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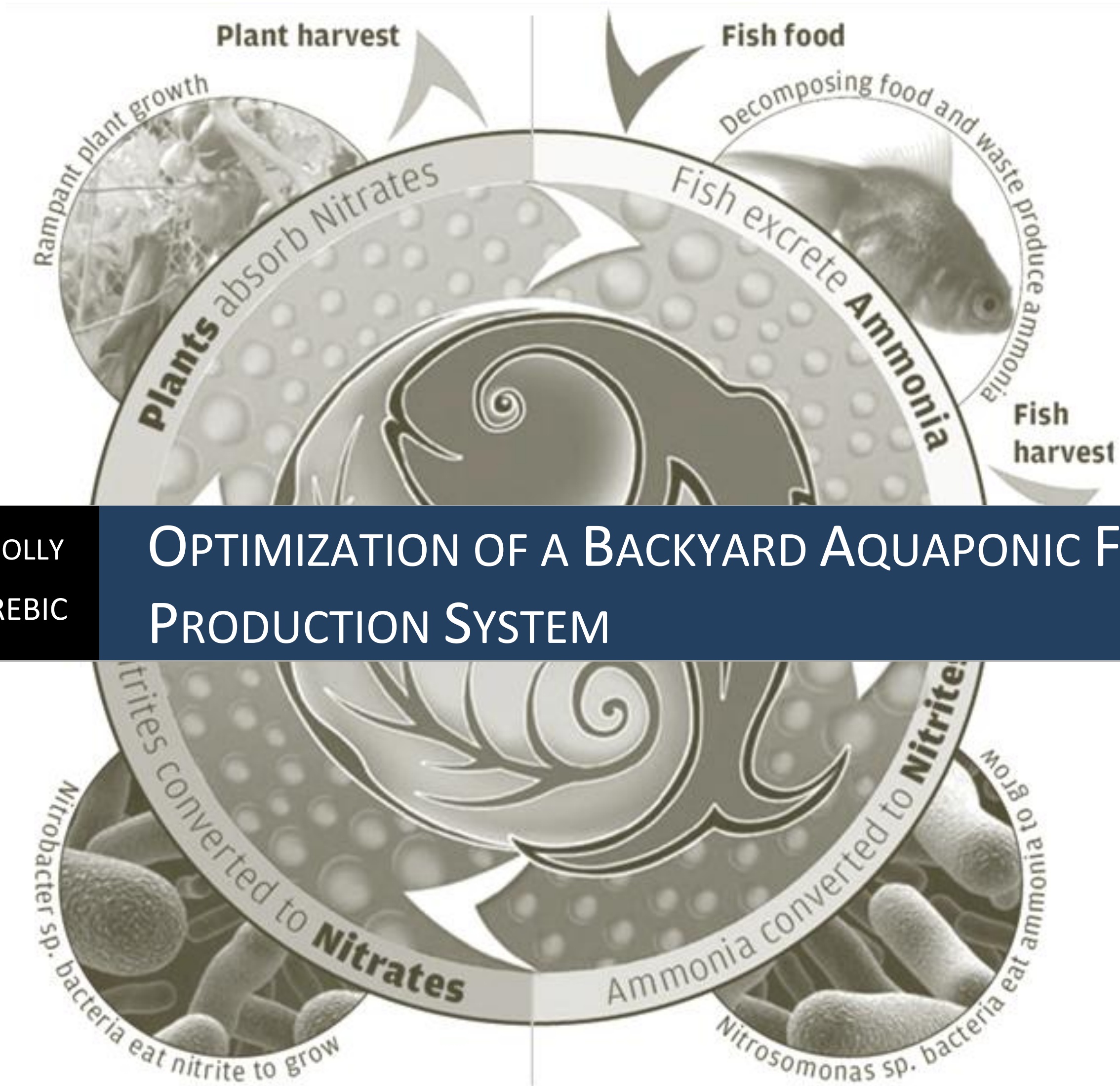

OPTIMIZATION OF A BACKYARD AQUAPONIC FOOD PRODUCTION SYSTEM

KEITH CONNOLLY
TATJANA TREBIC

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Presented to Dr. Vijaya Raghavan

Faculty of Agricultural and Environmental Sciences
Macdonald Campus, McGill University

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Table of Contents

Executive Summary

The current and escalating extent of soil degradation, water scarcity and climate-related challenges plaguing agricultural productivity in every corner of the world and particularly in the most underdeveloped and resource-scarce regions demands for a re-evaluation of the way we produce the foods that keep us alive and seems to beg for what could be referred to as another green revolution.

The need for the development of innovative, resource efficient and locally appropriate agricultural solutions is immense and this need is greatest in densely populated, resource-poor nations with small economies. Tropical island nations face increasing confrontations by climate change and obstacles to the sound stewardship of their natural resources and environment and trends in land use allocation indicate the deteriorating status of agricultural activities as lucrative compared to industries such as tourism, real estate and off-shore financing. The end results are the massive rates of food importations from distant locations, the decline of regional agricultural autonomy and a loss of connection between consumers and the origin, nutritional value and safety of their food.

The small eastern Caribbean nation of Barbados faces many of these challenges, yet with a highly educated workforce and a climate conducive to year-round food production, it has the potential to transform its agricultural industry by employing new food production technologies that can be applied to the local context while placing minimal stress on the country's already scarce water and agriculturally-productive soil resources.

Aquaponics is a concept relatively new to modern food production methods and provides answers to many of the above-mentioned problems. The technology combines the two well-established practices of aquaculture and hydroponics to yield a method of food growing that greatly reduces the use of water resources, demands no soil at all, and produces high yields of fresh, nutritious crops in the form of vegetables, fruits, herbs and fish.

Aquaponics on a small scale can serve as a family's solution to the need for an inexpensive, nutritious and reliable food source that has the capacity to provide a full meal (vegetables and protein) without many inputs. The optimization of one such small-scale, backyard aquaponic food production system is the subject of this report whereby an improved design is delivered in response to practical experience gained during an internship with the Baird's Village Aquaponic Association in Barbados over the Fall of 2009.

This report details the improvements in the configuration and overall health of the backyard aquaponic systems seen in Barbados through the inclusion of an effective aeration system, a method of water-level regulation, a different and more efficient system of water pumping/distribution, as well as measures for the assurance of high system water quality and increased crop yields. The importance and appropriateness of aquaponics as a solution in Barbados is explored along with the key parameters required for a high-performance aquaponic food production system.

1. Introduction

1.1 Food Security

Populations around the world face questions of food security today on a scale that has not been seen in recent human history. The evolution of how we feed our populations and the technologies we use to do it have created a unique set of circumstances that bring with them unique challenges, and despite significant advances in food production and our knowledge of food nutrition and food safety, hunger continues to plague millions of people around the world. It is thought that over a billion people in the world are currently undernourished (World Food Programme, 2010). Many factors contribute to hunger and decreasing food security in the world today including conflict, poverty, poor agricultural infrastructure and over-exploitation of the environment.

The concept of food security is defined by the Food and Agriculture Organization of the United Nations (FAO) in the following way:

"Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life. Household food security is the application of this concept to the family level, with individuals within households as the focus of concern."

Key among the issues that threaten food security are the intensive resources needed for agricultural activities. Agriculture is by far the largest strain on the world's precious freshwater resources, currently accounting for 70% of the world's freshwater consumption (Pimentel, Berger, Filberto, & Newton, 2004). Some predictions have human consumption of the world's freshwater resources at over 90% by 2025 (2003 International Year of Freshwater, 2003). Increasing water scarcity has given rise to an unprecedented water conservation movement, although consumption levels remain at all time highs.

Agriculture's dependence on healthy soil presents another problem in food production, as current estimates are that 38% of global agricultural land is degraded. Soil degradation is the change induced by the natural decrease in the soils' potential for productive use, and normally results in reduced yields due to lack of or insufficient nutrients or water availability. Improper land use and poor land management have been singled out as the most important factors leading to soil degradation (The World Bank, 2010). To add value to the soils' nutrient stock, agricultural trends have been to add increasing amounts of fertilizer, which, along with herbicides and pesticides, has contributed to significant and disquieting environmental problems.

Access to food is another obstacle that families and countries face when considering food security. Often it is difficult or unfeasible to grow food locally and a global trend for many has been to obtain food that has been grown far from the point of purchase. However, many developing countries lack the infrastructure such as roads or storage facilities to make this scenario effective and sustainable. In addition, this situation makes millions of people vulnerable to market related supply problems associated with distant producers.

1.2 Small-Scale Agriculture

Modern agriculture has slowly evolved to fit a capitalist, industrial model where farming is done on large scales by relatively few farmers. Multi-national corporations now control such a large portion of the food production process that the people they feed have become increasingly dependent and vulnerable to their abilities and philosophies. Industrialization of any process theoretically is the most efficient use of our resources, however the allocation of our food production to a few powerful institutions has resulted in the development of significant food security and environmental problems. Decreasing genetic diversity in our food production, genetically altered food, and the large energy requirements to package, preserve, and transport food are just some of the issues brought on by the industrialization of our food system.

Given the problems associated with intensive farm practices, and given the global scarcity in soil and water resources along with the problems associated with under-developed regions where hunger prevails, there has been a large push toward more sustainable farming practices in an effort to feed more people with increasing efficiency while reducing our impact on the environment. Small scale farming is an alternative to intensive farming. It acknowledges agriculture's dependence on finite resources.

Urban agriculture is defined as the practice of cultivating, processing, and distributing food, in or around (peri-urban), a village, town or city (Bailkey & Nasr, 2000). It is being recognized as one of the activities that has the potential to contribute toward socio-economic development in urban areas of the developing world and has the capacity to contribute to alleviating food insecurity and poverty. Studies show that urban agriculture contributes significantly to household income and gives families access to inexpensive food, consequently reducing poverty (Hampwaye, Nel, & Ingombe, 2009).

Such an agricultural method is the subject of the design project that follows. Aquaponics is the combination of hydroponic and aquaculture systems, whereby fish tank water that has become nutrient rich by the excretion of fish is circulated into a growing area where the nutrients are absorbed by plants that are cultured hydroponically. At the same time the grow bed acts as a biofilter and cleans the water so it can be recirculated back to the fish tank. The closed system uses a fraction of the water, no soil, and produces two food sources for consumption; the crops grown in the bed, and the fish reared in the tank. Aquaponics is garnering growing attention around the world because of its efficient use of resources. It provides a simple and practical solution to the food security issues previously discussed and has the potential to increase the health and stability of families by feeding them and helping them become financially secure.

1.3 Objective of Project

In the Fall of 2009, Keith Connolly and Tatjana Trebic, the authors of this project, took part in the Barbados Field Study Semester where they were partnered with the Baird's Village Aquaponic Association (BVAA), which had just received a United Nations Development Fund grant to develop a community sized aquaponics operation in the community of Baird's Village. During the internship, Keith and Tatjana did promotional work with the organization and helped in the construction of several systems, including one that they housed at McGill University's Bellairs Research Institute on which they conducted water quality tests. Tilapia were used in all these systems and in the McGill system okra and basil were grown.

Mr. Hinkson, the founder of the Baird's Village Aquaponic Association, had been working with aquaponics for several years, but didn't have a very scientific approach to minimizing his inputs and maximizing his outputs. Thus was born the objective of this project:

To design an improved aquaponics system and make management recommendations with the goal of optimizing fish and plant biomass outputs.

2. Background

2.1 Agriculture in Barbados

2.1.1 Economy and Human Resources

The easternmost Caribbean island nation of Barbados (see Figure 39 in Appendix A) is considered to be the most developed of the Caribbean states, having one of the highest per capita incomes in the region. Its political stability, relative proximity to North American markets and exceptional natural beauty/biodiversity make it a desirable market for foreign investment. Foreign exchange includes offshore financing and information services as well as significant trading with the United States, Canada and other Caribbean states, with services making up 80% of national exports. Tourism and the light industry make up 75% of the national GDP while agriculture contributes a mere 6% (Central Intelligence Agency, 2010).

Barbados has economic strengths in that it shares the same time zone as the eastern United States and Canadian financial centers, has English as its official language, making communications with Canada, the United States and the United Kingdom seamless, and a has a highly educated workforce with a literacy rate of 99.7% (Central Intelligence Agency, 2010).

The small size of Barbados and other nations in the region does not allow for economies of scale, however, regional cooperation through entities such as The Caribbean Community (CARICOM) allows for the free movement of labour and capital, the coordination of agricultural, industrial and foreign policies as well as access to a Common Market. Such collaboration among Caribbean states strives to improve standards of living in its member countries, enhance international competitiveness and increase productivity among other goals for the development and prosperity of the region (CARICOM, 2009).

2.1.2 Natural Resources

The densely populated island nation of Barbados (627 people/km^2) has limited resources required for a prosperous agricultural industry (Central Intelligence Agency, 2010). This high population density and seasonal influx of foreign tourists - over 570,000 tourists stayed in Barbados in 2007 and over 600,000 cruise ship passengers visited the country that same year – places stress on the country's key national resources (Totally Barbados, 2010).

Barbados is known as the 15th most water scarce country in the world and freshwater withdrawal per capita is 333 m^3/year (Central Intelligence Agency, 2010). Internal Renewable Water Resources are on the scale of 0.082 km^3/year, groundwater from infiltrated rainfall supplies 0.074 km^3/year, while surface waters make up 5.8 million m^3/year (FAO, 2000). Average daily water use by the agricultural sector amounts to approximately 10.4 ML/day (or 10, 400 m^3/day) and an estimated 1026 ha are irrigated by potable water (UN, 2004). This makes up 5.9% of the country's total cropland (EarthTrends, 2003). Total renewable water resources amount to 0.1 km^3 (Central Intelligence Agency, 2010).

The land surface of the island is composed mostly (~83%) of coralline limestone, while the remaining 17% is made up of shales, sands and clays (FAO, 2000). The limestone that covers most of the nation is highly porous and allows for very rapid infiltration of rainwater, meaning that its capacity to retain water in the root zone is quite low (Ministry of Agriculture and Rural Development). The northeastern region of the island, called the Scotland District is made up of layers of shales, sands and clays. It is quite rugged and is characterized by high overland runoff, frequent landslides and surface soil erosion problems (FAO, 2000).

The long history of intensive plantation-style monoculture production over the past 300 years in Barbados has made extensive contributions to soil quality problems in Barbados. These include the erosion of topsoil, a decrease in soil fertility, and the consequent application of large amounts of fertilizer and pesticides in order to maintain productivity (Homer, 1998).

2.1.3 Climate

Barbados has a tropical oceanic climate with little variation in temperatures due to the cooling easterly trade winds from the Atlantic Ocean. The rainy season lasts from June to December, but the island is considered to be relatively arid in comparison to other Caribbean nations. (FAO, 2000) The country is part of the hurricane belt, however, the frequency of hurricanes hitting Barbados is extremely low.

Average temperatures during the day reach about 27 ^oC (see Figure 40 in Appendix A for data on temperature, wind speed, humidity, rainfall, and other weather parameters typical to Barbados) and range approximately from 20 to 32^oC.

In a typical year, an average rainfall of 760 mm along the coastal areas to 2000 mm in the central parts of the island are common (Economic and Social Development Department (FAO), 2005), but rainfall amounts may be lower than 25 mm per month during the dry season (FAO, 2000).

On average throughout the year, Barbados receives 8 to 9 hours of sunshine each day (see Figure 40 in Appendix A).

2.1.4 Terrain

The island of Barbados is mostly flat with a gentle upwards slope from the coast towards the inland (Central Intelligence Agency, 2010). The predominant coralline limestone regions are divided into three terraces rising towards the interior of the island with a peak elevation of 343 m above sea level (AXSES Systems Caribbean Inc.), and are lined with deep gullies running from high elevations at the Scotland District to the coast (FAO, 2000).

2.1.5 Crop Production in Barbados

The colonial history of Barbados has left behind a reliance on monocrop, plantation-style agriculture which focuses on the production of a single cash crop in large amounts. The agricultural industry in Barbados therefore still consists primarily of sugar cane cultivation and the sugar, rum and molasses production industry. In the 2007/2008 growing season, 31.7 thousand tonnes of cane were harvested on 5.9 thousand hectares of land (IICA, 2009). Sugar, a cash crop, most of which is exported, is however on the decline and its future as a significant sector of the country's economy is in peril due to poor quality soils, high cultivation costs, sporadic droughts and low global sugar prices (FAO, 2008). The proportion of land in the country that is arable is 37% (about 22, 472 ha), while only 2.3% of the land is used to grow permanent crops (FAO, 1999).

Other crops include cotton, root crops, corn, onions, other vegetables, bananas, plantains, figs, other fruits, cut-flowers and foliage (Homer, 1998).

Production of food crops in the country is quite low as Barbados imports around 80% of its food (IICA, 2009), including large amounts of fruits and vegetables (Závodská & Dolly, 2009). Only 10% of the labour force in Barbados is involved in agricultural activities as agriculture must compete with more profitable industries and forms of land use such as the growing tourism and real-estate sector (CIA World Factbook, 2009).

The reliance on outside factors and world markets associated with such high levels of food importation place the country in a position of dependency and hinders progress towards self-sufficiency in terms of food production. Barbados' agricultural trade deficit in 2004 was US $67.5 million (FAO, 2008).

Future plans for the promotion of small-scale farming by the Ministry of Agriculture and Rural Development will encourage local production of food crops and small livestock, which will give Barbadians increased food security and greater independence in the generation of their household incomes (Závodská & Dolly, 2009).

Traditionally, small-scale farming faces challenges regarding the necessity to incorporate high-input technologies into their production in order to be able to compete on the global market. These technologies involve high costs and significant initial investments that cannot be afforded by all rural food producers and which increase production costs and therefore the cost of locally produced crops. This makes small farmers uncompetitive against cheaper imported items (Závodská & Dolly, 2009).

There is a great local need for innovative agricultural solutions that can be applied to the Barbadian context and which ensure the feasible, small scale production of food by average Barbadian families. An appropriate and accepted solution will therefore contribute to decreased dependency on foreign imports which involve transportation across great distances and are generally highly unsustainable.

Aquaponics has the potential to lessen the challenges associated with small scale farming in Barbados and generally in the Caribbean. The system requires minimal land and water resources, and no soil resources, which is desirable for highly populated and arid regions such as Barbados. Aquaponic systems provide a source of protein as well as fresh fruits, vegetables or herbs. As meat on the island is relatively expensive, protein in the form of freshwater fish would provide a healthy alternative and reduce stress on dwindling saltwater and freshwater fish supplies.

2.2 Food Production Methods

2.2.1 Aquaculture

Aquaculture is the cultivation and rearing of aquatic plants and animals in a fully or semi-controlled environment. Many species are produced around the world by means of aquaculture including both freshwater and saltwater fish, crustaceans, and molluscs, along with plants such as seaweed. The origins of aquaculture date back thousands of years. There are different theories as to how the practice came about but it is generally thought to have developed independently in several parts of the world, usually by a low-lying area of land being flooded and stocked with fish during high tide or rainy season and the surrounding human population implementing preliminary aquacultural practices to maintain the fish in order to have a reliable food source (Herminio, 1988).

Freshwater finfish, particularly Chinese and Indian carp species, account for the greatest share of total aquaculture production, followed by molluscs. Although low in production quantity, some of the minor product groups, such as shrimp and marine fish, have a disproportionate economic importance because of their high unit value. The most harvested species in recent years have been the Pacific cupped oyster and the silver carp. By 2006 aquaculture was provided nearly 50 percent -- or 51.7 million tonnes -- of all world fisheries production (Aquaculture resources, 2010).

The latter half of the 19th century saw the capacity of commercial fishing increase at unprecedented rates. The result was the plummeting of fish stocks around the world forcing some fisheries, such as the North Atlantic cod fishery, to be completely shut down to recover. The state of the world's oceans is in dire circumstances, whereas demand and consumption for seafood is at an all time high. Aquaculture will be a powerful tool to reconcile this paradox. Current predictions are that aquaculture production will need to reach 80 million tonnes by 2050 to keep pace with seafood consumption. (Aquaculture resources, 2010).

Many different forms of aquaculture take place at varying levels of intensity and scale. In mariculture, organisms are usually cultured in sheltered marine environments, whereas integrated multi-trophic aquaculture combines multiple organisms in a tank attempting to use the waste from one, such as fish, for the input of another, such as seaweed.

Many significant issues are present within the world of aquaculture. Decreasing genetic variation associated with fish farming, competition between wild and farmed animals, propagation of diseases associated with aquaculture's high stocking densities, and waste management are but to name a few. In-shore aquaculture requires massive amounts of water exchange to keep water quality at non-toxic levels. Finding uses for the wastewater produced in aquaculture has proved to be a laborious and cumbersome endeavour.

2.2.2 Hydroponics

The word hydroponics is taken from the Greek words *hydro*, meaning water, and *ponos*, meaning labour. It is a method of growing plants using a mineral nutrient solution in water, without soil. In traditional agricultural methods soil is used as the medium whereby nutrients are dissolved in water, which can then be taken up by the plant roots, although the soil itself is not necessary. If nutrients are added to the water in which the plants are grown, then the soil medium is not needed. Although the technique is thought to be a technologically advanced manner to grow plants, hydroponic methods, or at least ones with their roots in hydroponics, have been used for centuries and are quite simple to employ. The hanging gardens of Babylon, the floating gardens of the Aztecs of Mexico and those of the Chinese are all precursors to modern day hydroponic cultures.

For the purposes of this paper the term hydroponics is applied to systems using growing media, in our case coconut husk, as will be discussed later. Systems using some form of growing media that is not soil are designated as simply 'soilless culture'. Both soilless culture methods and hydroponics methods use a nutrient solution but hydroponics is generally thought of as a subset of soilless culture since it does not employ media to support the root structure of the plants.

The ability to grow plants in areas where soil is not conducive for in-ground agriculture is the great advantage of hydroponics. Also, it is much more efficient in its water use as water stays in the system and can be reused, as opposed to it percolating through the soil and ultimately replenishing the groundwater reserves. Having greater control over nutrient levels results in healthier crops, fertilizers which often contribute to pollution are not used, pesticides are not needed to deal with pests, and ultimately, much higher and more stable crop yields are achieved.

Hydroponic methods have been the subject of much research during the last century as more focus has been put on our agricultural methods. As a result, many advances have been made in the field and current hydroponic methods take many forms. The types of systems possible will be further discussed while outlining the hydroponic component of aquaponics systems, however as noted above, whether the system uses a media or not is a primary distinction. If there is no media employed in an aquaponic system, the plant roots are exposed to the nutrient solution directly. Among these types of systems are the nutrient film technique (NFT), flood and drain technique, deep water culture technique and raft technique.

2.2.3 Aquaponics

Aquaponic systems combine the two forms of agricultural production mentioned above, recirculating aquaculture and hydroponics. Aquaponics provides a solution to the main issues these two systems face; the need for sustainable ways of filtering or disposing of nutrient-rich fish waste in aquaculture and the need for nutrient-rich water to act as a fertilizer with all of the nutrients and minerals needed for plants grown through hydroponics (Nelson, 2008). Combining these two systems provides an all-natural nutrient solution for plant growth while eliminating a waste product which is often disposed of as wastewater.

In these systems, the fish grown in a freshwater tank secrete wastes through urine and through their gills into their surrounding tank water. Over time, these waste compounds, which are toxic to the fish accumulate and compromise fish health, but can be used as an organic fertilizer for plants (Nelson, 2008). This nutrient-rich effluent is used to irrigate a connected hydroponic bed while fertilizing its plant crops at the same time. The nutrients, largely in the form of ammonia are converted by denitrifying bacteria in the hydroponic grow bed into forms readily uptaken by plants for energy and growth. Essentially, the hydroponic bed and its crops serve as a biofilter for the fish waste water before it is returned, cleaned back into the fish tank. Thus, the waste of one biological system becomes nutrients for another biological system (Diver, 2006). See Figure 1 for a conceptual diagram of the nutrient/water flows in a general aquaponic system.

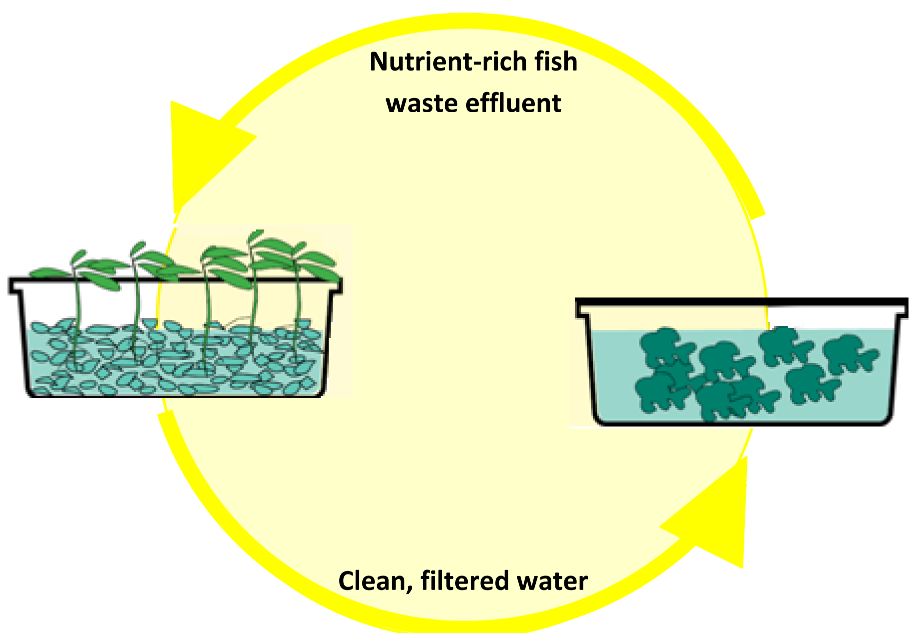


Figure 1: Conceptual diagram of nutrient recycling in aquaponic systems (Adapted from (Suits, 2010))

Aquaponics allows for the growth of a full meal (protein from fish and fibre, nutrients and minerals from vegetable, fruit, or herb production) in one closed-loop system, where the cultivation of two types of crops (fish and plants) is accomplished using only one body of water and one infrastructure. Crops are grown in a concentrated manner without compromising the health of the system and while greatly reducing the required input of water resources (Nelson, 2008) and increasing the value gained from the continuously cleaned and recycled water (Considine, 2007).

Aquaponics is an extremely resource-efficient and sustainable method of producing crops on any scale (Suits, 2010) that imitates the plant-fish interactions found in a natural waterway. See Figures 2 and 3 for various sizes of aquaponic systems.

Figure 2: A small system, built using recycled barrels (Hughey, 2005).

Figure 3: A commercial-sized raft aquaponics system (Rakocy, Masser, & Losordo, 2006)

When the system is in balance, high production of fish and plant crops at high stocking densities can be obtained without the use of chemical fertilizers, herbicides or pesticides (Nelson, 2008). A small aquaponic system in the backyard of a Barbadian family could go a long way in providing exceptionally fresh food daily and promoting local food production as well as supporting the local economy (Diver, 2006). This type of backyard agriculture allows for the production of various plant crops in a small space that can be used in the home kitchen or can be sold on the local market.

Aquaponic systems can provide food year-round (even during the dry season) in arid regions where water and soil resources may be scarce and can act as the key to self-sustenance for communities living in developing regions of the world and normally depending on world food markets (Hughey, 2005). The lack of a need for soil in these systems implies that they can be used in urban regions and in places with poor soil quality (Nelson, 2008).

In order to feed the world's growing population, there will be a great need for highly productive, urban and sustainable food production systems (Nelson, 2008). Increasing health consciousness and world demands for fish supplies require a solution such as aquaponics which integrates two separate systems which individually can meet these needs partially, but combined can provide an answer to the greater picture with increased resource-efficiency and at a lower cost (Diver, S., 2000), all while giving individuals and families greater control over the quality, safety and origin of their food.

2.2.4 Comparison of Food Production Methods

Aquaponic food production is very versatile in that it can be used on a commercial scale or at the level of home food production. It combines many of the advantages of other methods of food production (such as aquaculture and hydroponics) with additional advantages unique to aquaponics.

In comparison to hydroponics, aquaponics also does not require soil for the abundant, year-round growth of food and provides the elements minerals and nutrients as well as the structural support that traditionally is provided by soil. Both systems also allow for high crop densities and the conservation of water. No water is lost in these systems to soil outside of the root zones or to weeds which populate soil systems. Additionally, the risk of soil-borne disease is not present (Nelson, 2008).

The large amounts of time and resources that hydroponic growers spend mixing the perfect fertilizer solution from manufactured or mined compounds in order to meet all of the nutritional requirements of the plants are reduced simply and significantly in aquaponics (Nelson, 2008). Aquaponics does not require the addition of synthetic, chemical fertilizer as the fish waste from the rearing tank provides adequate amounts of the essential ammonia, nitrate, nitrite, phosphorus, potassium and micronutrients as well as some secondary nutrients for the healthy growth of hydroponic plants (Diver, 2006). The use of synthetic herbicides and pesticides is also unnecessary and would greatly compromise the health of the fish who are highly sensitive to water quality. Aquaponics is therefore essentially an organic form of hydroponics (Nelson, 2008) whose only fertility input is fish feed containing about 32% protein. Aquaponics also provides an entirely separate crop in addition to plant crops – the fish (Spade, 2009).

In comparison to aquaculture, an aquaponic system can house fish at a high stocking density provided that the water is regularly filtered and aeration is regularly performed along with the monitoring of all water quality parameters relevant to the health of the fish. Both systems can be housed nearly anywhere due to the small amount of space they require and can therefore provide fresh fish to a community on a regular basis.

Recirculating aquaculture, however has been criticized for its high rate of failure as the high stocking of fish leaves little room for error in terms of water quality and therefore of fish health. Water in these systems must be mechanically or biologically filtered with extreme care and all parameters must be carefully maintained. A large waste stream of fish waste is also produced in aquaculture and it needs to be disposed of somehow. Additional water inputs are needed to ensure water quality. An aquaponic system provides solids removal and biofiltration of the fish waste effluent as well as additional cleaning by the assimilation of nutrients into plant biomass. The waste stream from aquaculture is eliminated and an additional type of crop (plants) is obtained (Nelson, 2008). In terms of resource efficiency, aquaponic systems use 1% of the water required in pond aquaculture to raise the same yield of tilapia fish – a species commonly used in recirculating aquaponic systems (Diver, 2006).

Aquaponics combines the advantages of both hydroponics and aquaculture, while eliminating the disadvantages of both systems. It also reduces operating costs in comparison to either of these methods alone. A comparison of the above mentioned systems along with comparison to organic farming is summarized in Table 1 below.

Table 1: Comparison of various forms of food production (adapted from "Comparison of Methods" table in Nelson, 2008).

	Advantages	Disadvantages
Organic Farming	- Presumed as a healthier method of growing food than commercial farming and thus has become popularized. - Uses organic wastes as fertilizer. - Uses natural pest control. - Tends to produce better tasting and at times more nutritional crops.	- Requires more land than conventional farming. - Often higher costs to grow and certify crops. - Agribusiness is quickly replacing small-scale organic operations.
Inorganic Hydroponics	- High volumes of food are produced in a small space. - Has potential for year-round production if controlled.	- Highly dependent on costly manufactured/mined fertilizers.
Recirculating Aquaculture	- High biomass of fish produced in a small space.	- High rate of failure due to small margin for error. - Large waste stream produced.
Aquaponics	- All of the advantages of the other methods and additionally: - Reuse of fish waste as nutrients for plants. - Fish don't carry the pathogens (e.g. *E.coli* and *Salmonella*) found in warm-blooded animals. - Imitates a natural cycle and is the most sustainable of the four methods. - Consistent fish biomass in the fish tanks lets plant growth thrive.	- Operator must have knowledge of both fish and plant production. - Major fluctuations in fish stocks in the tank can disrupt plant growth.

3. Aquaponic Systems

3.1 System Designs

There exist several system designs for recirculating aquaponics systems. The designs are based on hydroponic systems, the difference being that the water source for the aquaponics system come from the fish tank and is eventually returned to its source of origin.

3.1.1 Media Filled Systems

The hydroponic component is first distinguished by whether it employs a media or not. This becomes very important in aquaponic systems because the presence of a media that plant roots are grown in can possibly eliminate the need for a separate settling tank and biofilter. Sludge and solid from the fish tank get caught in the media and are processed by bacterial communities that develop in the media, thereby acting as a biofilter and eliminating the need to remove the solids in a separate system. If the system does not employ a media and plant roots are exposed directly to the water, then a settling tank and biofilter are necessary to return the water quality to sufficient levels in which fish can live (Rakocy, Masser, & Losordo, 2006).

Figure 4: Various grow media in media-filled systems (Hydroponics: Andrew Smith, 2006)

3.1.2 Flood and Drain (also known as Ebb and Flow)

In flood and drain systems, plant roots are exposed to a static nutrient solution for hours at a time before the solution is drained away, which could happen several times a day. The technique can be used regardless of whether a media is used in the system, and plant roots could either be completely submerged, or partially submerged, leaving a portion exposed to the atmosphere. Flood and drain systems are noted for their simplicity, reliability and user-friendliness.

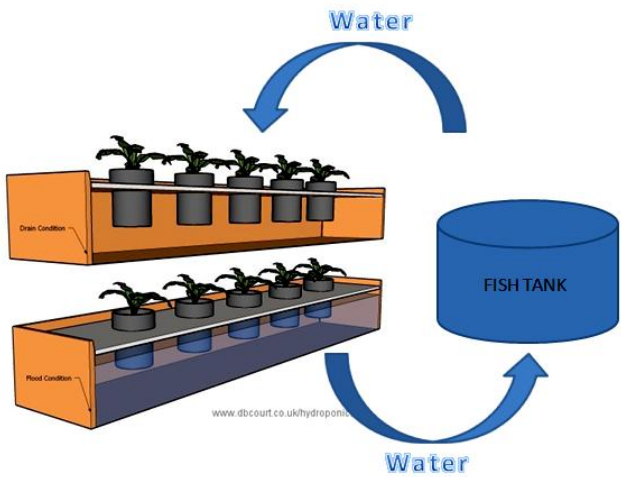


Figure 5: Different stages of a flood and drain system (Types of Hydroponics Systems: Dave's Hydroponics Experiment, 2010)

3.1.3 Nutrient Film Technique (NFT)

Nutrient film technique consists of the plant roots being exposed to a thin layer of nutrient water than runs through most often a PVC pipe. The idea is that the shallow flow of water only reaches the bottom of the thick layer of roots that develops in the trough while the top of the root mass is exposed to the air, thereby receiving an adequate oxygen supply. Channel slope, length, and flow rate must all be calculated to make sure the plants receive sufficient water, oxygen, and nutrients. If properly constructed, NFT can sustain very high plant densities. In aquaponic NFT systems, the biofilter becomes crucial as there is no large surface area whereby bacteria communities can develop (Nelson, 2008).

Figure 6: A pipe NFT system
(What is Aquaponics: The Fish Farm, 2010)

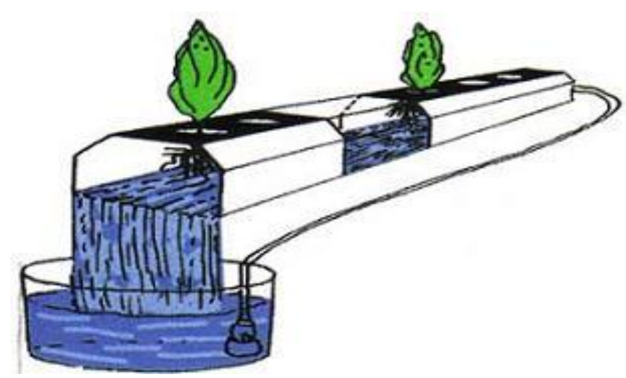


Figure 7: A trough NFT system
(About Hydroponics: Get up and Grow, 2007)

3.1.4 Floating Raft System

Another system that has great potential for commercial use is the floating raft system. In this system plants are grown on floating Styrofoam rafts. The rafts have small holes cut in them where plants are placed into net pots. The roots hang free in the water where nutrient uptake occurs. A major difference between the raft systems and the NFT and media based systems is the amount of water used. The water level beneath the rafts is anywhere from 10 to 20 inches deep and as a result the volume of water is approximately four times greater than other systems. This higher volume of water results in lower nutrient concentrations and as a result higher feeding rate ratios are used. Bacteria form on the bottom surface of the rafts but generally, a separate biofilter is needed. Also, the plant roots are exposed to some harmful organisms that reside in the water, which can affect plant growth.

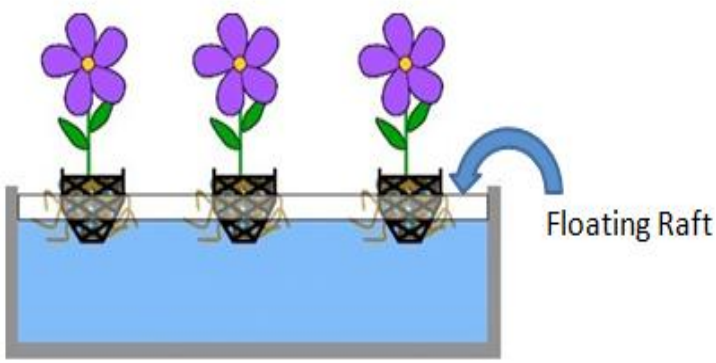


Figure 8: Schematic diagram of the floating raft system (Growing Arrangements: Sara's Aquaponic Adventure, 2008)

Figure 9: A larger floating raft system (Hydroponic Photo Gallery: The Torch Work Shop)

3.2 Fish

3.2.1 Fish Selection

The type of fish used in an aquaponic system depends on the climate which will surround the aquaponic system and therefore the temperature the grower is able to maintain, the kinds of fish that the local fisheries department has specified as legal (there are sometimes restrictions on the cultivation of fish that are not native to the region), the type of fish desirable for consumption by consumers and the type of fish feed available to the grower (Nelson, 2008).

There are a number of freshwater fish – both warm-water and cold-water species – that can be adapted for cultivation in recirculating aquaculture systems. These include tilapia, trout, perch, Arctic char (Diver, 2006), blue gill, largemouth bass, channel catfish, koi carp, goldfish, barramundi, murray cod, jade perch (Nelson, 2008), crappies, rainbow trout, pacu, common carp and Asian sea bass (Rakocy, Masser, & Losordo, 2006). Others beyond this list include warm-water fish that are hardy and can adapt to commercial fish feed and high levels of crowding (Nelson, 2008), including some ornamental fish (Rakocy, Masser, & Losordo, 2006). The hybrid striped bass is one species that reportedly does not perform well in aquaponic systems as it cannot tolerate high potassium levels – a common supplement used for plant growth (Rakocy, Masser, & Losordo, 2006).

Most commercial systems, however, culture tilapia. Tilapia is a tropical fish originating from the Near East and Africa (Nelson, 2008) that can be well adapted to recirculating tank aquaculture and is exceptionally resilient against fluctuations in dissolved oxygen levels, temperature, pH and dissolved solids (Diver, 2006). Figure 10 below shows a typical tilapia species used in aquaculture.

Figure 10: Red Tilapia fish at harvest (My Mom-Friday, 2009)

The temperature range that tilapia enjoy also correlates to ideal temperatures for the growth of aquaponic plants. Tilapia are the fastest growing of the species used in aquaponic systems (Nelson, 2008) and due to their resilience, their use and therefore the literature available on their cultural procedures is much more developed and thorough (Diver, 2006). The white-fleshed meat of tilapia is popular due to its desirable culinary properties of taste and texture. Virtually unknown in the US in the 1990's, tilapia is now the 6th most consumed seafood product in the country and its popularity continues to grow (Nelson, 2008).

A member of the cichlid family, tilapia is the most widely cultured fish in tropical and subtropical areas of the world and has also been introduced to Japan, India and throughout Asia, Russia, Europe and also the Americas (Nelson, 2008).

3.2.2 Culturing Conditions for Tilapia

Although very dependable and resilient to changing conditions, tilapia – like all other fish species – have certain conditions at which they grow best.

3.2.2.1 Water Quality

Good water quality must be maintained at all times in a recirculating fish tank to maintain optimal growth conditions and health of the fish. Regular water quality testing is essential and can be performed using water quality testing kits obtained from aquacultural supply companies. The most critical water quality parameters to monitor are dissolved oxygen concentrations, temperature, pH, and nitrogen from ammonia, nitrate and nitrite. Nitrogen in the form of nitrate and nitrite usually does not present a water quality problem in aquaponic fish tanks as nitrite is quite quickly converted to nitrate and nitrate itself is only seriously toxic to fish at very high levels (300-400 mg/L). The biofiltration mechanism in aquaponic systems also removes nitrates quite well and can keep their concentration at much lower levels than this (DeLong, Losordo, & Rakocy, 2009). Thus the most important water quality parameters to design and make practice recommendations for are temperature, dissolved oxygen and ammonia. Other important parameters include salinity, phosphate, chlorine and carbon dioxide. Other factors that influence the quality of fish tank water include the stocking density of the fish, their growth rate, the rate at which they are fed, the volume of water in the system and environmental conditions (Diver, 2006). The ideal values for tilapia water quality parameter requirements critical for the design of aquaponic systems (which are explained below) are summarized in Table 2.

Table 2: Summary of ideal water quality conditions for an aquaponic fish tank

Parameter		Optimal Range for Fish Tank in Aquaponic Systems
DO		6.0-7.0 mg/L
Temperature		22.2-23.3 °C
pH		6.5 - 7
NO_3^-		<150 mg/L
Ammonia	NH_3	<0.04 mg/L
	NH_4^+	<1.0 mg/L

3.2.2.1.1 Dissolved Oxygen (DO)

Optimal DO concentrations needed for fish growth and health and tolerance limits for survival have been established. These values can be used as guidelines in monitoring and in designing for improvements in the oxygen levels available to fish before they reach a critically low level. Fish will display signs of struggle under dangerously low DO concentrations. These include surfacing, gulping air and crowding towards areas where the water source spills into the tank and where DO levels are temporarily higher (Post, 1983). Such low levels of oxygen should never be reached in aquaponic systems and an aeration system should be put in place to ensure optimal DO concentrations.

Tilapia can survive acute exposures to DO levels as low as 0.5 mg/L, but they prefer a range of 3-10 mg/L (Nelson, 2008), with ideal growth occurring at levels higher than 5.0 mg/L (DeLong, Losordo, & Rakocy, 2009). For aquaponic systems in general, a DO level of 80% saturation (6-7 mg/L) is optimal (Nelson, 2008).

3.2.2.1.2 Temperature

Different tilapia species have different temperature ranges required for optimal growth. None of the species can survive under 10 °C (Nelson, 2008). They do well in a range of 17-32 °C, depending on the species (Nelson, 2008), but ideal growth occurs at 26.7 °C and higher (DeLong, Losordo, & Rakocy, 2009). In aquaponics, tilapia are usually raised between 22.2 and 23.3 °C in order that the needs of the fish, the nitrifying bacteria and the aquaponic plants are met, as plants perform better at slightly lower temperatures (Nelson, 2008).

These slightly lower temperatures also allow for a higher dissolved oxygen content, as the solubility of oxygen in water decreases with increasing temperature (DeLong, Losordo, & Rakocy, 2009).
Rapid changes in fish tank water temperature may cause thermal trauma in fish and will lead to possible disruptions of the cardiovascular and nervous systems, the reduction of their enzymatic activities, the permanent impairment of bodily functions or in death (Post, 1983).

3.2.2.1.3 pH

Most fish grow best at a pH of 7.5-8.0. Tilapia can tolerate a large pH range (from 5 to 10), with ideal functioning occurring between pH 6 and 9. In a recirculating aquaculture system that involves filtration through a biofilter (such as a hydroponic, media-filled grow bed), the pH of the fish tank water must agree with the pH suitable for the survival of the nitrifying bacteria growing in the biofilter. Plants in aquaponic systems do best at pH 6.0-6.5 and the nitrifying bacteria perform best at pH 6.8-9.0. Thus, a degree of compromise must be made to satisfy all three systems. Often in aquaponic systems a water pH of 6.5 to 7 is maintained (Nelson, 2008).

Excessively high or low pH values result in stresses and damage to fish skin and gills, the inability to absorb oxygen, and the rupturing of capillaries on fins and skin among other negative side effects (Post, 1983). It is important to note that the pH of the tank water also affects the solubility of other substances in the fish environment and some of these (e.g. ammonia) are toxic to fish. At very high or very low values of pH, the toxicity of some of these substances to fish increases greatly, but at a neutral pH of 7, the less toxic forms of these compounds dominate (Droste, 1996).

In aquaponic systems, since the process of nitrification by the bacteria in the biofilter is an acid-producing process, base needs to be periodically added at some point in the system in order to maintain a pH of 7. Potassium hydroxide (KOH) and calcium hydroxide ($Ca(OH)_2$) are often used for this purpose. Adding bases of K and Ca also supplements these essential nutrients that may otherwise be insufficient in fish waste effluent (Rakocy, Masser, & Losordo, 2006).

3.2.2.1.4 Ammonia

Ammonia is a product of the fish waste and can be highly toxic to fish when it accumulates in their culture water. The unionized form of ammonia (NH_3) is highly toxic to fish and other aquatic life, while the ammonium ion (NH_4^+) is much less so (DeLong, Losordo, & Rakocy, 2009). In the aquaponic system pH of 7, the majority of ammonia nitrogen is in the ammonium ion form. High pH values increase the proportion of ammonia nitrogen that is in the toxic unionized ammonia form (Droste, 1996).

Regular exposure to NH_3 concentrations exceeding 1 mg/L will lead to gill disease and fish will begin to die at levels as low as 0.2 mg/L, with other functions ceasing to operate at even lower values (Popma & Masser, 1999). Thus, one should strive for a concentration of NH_3 that is as close to zero as possible in aquaculture systems (Graber & Junge, 2009). Tilapia can maintain their health at an ammonia concentration range of 0.00-0.04 mg/L (Nelson, 2008). Concentrations of the ionized form of ammonia should be maintained below 1 mg/L NH_4^+ (Graber & Junge, 2009).

3.2.2.1.5 Water Quality in BVAA Systems

Water quality experiments on the fish tank water in the aquaponic systems of the BVAA in Barbados were performed between November 16th and December 3rd, 2009. The experiments included tests of the following parameters: temperature, pH, salinity, nitrate, ammonia, phosphate and dissolved oxygen. The only parameter which was problematic and showed consistent values out of the acceptable range for tilapia cultivation was dissolved oxygen concentration. See Table 11 and Figures 41 to 46 in Appendix B for the results of these water quality tests.

3.2.2.2 Feed

Tilapia fish are largely omnivores and respond well to commercial fish feed. Their diets need to be well balanced in terms of amino acids, proteins, fats, vitamins, minerals and carbohydrates. Expertly formulated feeds that provide all of these components for tilapia are quite common. In natural environments, wild tilapia may feed on algae (low in protein) and small animals such as worms (high in protein)and small-scale aquaponic growers may choose to feed their fish with a mixture of these materials, however optimum tilapia growth will be obtained by the use of commercial feed pellets. Fish in culture require less food than wild fish as they need less energy to survive and obtain food, thus the controlled use of fish feed pellets gives the grower complete control of the nutrient inputs into the aquaponic system (Riche & Garling, 2003).

In recirculating aquaculture, feeding rates for tilapia will vary with fish size. Food to be given is measured as a percentage of the average body weight of the fish in the tank. Also, as the average fish weight increases, the percent body weight fed to the fish decreases. The daily feed ratio should therefore be adjusted to account for fish growth. Table 3 gives an example of this type of feeding schedule.

Table 3: Example of daily feeding allowances for different sizes of tilapia. (Source: National Research Council (1993) Nutrient Requirements of Fish. National Academy Press, Washington, D.C.)

Size of fish (grams)	Amount of daily feed (% of fish weight)
0–1	30–10
1–5	10–6
5–20	6–4
20–100	4–3
larger than 100	3–1.5

In aquaponic systems, tilapia fish grow best when fed three times daily ad libitum (the amount of food that they will eat in 30 minutes) (Rakocy, Bailey, Shultz, & Thoman, 2004), where the feed is composed of 32% protein (Spade, 2009). Determining amounts of fish feed per tank per day over the growing period of the tilapia based on average fish weight is considered an over-complication by aquaponics experts. Instead, empirical values have been established for the amount of daily fish feed per area of hydroponic grow bed. This allows for the calculation of the number of fish the system can grow and consequently the volume of water needed to stock the fish. Overfeeding fish will result in uneaten food (will compromise water quality), lower feed efficiency, reduced health of fish and increased costs (Riche & Garling, 2003).

3.3 Plant Crops

3.3.1 Nutritional Requirements

All plants may have different nutritional requirements; for instance leafy green vegetable require more nitrates than fruiting plants. However all plants in aquaponic systems need 16 essential nutrients for maximum growth. These come in the form of macronutrients, which in addition to carbon, hydrogen, and oxygen, which are supplied by water, carbon dioxide, and atmospheric air, include nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), phosphorous (P), and sulphur (S). There are seven micronutrients necessary as well and they are chlorine (Cl), iron (Fe), magnesium (Mn), boron (B), zinc (Zn), copper (Cu), and molybdenum (Mo). These nutrients have to be balanced, as an excess of one may interfere with the uptake of another, as is the case when potassium affects the bioavailability of magnesium or calcium. Iron concentrations in aquaponic wastewater are insufficient for plant growth and therefore iron has to be supplemented to a concentration of 2 mg/L. (Rakocy, Masser, & Losordo, 2006).

3.3.2 Crop Selection

Many types of plants can grow successfully in aquaponic systems. The Crop Diversification Center in Brooks, Alberta has reported growing over 60 different food crops in their aquaponics trials (Nelson, 2008). Originally it was thought that only leafy green vegetable and herb crops could be grown, but it has since been proven that a wide variety of fruiting crops, beans, and flowers can be grown effectively.

Although many crops can be grown in an aquaponic system, some are more suitable than others. When choosing a crop to cultivate, the grower's objective should be taken into account first and foremost. If the objective of the venture is to turn a profit, as it is with commercial scale systems, then crops that have a high market value and short harvesting time will be more appropriate. These include herbs such as basil, chives, cilantro, and parsley whose harvest times are between 25 and 40 days (Rakocy, Masser, & Losordo, 2006). Lettuce is the most grown crop in aquaponics due to both its short harvesting time (3-4 weeks) and high demand in western diets; because a large portion of its final mass is harvestable and edible, it is a very lucrative crop. Another reason these crops do well is because the lack of a fruiting stage keeps nutrient requirements consistent, resulting in a more reliable harvest. Other leafy green vegetable of this nature are Swiss chard, Pak Choi, Chinese cabbage, collard and watercress, which in addition to the aforementioned advantages, also experience less pest problems than fruiting plants (Rakocy J. E., 1988-89).

Figure 11: Vibrantly coloured leafy vegetables and extensive root systems in aquaponic systems (Somma, 2008) and (Wilson, 2010)

While fruiting crops of all kinds are successfully grown in aquaponic systems, they are mostly cultivated by hobbyists growing for consumption or by researchers. Because these plants have longer harvesting times, they are better suited to growth in areas that have a longer growing season such as the tropics where growing can be carried out all year long. Melons, tomatoes, okra, peppers and corn are all popular fruiting crops crown in aquaponic systems (Nelson, 2008)

3.4 Bacteria

Autotrophic bacteria that convert fish waste into nutrients for plant uptake are crucial and without them, an aquaponic system will not function. Appropriate environmental conditions must be maintained to ensure the abundant growth of microbial populations in the biofilter. Nitrifying bacteria growing on the large surface of the biofilter media and in association with the plant roots will perform all of the necessary nutrient conversions for the feeding of plants and for the filtration of fish tank effluent. The grow bed media in media-filled aquaponic systems functions as a fluidized bed bioreactor - it removes dissolved solids and houses nitrifying bacteria involved in the conversion of nutrients (Diver, 2006) through a process known as the nitrogen cycle. Figure 12 shows a conceptual diagram of the nitrogen cycle as it pertains to aquaponic food production.

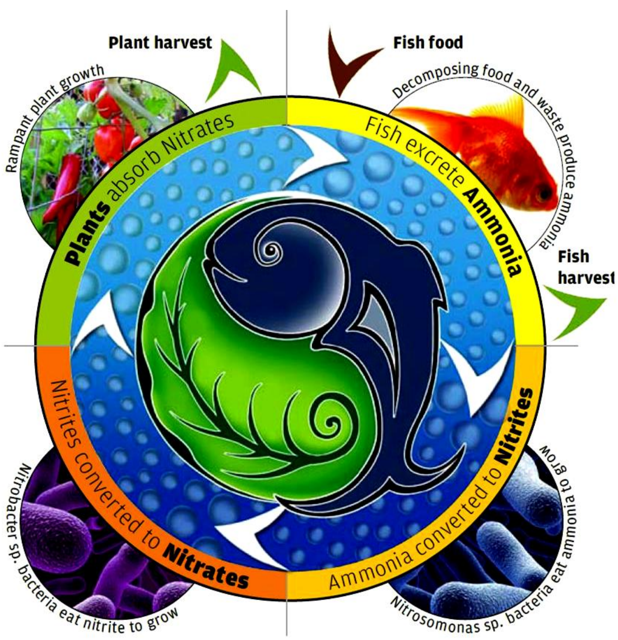


Figure 12: The nitrogen cycle in aquaponic systems (Steve, 2007)

Fish tank effluent will contain total ammonia (NH_3 and NH_4^+) excreted through fish urine and gills and formed from the decomposition of organic solids such as fish waste and uneaten food. Nitrifying bacteria, particularly *Nitrosomonas sp.* convert the toxic ammonia, using it as an energy source to nitrite (NO_2^-) - another compound toxic to fish - by using oxygen in an oxidation process. The nitrite is then quickly oxidized by another type of nitrifying bacteria, namely *Nitrobacter sp.* to form nitrate (NO_3^-), the preferred form of nitrogen for plant uptake (Losordo, Masser, & Rakocy, 1998).

When fish are initially introduced into an aquaponic system, the ammonia levels in the water increase for the first week or so, after which they begin to decrease while nitrite levels rise. Once two weeks to 20 days have passed, the nitrite levels will fall as well, while nitrate levels increase. At four weeks or between 20 and 30 days, the nitrogen compounds will relatively stabilize in concentration. Figure 13 below shows a graphical representation of the action of nitrifying bacteria in the nitrogen cycle.

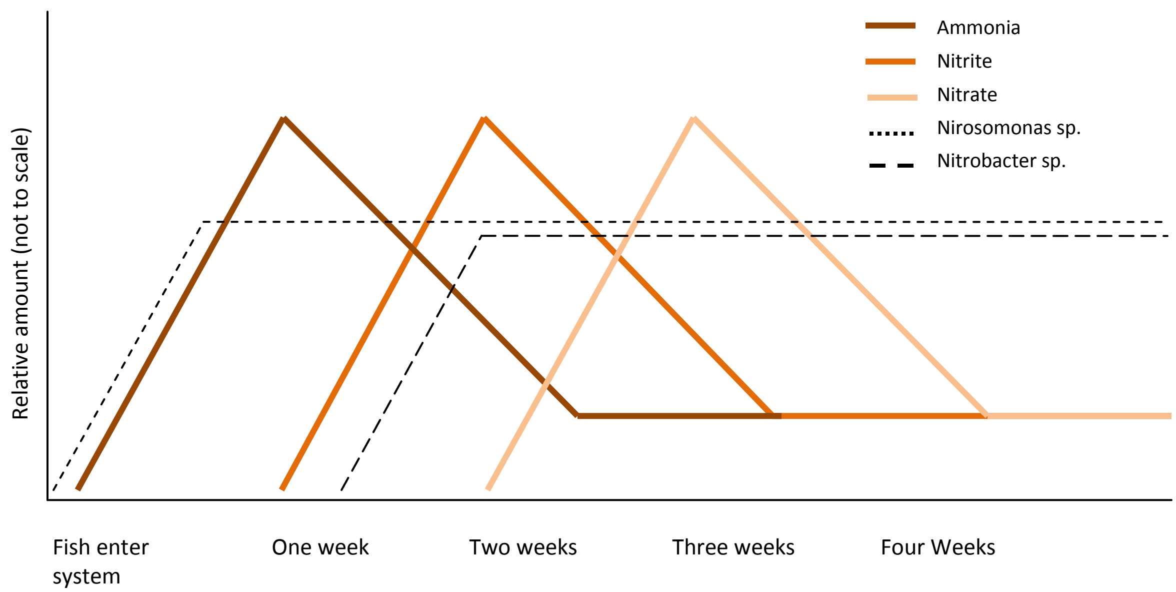


Figure 13: A not-to-scale graphical representation of the nitrogen cycle resulting from the addition of fish to an aquaponic fish tank (Nelson, 2008).

An active microbial population should be established in the biofilter before fish are added to the system. When fish are already present in the aquaponic fish tank, re-stocking with new fish should never be done at peak levels of ammonia or nitrite (Nelson, 2008).

Nitrifying bacteria need oxygen for their metabolic processes, therefore the biofilter media that they are housed in needs to be porous and well aerated. They also require a certain pH range. This is from pH 7 to 8 (Nelson, 2008), where the performance of the microbes in oxidizing unwanted compounds begins to decrease below a pH of 6.8. The optimal conversion of toxic to non toxic compounds occurs at 25 °C (Nelson, 2008).

The microbial populations found in aquaponic systems are virtually never pathogenic. The pathogens that are carried by warm-blooded animals and which have recently created numerous upsets in the food industry due to contamination in food processing and packaging plants are not present in fish or fish waste (Nelson, 2008). “From the perspective of food safety in aquaponic systems, there seems to be much less likelihood of contamination of vegetable and other aquaponic crops, and fish, with pathogenic bacteria of domestic animal origin, and with microscopic parasites such as *Cyclospora sp.* of human origin, and *Cryptosporidium sp.* of domestic animal origin, in aquaponic systems, especially in indoor systems, compared with the potential of such contamination in the traditional field methods of growing such crops.” (Chalmers, 2004)

4. The Design

The design process varies greatly from and is highly dependent on the nature of the project and how it came about, the person or people who encounter the need to design something and the situation they find themselves in. Despite this varying nature, a framework for the design process can be put forth that encompasses some key elements commonly encountered.

Problem Identification:

On a global scale, the problem that this project addresses is food security, as stated previously. On a much smaller scale, the problem that was being addressed by the project was the inefficiency and unscientific approach that was encountered while being exposed to aquaponics in Barbados.

Analysis and Research:

Upon returning from Barbados, the aquaponics systems that were now somewhat familiar, were analysed with renewed scrutiny. It was evident that the system could be improved and there were suspicions towards what might achieve this improvement. Some research, both formal and informal had already been conducted, but to accomplish the objective of optimizing the system, a significantly more detailed literature review was conducted. Parameters such as the feeding rate ratio, fish stocking densities, system aeration, and the sizing of the system along with the harvesting of fish and vegetables were explored, and several experts were consulted, including Dr. James Rakocy, who is considered the world’s foremost expert in the optimization of food production from aquaponic systems and who teaches at the University of the Virgin Islands, as well as several professors in the McGill University Plant Science Department.

Specification:

Satisfied that sufficient research was done, key parameters, such as the ones discussed previously, were identified within the scope of the projected design. Decisions were made in regards to the qualitative and quantitative nature of these parameters, which will be discussed in subsequent sections.

Presentation:

The present report is the fruit of months of labour, whereby all the ideas, decision, and work are being manifested in a final design.

4.1 System Stocking Density

4.1.1 Growing Area

The growing area is the starting point for a system design because other parameters are based on the area over which plants can be grown. A growing area of 6 m^2 was chosen for the design arbitrarily, with dimensions of 2 m in width by 3 m in length. It was chosen because it was thought to be an appropriately sized area for families to maintain in a backyard.

4.1.2 Basil, Okra and Coconut Husk

Basil and okra were chosen as the crops in the systems design. They were chosen arbitrarily simply because it was known that they were appropriate for tropical climates and there was a large amount of available literature from previous aquaponics and hydroponics studies. Coconut husk was chosen due to its availability and previous use in the systems in Barbados.

4.1.2.1 Okra

Okra is an annual tropical vegetable which is cultivated in the Southern United States, the Caribbean and Africa. The fruits (picture in Figure 14 below) are harvested when immature and eaten as a vegetable. The plant does not grow in cool areas or high altitudes, but it is extremely heat and drought resistant and is therefore grown in many countries with difficult growing conditions (Sionit, 1981). Okra plants can grown to be over 4 feet tall or can be topped and grown shorter and wider. The plant can survive between temperatures of 20^0 – 30 °C and pH levels of between 6.5 and 7.5. Palatability of the fruit decreases if the plant is left to grow to maturity, which takes about 90 days (Gardening: About.com, 2010).

Figure 14: Harvested okra pods (Pesto: Salt and Pepper Blog)

4.1.2.2 Basil

Basil is one of the most popular herbs in the spice cabinets of North and South America as well as the Caribbean. It is sold fresh-cut (Figure 15) and dried in both supermarkets and farmers' markets. Over 40 different cultivars are known, but the most commercial cultivar belongs to the species *O. basilicum*. Basil is not just used for culinary needs; it can also be used as an ornamental herb, and the extracts are used in traditional medicines and essential oils. The range of average temperatures that basil can survive in is between 20 – 24 °C and the preferred pH range is 5.5 to 7.0 (Gardening: About.com, 2010).

Figure 15: Freshly-cut basil leaves (Okra Varieties: Diet, Desert and Dogs Blog)

4.1.2.3 Coconut Husk

This system is one that is media based, as opposed to a raft or NFT system, which use nothing to support the root structure of the plants. The grow media can be thought of as a direct structural replacement for soil.

The system design uses coconut husk as media. The choice of coconut husk is somewhat unorthodox as most media systems utilize sand, gravel, perlite, or expanded clay pebbles. Coconut husk is used because it is a readily available and cheap material that can be found all over the Caribbean. It also is easier to manipulate as it is much lighter than its alternatives.


Figure 16: Coconut husk fibres (Block, 2009)


Figure 17: Coconut husk chips (Loren, 2010)

In reality, because the coconut husk is organic in origin, as it degrades it will contribute nutritionally to the system. This allows for abundant microbial communities to exist in the grown bed, which is also acting as a biofilter. Husk comes in the form of chipped pieces, which vary in size, and fibrous stands. The variation of the media sizes and forms, along with its gradual degradation, results in a variation of the material's porosity. Water moves through the media quite easily, however as the material degrades, some anaerobic zones may form. Aerating the grow bed helps with this aspect, however, because the solid waste from the fish tank is transferred to the media, as it and the husk degrade, the system will gradually clog and the media will need to be replaced every few years.

4.1.3 Component Ratios

The feed conversion ratio, feed rate ratio, and critical standing crop are co-dependent parameters, meaning that they are linked, and altering one, will necessitate changes in the other two. This design uses values for these parameters based on research done by Dr. James Rakocy at the University of the Virgin Islands and which are widely used around the world in aquaponic systems. A feeding rate ratio of 25 g/m^2 per day, a conversion ratio (FCR) of 1.7, and a critical standing crop of 60 kg/m^3 are used.

4.1.4 Feed Rate Ratio and Annual Fish Feed Mass.

A feed rate ratio of 25 g/m^2 grow bed area per day is used. The UVI system uses the analogous ratio of 100 g/m^2 per day for a floating raft system, which has four times the amount of water. Using this feed rate ratio, we are able to calculate the annual amount of fish feed used in the system:

$$Annual\ Feed\ Weight = \frac{25\ g}{m^2 * d} * \frac{365\ d}{yr} * \frac{6\ m^2}{growbed} * \frac{1\ kg}{1000\ g} = 54.75\ kg/year$$

4.1.5 Feed Conversion Ratio

A feed conversion ratio (FCR) of 1.7 is used, meaning that for every kilogram of fish biomass growth desired, 1.7 kg of feed is needed. A FCR of 1.7 corresponds to a feeding rate efficiency of 0.59 (1.7^{-1}), meaning that for every kg of fish feed used, 0.59 kg of fish biomass is produced.

4.1.6 Fish Biomass Production

Using the feeding rate efficiency and the amount of fish feed used in the system, the system's net biomass production is calculated as follows:

$$Annual\ Biomass\ Production = \frac{54.75\ kg\ fish\ feed}{yr} * \frac{0.59\ kg\ biomass}{kg\ fish\ feed} = 32.3\ kg\ biomass$$

Finally, to arrive at the number of fish the system will be able to produce in a year, we use the net biomass gain each fish will experience. Fingerlings will enter the system at 20 g and will be harvested at a market weight of 450 g, meaning there is a net weight gain of 0.430 kg/fish.

$$Number\ of\ Fish\ per\ year = \frac{32.3\ kg\ of\ biomass}{0.430\ kg\ biomass/fish} = 75.1 = 76\ fish$$

4.1.7 Fish Stocking and Harvest

Stocking density in a fish tank is measured in units of fish biomass per volume of water; kilograms per meter cubed in our case. The stocking density is an important aspect for fish growth for several reasons. Water quality decreases proportionally when stocking densities are increased, in part due to a higher production of waste, increasing the levels of potentially toxic substances, such as ammonia and nitrite. Another reason fish health is compromised when stocking densities are increased is because higher stocking densities result in more consumption of oxygen and a lack of oxygen will result in stunted growth and reduced fish health. Understocking the system however will result in a lower feed conversion ratio and reduce the efficiency of the system.

4.1.7.1 Critical Standing Crop

The critical standing crop is the maximum biomass of fish a system can support without restricting fish growth. Operating a system near its critical standing crop uses space efficiently, maximizes production and reduces variation in the daily feed input to the system, which is an important factor in sizing the growing area (Rakocy, Masser, & Losordo, 2006).

A critical standing crop of 60 kg/m^3 is used in this design. This is a generally accepted value among aquaponic systems and, as previously discussed, correlates to the desired feed rate ratio and feed conversion ratio.

4.1.7.2 Fish Harvesting -Multiple Rearing Tanks

To keep the stocking density in our system near the critical standing crop, a multiple rearing tank method will be employed. Under this system, several ages of fish will be raised simultaneously. The design will have four different cohorts of fish. As previously mentioned, the fish fingerlings will enter the system at 20 g and will be harvested at 450 g. This growth takes approximately 170 days, meaning that fish will be raised in each cohort 42 days, or six weeks, apart (170/4 = 42.5 days). Every six weeks, the largest cohort will be harvested, and the smallest cohort will be restocked. The number of fish in each cohort is found in the following way:

$$Number\ of\ fish\, per\ harvest = \frac{76\, fish}{year} * \frac{6\, weeks}{harvest} * \frac{1\, year}{52\, weeks} = 8.77 = 9\, fish/harvest$$

The volumes of water needed for the desired stocking density were calculated at the end of the 42 day period, when each cohort is at its heaviest. Table 4 summarizes this information.

Table 4: Mass of fish in each cohort at the end of each six week period and volume of water required per cohort at maximum stocking density

Cohort	Final mass/fish (kg)	Total mass (kg)	Stocking Density (kg/L)	Volume of Water (L)
1	0.07	0.63	0.06	10.5
2	0.170	1.53	0.06	25.5
3	0.300	2.70	0.06	45.0
4	0.450	4.05	0.06	67.5
			Total Volume of Tank	148.5

However, in the beginning of the rearing period the stocking density is quite a bit less, as Table 5 demonstrates.

Table 5: Stocking densities of each cohort at the beginning of each six week cycle

	Initial Weight/Fish (g)	Net Weight (kg)	Cohort Water Volume (L)	Density (kg/L)
Cohort 1	20	0.18	10.5	0.017143
Cohort 2	70	0.63	25.5	0.024706
Cohort 3	170	1.53	45	0.034
Cohort 4	300	2.7	67.5	0.04
Total		5.04	148.5	0.033939

4.1.8 Plant Stocking and Harvest

Higher plant densities often mean that the yield per plant will be lower while producing a higher yield per area. Plant densities used for okra and basil have large variation. Based on experience, a density of 12 plants/m^2 will be used for both basil and okra. This is believed to be on the lower end of acceptable ranges for basil and on the higher end for okra. The 6 m^2 growing area will be split evenly between the two plant species with 3 m^2 being used to grow 36 okra plants and the other 3 m^2 growing 36 basil plants. Based on previous hydroponic and aquaponic studies, it is assumed basil can be harvested 12 times a year and okra 3 times a year.

Nutrient requirements will be more consistent in the grow bed if staggered harvesting techniques are used, with groups of plants being simultaneously cultivated at different periods in their life cycle. The following calculations are used to determine harvesting schedules:

$$Basil\ Harvest = 36\ plants * \frac{12\ harvests}{year} * \frac{year}{52\ weeks} = 8.3 = 9\ plants/week$$

$$Okra\ Harvest = 36\ plants * \frac{4\ harvests}{year} * \frac{year}{52\ weeks} = 2.8\ = 3\ plants/week$$

The configuration of plants in the grow bed could take several forms. The easiest is a simple 12 x 6 configuration, with each plant being separated by 0.23 m on the long axis and 0.29 m on the short axis. The following diagram provides a schematic of the grow bed. The harvesting schedule is represented by boxes around the plants, okra plants in groups of three and basil plants in groups of nine.

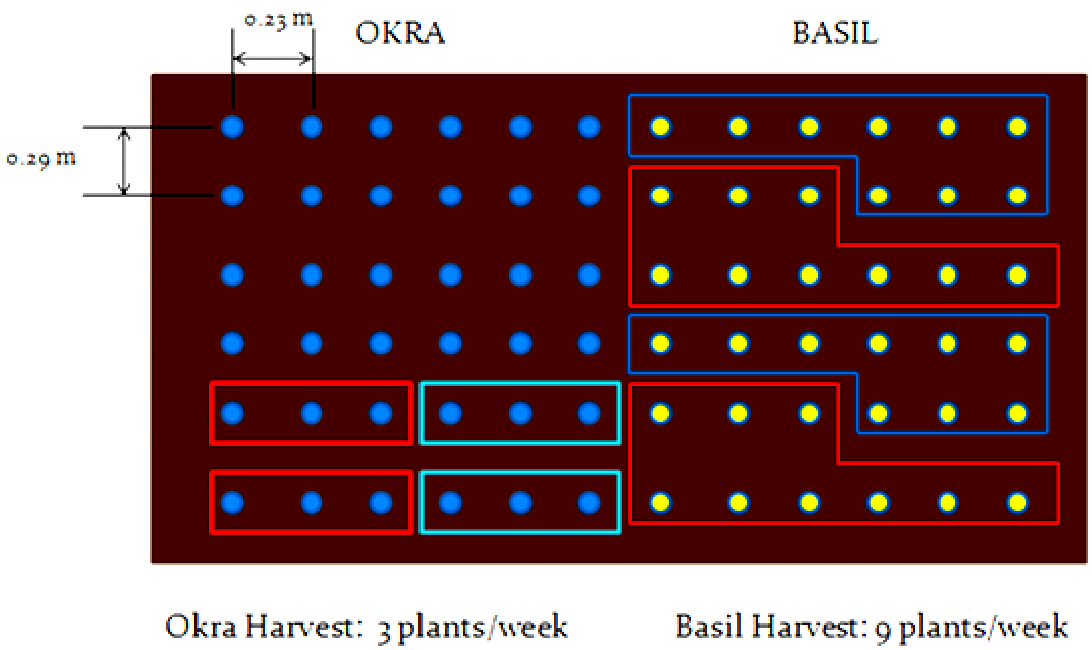


Figure 18: Crop planting distribution and harvest schedule

4.2 Water Flow Rate

The rate of water turnover should be designed to ensure good water quality. Water should be passed through the hydroponic grow media enough times per day to be adequately filtered and therefore to ensure appropriate removal of waste compounds that are toxic to fish. Excessively high flow rates, however will reduce to too great of an extent the amount of time toxic wastes in fish tank effluent spend in contact with microbes in the biofilter. This will cause some of these compounds to be flushed back into the fish tank before they are converted to safer forms or assimilated by the hydroponic plants.

In a backyard-sized media-filled aquaponic system, the water flow rate (Q_w) should be such that a volume of water equal to the fish tank volume goes through the biofilter twice in an hour.

In this design, the volume of water in the fish tank is 150 L. This would therefore correspond to a 300 L/hr or 0.30 m^3/hr flow rate.

Thus, $\boldsymbol{Q_w = 0.30\ m^3/hr}$

Increasing water flow rates tends to increase the removal of BOD_5, TSS, NH_3-N and NO_2^- - N, while decreasing flow rate increases the removal of P_{TOT}, NO_3^- - N (Endut, Jusoh, Ali, Wan-Nik, & Hassan, 2009). Water flow rates may need to be adjusted if water quality tests show that greater removal of any nutrients is required to meet water quality requirements for the tilapia. There may always be a compromise between fish tank water quality and optimal nutrient delivery to the plant crops.

4.2.1 Hydraulic Loading Rate

The hydraulic loading rate (HLR) of the fish tank effluent onto the surface of the grow media will determine the rate at which fish wastewater enters the coconut husk grow medium. Although hydraulic loading rates have shown to have no significant effect on fish production performance, the specific growth rates of fish or the efficiency with which fish utilize food for biomass growth (feed conversion ratio), research experiments in Malaysia have concluded that plant growth is significantly affected by the rate at which water is supplied to the surface of the grow bed in recirculating aquaponic systems (Endut, Jusoh, Ali, Wan-Nik, & Hassan, 2010). Since the largest proportion of the capital a backyard aquaponic grower can earn comes in the form of plant outputs, designing for plant growth is recommended and this includes having an appropriate HLR.

Overly high hydraulic loading rates decrease the contact time between microbes in the grow bed and the nutrients they are supposed to convert. Therefore plant growth decreases significantly with very high HLR. The hydraulic loading rate at which optimal plant growth occurred was 1.28 m/day. At this HLR, the highest fish production and highest overall percentage of nutrient removal was observed as well (Endut, Jusoh, Ali, Wan-Nik, & Hassan, 2010).

Hydraulic loading rate of a system is calculated by dividing the flow rate of water, Q_w through the system by the surface area of the grow bed, $A_{grow\ bed}$. In this design, the flow rate of water is 0.3 m^3/hr and the grow bed surface area is 6 m^2.

$$\boldsymbol{HLR = \frac{Q_w}{A_{grow\ bed}} = \frac{0.3\ m^3/hr}{6m^2} * \frac{24\ hr}{day} = 1.2\ m/day}$$

This gives a HLR very close to the ideal for recirculating aquaponic systems.

4.2.2 Hydraulic Retention Time

The amount of time that the fish tank effluent water spends in the grow bed medium defines the amount of time compounds in that water have to be converted and removed from solution by the hydroponic biofilter. Very high hydraulic retention times (HRTs) would reduce the rate at which water and therefore air gets pushed through the pore space in the grow media. This could result in the formation of anaerobic zones where denitrification would occur, converting valuable plant nutrients in the form of NO_3^- into atmospheric nitrogen (Endut, Jusoh, Ali, Wan-Nik, & Hassan, 2010). Very low hydraulic retention times would reduce removal efficiency by reducing filtration time.

In an earlier experiment by Endut et al., it was concluded that the removal of nutrients occurred most efficiently when the water flow rate was 1.6 L/min, which for their system corresponded to a HRT of 0.575 hr or 34.5 minutes per grow bed (Endut, Jusoh, Ali, Wan-Nik, & Hassan, 2009).

Hydraulic retention can be calculated by dividing the product of the surface area of the grow bed (A_s), the depth of water in the grow bed (h_w) and the porosity of the grow bed media (ϕ) by the water flow rate.

In this design, the grow bed surface area is 6 m^2, the depth of water is 5 cm (just below the plant root zone), the average porosity of coconut husk chips is 0.47 (Colombo Quality Coir Products, 2010), and the water flow rate is 0.300 m^3/hr.

Thus;

$$\boldsymbol{HRT = \frac{A_s * h_w * \phi}{Q_w} = \frac{6m^2 * 0.05m^2 * 0.47}{0.30\ m^3/hr} * \frac{60\ min}{1\ hr} = 28.2\ min}$$

The fish effluent water will remain in the coconut husk for just under half an hour. This is a suitable HRT for the conversion of fish waste compounds.

4.3 System Components

4.3.1 System Configuration

The individual components of the aquaponic system will be connected and oriented with respect to each other in such a way as to ensure the desired water and air flow rates and optimize efficiency within limits reasonable and practical for a backyard installation.

Generally in an aquaponic system, water flows from the fish rearing tank through a mechanism that removes solid fish wastes and general tank debris, after which it enters a biofilter where the resident microbial population converts fish waste components into nutrients useful for plant growth before it enters the hydroponic bed where plant roots receive these nutrients as they are being irrigated. Clean water from the hydroponic bed flows out into a sump tank used to maintain constant water levels before it gets transferred back into the fish rearing tank. In this aquaponic system the solids removal, biofilter and hydroponic bed will all be combined in the coconut husk –filled grow bed. Figure 19 below shows the general flow of water in the aquaponic system.

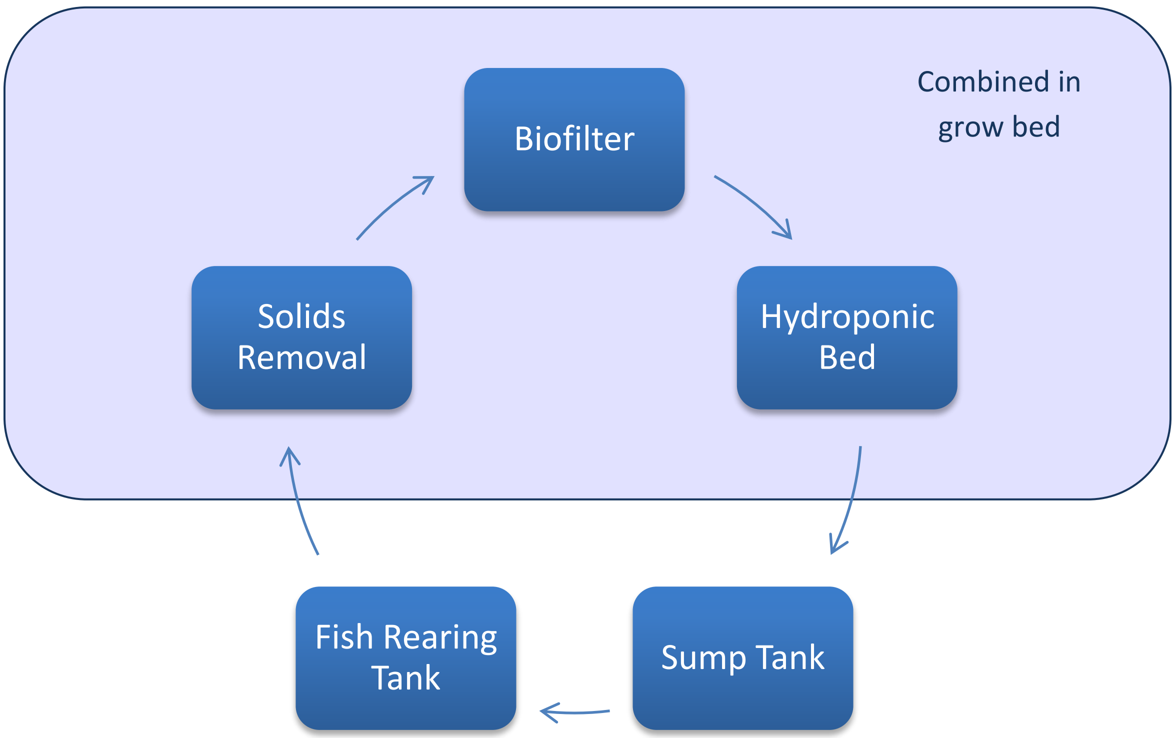


Figure 19: Flow chart of general system components arrangement (Adapted from: Figure 2 - Optimum arrangement of aquaponic system components (Rakocy, Masser, & Losordo, 2006))

In terms of vertical orientation, the rectangular fish rearing tank will be placed on the ground, therefore rising 50 cm above ground. At 37.13 cm above ground, (the surface level of the water in the fish rearing tank), water will spill out by gravity through a 2-inch (5.08 cm) diameter PVC pipe into a perforated water distribution grid (made up of the same 2-inch PVC piping) onto the surface of the grow bed. PVC is the material used for all of the 2-inch water distribution pipes and it is a material that is food-grade and therefore safe for the application of water to crop plants (Hudson Extrusions Inc., 2009). The grow bed which will be filled to the brim with coconut husk will be placed 7.13 cm above the ground level on ten cinder blocks (the grow bed itself being 30 cm deep) so that its top lines up with the bottom of the water pipe system.

As water fills the grow bed, it will reach a certain height (5 cm from the bottom of the grow bed), where it will spill out through a short piece of 2-inch PVC pipe and pour into the sump tank. The 112 cm long, 50 cm in diameter sump tank will be inserted into a hole dug into the ground so that its top edge will vertically be in line with the bottom of the pipe ejecting water from the grow bed. Water height in the sump tank will on average be 107 cm – the same height off the ground level as the bottom of the grow bed (~7 cm).

Water from the sump tank will be pumped by an airlift pump from the bottom of the sump to the top of the fish rearing tank (a total height of 149.87 m). In the system, only water from the sump tank to the fish rearing tank is pumped, the rest of the water transfers are driven by gravity. See Figure 20 below for a side view of the system configuration in terms of the components discussed above. Fish rearing tank screens and the air distribution network are omitted for clarity.

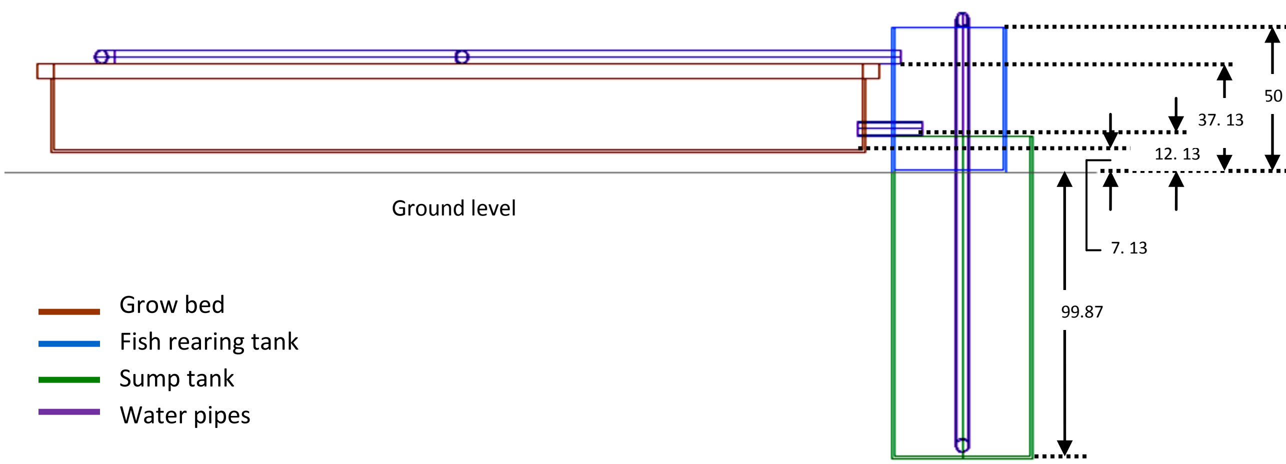


Figure 20: Aquaponic system side view (grow bed, fish rearing tank, sump tank and water distribution pipes) with heights in centimetres.

Horizontally, the main system components are oriented to save space, with the fish rearing tank and sump tank along the shorter side of the rectangular grow bed. See Figure 21 for the bird's eye view of the assembled main system components. Figure 22 shows an isometric view of all of the system components in place. Water distribution lines are drawn in purple.

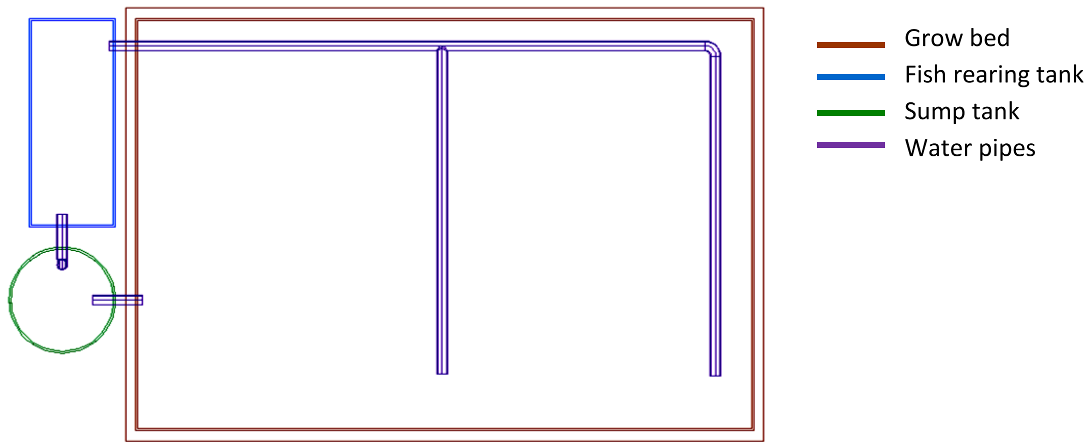


Figure 21: Aquaponic system top view (grow bed, fish rearing tank, sump tank and water distribution pipes)

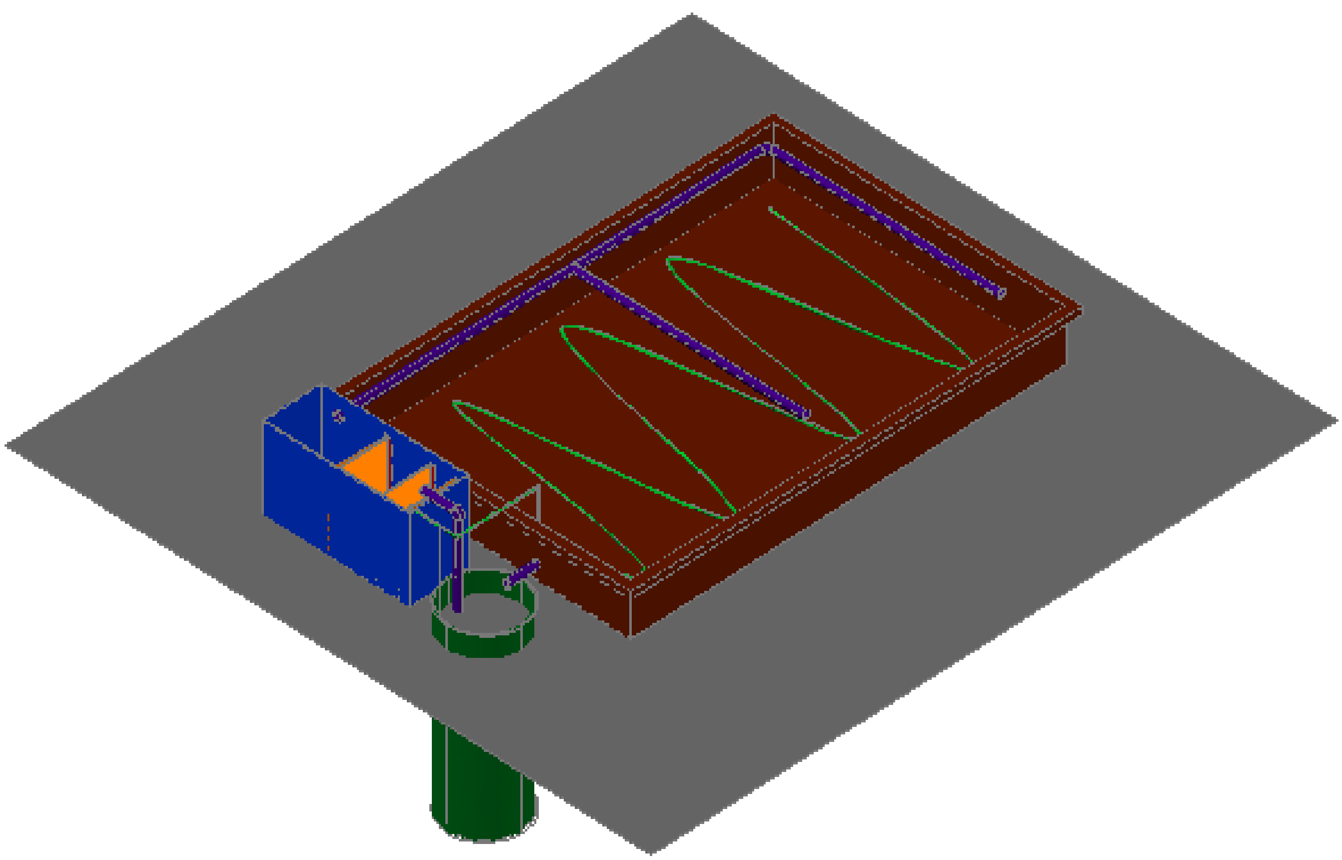


Figure 22: Aquaponic system isometric view (all components)

4.3.2 Fish Tank

The final fish tank design (Figure 23) incorporates a modified multiple rearing tank theme. This was necessary to enable the fish biomass to remain near the critical standing crop.

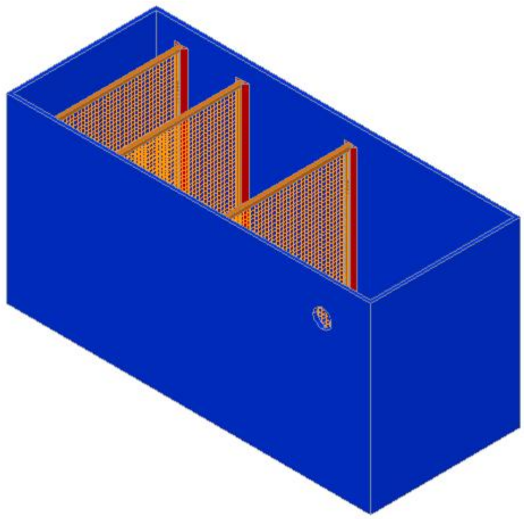


Figure 23: 3D Isometric view of fish tank design

A single rectangular tank with dimensions of 1 m in length, 0.4 m in width, and 0.5 m in height (Figures 24 and 26) is separated in to four rearing areas, each holding a separate fish cohort.

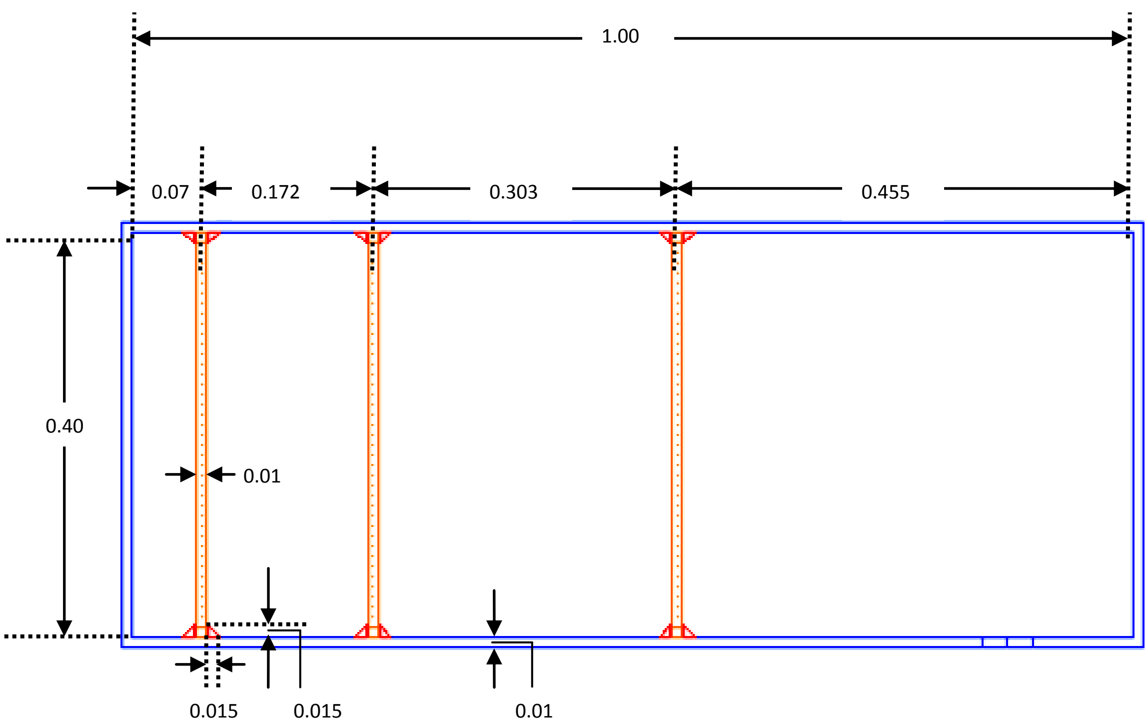


Figure 24: Top view of fish rearing tank with dimensions and cohort spacing with dimensions in meters

These areas are analogous to the separate tanks in the multiple rearing tank approach discussed earlier. Each area is separated by a screen that fits between two slots placed on the tank walls. Every six weeks, when the largest cohort is harvested, the screen is lifted and the smaller cohort is moved along to the next largest compartment. The smallest compartment is then restocked with tilapia fingerlings. This system reduces the stress on both fish and grower as fish do not have to be physically moved from one tank to another. The screens (Figure 25) allow for water to pass between compartments so that the outflow, which leaves the tank in the largest compartment, is of homogeneous quality.

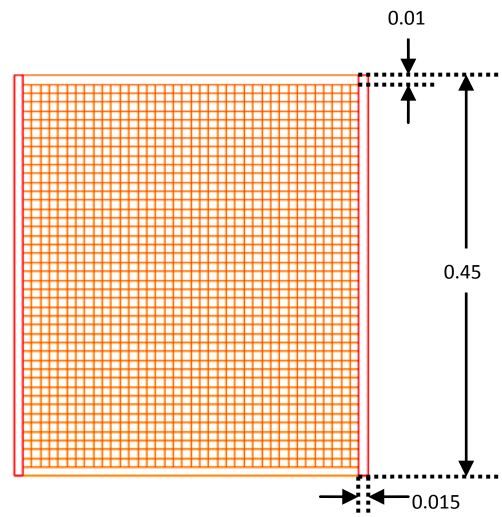


Figure 25: Cohort-separating screens with dimensions in meters

The side view (Figure 26) shows an outlet at a height of about 37 cm from the bottom of tank, where a distribution pipe will carry the water to the growing area. With a water height of 37 cm, a width of 40 cm, and the known water volume necessary to give a final stocking density of 60 kg/m^3 in each cohort, the compartment length and position of the screens was calculated.

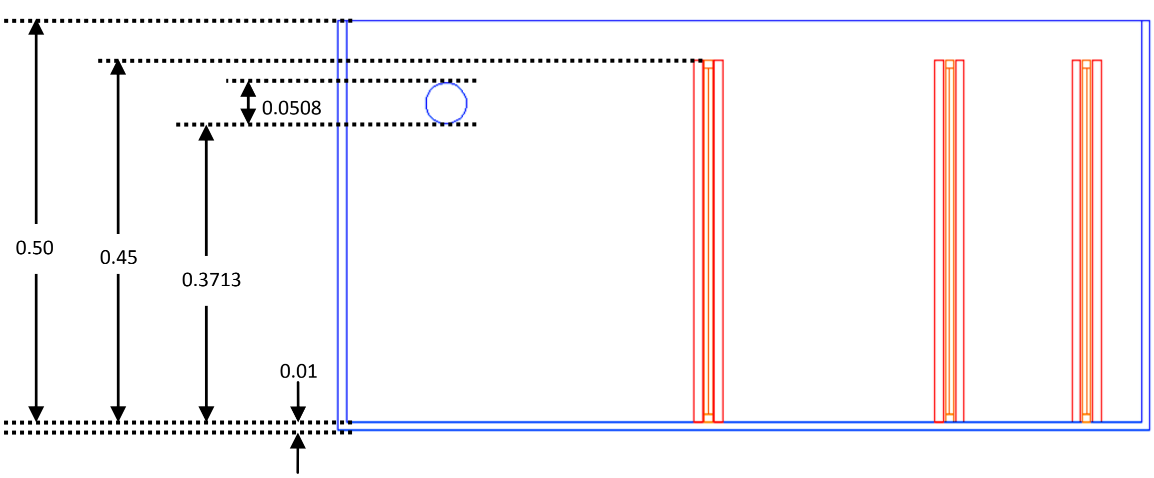


Figure 26: Side view of fish tank with dimensions in meters

The fish tank is made from polyethylene materials. This provides good structural support to hold the large volume of water that the system requires to house the fish. Polyethylene is also chemically inert which means over time, its chemicals will not be transferred to the system water and because the mould is made from one piece, there will be no loss of water due to leakage. Ideally, a tank with a conical bottom would have been chosen for efficient collection of solid waste, however the cost of custom shaped tanks such as this are too high. Scavenger fish can alternately be placed in compartments to remove the solid waste that accumulates there.

4.3.3 Grow Bed

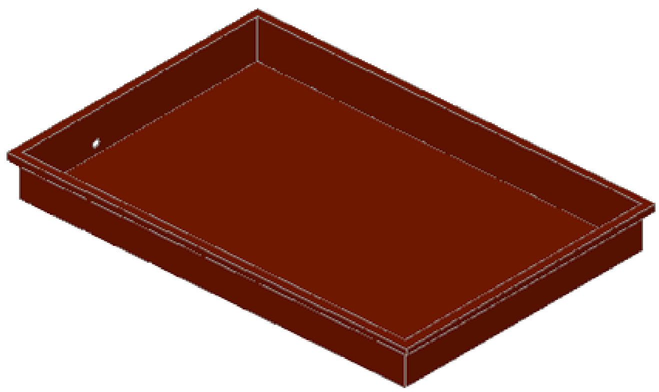


Figure 27: 3D isometric view of grow bed

The grow bed is made from the same polyethylene materials as the fish tank for the same reasons as the fish tank. As previously discussed, it has a growing area of 6 m^3 and dimensions of 2 m in width, 3 m in length, and 0.3 m in height (Fig. 28 and 29). It also has an outlet hole 5 cm from the bottom where a water distribution pipe will attach and allow water to flow by gravity to the sump tank. The 30 cm depth will allow for sufficient and healthy root growth for most plants.

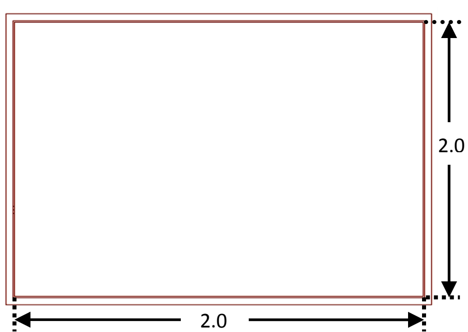


Figure 28: Top view of grow bed with dimensions in meters

Figure 29: Side view of grow bed with dimensions in meters (not to scale)

4.3.4 Sump Tank

The sump tank has a diameter of 0.50 m and a height of 1.12 m (Figures 30 and 31). The purpose of the sump tank is to regulate any fluctuations in the system's water volume. The idea is to have these fluctuations occur in the sump tank and not the fish tank. It is the only place in the system where water is pumped from one spot to another. The pipe that is placed in it must be mostly submerged which necessitates having a deep tank in relation to the distance that water must be lifted, as opposed to having a tank with a larger diameter. The sump tank is also a good place to adjust he pH of the system by adding an acid or base.

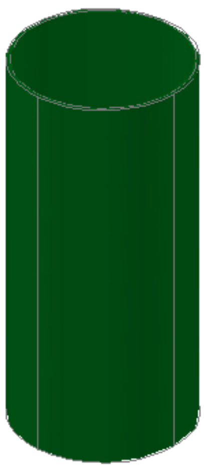


Figure 30: 3D view of sump tank

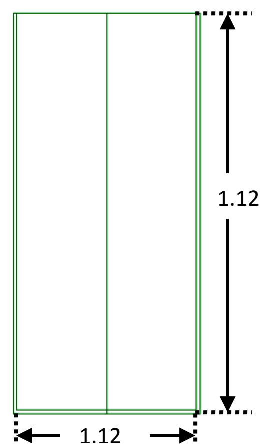


Figure 31: Sump tank with dimensions in meters

4.3.5 Aeration System

An aeration system will be put in place in order to maintain adequate oxygen levels throughout the system. The water tests performed on the backyard aquaponic system in Barbados showed consistently low dissolved oxygen levels - far below acceptable concentrations for the health of the fish, plants and bacteria. The gradual compaction of grow bed media (and its decomposition if the media is organic in nature) in media-filled aquaponic systems combined with its constant submergence in water creates anaerobic zones in the grow bed which interfere with the aerobic activities of the nitrifying bacteria and potentially causes the destruction of plant roots.

In the systems of the BVVA, there was no aeration other than what was obtained by water spilling from one component of the system into another due to a height difference. In those systems, the only fluid movement was that of water being pumped from the fish tank onto the hydroponic grow bed by a water pump and falling back into the fish tank by gravity.

4.3.5.1 Air Pump

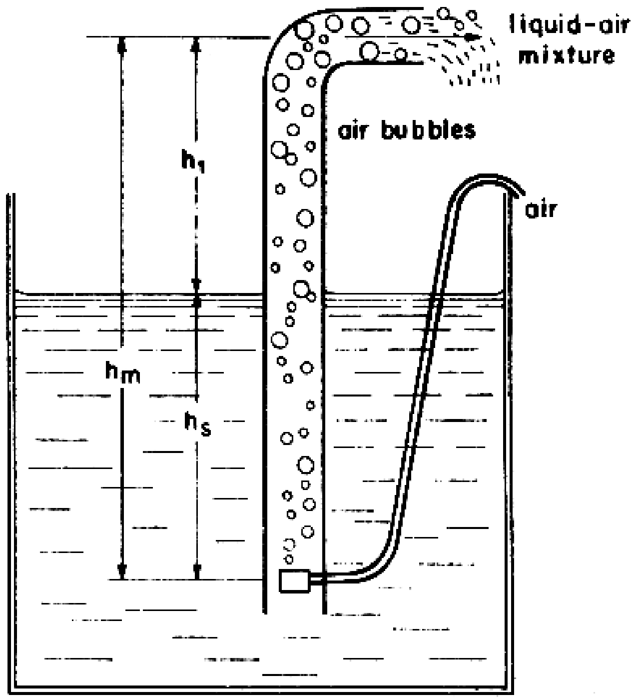
In this design, an air pump will be used instead of a water pump. The air pump will use much less energy than the water pump previously used (Nelson, 2008)– about ¼ of the energy in this design, in comparison to the system in Barbados. Aeration will be provided for the fish tank water, the water being applied to the grow bed and for the grow bed medium itself. The compressed air coming out of the air pump will be distributed to supply air to the following components by about 50 ft of rubber silicone tubing and the flow to the individual components will be controlled by air valves:

1) Airlift
2) Air diffusers in the fish tank
3) Air distribution grid in the grow bed

4.3.5.2 Airlift

The primary purpose of the air blower will be to drive the air lift pumping system that will circulate water through the system. Secondary purposes will be to aerate water in the fish tank and supply air to the grow bed media.

Air lift pumps are innovative and easily designed. They are a low cost alternative to a water pump and they manage to lift water and aerate it at the same time (Nelson, 2008). Airlift pumps are known well among aquaculturists. The basic principle of an airlift is the injection of air into the bottom of a submerged water pipe, from where the air bubbles will rise to the top, lifting with them the water in the submerged pipe. The increased oxygen level of the water in the pipe makes it less dense than the water in the surrounding tank. Thus this aerated water will rise by buoyancy, creating a net upwards displacement of water (Wurts, McNeill, & Overhults, 1994). This lifting of water by compressed air is very low in energy requirements. The only energy needed is for acceleration and to overcome friction (Nelson, 2008). The diagram in Figure 32 illustrates the simple premise of the system.



Where:

h_1 = Height of the water lift

h_m = Total height

h_s = Height of submergence

Figure 32: Conceptual diagram of an air lift pump (dela-Cruz, 1982)

Air lift pumps work very well when the height that the water has to be lifted is small in comparison to the height of submergence ($h_1/h_m << h_s/h_m$). The airlift pump is located in the sump tank and the height differences between the three components; the sump tank, fish tank, and grow bed, were in part designed to minimize the height necessary to pump water from the sump tank to the fish tank. To maintain the efficiency of the airlift, the water pipe should not exceed 3 inches in diameter (Nelson, 2008). In this design, water piping is 2 inches in diameter.

The vertical arrangement of the height of water in the sump tank and the height of the lift (from the sump tank water level to the top of the fish tank) is pictured in Figure 33. These heights can be compared to the vertical arrangement of the rest of the system in Figure 20 under System Configuration.

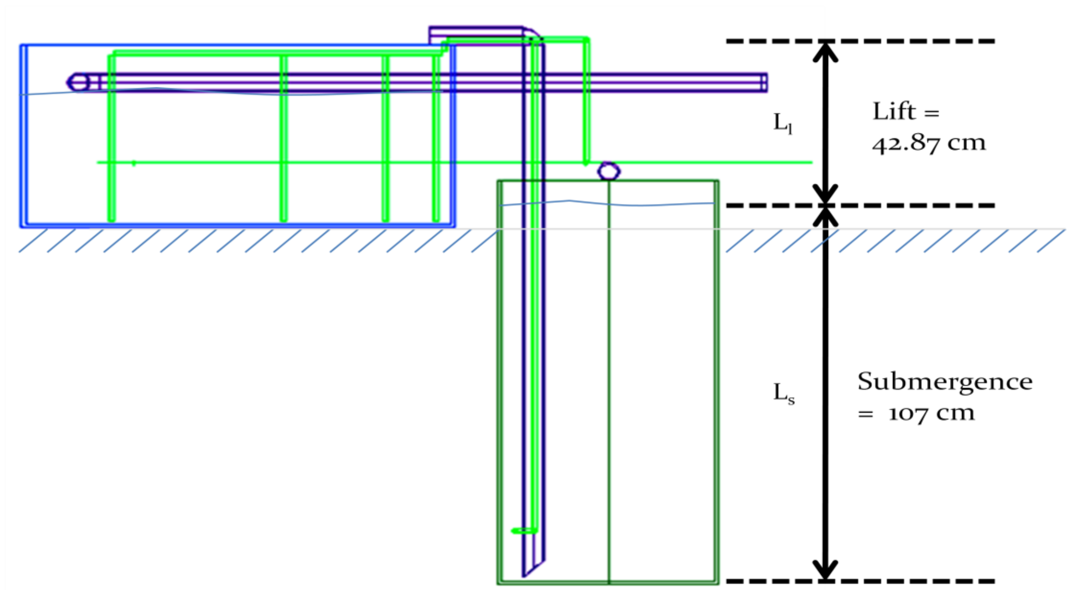


Figure 33: Heights of submergence and lift for airlift pump calculations

The ratio of these heights, referred to as the submergence ratio is important in calculating the flow of air required by the pump to lift water at a certain flow rate. The submergence ratio is given by:

$$Submergence\,ratio = \frac{Submergence}{Submergence + Lift} = \frac{107cm}{107cm + 42.87\ cm} = 0.71$$

4.3.5.2.1 Air Flow Requirement

The desired water flow rate of the system is 0.30 m^3/hr as determined previously. Two methods were used to calculate the air flow rate required to move water at 0.30 m^3/hr. The first using the following formula (La-Wniczak, Francois, Scrivener, Kastrinakis, & Nychas, 1999):

$$Q_a = \frac{Q_w(\rho_w - \rho_w a_s)}{F(\rho_w a_s - \rho_a)} + Q_{amin}$$

Where :

Q_a = air flow rate

Q_{amin} = minimum air rate to obtain water lift at chosen pipe diameter and submergence ratio (1.351 m^3/hr, from Table 1 (La-Wniczak, Francois, Scrivener, Kastrinakis, & Nychas, 1999))

Q_w = water flow rate (0.30 m^3/hr)

ρ_w = density of water (1000 kg/m^3)

ρ_a = density of air (1.2 kg/m^3)

a_s = submergence ratio (0.71)

F = dimensionless coefficient assuming negligible losses (1)

Gives;

$$Q_a = \frac{0.3\ \frac{\mathrm{m^3}}{\mathrm{hr}}(1000\ \frac{\mathrm{kg}}{\mathrm{m^3}} - 1000\frac{kg}{\mathrm{m^3}} * 0.6)}{1(1000\frac{kg}{\mathrm{m^3}} * 0.6 - 1.2\frac{kg}{\mathrm{m^3}})} + \ 1.351\ \frac{\mathrm{m^3}}{\mathrm{hr}} = \ 1.551\ \frac{\mathrm{m^3}}{\mathrm{hr}}$$

A second method was used to find the airflow rate as well for verification purposes. This method used an excel spreadsheet template from an airlift pump company website to input key parameters (see Table 13 in Appendix D). This method produced a slightly higher airflow rate at 2.07 m^3/hr, but the numbers were sufficiently close.

Hi-Blow USA Inc has a line of air blowers for different uses. The blower that will be used in this system is the Hi-Blow HP 40. Appendix D shows the performance chart for the blower. At the given water pressure of approximately 1.5 psi (107cm water height);

$$\mathrm{P}\ = \frac{\mathrm{L_s} * \mathrm{sg}}{2.31} = \frac{107\ \mathrm{cm} * 1}{2.31} * \frac{1\ \mathrm{in}}{2.54\ \mathrm{cm}} * \frac{1\ \mathrm{ft}}{12\ \mathrm{in}} = 1.52\ \mathrm{psi}$$

the pump has a capacity of 2.9 m^3/hr air. This airflow rate will sufficiently supply the airlift pump and have enough capacity to aerate the fish tank and grow bed as well.

The pump will be positioned outside of the sump tank with one air distribution tube leaving it. The tube will then split in to three tubes, two being of smaller diameters and feeding the fish tank and grow beds, and a third main tube that feeds the air lift pump. The primary air distribution tube is split once more and inserted into two symmetrical holes drilled at the same height into the sides of the sump tank water pipe as close to the bottom as possible. The sump tank water pipe is cut at an angle (see Figure 33 above) to allow for less turbulent water flow into the pipe. Figure34 shows the configuration of the air distribution system in green.

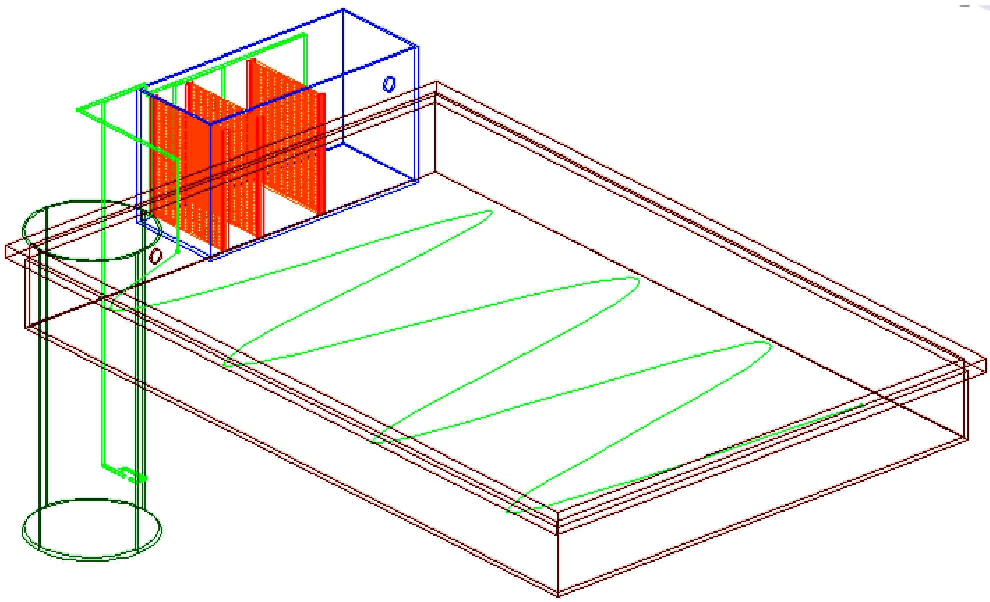


Figure 34: A 3D line model of the aeration system within the aquaponic system

4.3.5.3 Fish Tank Aeration

The silicone rubber air distribution tube that aerates the fish tank is further divided into four and each of the four tubes are placed vertically into one cohort section of the tank for even air distribution (see Figure 33). Air flow to the fish tank will be controlled by a valve on the main tank tube and can be increased over the 6-week growing period of the fish. To diffuse the air coming out of the tubes and maximize aeration of the water, air stones are attached to the bottom of each thin silicone rubber air tube as in Figures 35 and 36.

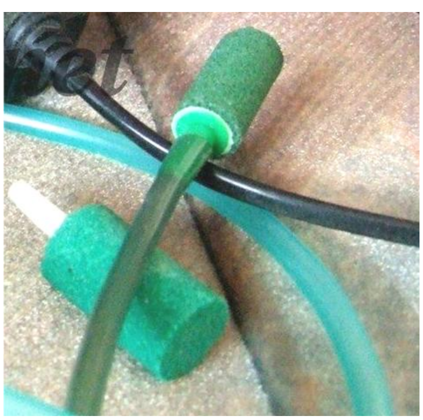


Figure 35: Air stones attached to tubing

Figure 36: Air stones diffuse air

Air stones create microbubbles of air as the flow of air passes through them and are the most inexpensive method of diffusing air in a fish tank (Nelson, 2008).

4.3.5.4 Grow Bed Aeration

The silicone rubber air tube feeding the grow bed will be placed within the grow bed media 20 cm below the surface of the coconut husk. The perforated tube will wind throughout the grow bed to provide even aeration of the media and the plant roots (see Figures 37 and 38 below). Air flow to the grow bed will be controlled by a valve and can be increased as the coconut husk compacts over time or decreased when the compacted husk is replaced occasionally by new husk.

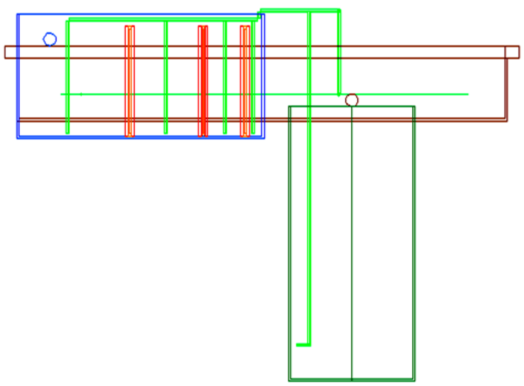


Figure 37: Side view of aeration system showing level of aeration tube placement at 20 cm below grow bed surface

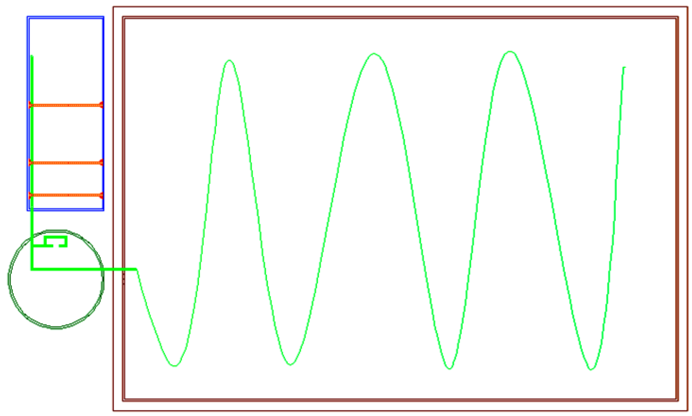


Figure 38: Top view of aeration system showing even distribution of winding perforated air tube

5. Other Considerations

5.1 Temperature Regulation

Fortunately, the climate in Barbados allows for year-round production in a backyard aquaponic food production system. Tilapia being a tropical fish finds average temperatures in the south Caribbean quite favourable to growth and health. Average daily temperatures for each month of the year are plotted in Figure 40 in Appendix A. Average daily low temperatures do not usually go below 21 °C. As daytime temperatures, particularly during the dry season can get quite high (~ 32 °C), a minimal degree of temperature control for the water in the system will be needed.

Tilapia prefer temperatures of 25.5-26.6 °C, bacteria perform nutrient conversions best at ~ 25 °C and aquaponic plants grow best at ~ 21 °C. As a compromise, average temperatures of the water in an aquaponic system should be maintained at around 22.2 – 23.3 °C (Nelson R. L., 2008).

When choosing the location of the backyard aquaponic system, care should be made to place the components containing just water (fish tank and sump tank) in as much shade as possible, while the grow bed should be placed in a location that will allow it to receive as much sun as possible. In this design, the sump tank is almost 1 m underground which will help keep the water in the system cooler by preventing it from heating too much during the day. The sump tank and the fish tank can be sheltered for shade but not covered completely to avoid reduction of water aeration.

5.2 pH Regulation

The acid-producing nitrifying activities of the bacteria in the coconut husk medium tend to lower the water pH as it passes through the biofilter, which is not ideal for the fish. Base should be added in the sump tank and not in the fish tank as to avoid pH shocks in the fish.

The pH should be maintained close to 7 and this can be achieved with the additions of bases such as calcium hydroxide ($Ca(OH)_2$) and potassium hydroxide (KOH). These bases should be applied several times weekly on an alternating basis. The frequency with which they are to be added can be determined by monitoring water pH to see how quickly it changes. The amount of base to be added can be determined by performing acid-base titrations on the fish tank water and seeing what quantity of base will produce the desired increase in pH. These tests are provided in water quality testing kits available for sale from aquacultural supply companies.

One base that should never be used for pH control in these systems is sodium bicarbonate ($NaHCO_3$) as a high concentration of sodium ion (Na^+) in the presence of chloride ions (Cl^-) forms salt (NaCl). Sodium concentrations above 50 mg/L are toxic to fish and they interfere with the uptake of several nutrients by plants (Rakocy, Masser, & Losordo, 2006). The exposure of backyard aquaponic systems to Barbadian rainstorms will also act as a source of dilution of accumulating compounds.

5.3 Water Quality Testing and Debris Control

Additional management recommendations for the maintenance of overall system health include cleanliness (in order to reduce the risk of pathogen introduction to the system) and regular upkeep of system components. Air diffusion tubes in the fish tank should be regularly cleaned to remove accumulated biofilms and air stones should be occasionally replaced if they become clogged from the outside by biofilms. Coconut husk should be replaced with an attempt at minimal disturbance to the plant crops if waterlogging in the grow bed is observed. The most important indicator of overall system health is the quality of the water in the fish tank. It is highly recommended that the installation of a backyard aquaponic food production system be accompanied by the acquisition of a water quality testing kit that allows for the regular measurement of the following critical parameters; pH, phosphates, nitrogen (in the forms of nitrite, nitrate, ammonia), temperature, dissolved oxygen and salinity.

Debris accumulation in the fish tank and sump tank can negatively impact water quality and should be reduced by the use of screens or netting placed on top of both tanks. Scavenger fish that do not interfere with tilapia cultivation can be kept in the fish tank to consume excess fish food and other organic debris that collects on the bottom over time.

6. Cost Benefit Analysis

6.1 Costs

To assess the viability of housing a system, a cost benefit analysis was performed. Cost benefit analyses are useful tools for determining the financial feasibility of a venture. The cost of all inputs to the system are tallied and weighed against the value of the system's outputs. In this case, there are several inputs, including initial material costs, electricity, and fish feed. The outputs are in the form of vegetable and tilapia production. Many assumptions must be made in order to make reasonable estimations for many of the inputs and outputs. A thorough explanation of the system components will be explored in this section. Because an initial design took place in Barbados and the optimized design is for tropical Caribbean climates, prices will be displayed in both Canadian and Barbadian dollars.

6.1.1 Initial Material Costs

Table 6: Initial costs of backyard aquaponic system

Materials	Cost (BDS $)	Cost (CND $)
HDPE Grow Bed	795.00	397.50
HDPE Fish Tank	240.00	120.00
HDPE Sump Tank	220.00	110.00
Pump	578.00	289.00
Distribution Network	270.00	135.00
Air Diffusion Hose	150.00	75.00
Cinder Blocks (10)	50.00	25.00
Air Stone	10.00	5.00
Air Valves	20.00	10.00
Extension Cord	50.00	25.00
Grow Media	15.00	7.50
Seedlings	20.00	10.00
Tilapia fish	80.00	40.00
Total	**2,498.00**	**1,249.00**

Assumptions and notes:

- Grow beds of the exact dimensions could not be found and priced, so for pricing purposes, the price of three 2 m^2 grow beds were used.
- 10 cinder blocks at \$2.50/ea were used in place of stands to adjust the levels of the components.
- 50 ft of air hose was used at a price of \$1.50/ft.
- Growing media (coconut husk) was priced at a cost of \$30/tonne. 1 tonne occupies approximately 7.3 m^3.
- 72 Seedlings were used at a cost of approximately \$0.15/seedling.
- Tilapia fingerlings were purchased at approximately \$1.00/fish.

It should be noted that over 50% of initial set up costs are due to the grow bed, fish tank, and sump tank. These costs could be greatly reduced by a grower with a little ingenuity. The grow bed, at a cost of \$397, is the single biggest expense of the system, however this cost is mostly attributed to the high cost of fabricating the mould to make the bed. The only necessity of the bed is that it be able to hold the grow media that the plants grow in and that the water not leak out of it. This type of structure can easily be constructed by creating an area bordered by walls made from cinder blocks or even soil for example. The area would then have to be lined with an impermeable polyethylene liner, which generally retails for around \$5/m^2. A 6 m^2 by 0.3 m deep grow area could be lined for less than \$40. Similar logic could be used for the sump tank. The tank's only design characteristic is that its depth be as large as possible compared to the height that the water is lifted to the fish tank. A hole dug in the ground could even be lined with the polyethylene liner. Polyethylene liner is however discouraged in fish tank use because fish tend to bite holes causing leaks in the tank. If liner is used in the grow area, care is needed to ensure that the seal between the liner and effluent pipe is tight to avoid leaks as water exits the grow bed area.

6.1.2 Annual Costs

An additional input to the system is the cost of electricity used to run the air blower that circulates the water throughout the system and aerates the fish tank and grow bed. The cost of electricity is assumed to be \$0.21/kWh, which falls in line with what Barbados Light & Power charges (Barbados Light and Power). The Hi-Blow HP 40 pump's power consumption is rated at 0.8 amps, using 120 V (0.096 kW). The annual electricity costs then become:

$$Annual\ Electricity\ Cost: \quad \frac{\$0.21}{kWh} * \frac{8760\ hr}{yr} * 0.096\ kW = \$\ \mathbf{176.60/year}$$

The final annual cost for the system is the fish feed given to the tilapia each day. A fish feed rate ratio of 25 g/m^{2}d is used in media filled systems and it is assumed that a 22.5 kg bag of fish feed could be purchased for approximately $26. The cost of annual fish feed used is as follows:

$$Annual\ Fish\ Feed\ Cost: \quad \frac{0.025\ kg}{m^2 * day} * \frac{6m^2}{grow\ bed} * \frac{365\ days}{year} * \frac{bag}{22.5\ kg} * \frac{\$26}{bag} = \$\mathbf{63.27\ /year}$$

6.2 Outputs

6.2.1 Fish Production

There are 8.67 fish harvests per year; one every 6 weeks. For simplicity, we assume that there will be 9 harvests. With 9 fish in each harvest, a total of 81 fish will be produced annually by the system. Monetary values for tilapia fish were ascertained by surveying local supermarkets in Barbados. Whole fish prices, as opposed to fillet prices, were used; $10/kg. Harvest weight per fish is predicted to be 0.450 kg. The value of annual fish production will therefore be as follows:

$$Value\ of\ Fish\ Production\ = \frac{9\ havests}{year} * \frac{9\ fish}{harvest} * \frac{0.450\ kg}{fish} * \frac{\$10}{kg} = \$364.50/year$$

6.2.2 Vegetable Production

To estimate vegetable production it was assumed that a plant density of 12 plants/m^2 will be used. This is an empirical figure determined from practical experience with aquaponics. For the sake of the cost benefit exercise, it is assumed that a system uses half of its area to grow okra and the other half to grow basil. In reality, systems can be used to grow a number of different crops, all with different yields and market prices, but for the sake of simplicity, and because of the information available, okra and basil are used as representative crops. Again, prices for okra and basil were determined by looking at Barbadian supermarket prices and were found to be $ 3.40/kg for okra and $ 26.75/kg for basil. A growing area of 6 m^2 will be assumed to hold 36 basil plants and 36 okra plants. Per plant final production values, which were taken from Dr. James E. Rakocy's work with aquaponics at the University of the Virgin Islands, were found to be on average 700 g for okra and 250 g for basil. According to the UVI study, okra is harvested once every 3 months and basil, once a month. Table 7 summarizes the annual financial gains from the two crops.

Table 7: Summary of annual outputs from okra and basil

Crop	# of Plants	Harvests/Year	Weight/Plant (kg)	Total Weight (kg)	Market Price ($BDS)	Annual Value ($CND)	Annual Value ($BDS)
Okra	36.00	4.00	0.70	100.80	3.40	342.72	685.44
Basil	36.00	12.00	0.25	108.00	26.75	2889.00	5778.00

The large difference between the values of the two crops demonstrates how much more profitable it is to grow herbs and leafy green vegetables as opposed to fruiting crops, as previously discussed.

6.3 Summary of Analysis

Tables 8 to 10 summarize the cost benefit analysis.

Table 8: Summary of first year costs and outputs

1st Year Inputs	Cost (BDS)	Cost (CND)	Outputs	Value (BDS)	Value (CND)
Startup Materials	2498.00	1249.00	Okra	1370.88	685.44
Electricity	353.20	176.60	Basil	11556	5778
Fish Food	126.54	63.87	Tilapia	729	364.5
Total	**2977.74**	**1489.87**		**13655.88**	**6827.94**

Table 9: Summary of second year costs and outputs

2nd Year Inputs	Cost (BDS)	Cost (CND)	Outputs	Value (BDS)	Value (CND)
Electricity	353.20	176.60	Okra	1370.88	685.44
Fish Food	126.54	63.87	Basil	11556	5778
			Tilapia	729	364.5
Total	**479.74**	**240.47**		**13655.88**	**6827.94**

Table 10: Summary of profits for the first two years

Profits	BDS	CND
1st Year	10678.14	5338.47
2nd Year	13176.14	6587.47

These tables show the distinction between the first and second year of production because initial start-up costs, which are quite significant, are only incurred in the first year. For this reason, financial gains subsequent to the first year ($6587.47) are significantly higher than those experienced in the initial year of production ($5338.47).

At this point it should be reiterated how much this analysis relies on the stated assumptions. Basil is obviously much more profitable than okra, which makes the system highly lucrative. If a family were to simply use the system to produce food for their own consumption, not much of the area would be devoted to herbs, which are much more profitable. Planting densities, production plant weights, and material costs are all values that can vary and will affect a cost benefit analysis. Nevertheless, the system appears to be quite financially worthwhile.

7. Conclusions

Re-examining our objective provides a good framework to conclude the project. Starting the project the goal was to scrutinize an aquaponics system so we could identify exactly where key design decisions could be made in order to increase the efficiency of the system and maximize the output. All design decisions were inevitably compared to the familiar systems that had been encountered in Barbados. The final design included elements that were not considered in previous systems, most notably the replacement of the water pump with and air pump that has the capabilities to aerate the fish tank water, the grow bed, and circulate the water throughout the system. The elevation levels of the grow bed, fish tank and sump tank were also meticulously set to minimize the power requirements to circulate the water. And finally, the sequential harvesting of both the fish and plants is expected to make a considerable augmentation to the system's output as it regulates system parameters such as the stocking density of the fish and the nutritional needs of the plants. The additional design decision are expected considerably improve water quality, thereby positively affecting fish growth and production.

Food security poses a very real and serious threat in the world today. What makes aquaponic food production so attractive is its ability to address these issues of resource conservation and access to a reliable and quality food source. In addition to this, the simplicity of an aquaponic system makes it accessible and user friendly so it has the potential to help families who are most in need of it. Although Barbados is the most developed of the Caribbean nations and the quality of living is generally considered very good, mean income is still only around $7,500 (USD) (Barbados Vital Statistic, 2007), and therefore the addition of a few thousand dollars in the form of food or revenue has the ability to significantly impact the lives of families. It has been shown time and again that it can be a profitable endeavour and, if desired, a lucrative vegetable and fish production company can be developed using aquaponic methods. The potential is high for this type of agriculture and it will likely gain notoriety as global circumstances continue to necessitate an increasing amount of innovation, conservation, and consciousness.

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Appendices

Appendix A: Barbados Background Information

Figure 39: Location of Barbados in the Caribbean
(From: http://www.travelguide2barbados.com/p1_maps.php)

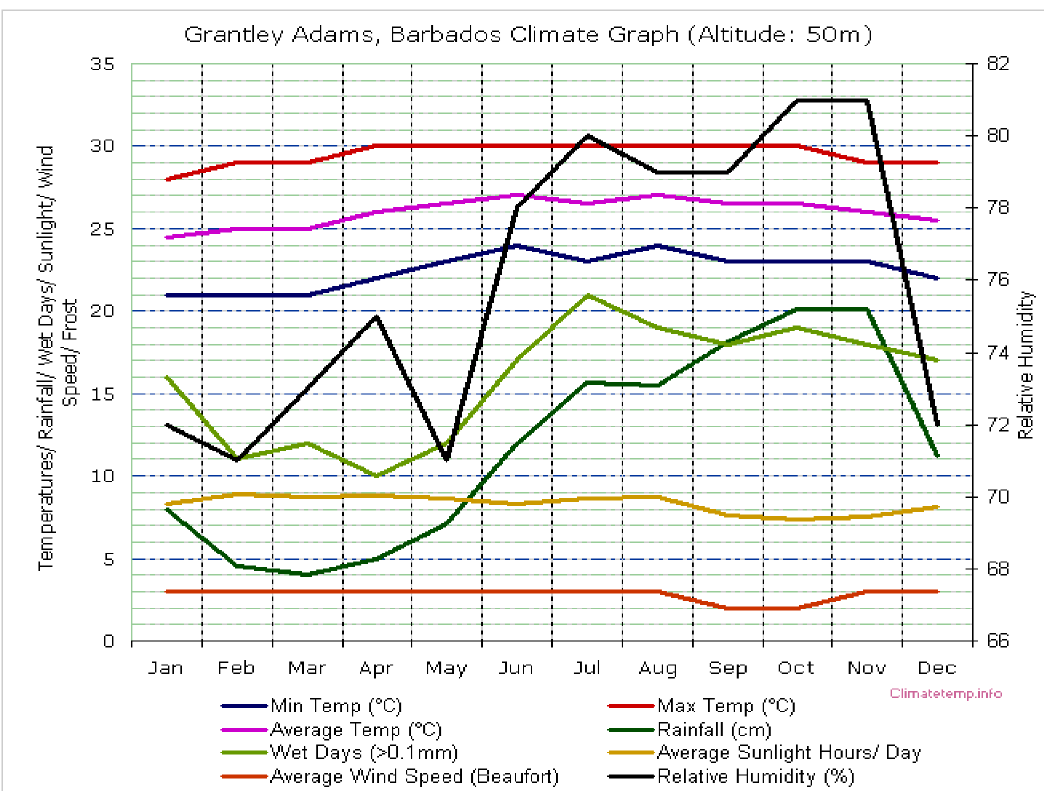

Figure 40: Barbados Climate Graph (Metric) (From: http://www.climatetemp.info/barbados/)

Appendix B: Water Quality Experiment Results from Barbados System

Table 11: Summary of results on water quality in BVAA aquaponic fish tank

Parameter		Range found in fish tank	Optimal range
Temperature		27.05-29.73 °C	27-29 °C
pH		7.38-7.65	6.8-9
Salinity		0.37-0.43 PSU (ppt)	< 10 ppt (PSU)
PO_4^{3-}		9.15-9.17 mg/l	50 µg/l
NO_3^-		0.77-1.23 mg/l	<150 mg/l
Ammonia	NH_3	0.002-0.0045 mg/l	<0.08 mg/l
	NH_4^+	0.098-0.220 mg/l	<1.0 mg/l
DO		2.31-2.94 mg/l	5.0-7.5 mg/l

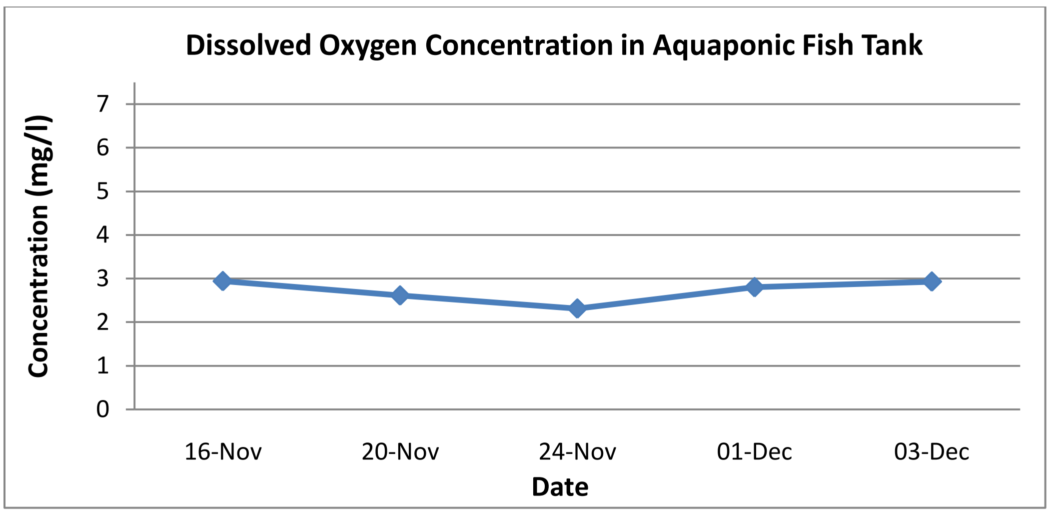

Figure 41: Dissolved oxygen concentrations over test period

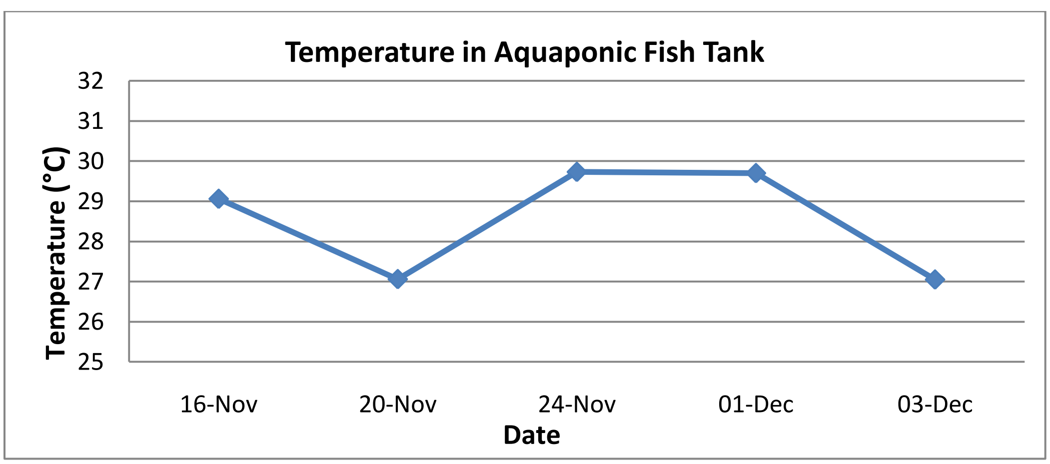

Figure 42: Fish tank temperature over test period

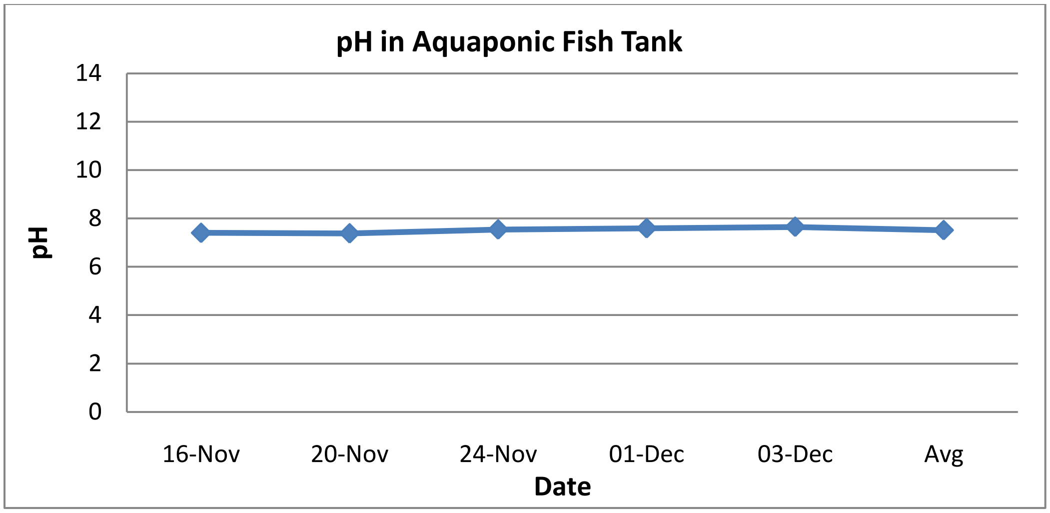

Figure 43: Fish tank pH over test period

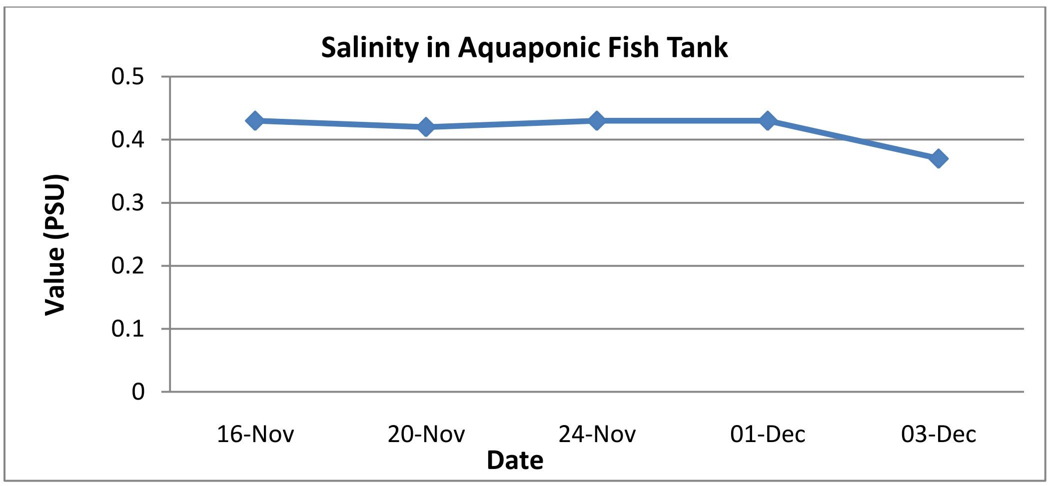

Figure 44: Fish tank salinity over test period

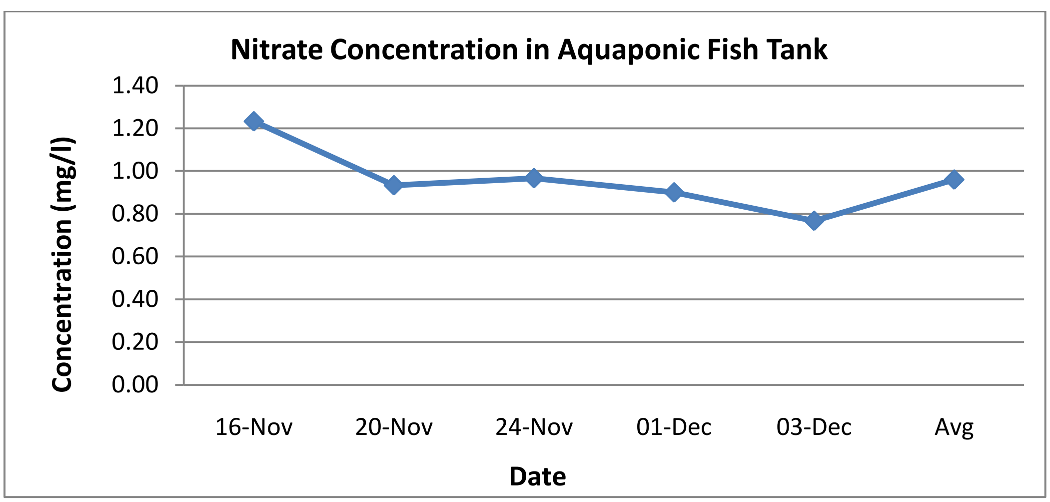

Figure 45: Nitrate concentrations over test period

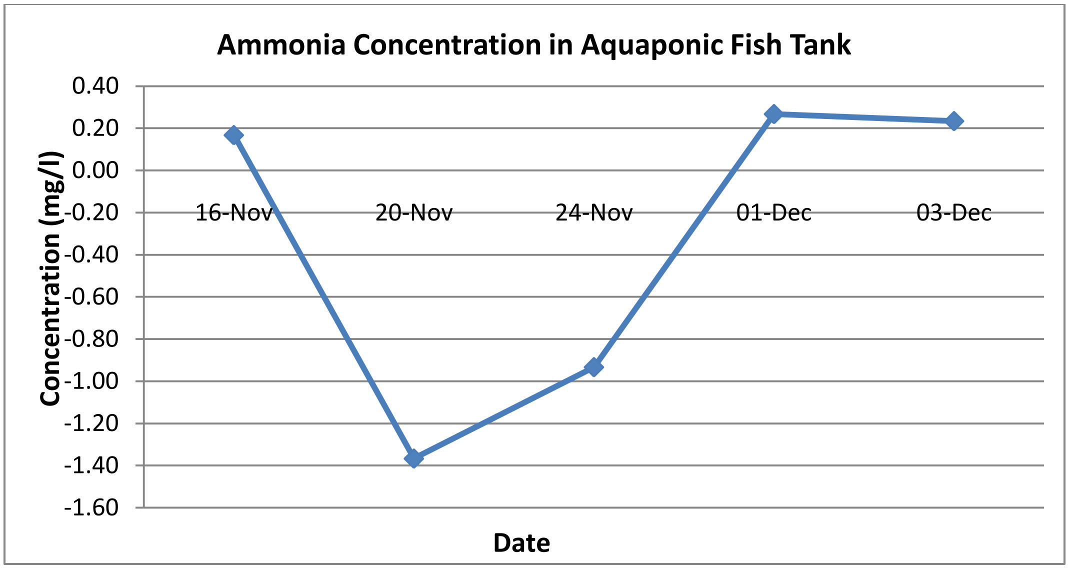

Figure 46: Ammonia concentrations over test period

Appendix C: Fish Growth Estimations

Table 12: Fish Growth Estimations (based on SRAC-282: Tank Culture of Tilapia

	Growth Period			
	Day 1-30	Day 31-60	Day 61-110	Day 111 - 170
Initial/Final Weight (g)	20/50	50/100	100/250	250/450
Growth Rate (g/day)	1	1.75	3	3.25

Cohort 1		Cohort 2		Cohort 3		Cohort 4	
Day	Weight (g)	Day	Weight (g)	Day	Weight (g)	Day	Weight (g)
1	20	1	71	1	172	1	302
2	21	2	72.75	2	175	2	305.6
3	22	3	74.5	3	178	3	309.2
4	23	4	76.25	4	181	4	312.8
5	24	5	78	5	184	5	316.4
6	25	6	79.75	6	187	6	320
7	26	7	81.5	7	190	7	323.6
8	27	8	83.25	8	193	8	327.2
9	28	9	85	9	196	9	330.8
10	29	10	86.75	10	199	10	334.4
11	30	11	88.5	11	202	11	338
12	31	12	90.25	12	205	12	341.6
13	32	13	92	13	208	13	345.2
14	33	14	93.75	14	211	14	348.8
15	34	15	95.5	15	214	15	352.4
16	35	16	97.25	16	217	16	356
17	36	17	99	17	220	17	359.6
18	37	18	100.75	18	223	18	363.2
19	38	19	100	19	226	19	366.8
20	39	20	103	20	229	20	370.4
21	40	21	106	21	232	21	374
22	41	22	109	22	235	22	377.6
23	42	23	112	23	238	23	381.2
24	43	24	115	24	241	24	384.8
25	44	25	118	25	244	25	388.4
26	45	26	121	26	247	26	392
27	46	27	124	27	250	27	395.6
28	47	28	127	28	253.25	28	399.2
29	48	29	130	29	256.5	29	402.8
30	49	30	133	30	259.75	30	406.4

31	50	31	136	31	263	31	410
32	51.75	32	139	32	266.25	32	413.6
33	53.5	33	142	33	269.5	33	417.2
34	55.25	34	145	34	272.75	34	420.8
35	57	35	148	35	276	35	424.4
36	58.75	36	151	36	279.25	36	428
37	60.5	37	154	37	282.5	37	431.6
38	62.25	38	157	38	285.75	38	435.2
39	64	39	160	39	289	39	438.8
40	65.75	40	163	40	292.25	40	442.4
41	67.5	41	166	41	295.5	41	446
42	69.25	42	169	42	298.75	42	449.6

Appendix D: Air Pump Specifications

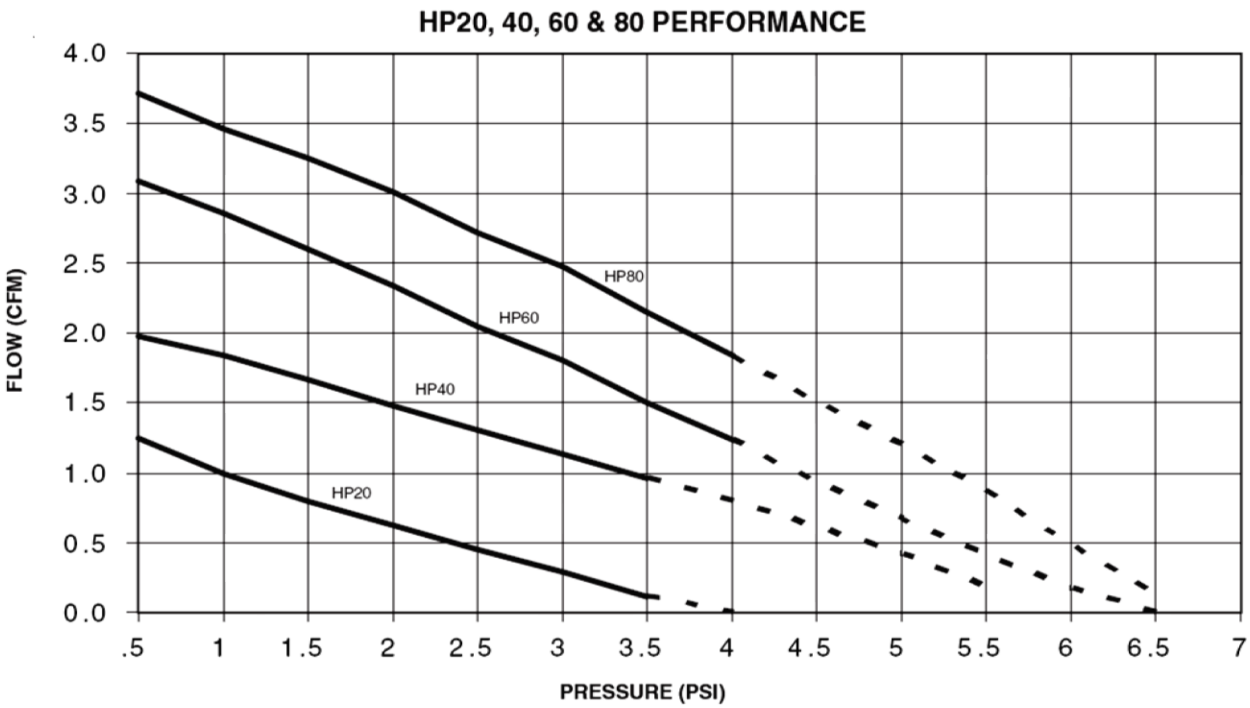

Figure 47: Performance chart for Hi-Blow HP 40 pump

Table 13: Alternate method for air flow calculations (The Geyser Pump, 2010)

Pumping rate	1,904	gallon/day
Pipe diameter	2.00	inch
submergence	3.5	ft
lift	4.9	ft

Input data

cross-sectional area of pipe	0.022	ft2
Pipe volume	0.08	ft3
Pipe volume	7.48	gallon
Vl (Flow rate)	1	GPM
A (Pipe area)	0.022	ft2
L (Lift)	4.9	ft
D (Pipe diameter)	2	inch
Lf (density of fluid)	100	
S (submergence)	3.51	ft
Lg (Gas density)	0.0765	
Value of Ordinate	24,697	2.47E+04
Value of Abscissa	100<Y<10,225	3.55
	10,225<Y<73,637	3.42
	73,637<Y<117,690	3.34
	117,690<Y<123.645	0.00
	123,645<Y<128,308	0.00
	128,308<Y<99,018	3.21

Don't change anything

Graph reading	3.42

Vg (Gas flow)	1.22	ft3/min
Pressure	1.52	psi

Answer