used to monitor type of insect and level of infestation. Screens can be an effective physical control and can be used on outdoor systems or to cover vents in a greenhouse. Mesh size is an important consideration and should be as small as possible without restricting air flow and ventilation. Screen size for common pests are 0.15 mm for thrips, 0.73mm for white flies and aphids, and 0.8 mm for leaf miners. The most effective monitoring tool however, is the "farmer's shadow" (close monitoring by operators). Physical controls can also include a sanitation area for workers and production of plant seedlings in-house.

Biological/Chemical Controls

IPM strategies can also incorporate biological and/or microbial controls. These controls have many ecological advantages, including their host specificity, environmental beneficence, ability to be used in conjunction with chemical application, and that they are nontoxic and nonpathogenic to wildlife, humans, and other organisms not closely related to the target pest. Considering that these are precise, targeted control measures, cost can often be substantial.

Biological controls utilize insect predators of the target pest to control population numbers. While effective, use of beneficial insects may be cost prohibitive for smaller or hobby aquaponic systems. This strategy requires a tight predatory-prey ratio, as prey can be quickly depleted, leaving the beneficial insects with no food source. Predatory bugs such as spiders, ladybugs, praying mantis, bumblebees, and parasitic wasps are effective in combating pests.

Certain plants such as lavender, basil, rosemary, marigold, chrysanthemum, petunias, and carnivorous plants have natural oils and tactics that repel pests such as aphids, thrips, whiteflies, spider mites, and caterpillars. A natural pest repellant can be achieved by having large quantities of these plants inside and outside a plant production area.

Chemical Applications

Pesticides derived from biological or microbial sources are also effective and widely available. Biopesticides are derived from natural materials such as animals, plants, bacterial, and certain minerals. Common biopesticides include biofungicides (Trichoderma), bioherbicides (Phytopthora), and bioinsecticides (*Bacillus thuringiensis*, B. sphaericus). B. thuringiensis (Bt) has become an increasingly common mechanism to target specific vegetable pests. Bt consists of a spore that contains a toxic protein crystal. Certain insects that consume the bacteria release toxic crystals into their gut, blocking the system, which protects the pest's stomach from its own digestive juices. The stomach is penetrated, causing insect death by poisoning from stomach content and spores themselves. This same mechanism is what makes Bt harmless to birds, fish and mammals, whose acidic gut conditions negate the bacteria's effect.

Microbial pesticides come from naturally occurring or genetically altered bacteria, fungi, algae, viruses or protozoans. These compounds can take different modes of action, including release of toxic compounds, disruption of cellular function, and physical effect. Beauvaria bassiana, for example, is a fungus that gets under the chitin (shell) of hard-bodied insects, resulting in dehydration and death.

Chemical pest controls used for aquaponic farms include neem oil and extracts, soaps, pyrethrum-based products, and anything that is OMRI approved. These chemicals should be used in moderation and label instructions should be followed to avoid any plant or fish damage. Before any chemical is applied to the aquaponic system, the impact on the fish and biofilter must be considered. Limiting contact between the chemical and water is critical and may be more difficult in deep-water culture and media-based systems. The following is an example on how to calculate if a pesticide is safe to apply to the aquaponic system (Storey 2016).

Note: Refer to the Safety Data Sheet (SDS) and find the LC50 value or the lethal concentration of a pesticide at which 50% of the tested population dies. Rainbow trout or tilapia are often reported. The lowest concentration over the shortest time should be used.

Example 1: Pyrethrum – the active ingredient in Pyganic 1.4

Step 1: Determine the LC50 value from the chemical's SDS sheet – 0.0014 mg/L

Step 2: Determine the LC50 value for your system. Take the volume of your system in liters and multiply it by the LC50 (96 hr) value. Let's use a 2,000-gallon (7,580 L) system as an example.

7,580 L/sys. X 0.0014 mg/L = 10.61 mg/system

Step 3: Take the pyrethrin concentration and determine how much pyrethrin is being mixed.

The label recommends mixing 1–2 fluid ounces of Pyganic 1.4 with every gallon of water in compressed sprayers, which is between 2–4 Tbsp/gallon. In a 2,000 gallon system, the entire crop can be sprayed with 0.75 gallons of mix, which at the highest application rate is around 3 Tbsp (or 1.5 fluid ounces).

The label tells us that 0.05 lbs of active ingredient (pyrethrin) is the equivalent of 59 fluid ounces.

0.05 lbs pyrethrin/59 fluid ounces = 0.0008475 lbs pyrethrin/fluid ounce

0.0008475 lbs pyrethrin/fluid ounce X 453,592 mg/lb = 384 mg pyrethrin/fluid ounce

Step 4: Determine how much pyrethrin is being applied to the system.

1.5 fluid ounces/system X 384 mg pyrethrin/fluid ounce = **576 mg pyrethrin/system**

Step 5: Compare application concentration to LC50 of your system.

576 mg pyrethrin/system is much larger than the LC50 value for a 2,000-gallon system (**10.61 mg/system** from step 2). This means that this product is NOT a good choice for application.

Example 2: Azadirachtin – active ingredient in AzaMax Biological Insecticide, Miticide, and Nematicide

Step 1: Determine the LC50 value from the chemical's SDS sheet – 4 mg/L (96 hours) for rainbow trout.

Step 2: Determine the LC50 value for your system. Take the volume of your system in liters and multiply it by the LC50 (96 hr) value. Let's use a 2,000-gallon (7,580 L) system as an example.

7,580 L/sys. X 4 mg/L mg/L = 30,320 mg/system

Step 3: Take the pyrethrin concentration and determine how much pyrethrin is being mixed. The label recommends mixing 1–2 fluid ounces of AzaMax with every gallon of water in compressed sprayers, which is between 2–4 Tbsp/gallon. In a 2,000 gallon system, the entire crop can be sprayed with 0.75 gallons of mix, which at the highest application rate is around 3 Tbsp (or 1.5 fluid ounces).

The label tells us that the product contains 0.35 g of azadirachtin per fluid oz. Convert g to lb:

0.35 g azadirachtin/ounce ÷ 454 g/lb = 0.0007716 lbs pyrethrin/fluid ounce

0.0007716 lbs pyrethrin/fluid ounce X 453,592 mg/lb = 350 mg pyrethrin/fluid ounce

Step 4: Determine how much pyrethrin is being applied to the system.

1.5 fluid ounces/system X 350 mg pyrethrin/fluid ounce = 525 mg pyrethrin/system

Step 5: Compare application concentration to LC50 of your system.

525 mg pyrethrin/system is much smaller than the LC50 value for a 2,000-gallon system **30,320 mg/system** from step 2). This means that this product is SAFE to use in your aquaponic system. Even if a product is generally safe, limiting exposure to the water and organisms is still critical.

Common Pests

Mites: Mites are a very common pest, affecting hundreds of plants. These small arthropods are very small, often measuring less than 1 mm in length, and have sucking mouthparts. Damage to plants by mites includes brown stippling on leaves, upturned leaf margins, stunted plant growth, and webbing between plant structures (spider mites). Symptoms can mimic those of viral infections, particularly those caused by the broad mite, so identification should be done under a microscope. Mites typically have a 10-to-14 day life cycle and thrive in dark, humid conditions. Treatment options include neem oil and predatory insects such as ladybird beetles, lacewings, pirate bugs, predatory thrips, mites, and big-eyed bugs. Common types include Spider mite, Broad mite, Russet mite, and Cyclamen mites.

Aphids: A primary nemesis of most vegetable gardeners and plants, aphids can be very destructive to plants. Aphids are typically pear-shaped with two tail-like protrusions at the bottom of their abdomen (Figure 19a). The life cycle is very short, ranging from 10 days to three weeks. Their reproduction capacity makes them a particularly hard insect to control. Aphids can reproduce sexually or asexually and can switch between the two depending on the environment (Van Emden and Harrington 2017). Most aphids are born pregnant. Females will either create daughter clones that produce both male and female offspring, leading to sexual reproduction and eventually egg deposition, or female aphids will simply create live birth clones of themselves without the help from males. Female clones can survive the winter and continue the cycle by creating more clones.

Aphids are commonly found in colony clusters on new growth, base of buds, and on the underside of leaves. Feeding occurs through rasping mouth parts that drain essential nutrient and glucose from the phloem. As a result, leaves of plants infested with aphids often look shriveled, discolored, or stunted. Aphids excrete a substance called honeydew, a sugar-rich, sticky liquid that attracts ants. The ants protect aphids from predators.

Luckily, ladybird beetles (ladybugs) are natural aphid predators. Other treatment options include avoiding high nitrogen levels, physically removing aphids with a strong spray of water, applying a soap-water solution to plants, and applying of neem oil (Flint 2013).

Caterpillars: Caterpillars, the larval stage of butterflies and moths, can demolish leafy crops within a short window (Figure 19b). Their voracious eating habits make them one of the most significant agriculture pests. Adults feed on pollen nectar and are not a danger to plants; however, if you see adults, you likely have caterpillars as well. A caterpillar causes leaf damage that appears as holes or large missing section. Frass, or fecal deposits, appear as small brown/black pellets and are present near damaged tissue.

Common pests include cabbage looper and cabbage worms (Figure 19c) on Brassica sp., cutworms (Figure 19d), diamondback moths (Figure 19e), hornworms (Figure 19f), beet armyworm (Figure 19g), and inchworms (Figure 19h).


FIGURE 19a
Aphids


FIGURE 19b
Leaf damage due to caterpillar


FIGURE 19c
Cabbage worm


FIGURE 19d
Black cutworm


FIGURE 19e
Diamondback Moth


FIGURE 19f
Hornworm


FIGURE 19g
Beet armyworm


FIGURE 19h
Inch worm


FIGURE 19i
White flies

Common treatments include hand removal, B. thuringiensis (Bt), assassin bugs, and lacewings. Chemical application is not recommended, as it is often more damaging to beneficial insects than target pests and leads to chemical resistance.

White flies: White flies are sap-sucking insects that are significant pests in a wide variety of vegetable crops (Figure 19i).

There are three primary whitefly species that impact vegetable crops in the U.S.: the sweet potato, greenhouse, and the banded-winged whitefly (Natwick *et al.* 2016). Adults of these species are small (1.52 mm) with yellow bodies and wings covered in a white, waxy powder. Most life stages are found on the undersides of leaves, where the adults and nymphs feed. Commonly affected crops include beans, broccoli, cabbage, cauliflower, cucumber, eggplant, melon, peppers, squash, tomato, and watermelon.

Plants with heavy infestation levels may appear stunted, have yellowing or silvering of the leaves, and have defoliation resulting in reduced yields. Honeydew, excreted during feeding by whiteflies, can reduce the quality and marketability of vegetable crops. Perhaps the most damage caused by whiteflies is their role as a vector for more than 100 different plant viruses.

Natural enemies can be effective in reducing or controlling pest levels in greenhouses. Common biological controls are predators (lacewings, bigeyed bugs, lady beetles), parasites (specifically Encarsia formosa, a parasitic wasp), and fungal entomopathogens. Insecticidal soaps and oils can provide some control of whiteflies, but active compounds must cover the undersides of leaves where the insects hide.

Thrips: Thrips are tiny narrow insects that are a common and persistent pest of vegetable crops in both greenhouse and outdoor systems (Figure 19j). Of the hundreds of species affecting vegetable crops, the Western Flower thrip and the Onion thrip are the most pervasive. Thrips, like other insects mentioned here, are sucking insects that drain water and nutrients from the leaves, leaving them discolored with silvery feeding scars and wilting of plant components.

FIGURE 19j
Thrips

All life stages may be damaging, as eggs are commonly laid inside plant tissue, leaving a scar. Typically, the larval and adult life stages are going to be the most damaging due to plant feeding behavior and the risk of transmitting viruses to the plant. Thrips complete their lifecycle in 3-5 weeks.

Thrips can be hard to see directly on the plant, depending on the species. Shaking the leaf over a white piece of paper can help make them more visible. Treatment options vary according to species. Biological controls include lacewing larvae, pirate bugs, and predatory thrips.

Management of the culture environment and prevention is key to preventing thrips. Use of sticky traps placed at the base of plants or examination of the underside of leaves for feeding scars are ways to monitor for presence of thrips. Thrips can be prevented by using proper sanitation protocols for culture equipment, only using seedlings grown in-house, and preventing weedy areas or overgrown vegetation near the plants or greenhouse.

Chemical applications can be effective at treating thrips however most treatments do not kill them outright and instead prevent them from feeding and thus starving the insect. Due to their lifecycle stages that exist within the plant, multiple applications may be necessary to eliminate them from the system or control an outbreak.

A more comprehensive overview of vegetable pests can be found at:
https://entomology.ca.uky.edu/ent60
https://www.uvm.edu/~entlab/Greenhouse%20IPM/pestsandbiocontrols.html
https://content.ces.ncsu.edu/insect-and-related-pests-of-vegetables

Disease Problems and Management

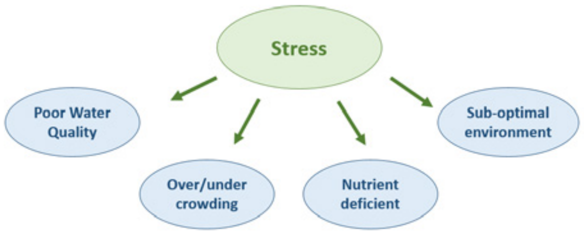
Fish Disease and Treatment

Fish culture is inherently a messy business. Bacterial pathogens and parasites that affect fish are naturally occurring and opportunistic by nature. Good management, proper husbandry practices, and daily observation of fish can prevent many issues associated with fish health. Proper management techniques in the fish production of the aquaponics system should include: system design, water quality monitoring and correction, equipment maintenance, feed storage, fish observation to remove sick or dead fish, and worker sanitation. Common external physical signs of fish disease include:

- Hemorrhage: an abnormal discharge of blood
- Lesions: a defined area of diseased tissue such as an ulcer, blister, or canker
- White spots or pustules
- Pale or swollen gills: often seen with fish “gulping” at the surface of the water for air
- Dark coloration
- Excess mucus on the skin or gills
- Sloughing of skin
- Emaciation
- Distended abdomen
- Exophthalmia: pop-eye

There are four major groups of pathogens related to fish culture: fungi, bacteria, viruses, and parasites. Common fish diseases and their treatment are listed below. Typically, diseases seen in aquaponic production systems are a result of environmental or physical stress (Figure 20). Stress can stem from 1) rough or excessive handling, 2) confinement of non-domesticated species of fish into tank systems or inappropriate stocking densities, 3) improper feed supply, feeding regiment, or nutrition and 4) poor or unsuitable water quality conditions.

FIGURE 20
Factors leading to fish disease



In preparation for stocking fish, biofilters must be broken in (populated with established bacteria before fish are stocked in the system) and water quality parameters must be within acceptable ranges for the species of fish being cultured. Once fish are on-site, and before they are stocked into new or existing production, they should be quarantined and treated prophylactically for external parasites using salt, formalin, potassium permanganate, or other approved treatments. Treatment must happen outside of the production system, as chemicals introduced in the aquaponic system will cause the biofilter to crash and the whole process will have to be started over. Fish should also be observed for any physical abnormalities in appearance or behavior. Many diseases are first detected by observing abnormal swimming patterns. Signs of abnormal behavior include whirling, flashing, bobbing, gasping, or side-swimming. Quarantine facilities and general good fish-handling protocols should include 1) washing hands before and after interaction with tanks, equipment, feed, or fish, 2) using nets and other equipment only in the quarantine or production area, 3) thoroughly drying or even bleaching between uses (via bleach buckets or spray bottles) to kill bacteria, fungus, and parasites, and 4) working in quarantine areas as the last task of the day to prevent cross-contamination. Arthur *et al.* (2008) provide a comprehensive overview of quarantine procedures for live aquatic animals.

Once fish have been stocked and the system is in operation, it is critical that water chemistry be conducted regularly and that resultant numbers are checked as acceptable for both fish and plants. Any necessary adjustments should be made as soon as issues are identified, as water chemistry problems will not self-correct. Early detection and intervention is the best measure to make sure that production is maximized for both time-to-market and crop yield.

During production, fish that are crowded into tanks for intensive culture can get stressed, which is manifested several ways. Stressed fish can go off feed (stop eating); hit the sides of tanks, causing abrasions to their body or fins; nip at each other in aggression; and even jump out of tanks, resulting in death. Stressful culture conditions weaken the fish's immune systems, leaving them more susceptible to bacterial and fungal infections. Typically, at the first sign of illness, fish will stop eating. At this point, medicated feed is useless, and a chemical treatment is required.

Another way fish become diseased through stress is poor water quality conditions. This can be a result of poor water chemistry and inadequate water conditions. For example, fish become stressed during acute or chronically low levels of dissolved oxygen and are more susceptible to disease. Another example is occasional overfeeding of fish. The excess protein breaks down into total ammonia-nitrogen, which breaks down further into toxic components of un-ionized ammonia-nitrogen and nitrite-nitrogen. The biofilter component is not sufficient to convert these compounds to nitrate, leading to stress on the fish from poor water quality. These toxic components are further exacerbated by issues such as high pH and increasing temperatures.

To prevent stress on the fish, a general rule of thumb is to stop or reduce feed input in the system:

- When temperature is outside of species range
- When fish are sick or stressed
- 24-48 hours before/after transport
- 24 hours before sampling
- 3-4 days before processing
- When low DO is present
- When water quality parameters are sub-par

If fish stocked into production become sick, they should be removed from the system immediately for treatment or disposal. Water amendments should be made promptly, stocking rates should be checked, water flow should be checked, and water exchanges may be necessary. There are no good treatment options for treating systemically in production, as chemicals cannot be used with coupled aquaponic systems. Fish can be removed or isolated, treated in containment, and reintroduced at a later date.

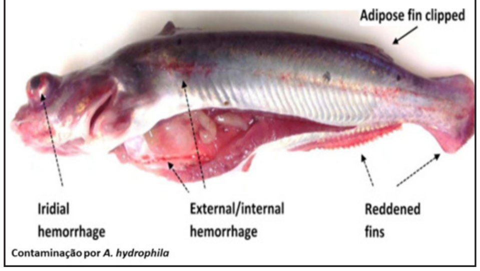
System design plays a role in disease prevention. Tanks used for fish culture should be round and preferably have a conical bottom for removal of settle-able solids. Design should be such that tanks are easy to disinfect, can be isolated individually from the rest of the system, and have windows to view fish in the water column.

Common Fish Diseases and Their Treatment

FIGURE 21a
Ich

FIGURE 21b
Columnaris

FIGURE 21c
Aeromonas



Parasites

Ich (white spot disease): Ich is caused by the parasite *Ichthyophthirius multifiliis* (Ich). Ich appears on infected fish as small white specks on their skin and/or gills (Figure 21a). Fish may exhibit "flashing" behavior, characterized by a quick rubbing or scratching movements against the tank bottom, wall, or surface of the water (Durborow *et al.* 2000). Excess mucus is commonly present; however, the only clear sign may be a dead or dying fish. Treatment for Ich is difficult; however, elevating water temperature to above 85°F can kill Ich by disrupting its life cycle. Chemical treatments for quarantine tanks or decoupled systems include multiple treatments of formalin, copper sulfate ($CuSO_4$), or potassium permanganate ($KMnO_4$). Check appropriate dose rates before administering. These chemicals should not come into contact with plant components and must be administered in an isolated tank. Simply harvesting the fish may be the simplest solution.

Whirling disease: Caused by Myxobolus cerebralis, whirling disease primarily infects salmonids (trout and salmon) and can enter the aquaculture system through affected fish. Symptoms include abnormal swimming, darkening of posterior part, and skeletal deformation (Idowu *et al.* 2017). There is no true effective treatment for whirling disease. Producers should only purchase salmonid fingerling from hatchery that are certified whirling disease free and use treated water or ground water for production.

Bacterial Infections

Columnaris: Infections from Flavobacterium *columnare* are common in aquaculture-reared fish. Common symptoms include red or pale ulcers on the skin; yellowish mucus on the skin, gills, and/or mouth; and necrosis/erosion of the gills. Saddleback is a common lesion caused by columnaris and appears as a pale white saddle-like band encircling the body (Figure 21b). The bacteria can cause disease under normal culture conditions, but more likely when fish are stressed by low oxygen, high ammonia, high nitrite, high water temperatures, rough handling, mechanical injury, and crowding. (Durborow *et al.* 1998). Columnaris is typically treated with chemical treatment of the water using KMnO4 or by using Terramycin® (oxytetracyline HCl). Medicated feed that contains the antibiotics Aquaflor®, Terramycin® or Romet® may be effective. Chemical treatments or antibiotic feed should not come into contact with plant components and must be administered in an isolated tank.

Aeromonas: *Aeromonas* is a genus of bacteria that is widespread and is commonly isolated from freshwater culture environments. The disease caused by these bacteria in fish is called Motile *Aeromonas* Septicemia (MAS) (Hanson *et al.* 2019). Aeromonas infections are probably the most common bacterial disease diagnosed in cultured warmwater fish. Fish with septicemia often have hemorrhages (red areas or spots) on the skin, eyes, and fins; a dis¬tended abdomen; flared scales due to edema in the scale pockets (dropsy); and/or a red, inflamed anus (Figure 21c). Internally, the muscle and visceral tissue are often red, and the body cavity may contain bloody fluid. Typical MAS can be attributed to a predisposing factor, such as a handling event, temperature shock, water quality stressor, spawning, or aggression. Treatment is currently limited to three antibiotics: Aquaflor®, Terramycin® and Romet®-30. Proper withdrawal times for each antibiotic must be observed before treated fish can be processed/harvested. Chemical treatments or antibiotic feed should not come into contact with plant components and must be administered in an isolated tank.

Enteric Septicemia of Catfish (ESC): ESC is also known as “Hole-in-Head Disease” and is caused by the bacteria *Edwardsiella ictaluri*. It most commonly affects catfish species and is accountable for one-third of reported fish diseases in the southeastern U.S. Behavioral signs of infection include head-chasing-tail or whirling rather than swimming, as well as “star gazing.” External signs include red or white shallow ulcers, a hole appearing in the top of the head, and fluid buildup in the abdomen, causing severe distension. Treatment is typically administering medicated feed containing the antibiotics Aquaflor®, Romet®, or Terramycin®. Chemical treatments or antibiotic feed should not come into contact with plant components and must be administered in an isolated tank.

Viral Infections

Tilapia Lake Virus (TiLV): TiLV is one of the only significant viruses that affect tilapia in both wild and cultured situations. It is caused by *Tilapia tilapinevirus* and has been seen in Asia, Africa, and South America. It is transferred quickly through infected populations, and there is no treatment at the time of this publication.

Plant Disease and Prevention

Plant disease problems can be difficult and time consuming to treat. Preventing issues from arising is the first step in proper plant care. Many foliar plant diseases are present during conditions of high temperature and humidity. Providing proper ventilation and reducing humidity will prevent conditions that allow mold and disease to spread to other plants.

Plant nutrition plays a direct role in disease resistance in plants (Agrios 2005). Providing the correct balance of nutrients is important not only for growth but also to decrease susceptibility and increase recovery from certain plant disease. Table 10 describes the role of certain nutrients for prevention of plant disease. Below are common plant diseases in aquaponic systems.

Table 10: Role of nutrition in plant disease resistance.

Nutrient	**Effect**
Nitrogen	Overfertilization makes more succulent tissues that are more prone to fungal attack. Nitrogen starvation results in stunted plant that are more prone to attack from opportunistic micro-organisms.
Phosphorus	Improves nutrient balances and accelerates maturity of the plants.
Potassium	Accelerates wound healing and reduce the effect of frost damage. Delays maturity and senescence of plants.
Calcium	Reduces the severity of some root and stem fungal diseases. Affect the cell wall composition in plants that resist fungal penetrations.
Silicon	Helps plants produce specific defense reactions, including the releases of phenolic compounds against pathogens.


FIGURE 22a
Bacterial canker in leaf.

Bacterial canker: The bacteria that causes bacterial canker, Pseudomonas syringae, enters the plant through existing wounds caused by pruning, harvesting, or injury. Signs of bacterial canker include marginal browning or necrosis on leaves, elongated tan regions or splitting of the stem, and/or small white spots on the fruit (Figure 22a). The most common cause is unsanitary growing condition or harvesting tools.

Grey mold: Caused by the pathogenic fungus, Botrytis cinerea, grey mold can be found almost anywhere plants are grown. Prevalent during damp, cool weather, grey mold can spread quickly through the crop, affecting stems, leaves, and fruits. Leaves may have brown lesions that spread over the entire surface, causing the leaf to wilt (Figure 22b). If not controlled, spores will spread to flowers and fruits, where fuzzy, grey growth will appear (Figure 22c). Improving ventilation with fans and air flow within the plant structure through pruning are preventative measures. In addition, removing fallen or diseased plants and avoiding injury to trellised plants is critical in preventing grey mold.

Powdery and downy mildew: These two types of mildew affect nearly all vegetable crops. Primarily affecting the leaves of the plant, they are more prevalent in humid conditions. Powdery mildew is circular and white in appearance and can appear anywhere on the leaf surface. The leaf may yellow if the fungus has been present for a long time. A downy mildew spot is angular and grey in appearance and the fungus is limited by the leaf vein. Leaves may appear yellow before the presence of the fungus is evident (Figure 22d).

FIGURE 22b, c
Grey mold.

FIGURE 22d
Powdery and downy mildew on grape leaf.

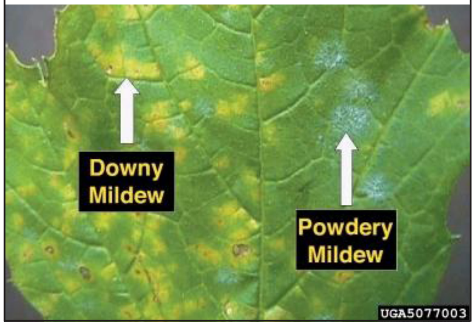


FIGURE 22e
Pythium on lettuce roots.

Pythium: The causative agent for root rot in plants, *Pythium* sp. are found naturally in the culture environment and impact a wide variety of plants. Symptoms include brown, rotting roots that slough off easily when disturbed (Figure 22e). Plants may appear stunted or nutrient-deficient. Different species of *Pythium* are prevalent at specific temperatures; however, in aquaponics they commonly appear at water temperatures above 78°F and conditions with high organic solids. Controlling temperature and implementing effective solids removal will limit *Pythium* sp. in an aquaponics system.

Steps to Prevent Plant Disease in Aquaponic Systems:

- **Control temperature and humidity of the growing environment.** High temperature and humidity often are the ideal environment for growth and spread of fungal and bacterial disease in plants. Particularly in a greenhouse or indoor facility, forced air ventilation and prevention of evaporation will reduce these parameters. It is also important to control these in and around the plant structure. This is accomplished through appropriate plant spacing and pruning fruiting crops with dense foliage.
- **Sanitation.** Implementing sanitation standard operating procedures (SSOPs) will help prevent disease outbreak in vegetable production units. Sanitizing propagation and harvesting tools and growing equipment such as rafts and NFT channels will also help prevent disease outbreak.
- **Remove dead or diseased plants.** Prompt removal and disposal of affected plants can help the spread of disease in the facility.
- **Choose appropriate plant species.** If external environmental conditions cannot be controlled, choosing resistant or appropriate varieties will save practitioners time and money.
- **Seed quality and storage.** Buy quality seeds and store them under refrigeration to prevent the seeds from molding and to increase germination.

Food Safety and Sanitation

Sanitation and cleanliness of an operation is critical to ensure Good Agricultural Practices (GAP) regarding food safety (Hollyer *et al.* 2012). This is important because as of 2018, the CDC estimated that each year, 48 million people get sick from a foodborne illness, 128,000 are hospitalized, and about 3,000 people die. If the aquaponics industry wants to become a larger part of global food production and the fresh-cut sector, it is critical to maintain a good reputation and positive public perception of food safety for both fish and plants cultured within the same system.

The largest food safety concern within aquaponics is the spread of zoonotic pathogens (*E. coli*, salmonella, etc.), which can be present in harmful quantities within the water. The contamination can happen from people contacting the water or from consuming plant leaves that have been in contact with the aquaponic water (Hollyer *et al.* 2012). Analyzing water and plant samples annually will help producers build a strong understanding of potential sources of contamination.

Prevention is the best tactic for biosecurity and food safety, which is why every aquaponics operation should have SSOPs (Sanitation Standard Operating Procedures) and follow the seven principles of HACCP (Hazard Analysis and Critical Control Point). SSOPs are written rules for food processing that an operation develops and implements to prevent any contamination of their tools or production space. HACCP dictates the maximum/minimum values to which biological, chemical, or physical parameters must be maintained at a critical control point to prevent food safety hazards. Examples of sanitation procedures to eliminate the spread of disease, pests, and food safety issues for both fish and plants include:

- Annual pathogen and bacterial tests
- Continuous improvements to SSOPs and HACCPs
- Overall production space cleanliness and biosecurity
- Tool sanitation
- Human sanitation
- Sanitation education
- Proper food storage

Sanitation is especially important when considering that most aquaponics systems are recirculating, and what is normally done in recirculating aquaculture to treat sick fish cannot be done easily in recirculating aquaponics due to the integrated plant production. Therefore, a net dip should be present on-site to prevent the spread of fish pathogens through fish contact with a contaminated net. Virkon is one example of a fish-safe net sanitation product that can be applied to a net according to the manufacturer's instruction. Keeping tank rims clean of uneaten fish food is a simple way to reduce potential fungus and pest growth. Monitoring and maintaining feed quality will reduce risks associated with fish getting sick from ingesting moldy food.

FIGURE 23
Sanitizing harvesting tools

Creating and following a detailed plan of how fish and plants are processed will drastically reduce food safety concerns. Fish processing requires producers to follow strict HACCP regulations and inspections, which is prohibitive to most aquaponic producers due to the amount of fish per harvest and overhead costs associated with fish processing. Therefore, many aquaponics farms will sell whole fish either live or on ice. Fish processing regulations may vary from state to state. Plant processing will be regulated by SSOPs, which will include washing hands before harvesting or after touching water; washing tools in soap or diluted bleach solution; maintaining a clean harvest area; and cleaning rafts/grow media with disinfectants (soap, hydrogen peroxide, etc.) (Figure 23).

Potential hazardous foods (PHF) are foods that will spoil, causing food safety issues, if kept at room temperature for certain amounts of time (Busta *et al.* 2003).This would include both fish and plants (vegetables, microgreens, fruits) produced within aquaponic systems. Improper cooling of foods is the number one cause (>30%)

of foodborne illness. Time and temperature are the two factors influencing food spoilage the most. Humidity of the storage environment and equipment will also impact food shelf life. Microgreens and sprouts are especially of concern when considering food safety, as they require no processing or heat-treatment prior to consumption and have a shorter shelf life, making them more susceptible to bacterial spoilage.

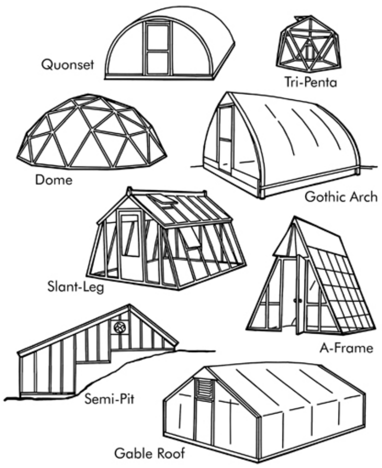
Utilizing education, training, and readily available information for employees about food safety practices is the best strategy for prevention. Signs reminding employees to maintain cleanliness can also help. Additionally, educating employees on where the highest risks of food safety contamination can occur within any operation is key. Cost implications food safety procedure and compliance should be included within a budget.

IX. Controlled Environment Growing

Types of Greenhouses

Free-standing greenhouses come in a variety of shapes and sizes (Figure 24). Choice of greenhouse depends on snow load and wind speed of a particular location. Free-standing greenhouses are less expensive than larger structures and are easier to optimize environmental parameters for different crop species. If multiple stand-alone structures are used, increased sanitation protocols are required to prevent insect pest and disease issues from being transferred between structures by workers.

FIGURE 24
Different styles of greenhouses



Gutter-connected greenhouses provide a more efficient use of space and reduced overall heating costs during winter compared to stand-alone structures (Figure 25). The upfront cost of this greenhouse style is high and may be cost prohibitive for growers on a limited budget.

Lean-to greenhouses have one wall that borders a building. Light reduction is not severe if the dark wall is the north wall. These types of structures may be useful for decoupled aquaponic systems, as environmental parameters can be controlled independently in each structure.

FIGURE 25
Gutter connected greenhouse

Greenhouse Covering Options

Greenhouse coverings come in a variety of materials, including glass, rigid plastic (fiberglass, polycarbonate, or acrylic), and plastic films. The appropriate choice depends on your climate zone and budget. Regions with a colder climate will require the covering to provide increased insulation and low heat transfer measured by the R-value and U-value, respectively. The R-value measures how well the material insulates. The higher the R-value, the more insulation the material provides. The U-value quantifies heat transfer and describes how much heat is lost or gained. Materials with a lower U-value will be more energy efficient. Approximately 75% of plastic used for covering greenhouses in the U.S. is air-inflated double-layer polyethylene plastic. 6ml polyethylene plastic covering is inexpensive and has an R-value of 1.4 and a U-value of 0.5 (high insulation capacity and energy efficient). A single layer fiberglass covering is moderately expensive and has an R-value of 0.83 and a U-value of 1.2 (moderate insulation capacity and not energy efficient) (Table 11). Choosing the right material for your climate zone is critical to reduce heating costs during winter. Energy cost is the second greatest production expense, just behind labor.

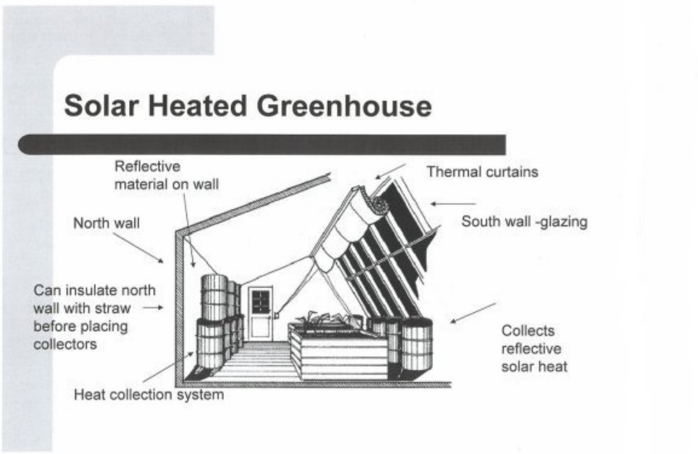
Table 11: Comparison of greenhouse glazing materials.

Material	Life	R value	U value	Advantages	Disadvantages	Cost
Glass Single layer, tempered	(Until it breaks)	0.95	1.13	Strong, attractive, good seal, 90% light penetration	Breaks, difficult to install, heating	$$$ - $$$$
Rigid plastics Fiberglass	6-15 years	0.83	1.20	Lightweight, strong, light penetration	Opaque, degrade/yellow over time-6yrs, needs resin recoat	$ - $$
Rigid single-wall						$ - $$
Rigid double-wall acrylic	20 yr	1.4-1.9	0.75-1.0	Transparent, 30% energy savings with double layer, Bends	Extra layer reduces light pentration to about 80%	$$ - $$$$
Rigid double or triple wall polycarbonate with UV coating	10-15 yr	1.4-1.9 Triple 2.5	0.53-0.70	Same as acrylic, may bend more easily than acrylic	Same light as acrylic, but will yellow without UV coating, about 80%	$$ - $$$$
Plastic films (rolls) Single layer, 6 ml	1-4 yr	.85	1.20	Good light penetration (90% 1-layer) inexpensive	Needs to be replaced frequently, condensation	$
Double layer, 6 ml (polyethylene)		1.4	0.5-1.0	Reduces condensation, increases warmth	Reduces light 10& with each layer (80% total)	$

Heating and Cooling Options

Heating: For small or backyard-size producers, implementing a passive heating system can help reduce heating costs during cold months. In this type of system, sunlight enters the south wall. The north wall has reflective material to trap and store heat. Black barrels filled with water absorb heat from sunlight during the day and slowly release the heat during the night. Thermal curtains can be hung on the south wall to trap heat during the night (Figure 26). While helpful to reduce heating costs, this practice would not be practical for large producers as it takes up valuable production space in the facility and is not able to maintain a consistent and reliable temperature.

FIGURE 26
Passive solar greenhouse

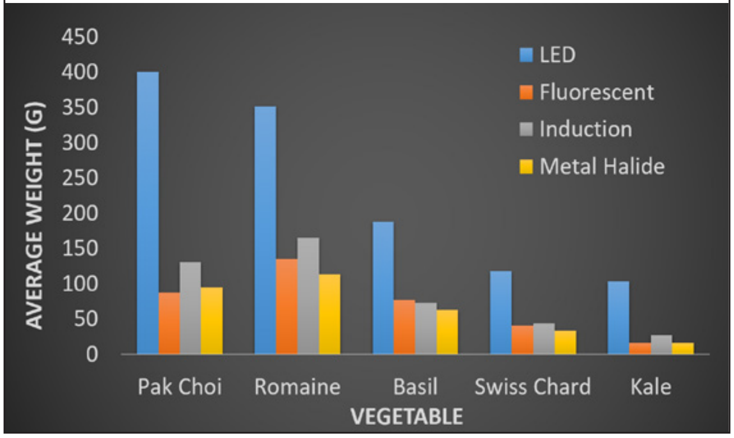


Larger producers that have year-round, consistent production will need to maintain a temperature independent of what can be gained from the sun. Forced air heaters powered by natural gas, propane, or electricity are most commonly used in the U.S. These heaters control the air temperature by a thermostat. Radiant heaters such as wood or natural gas broilers control the temperature by pumping hot water through pipes located throughout the structure. Broilers are popular, as wood is a cheap source of fuel compared to oil or natural gas.

FIGURE 27
Evaporative cooler

Cooling: The combination of manual and automatic ventilation is the most cost-effective way to cool down your greenhouse. Ventilation options include roll-up sides, ceiling vents, and vents along the long end of the greenhouse. Forced air ventilation fans pull air through the length of greenhouse using thermostat-controlled vents at the opposite end. Evaporative coolers are a relatively inexpensive way to provide cooling to the structure in hot, dry climates. Evaporative coolers work by pulling in outside air through a wet wall, cooling the air as it comes in. The wet wall is a frame that contains corrugated cardboard or synthetic material that is saturated by water dripping over its surface (Figure 27). Excess water is collected in a reservoir and pumped back over the cardboard. Evaporative cooling walls are not efficient in climates with high temperature and high humidity.

FIGURE 28
Plant growth under LEDs



Indoor Production

Moving production into an insulated building is suitable for producers who want to be close to urban markets, have a lack of arable land, or live in a climate not suitable for outdoor or greenhouse production. No matter where a plant is grown, it still requires optimal conditions to reach its maximum yield potential. In addition to the controls discussed above, producers must also provide light suitable for optimal plant growth. For plants, light stimulates seed germination, food production, flowering, chlorophyll manufacturing, and branch and leaf thickening.

Photosynthesis is stimulated by the type and frequency of light received. Light is emitted as waves of photons, or bundles of energy. The amount of energy in each photon determines the length of the wave from crest to crest. Lower energy wavelengths emit a blue light (400 nm) and higher energy wavelengths emit a red light (700 nm). Plants utilize wavelengths between 400-700 nm. Blue and red light is required in different ratios at different periods in the plant's life. Blue light is primarily responsible for vegetative growth. Red light triggers cell elongation, vegetative growth, and flowering.

Traditional plant grow lights are fluorescent (FL) or high intensity discharge (HID) fixtures. Compact T5, T8, and T12 FL bulbs are mainly used for seed propagation or vegetative growth. HID fixtures are often sold to accommodate both metal halide (MH) and high-pressure sodium (HPS) bulbs. Light produced by MH bulbs is the 400-550 range, suitable for vegetative growth. Light produced by HPS bulbs provide light in the yellow, orange, and red spectrum, more suited for flowering and fruiting stages. Both FL and HPS bulb have a lifespan of 20,000+ hours and generate a considerable amount of heat.

Advances in plant grow lights have made indoor production more cost effective through improved energy efficiency and higher plant yields. Induction fixtures (IND) are similar to FL bulbs but have become more popular, as they have no electrodes allowing them to last considerably longer (75,000+ hours). They also put off much less heat and are more energy efficient. Light emitting diodes (LED) lights were once too expensive for many growers; however, they are now considered the standard for plant grow lights. LED lights operate by passing an electrical current through two semi-conductors (one positive, one negative) which then emit light. The spectrum can be dialed into what is required by the plant at different stages, improving the quality and yield of the crop. In addition to improved energy efficiency, LED lights have a lifespan of 100,000+ hours.

Research conducted at Kentucky State University compared growth of six leafy greens and energy use for FL, MH, IND, and LED grow lights. LED lights produced significantly higher plant biomass (g/m2) compared to the other three lights (Figure 28: KSU unpublished, Oliver *et al.* 2018). As the cost of LED lights continue to decrease, production costs for indoor plant production will also decrease.

X. Marketing and Economics

Economic

There is relatively little information available on the economics of aquaponics, likely due to a lack of successful commercial production before 2014. Based on information summarized in Engle (2015) and Heidemann and Woods (2015), aquaponics profitability is achievable depending on geographic location, climate, initial investment, production cost, market demand, and consumer preference for goods. Production in USDA Zones 7-13 are typically most profitable in the U.S. due to reduced risk of losses associated with cold weather, power outages, and utility costs (Love *et al.* 2015). Another production factor is labor costs, which have been estimated at 46% of total operating cost and 40% of total annual cost (Tokunaga *et al.* 2015). Reduced delivery travel costs are associated with aquaponic production due to the capability of suburban and urban production.

An international survey of aquaponic growers found a significant relationship between sales of non-food products from aquaponics farms (i.e. training, workshops, system designs, consulting services) and the farms' profitability (Love *et al.* 2015). Crops grown in aquaponics can be very profitable; however, several studies have shown that the fish component is far less so. But while the crops may produce a larger profit than the fish (and the amount of space/area devoted to fish in the aquaponics system may be minimized), the **"advertising-value"** of the fish has a worth that exceeds the actual dollar amount brought in from fish sales. This may be even more true with systems located in the Virgin Islands and Hawaii that experience long, consistent daylight hours with little daily temperature fluctuation and where the price of fresh produce is very high.

Considering the inherent adaptability of aquaponic production, potential success should be carefully weighed from available information, a well-constructed business plan, and individual needs and inputs. An operating plan should include, but not be limited to, the investment required to construct facilities and purchase equipment, annual costs to operate the system, projections of market prices and competition, and realistic estimates of potential revenue. Based on information from three commercially surveyed aquaponic farms, the estimated payback period can be between two to five years.

Marketing

The most difficult aspect of any aquaponics operation is developing a realistic and practical marketing scheme (Engle 2015). Location is key for marketing because location determines what is in demand and the size of the market. Having close access to multiple cities significantly increases the market size as well as market demographics and in turn increases demand for product. If the location is within a remote area such as an island, then the market price for the product will be much higher compared to a location in an easily accessible area (Engle 2015). Since aquaponics production can be done year-round, growing and selling produce that is locally considered "out of season" can help achieve a higher price point. Offering a variety of niche crops such as microgreens, house plants, and herbs holds much potential to increase the market as well as profits.

In order to enhance the marketability of aquaponic produce, certain certifications will be extremely helpful. These certifications include organic and certified naturally grown (CNG). In order to maintain the organic label, extra funds will need to be used in order to satisfy the regulations, but overall the product will be able to be marketed as a high-quality product, raising the price consumers are willing to pay. The other option is to be certified as naturally grown, which means no synthetic chemicals are used in the operation, which stands true for most aquaponic farms. While organic is still the word most consumers know, being certified as naturally grown can still draw in top-dollar prices that consumers are willing to pay. No preservatives! No pesticides! No herbicides! Local! Homegrown! These are also labeling strategies that can be used to promote the sale of aquaponic produce. Clever and catchy labeling that is easily spotted in stores can help leave an impression in a consumer's mind about the product. Just having aquaponic-grown fish available from a business will make their hydroponically-grown crop more desirable to environmentally-conscience customers, so even though fish may be a small percentage of what the business produces, it serves as a “marketing tool” for all other sales from that business.

Selling directly to restaurants, farmers markets, and CSA markets has potential to generate more revenue compared to selling it wholesale. These routes allow for a closer personal contact with the consumer and allow the aquaponic producer to tell their story. Although wholesale can be much more reliable and easier to work with, the profits are drastically reduced, since the price of the product is sold at a much lower price. Selling wholesale also requires a much larger capacity than what most aquaponics farms have, which is why selling directly to the consumer is typically the market chosen for business.

XI. Certifications and Regulations

Organic Certification

Organic food sales in the United States rose by 5.9% in 2018, totaling $47.9 billion dollars. It is no surprise that aquaponic farmers want the organic label to bolster their marketing and sales, and equally no surprise that soil-based farmers do not want their selling power to be diluted. The heart of organic production is cultivating soil, so how can produce be certified organic if there is no soil? In 2015, a taskforce was assembled consisting of individuals representing both the soil-based organic industry and the hydroponic and aquaponic communities. The goal was to describe hydroponic and aquaponic systems and practices, examine how hydroponics and aquaponics align or conflict with USDA organic regulations, support their decisions with science, and explore alternatives. At its 2017 fall meeting, the National Organic Standards Board (NOSB) voted 8-7 against a proposal to prohibit hydroponic and aquaponic production in organic agriculture. Although aeroponics is prohibited, both hydroponics and aquaponics remain eligible for organic certification, while the USDA considers the NOSB decision. While aquaponics lends itself to a more sustainable growing methods, only OMRI approved items can be used during production. This prohibits the use of rockwool, hydroxide bases, chelated iron, and other common tools of the trade. Currently, only 17 of 80 certifiers will assist aquaponic farms with organic certification.

Certified Naturally Grown (CNG)

Known as the "grassroots alternative to organic," CNG certification follows organic standards but focuses on growers who sell directly to the consumer. CNG farmers are restricted from using synt8hetic herbicides, pesticides, fertilizers, or genetically modified organisms (GMOs). Farms with CNG certification undergo an annual inspection and pay an annual fee. Inspections can be conducted by other CNG farmers, Extension agents, master gardeners, or other qualified personnel. Sections of the CNG standards for aquaponics can be found at (https://www.cngfarming.org/aquaponics_standards).

Good Agriculture Practices (GAP)

Good Agriculture Practices (GAPs) are specific methods that, when applied to agriculture, create food for consumers or further processing that is safe and wholesome. Currently a voluntary certification, the Food Safety Modernization Act (FSMA), will require farms to comply with food safety and security measures outlined in the document. In 2011, the Produce GAPs Harmonized Food Safety Standards was released, which require producers to meet standards for biosecurity, sanitation, worker training, and documentation. Information on Produce GAP can be found at (https://www.ams.usda.gov/services/auditing/gap-ghp/harmonized).

Hazard Analysis and Critical Control Point (HACCP)

HACCP is a management system in which food safety is addressed through the analysis and control of biological, chemical, and physical hazards from raw material production, procurement and handling to manufacturing, distribution, and consumption of the finished product.

Standard Operating Procedures (SOPs) and HACCP

Determining risk factors in the production, processing, sale, and consumption of food items involves HACCP, SOPs, and Sanitation SOPs (SSOPs). Developing a protocol for each step of the operation and providing employee training is essential to provide a safe food product. The following are examples of how HACCP, SOPs, and SSOPs work in conjunction.

1. Chemical: Use of cleaner on surfaces. Could it be a hazard? Yes, but in our SSOP we have a second rinse step to remove residue, so it is not a CCP because it is handled someplace else in the plans.

2. Physical: Knife chips in the roots, cuttings, or fish fillets. Could it be a hazard? Yes, but in our SOPs in our work flow all knives are inspected at the start of all working and at three-hour breaks, or all products are passed through a metal detector. So, it is not critical control point.

Best Aquaculture Practices (BAPs)

Based on BAPs, the five pillars of responsible aquaculture are environmental responsibility, animal health and welfare, food safety, social responsibility, and traceability. Critical requirement include record keeping and traceability, worker safety and hygiene, and biosecurity. More information on BAPs can be found at (https://www.bapcertification.org/).

Propagation Permits

Commercial fisheries propagation permits are required by state wildlife agencies for culture and sale of aquatic organisms. Information provided includes the name and location of the business, water source, flooding likelihood, discharge information, how the brood stock was obtained, quantity and type of species produced, and the type of production system. Required information and cost of the permit will vary by state.

XII. References

Agrios, G. N. 2005. Plant pathology, Academic press.

Arthur, J. R., Bondad-Reantaso, M. G. & Subasinghe, R. P. 2008. Procedures for the quarantine of live aquatic animals: a manual, Food and agriculture organization of the United Nations.

Bregnballe, J. 2010. A guide to recirculation aquaculture. An introduction to the new environmentally friendly and highly productive closed fish farming systems. Eurofish, Copenhagen, Denmark.

Bryson, G. & Mills, H. 2014. Plant analysis handbook IV, Micro-Macro Publ. , Athens GA.

Busta, F., Bernard, D., Gravani, R., Hall, P., Pierson, M., Prince, G., Schaffner, D., Swanson, K., Woodward, B. & Yiannas, F. 2003. Evaluation and definition of potentially hazardous foods. Comp. Rev. Food Sci. Food Saf, 2, 1-109.

Chen, S., Coffin, D. E. & Malone, R. F. 1997. Sludge production and management for recirculating aquacultural systems. Journal of the World Aquaculture Society, 28, 303-315.

Cerozi, B. & Fitzsimmons, K. 2017. Phosphorus dynamics modeling and mass balance in an aquaponics system. Agricultural Systems, 153, 94-100.

Clark, S. E., Steele, K. A., Spicher, J., Siu, C. Y., Lalor, M. M., Pitt, R. & Kirby, J. T. 2008. Roofing materials' contributions to storm-water runoff pollution. Journal of irrigation and drainage engineering, 134, 638-645.

Dana, R. 2010. Micro-Scale Biogas Production: A Beginners Guide, ATTRA.

Danaher, J., Rakocy, J., Shultz, R., Bailey, D. & Pantanella, E. 2009. Dewatering and composting aquaculture waste as a growing medium in the nursery production of tomato plants. Pages 223-229. International Symposium on Growing Media and Composting 891.

Danaher, J. J., Shultz, R. C., Rakocy, J. E. & Bailey, D. S. 2013. Alternative solids removal for warm water recirculating raft aquaponic systems. Journal of the World Aquaculture Society, 44, 374-383.

Davidson, J. & Summerfelt, S. T. 2005. Solids removal from a coldwater recirculating system—comparison of a swirl separator and a radial-flow settler. Aquacultural Engineering, 33, 47-61.

Delaide, B., Goddek, S., Keesman, K. & Jijakli, H. 2018. A methodology to quantify aerobic and anaerobic sludge digestion performances for nutrient recycling in aquaponics. Biotechnologie, Agronomie, Société et Environnement, 22, 106-112.

Diessner, C. G. 2013. Small scale raft aquaponics: Evaluation of hybrid striped bass growth and plant uptake potential.

Durborow, R., Thune, R., Hawke, J. & Camus, A. 1998. Columnaris disease: a bacterial infection caused by Flavobacterium columnare. Southern Regional Aquaculture Center, Publication No. 479. Stoneville, Mississippi. US Department of Agriculture: Stoneville, MS, USA.

Durborow, R. M., Mitchell, A. J. & Crosby, M. D. 2000. Ich (White Spot Disease), Southern Regional Aquaculture Center.

Egna, H. S. & Boyd, C. E. 1997. Dynamics of pond aquaculture, CRC press.

Engle, C. 2015. Economics of aquaponics. SRAC Publication 5006.

Flint, M. L. 2013. Aphids: Integrated Pest Management for Home Gardeners and Landscape Professionals. University of California Davis, Davis, CA.

Fox, B. K., Howerton, R. & Tamaru, C. S. 2010. Construction of automatic bell siphons for backyard aquaponic systems.

Goddek, S., Delaide, B. P., Joyce, A., Wuertz, S., Jijakli, M. H., Gross, A., Eding, E. H., Bläser, I., Reuter, M. & Keizer, L. P. 2018. Nutrient mineralization and organic matter reduction performance of RAS-based sludge in sequential UASB-EGSB reactors. Aquacultural Engineering, 83, 10-19.

Goddek, S., Espinal, C. A., Delaide, B., Jijakli, M. H., Schmautz, Z., Wuertz, S. & Keesman, K. J. 2016. Navigating towards decoupled aquaponic systems: A system dynamics design approach. Water, 8, 303.

Graber, A. & Junge, R. 2009. Aquaponic Systems: Nutrient recycling from fish wastewater by vegetable production. Desalination, 246, 147-156.

Hanson, L., Hemstreet, W. & Hawke, J. 2019. Motile Aeromonas Septicemia (MAS) in Fish. Southern Regional Aquaculture Center.

Hollyer, J., Nakamura-Tengan, L., Meyer, D., Troegner, V. & Castro, L. 2012. Good agricultural practices (GAPs): A consumer discovery tool for learning about risk-reducing behaviors on commercial farms and in school gardens.

Idowu, T., Adedeji, H. & Sogbesan, O. 2017. Fish Disease and Health Management in Aquaculture Production. Int J Environ & Agri Sci, 1, 002.

Islam, M. Z., Lee, Y.-T., Mele, M. A., Choi, I.-L. & Kang, H.-M. 2019. The effect of phosphorus and root zone temperature on anthocyanin of red romaine lettuce. Agronomy, 9, 47.

Khiari, Z., Kaluthota, S. & Savidov, N. 2019. Aerobic bioconversion of aquaculture solid waste into liquid fertilizer: Effects of bioprocess parameters on kinetics of nitrogen mineralization. Aquaculture, 500, 492-499.

Kloas, W., Groß, R., Baganz, D., Graupner, J., Monsees, H., Schmidt, U., Staaks, G., Suhl, J., Tschirner, M. & Wittstock, B. 2015. A new concept for aquaponic systems to improve sustainability, increase productivity, and reduce environmental impacts. Aquaculture Environment Interactions, 7, 179-192.

Lennard, W. 2012. Aquaponic System Design Parameters: Fish Tank Shape and Design. Aquaponic Fact Sheet Series. Aquaponic Solutions.

Love, D. C., Fry, J. P., Li, X., Hill, E. S., Genello, L., Semmens, K. & Thompson, R. E. 2015. Commercial aquaponics production and profitability: Findings from an international survey. Aquaculture, 435, 67-74.

Maggio, A., Raimondi, G., Martino, A. & De Pascale, S. 2007. Salt stress response in tomato beyond the salinity tolerance threshold. Environmental and Experimental Botany, 59, 276-282.

Masser, M. P., Rakocy, J. & Losordo, T. M. 1999. Recirculating aquaculture tank production systems. Management of recirculating systems. SRAC Publication, 452.

Natwick, E., Stoddard, C., Zalom, F., Trumble, J., Miyao, G. & Stapleton, J. 2016. UC IPM Pest management guidelines: Tomato. UC ARN Publication 3470.

Oliver, L. P., Coyle, S. D., Bright, L. A., Shultz, R. C., Hager, J. V. & Tidwell, J. H. 2018. Comparison of Four Artificial Light Technologies for Indoor Aquaponic Production of Swiss Chard, Beta vulgaris, and Kale, Brassica oleracea. Journal of the World Aquaculture Society, 49, 837-844.

Pantanella, E. 2013. Advances in Freshwater Aquaponic Research. International Aquaponics Conference: Aquaponics and Global Food Security. Lecture conducted from University of Wisconsin Stevens Point.

Pantanella, E., Danaher, J., Rakocy, J., Shultz, R. & Bailey, D. 2011. Alternative media types for seedling production of lettuce and basil. Acta horticulturae.

Pattillo, D. A. 2017. An Overview of Aquaponic Systems: Hydroponic Components. NCRAC Technical Bulletins. 19.http://lib.dr.iastate.edu/ncrac_techbulletins/19

Pickens, J. 2015. Integrating effluent from recirculating aquaculture systems with greenhouse cucumber and tomato production.

Rackocy, J., Masser, M. & Losordo, T. 2006. Recirculating Aquaculture Tank Production Systems: Aquaponics-Integrating Fish and Plant Culture. SRAC Publication 454.

Rentsch, D., Schmidt, S. & Tegeder, M. 2007. Transporters for uptake and allocation of organic nitrogen compounds in plants. FEBS letters, 581, 2281-2289.

Sanchez, C. A. & Doerge, T. A. 1999. Using nutrient uptake patterns to develop efficient nitrogen management strategies for vegetables. HortTechnology, 9, 601-606.

Savidov, N., Hutchings, E. & Rakocy, J. 2005. Fish and plant production in a recirculating aquaponic system: a new approach to sustainable agriculture in Canada. Pages 209-221. International Conference and Exhibition on Soilless Culture: ICESC 2005 742.

Searchinger, T., Hanson, C., Ranganathan, J., Lipinski, B., Waite, R., Winterbottom, R., Dinshaw, A., Heimlich, R., Boval, M. & Chemineau, P. 2014. Creating a sustainable food future. A menu of solutions to sustainably feed more than 9 billion people by 2050. World resources report 2013-14: interim findings. Creating a sustainable food future. A menu of solutions to sustainably feed more than 9 billion people by 2050. World resources report 2013-14: interim findings, World Resources Institute (2014).

Shannon, M. & Grieve, C. 1998. Tolerance of vegetable crops to salinity. Scientia Horticulturae, 78, 5-38.

Shannon, M. C., Grieve, C. M., Lesch, S. M. & Draper, J. H. 2000. Analysis of salt tolerance in nine leafy vegetables irrigated with saline drainage water. Journal of the American Society for Horticultural Science, 125, 658-664.

Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. 2014. Small scale aquaponic food production; integrated fish and plant farming, Food and Agriculture organization of the United Nations, Rome.

Storey, A. 2016. How to Use Pesticides in Aquaponics Without Hurting Your Fish. https://university.upstartfarmers.com/blog/pesticides-in-aquaponics-without-hurting-fish. Access date: July 14, 2020.

Summerfelt, S., Bebak-Williams, J. & Tsukuda, S. 2001. Controlled systems: water reuse and recirculation. Fish Hatchery Management, Second Ed.. American Fisheries Society, Bethesda, MD.

Timmons, M. & Ebeling, J. M. 2013. Recirculating Aquaculture Third Edition, Ithaca Publishing Company, Ithaca, NY.

Timmons, M. B., Guerdat, T. & Vinci, B. J. 2018. Recirculating Aquaculture (4th Edition), Ithaca Publishing, Ithaca, NY.

Tokunaga, K., Tamaru, C., Ako, H. & Leung, P. 2015. Economics of Small-scale Commercial Aquaponics in Hawai ‘i. Journal of the World Aquaculture Society, 46, 20-32.

Van Emden, H. F. & Harrington, R. 2017. Aphids as crop pests, Cabi.

Watts, C., Bright, L. A., Coyle, S. & Tidwell, J. 2016. Evaluation of stocking density during second-year growth of largemouth bass, Micropterus salmoides, raised indoors in a recirculating aquaculture system. Journal of the World Aquaculture Society, 47, 538-543.

Wurts, W. A. & Durborow, R. M. 1992. Interactions of pH, carbon dioxide, alkalinity and hardness in fish ponds.

Wynne, F. & Wurts, W. A. 2011. Transportation of warmwater fish: equipment and guidelines, Southern Regional Aquaculture Center Publication No. 390.

Yeo, S. E. & Binkowski, F. P. 2010. Processing Aquaculture System Biosolids by Worm Composting—Vermicomposting. Technical Bulletins. North Central Regional Aquaculture Center.

Yogev, U., Barnes, A. & Gross, A. 2016. Nutrients and energy balance analysis for a conceptual model of a three loops off grid aquaponics. Water, 8, 589.

Extension Publications and Talks

Ako, H. Year. How to build and operate a simple small-to-large scale aquaponics system. Center for Tropical and Subtropical Aquaculture Center Publication 161. Available: http://www.ctsa.org/files/publications/CTSA_aquaponicsHowTo.pdf (Accessed June 29, 2016)

Ako, H. and A. Baker. 2009. Small-Scale Lettuce Production with Hydroponics or Aquaponics. Sustainable Agriculture SA-2. College of Tropical Agriculture and Human Resources. University of Hawaii at Manoa. Available: http://fisheries.tamu.edu/files/2013/10/Small-Scale-Lettuce-Production-with-Hydroponics-or-Aquaponics.pdf (Accessed June 29, 2016)

Burden, D. J. and D. A. Pattillo. 2013. Aquaponics. Agriculture Marketing Resource Center. Available: http://www.agmrc.org/commodities-products/aquaculture/aquaponics/ (Accessed June 29, 2016)

Conte, F. S. and L. C. Thompson. 2012. Aquaponics. California Aquaculture Extension. Available: http://fisheries.tamu.edu/files/2013/10/Aquaponics.pdf (Accessed June 29, 2016)

Diver, S. 2006. Aquaponics – Integration of Hydroponics with Aquaculture. ATTRA Available: https://attra.ncat.org/attra-pub/download.php?id=56 (Accessed June 29, 2016)

Durborow, R. M., D. M. Crosby, and M. W. Brunson. 1997. Ammonia in Fish Ponds. Southern Regional Aquaculture Center Publication Number 463. Available: https://srac-aquaponics.tamu.edu/serveFactSheet/3 (Accessed June 29, 2016)

Durborow, R. M., D. M. Crosby, and M. W. Brunson. 1997. Nitrite in Fish Ponds Southern Regional Aquaculture Center Publication Number 462. Available: https://srac-aquaponics.tamu.edu/serveFactSheet/2 (Accessed June 29, 2016)

Engle, C. R. 2015. Economics of Aquaponics. Southern Regional Aquaculture Center Publication Number 5006. Available: https://srac-aquaponics.tamu.edu/serveFactSheet/8 (Accessed June 29, 2016)

Goddek, Simon, Alyssa Joyce, Benz Kotzen, and Gavin M. Burnell. Aquaponics Food Production Systems Springer Nature, 2019. Available: https://library.oapen.org/viewer/web/viewer.html?file=/bitstream/handle/20.500.12657/22883/1007278.pdf?sequence=1&isAllowed=y (Accessed September 22, 2020)

Hargreaves, J. A. and C. S. Tucker. 2002. Measuring Dissolved Oxygen Concentration in Aquaculture Southern Regional Aquaculture Center Publication Number 4601. Available: https://srac-aquaponics.tamu.edu/serveFactSheet/6 (Accessed June 29, 2016)

Kelly, A. M. 2013. Aquaponics. University of Arkansas Pine Bluff Extension. Available http://fisheries.tamu.edu/files/2013/10/Aquaponics2.pdf (Accessed June 29, 2016)

Klinger-Bowen, R. C., C. S. Tamaru, B. K. Fox, K McGovern-Hopkins, R. Howerton. 2011. Testing your Aquaponic System Water: A Comparison of Commercial Water Chemistry Methods. Center for Tropical and Subtropical Aquaculture Publication. Available: http://www.ctsa.org/files/publications/TestingAquaponicWater.pdf (Accessed June 29, 2016)

Mischke, C. and J. Avery. 2013. Toxicities of Agricultural Pesticides to Selected Aquatic Organisms. Southern Regional Aquaculture Center Publication Number 4600. Available: https://srac-aquaponics.tamu.edu/serveFactSheet/5 (Accessed June 29, 2016)

Mullins, B. Nerrie, and T. D. Sink. 2015. Principles of Small-Scale Aquaponics Southern Regional Aquaculture Center Publication Number 5007. Available: https://srac-aquaponics.tamu.edu/serveFactSheet/9 (Accessed June 29, 2016)

Pattillo, D. A. Marketing Local Foods in Iowa – Seafood. December, 2017. Iowa State University Extension Publication FS 0018. https://store.extension.iastate.edu/product/15328 (January 10, 2018)

Pattillo, D. A. An Overview of Aquaponic Systems: Aquaculture Components. October 2017. North Central Regional Aquaculture Center Technical Bulletin Series Publication No. 124. Available: http://lib.dr.iastate.edu/ncrac_techbulletins/20/ (January 10, 2018)

Pattillo, D. A. and S. K. Rotole. Building and Caring for a Miniature Aquaponics System. October, 2017. Iowa State University Extension Publication FA 0014. Available: https://store.extension.iastate.edu/product/15306 (January 10, 2018)

Pattillo, D. A. An Overview of Aquaponic Systems: Hydroponic Components. March 2017. North Central Regional Aquaculture Center Technical Bulletin Series Publication No. 123. Available: http://lib.dr.iastate.edu/ncrac_techbulletins/19/ (June 16, 2017)

Pattillo, D. A. and M. Speltz. Iowa Fish Processing Frequently Asked Questions. October, 2016. Iowa State University Extension Publication FA 0005A. Available: https://store.extension.iastate.edu/Product/Iowa-Fish-Processing-Frequently-Asked-Questions (February 27, 2017)

Pattillo, D. A. 2015. Aquaponics Production Data: Loss or Profit? Iowa State University Extension. Available: http://ohioaquaculture.org/pdf/aquaponics/Aquaponics%20Production%20data%20-%20loss%20or%20profit%20Allen%20Patillo.pdf (Accessed June 29, 2016)

Pattillo, D. A. 2015. Aquaponics: Food Safety & Human Health. Iowa State University Extension. Available: http://ohioaquaculture.org/pdf/aquaponics/Aquaponics%20Food%20Safety%20and%20Human%20Health%20Allen%20Patillo.pdf (Accessed June 29, 2016)

Pattillo, D. A. Fish Health Considerations for Recirculation Aquaculture. December, 2014. Available: https://store.extension.iastate.edu/Product/Fish-Health-Considerations-for-Recirculating-Aquaculture (October 27, 2015)

Pattillo, D. A. Standard Operating Procedures - Fish Health Management for Recirculating Aquaculture. December, 2014. Available: https://store.extension.iastate.edu/Product/Standard-Operating-Procedures-Fish-Health-Management-for-Recirculating-Aquaculture (October 27, 2015)

Pattillo, D. A. Fish Monitoring Sheet (Sample). December, 2014. Available: https://store.extension.iastate.edu/Product/Fish-Monitoring-Sheet-Sample (October 27, 2015)

Pattillo, D. A. Fish Monitoring Sheet (Excel). December, 2014. Available: https://store.extension.iastate.edu/Product/Fish-Monitoring-Excel-Sheet (October 27, 2015)

Pattillo, D. A. Feeding Practices for Recirculating Aquaculture. December, 2014. Available: https://store.extension.iastate.edu/Product/Feeding-Practices-for-Recirculating-Aquaculture (October 27, 2015)

Pattillo, D. A. Standard Operating Procedures – Feeding Practices and Feed Management. December, 2014. Available: https://store.extension.iastate.edu/Product/Standard-Operating-Procedures-Feeding-Practices-for-Recirculating-Aquaculture (October 27, 2015)

Pattillo, D. A. Feeding Practices Monitoring Sheet (Sample). December, 2014. Available: https://store.extension.iastate.edu/Product/Feeding-Practices-Monitoring-Sheet-Sample (October 27, 2015)

Pattillo, D. A. Feeding Practices Monitoring Sheet (Excel). December, 2014. Available: https://store.extension.iastate.edu/Product/Feeding-Practices-Monitoring-Excel-Sheet (October 27, 2015)

Pattillo, D. A. Water Quality Management for Recirculating Aquaculture December, 2014. Available: https://store.extension.iastate.edu/Product/Water-Quality-Management-for-Recirculating-Aquaculture (October 27, 2015)

Pattillo, D. A. Standard Operating Procedures - Water Quality Management for Recirculating Aquaculture. December, 2014. Available: https://store.extension.iastate.edu/Product/Standard-Operating-Procedures-Water-Quality-Management-for-Recirculating-Aquaculture (October 27, 2015)

Pattillo, D. A. Water Quality Management Monitoring Sheet (Sample). December, 2014. Available: https://store.extension.iastate.edu/Product/Water-Quality-Management-Monitoring-Sheet-Sample

Pattillo, D. A. Water Quality Management Monitoring Sheet (Excel). December, 2014. Available: https://store.extension.iastate.edu/Product/Water-Quality-Management-Monitoring-Excel-Sheet (October 27, 2015)

Pattillo, D. A. Aquaculture Water Treatment Calculations. December, 2014. Available: https://store.extension.iastate.edu/Product/Aquaculture-Water-Treatment-Calculations (October 27, 2015)

Pattillo, D. A. 2014. Aquaponic System Design and Management. Iowa State University Extension. Available: https://www.extension.iastate.edu/forestry/tri_state/tristate_2014/talks/PDFs/Aquaponic_System_Design_and_Management.pdf (Accessed June 29, 2016)

Rakocy, J. E., M. P. Masser, and T. M. Losordo. 2006. Recirculating Aquaculture Tank Production Systems: Aquaponics – Integrating Fish and Plant Culture Southern Regional Aquaculture Center Publication Number 454. Available: https://srac.tamu.edu/serveFactSheet/105 (Accessed June 29, 2016)

Rakocy, J. E., D. S. Bauley, R. C. Shultz, and J. J. Danaher. A Commercial-Scale Aquaponic System Developed at the University of the Virgin Islands. Available: http://ag.arizona.edu/azaqua/ista/ISTA9/FullPapers/Rakocy1.doc (Accessed June 29, 2016)

Somerville, C. Cohen, M. Pantanella, E. Stankus, A. and Lovatelli, A. 2014. Small-scale aquaponic food production: Integrated fish and plant farming. Food and Agriculture Organization of the United Nations: Fisheries and Aquaculture Technical Paper 589. Available: http://www.fao.org/3/a-i4021e.pdf (Accessed June 29, 2016)

Stone, N. J. L. Shelton, B. E. Haggard, and H. K. Thomforde. 2013. Interpretation of Water Analysis Reports for Fish Culture Southern Regional Aquaculture Center Publication Number 4606. Available: https://srac-aquaponics.tamu.edu/serveFactSheet/7 (Accessed June 29, 2016)

Timmons, M. B. and J. M. Ebeling. 2013. Recirculating Aquaculture, 3rd Edition. Pp. 663-710. Northeastern Regional Aquaculture Center Publication No. 401-2013.

Tyson, R. 2013. Aquaponics – Vegetable and Fish Co-Production 2013. University of Florida Extension. Available: http://fisheries.tamu.edu/files/2013/10/Aquaponics-Vegetable-and-Fish-Co-Production-2013.pdf (Accessed June 29, 2016)

Wurts, W. A. and R. M. Durborow. 1992. Interactions of pH, Carbon Dioxide, Alkalinity and Hardness in Fish Ponds. Southern Regional Aquaculture Center Publication Number 464. Available: https://srac-aquaponics.tamu.edu/serveFactSheet/4 (Accessed June 29, 2016)

Recommended Videos

Danaher, J. 2015. Aquaponics – An Integrated Fish and Plant Production System. Southern Regional Aquaculture Center. http://www.ncrac.org/video/aquaponics-integrated-fish-and-plant-production-system (Accessed June 29, 2016)

Hager, J. V and Dusci, J. 2020. IBC Aquaponics: a step-by-step guide. https://www.youtube.com/watch?v=BwbvOMoU9oE

Pattillo, D. A. 2016. Aquaponics: How to Do It Yourself! North Central Regional Aquaculture Center Webinar Series. Accessed: http://www.ncrac.org/video/aquaponics-how-do-it-yourself (Accessed June 29, 2016)

Pattillo, D. A. 2013. Aquaponics System Design and Management. Iowa State University Extension. Available: https://connect.extension.iastate.edu/p5fba9a68a0/?launcher=false&fcsContent=true&pbMode=normal (Accessed June 29, 2016)

Rode, R. Aquaponics. 2013. Available: https://extension.purdue.edu/pages/article.aspx?intItemID=8789 (Accessed June 29, 2016)

Ron, B. T. 2014. Aquaponics: Paradigm Shift with Airlift. eXtension.org. Available: https://www.youtube.com/watch?v=ZWGs4NIkrLs&feature=em-upload_owner (Accessed June 29, 2016)

Ron, B. T. 2014. Aquaponics: Paradigm Shift with Airlift Pumps Part 2. eXtension.org. Available: https://www.youtube.com/watch?v=1EDlMqrngqQ&feature=em-upload_owner (Accessed June 29, 2016)

Shultz, C. Overview of Replicated Aquaponic Systems at Kentucky State University. Available: https://www.youtube.com/watch?v=gTg3eQZaR5E (Accessed 2/13/2018)

Storey, N. Biological Pest Control for Aquaponics. Bright Agrotech. https://blog.brightagrotech.com/pesticides-for-aquaponics/ (Accessed 2/13/2018)

Resource Pages

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/

Kentucky State University - Aquaculture Research Center http://www.ksuaquaculture.org/

Iowa State University Extension Online Store http://store.extension.iastate.edu/

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

North Central Regional Aquaculture Center 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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