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ASSESSING AFFORDABLE AQUAPONICS METHODS FOR THE PACIFIC ISLANDS

by

Mia Casey Avril

A thesis submitted in fulfilment of the
requirements for the degree of
Masters of Science

School of Marine Science
Faculty of Science, Technology and Environment
The University of the South Pacific

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DECLARATION OF AUTHENTICITY

Statement by Author

I, Mia Casey Avril, declare that this thesis is my own work and that, to the best of my knowledge, it contains no material previously published, or substantially overlapping with material submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

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Statement by Supervisor

The research in this thesis was performed under my supervision and to my knowledge is the sole work of Ms. Mia Casey Avril.

Signature: Date: 06 March 2018

Name: Professor Ciro Rico

Designation: Head of School, School of Marine Studies

DEDICATION

I would like to dedicate this thesis to my family, my parents Joseph and Berthelina Avril and my brother Dean Avril. Their love and support were critical in the completion of this project.

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ABSTRACT

Global fish stocks are declining for a number of reasons. In order to protect the remaining wild fish stocks, alternatives such as aquaculture have been developed. Aquaculture is one of the fastest growing sectors in animal food-production. However, aquaculture has negative impacts on the environment, which can be mitigated by developing systems where crops are used to clean the water. The 'cleaned' water can then be returned to the fish farm, thereby reducing the need for freshwater investments into the system. This integrated system is known as aquaponics.

The cost of an aquaponics system is high, thus acting as a deterrent to potential farmers. It is important to make aquaponics more appealing by reducing this cost, as the development of such methods is particularly helpful to persons with limited freshwater supply. Furthermore, the products of aquaponics are fresh vegetables and fish, which provide healthy food options.

This project seeks to develop a small scale aquaponics system that can be built primarily from locally available materials. This system was designed by Dr Wilson Lennard and a prototype was constructed at Homes of Hope, an organization which rehabilitates abused single mothers.

The approximate cost for establishing this system is FJD3000 inclusive of running costs for one year. This system was closely monitored for two 5-month growth periods and the quality of the water as well as the health of the fish and crops will be observed. Growth and survival rates of fish were recorded and analysed. The system proved successful in the production of leafy crops such as lettuce and basil, and fruiting crops, such as tomatoes and strawberries, and fish biomass was doubled during the grow out period. Once the batches of fish and crops were successfully harvested, a user manual was produced.

ACRONYMS

ANOVA	Analysis of Variance
FADs	Fish Aggregating Devices
FCR	Feed Conversion Ratio
FJD	Fijian Dollar
GIFT	Genetically Improved Farmed Tilapia
GDP	Gross Domestic Product
IBM SPSS	International Business Machines Statistical Package for the Social Sciences
LMMA	Locally Managed Marine Areas
MPA	Marine Protected Areas
PICTs	Pacific Island Countries and Territories
PLD	The Pacific Islands Pest List Database
PVC	Polyvinyl Chloride
SPC	Secretariat of the Pacific Community
TAC	Total Allowable Catch
TEK	Traditional Ecological Knowledge
US	United States of America
YSI	Yellow Springs Instrument

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Humans have effectively converted from food gatherers and hunters to food producers through agriculture (Atlason et al., 2017). This change has been fuelled not only by technological development but also by necessity, due to exploitation and depletion of natural food stocks. Over the years, despite the increasing reaches of globalization, most persons consume locally produced food (Funk & Brown, 2009). Therefore, the local food production sector, particularly in the developing world, is tasked with meeting increasing demands using depleting resources, as well as innovations to enhance the sector that are continuously being sought.

The volatility of food imports and fuel prices also emphasizes the need to enhance local food production (Funk & Brown, 2009). These strains are further compounded by the effects of climate change on the natural environment, as well as the plant and animal species used for food. While all areas of food production are being affected by these changes, one industry of particular importance is fisheries.

Fisheries are considered important because animal proteins contribute significantly to human wellbeing, and fish have been identified as a cheap, and thus popular, source of animal protein (Godfray et al., 2010). Fish and aquatic animals can be a cheaper form of animal protein than chicken, beef and other standard terrestrial sources, and are essential to the food security of many poor regions of the world, such as Africa and Asia (Belton & Thilsted, 2014). Fisheries are also important due to the nutritional benefits provided. Fish are a source of high quality protein, micronutrients and fatty acids that are critical for human brain development (Belton & Thilsted, 2014). In most Pacific Island Countries, fisheries contribute to the economy, food security and general livelihood of the people (Bell, Johnson, & Hobday, 2011).

Climate change, as well as the negative impacts of overfishing globally, has resulted in most stocks of commercially important fish species being considered fully or over exploited, and many others labelled as economically extinct or critically threatened (Dulvy, Sadovy, & Reynolds, 2003). Changes spurred by climate change in winds, water temperature, ocean acidity and other oceanic parameters may make it difficult for natural fish stocks to regenerate (McClanahan, Allison, & Cinner, 2015). Climate change in the Pacific is expected to result in intensified storms, which threaten coastal resources and cause reef degradation through changes in water chemistry (Bell et al., 2011). In order to not only protect the remaining fish stocks, but to also secure the availability of fish protein for the global market, alternative sources of fish production have to be developed.

Aquaculture

Aquaculture is one avenue for fish production that has been developed over the past 50 years. In 2004, aquaculture accounted for nearly half of the total global fish export (Diana, 2009), and accounts for over 20% of national GDP in most Pacific islands (Bell et al., 2013).

Aquaculture was first introduced to Fiji in 1953 as livestock feed for pig farming (Adams, Bell, & Labrosse, 2001). Funding from Japan was obtained for the development of aquaculture in the South Pacific region in the 1970s (Adams, Bell, & Labrosse, 2001) as a means of addressing food-security concerns. Potential for growth of the industry exists, as many of the species that can be grown in the South Pacific can be marketed at high value in Asian countries, and the wider world. Hawaii, the Marshall Islands, the Cook Islands and Guam also have conducted research on aquaculture development.

Reaching out to the fisher-folk, farmers and general local population to secure their interest and commitment is the next step in developing aquaculture. However, since cost remains a major deterrent, establishing a system that requires minimal cost/input, particularly from overseas, is an important step forward in the development sustainable aquaculture practices in remote communities in the South Pacific Islands.

Unfortunately, aquaculture can at times have negative impacts on the environment through the discharge of the waste water (Emerson, 1999). The effluent pollutes agricultural land and results in eutrophication of rivers and coastlines when it enters natural water bodies and leads to the explosive growth of algae (Burkholder &

Shumway, 2011). Such algal blooms have both direct and indirect impacts on habitats and species.

In addition, aquaculture may not be possible in places with sandy or porous soils that cannot retain water in ponds, or where water resources to fill ponds are very scarce. These challenges can be greatly addressed by integrated aquaculture systems, where crops in closed systems are used to extract nutrients and re-cycle the aquaculture discharge, that would otherwise be deposited into the environment. The 'cleaned' water can then be returned to the fish tanks, thereby reducing the need for freshwater investments into the system. This system is known as aquaponics and is the integration of aquaculture with hydroponics (Klinger & Naylor, 2012).

Aquaponics

Aquaponics was first introduced in 1984 by Watten and Busch in their report on the tropical production of tilapia and tomato (Nicolae et al., 2015). Aquaponics is described as the combination of aquaculture and hydroponics; aquaculture encapsulates the growing of aquatic plant and animals in modified natural systems or artificial systems, and hydroponics references the soilless cultivation of crops using fertilized water as a nutrient source (Atlason et al., 2017).

Aquaculture and hydroponics as individual entities can possibly threaten the environment, particularly where waste water disposal is concerned (Atlason et al., 2017). The combination of the two culture types into aquaponics significantly reduces the risk to the environment, since aquaponics systems are closed, and able to manage waste production internally. Many farmers have since explored the cultivation of fish with vegetables and other crops due to the added advantage of reducing the waste released into the environment (bioremediation), as most of the fish waste is utilized by the plants.

The cost of setting up and running such a combined system is high (Tomlinson, 2015), and thus acts as a deterrent to people, in particular those in small developing island states that lack the needed capital. It is therefore important to make aquaponics more appealing by reducing the capital required. It should also be noted that this venture is also particularly helpful for persons living in atolls with limited freshwater supply, or inland communities with limited coastal access.

Continuous work being is done to boost the accessibility of aquaculture and aquaponics. Currently in the South Pacific region, resources are being invested into developing aquaponics, particularly at a commercial level. In Hawaii, there have been advances in determining optimal feed for use in intensive commercial culturing of particular species of fish within aquaponics systems (Fox et al., 2012). There are also smaller scale farms within communities that address not only the need for food, but also foster social interactions among community members (Fox et al., 2012).

Aquaponics in Fiji

In a small island country like Fiji, aquaculture and aquaponics can enhance food production, and are considered a solution to the deficiency of animal protein in inland areas. These concepts were introduced to rural Fiji 30 years ago (Macaranas et al., 1997). The importance of aquaculture to Fiji extends beyond meeting local animal protein needs. Seaweed forms a major part of the Pacific diet, and the local supply in Fiji does not meet the current demand (Morris et al., 2014). Exploration of marine based aquaponics systems could not only sustainably boost the production for the local market (Schuenhoff et al., 2003) but also supply a potential export market to Asian countries (Morris et al., 2014). This would also help boost the local economy (Bunting & Shpigel, 2009).

Within Fiji, aquaponics still remains at a pre-commercial level (T. Pickering, personal communication, January 2017). One of the primary deterrents to the expansion of these systems is the cost attached. Southeast Asia and other parts of the world have recognized the importance of aquaponics as the future of aquaculture production. It is therefore beneficial to educate people to recognize aquaculture, and more specifically aquaponics, as an alternative means of food security and income generation. Further research is crucial to the development of more cost-effective aquaponics systems in order to encourage people to sustainably explore aquaponics as a source of income and food supply.

Organizations have been established both locally and within the region to boost research in fisheries related food security, and also to help protect wildlife, particularly aquatic species, and habitats. The local agency in Fiji geared at enhancing food security, particularly with respect to fisheries resources, is Women in Fisheries. Regionally, the Secretariat of the Pacific Community (SPC) is a multi-sectoral organization, whose mandate is to guide the Pacific in becoming a healthy and productive region through the application of science to a Pacific-specific context. It is well known for its work in the fisheries sector, public health, geoscience, and plant genetics for food security. International organizations have also either established local offices or funded research in many small islands states. Some of these include the United Nations of the Pacific, and the United Nations Food and Agriculture Organization. A common thread in the mandates for these organizations is the pursuit of food security, and reducing the occurrence of non-communicable diseases in Fiji, and the wider South Pacific.

The SPC in particular, is an advocate of reducing and eliminating the occurrence of non-communicable diseases through exercise and consumption of more local, fresh produce. In 2016 there was a cookbook published by the SPC to support this mandate (Bertrand-Protat, 2017). This further supports the applicability of aquaponics to Fiji and the Pacific, as the products are fresh vegetables and herbs, and fish, which is a low-fat source of animal protein. All of these have been highlighted as means of reducing the incidence of non-communicable diseases (Bertrand-Protat, 2017).

Project Overview

This project proposes the testing and further development of the ideas of one expert in the field, Dr. Wilson Lennard, who has designed a low-cost aquaponics system built from locally available material. This would inherently reduce the current cost of setting up an aquaponics system, and encourage more individuals to establish systems. This information can then be condensed and shared with interested people.

Homes of Hope was selected as the location for this project. Homes of Hope is a charity for women and children who are victims or potential victims of sexual abuse, and is run by American directors Mark and Lynnie Roche. The program is designed to be a refuge for women and their children, where they can receive counselling to help with the trauma. The women are also rehabilitated and armed with skills to make them functional and successful members of society, before they return to their communities. The children are educated at the on-campus preschool. More information on Homes of Hope can be found on their website: http://www.hopefiji.org/.

The rehabilitation programs offered are geared to provide the women with basic life skills and financial awareness. Some of the programs include cooking, computer skills, business administration, and farming. The farming program has many components, such a crop growing, livestock and poultry farming, and aquaculture. There are a number of fish ponds on the campus as well as a small conventional aquaponics unit, different from the one for this project.

This location was selected for the project as aquaponics fits closely with the operations at Homes of Hope. The residents are involved in the operation of the system, and those who are interested are trained to maintain the system. Given the proposed low cost of this system, interested mothers could pursue aquaponics as a means of sustenance upon returning to their village.

For the duration of this project, the principal investigator worked alongside assigned mothers at the home to carry out day to day tasks such as the feeding of fish. Upon completion of the project, the system was handed over to Homes of Hope to form an official part of their program.

Objectives

The primary aim of this project was to test the low-cost aquaponics system designed by Wilson Lennard (PhD) and to determine the optimal protocols for fish and crop production under Fijian conditions using a prototype. Additionally, a user-friendly manual to allow local villages to implement the system under their particular conditions was produced, based on the observations made during the construction and operation of this prototype system.

This aim was achieved through four specific objectives. These are:

- To effectively construct a prototype, low-budget system aquaponics as designed by Wilson Lennard
- To test the ability of the system to grow the desired crops, and fine-tune it as necessary
- To test whether shelter for crops is necessary to optimize production in this aquaponics system
- To develop a manual for set-up and operation of the developing world aquaponics system

This project was conducted over a 12-month period, during which time the allocated site was visited and prepared. Materials were then acquired and the system was constructed. Operations were commenced and continued over a 10-month period, while observations were continuously made and recorded. The findings were presented in a report, and a brief manual for constructing and operating a similar system under Fijian conditions was compiled. The manual also included some recommendations for optimizing productivity of the system, based on shortcomings observed during this project.

Justification

The success of this project has a broad range of applications. Most directly, the successful operation of this system will enhance the current operations at the Homes of Hope, and increase the range of activities available to residents there. During the completion of this project, some of the residents involved in the operation of the system sought additional information on the installation and management of the system, as a result of their interest in establishing similar systems for themselves. This system will become a part of the rehabilitation program, and be included in the list of skills taught to residents in order to make them financially independent members of society. They are then free to build personal systems upon leaving the home. Once the necessary construction tools are available, it is possible for the average woman within the working age group to put together a system similar to the one tested in this project, with some assistance.

In a similar way, this system can be introduced to schools, rehabilitation facilities, remand and correction centres, wellness centres, and other similar facilities. There it can have the two-fold purpose of helping the persons housed, treated or educated at these institutions, while providing some amount of food that can be used at these facilities, offsetting operational costs. If well established, these systems can also be used to generate a small amount of income (Coleman, 2017).

The system can also be introduced to persons living in remote communities in the interior of Fiji, with restricted access to fish protein. A low-cost system with minimal inputs or requirements can be introduced as a community project, providing village residents with safe, fresh vegetables and fish. This is also applicable in coastal villages to help reduce the demand on declining marine fisheries for food. There are also a few atolls, in Fijifor example Vanua Balavu in the Lau group, and other Pacific Islands such a Kiribati and Tuvalu, where fresh water is limited. Aquaponics is a sustainable means of food production under such conditions, with the simple, low cost design of the system making it an attractive option.

Aquaculture farmers can explore this system to enhance their current operations, in order to reduce environmental impacts while increasing food production and income. Hobbyists can also find this system useful.
This system, although tested for Fijian conditions, can be applied to other tropical parts of the world in similar ways, adjusting crop and fish species selection to suit local environmental conditions and market demands.

The downstream applications of this system are immeasurable, through the circulation of a manual produced as part of this project (See Appendix 5), which can be made available to interested persons, providing detailed instructions on the construction and operation of this system.

LITERATURE REVIEW

Food Security

Food security is a matter of global concern and scientists have been tasked with finding solutions to the world's growing demand for food. According to the United Nations in 1975, food security is defined as "*the availability at all times of adequate world supplies of basic food stuffs…, to sustain a steady expansion of food consumption…and to offset fluctuations in production and prices*"(Maxwell, 1996). However, Sen (1981) noted that food security is not achieved purely by food availability, but by access to food. The definition was then further modified in 1986 by the World Bank, stating that "*food security is access by all people at all times to enough food for an active and healthy life*" (Reutlinger, 1986). In 1996 the Food and Agriculture Organization, together with the World Health Organization, formally defined food security as "*when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active lifestyle*" (Maxwell, 1996).

There are four main pillars or elements of food security: availability, accessibility, utilization and stability (Schmidhuber & Tubiello, 2007). Availability refers to whether sufficient food is present through local food production and import. Local food production (agriculture) does not automatically mean that a country is food secure. Hong Kong and Singapore, for instance, have very little agriculture, but are food secure nations. On the other hand, India is a self-sufficient country with a large amount of food production, and yet cannot provide sufficient food to a large portion of the population (Schmidhuber & Tubiello, 2007). India's food insecurity may be due largely to the second pillar: accessibility. This refers to whether individuals have the requisite physical, social and economic resources in order to obtain a consistent supply of nutritious food.

Many of the world's poorest people live in areas that are so remote that they are physically disconnected from the national and international food market, while some poor persons within urban areas are physically close to, but cannot afford healthy food (Godfray et al., 2010). There is also the added strain of limited food, when cultivated grains are being used for biofuels and animal feeds, rather than for human dietary needs (Shiferaw, Prasanna, Hellin, & Bänziger, 2011). The third pillar, utilization, deals with the safety and quality of the food available to individuals. This can be compromised by poor sanitation, resulting in vector-borne and infectious diseases. It creates an unfortunate cycle where hunger renders individuals susceptible to diseases and diseases compound hunger (Schmidhuber & Tubiello, 2007). The fourth pillar is stability, which is the resilience of individuals to natural disasters and socio-economic shocks, such as reduced income. This fourth pillar is particularly vulnerable to the influences of potential climatic changes and depends on adaptation and mitigation strategies (Godfray et al., 2010).

The world's population increases every year, and with that comes a surge in the demand for food, among other resources (Naylor et al., 2000). Meeting the increasing food requirements is particularly challenging since the global population continues to grow, resulting in conflicting uses of available land (Alexander et al., 2015). Coupled with these issues, climate change influences need to be considered. Increased variability in climatic factors such as rainfall and temperature in different parts of the world is already resulting in declining productivity (Shiferaw et al., 2011).

At this time, more than 14% of the world's population does not have access to adequate protein and energy from their diets, with an even larger percentage suffering from micronutrient malnourishment (Godfray et al., 2010). Models suggest that by 2030, North America, Western Europe and Eastern Asia may have increased productivity, while the entire African continent, South and Central America, and Southern and Eastern Asia, may have slowed growth in yields, and potential declines overall (Funk & Brown, 2009). Predictions also suggest that by 2050, the world's population will be approximately nine billion, and will require 70-100% more food than is presently being produced (Godfray et al., 2010). Global food security currently depends on the ability to not only increase the productivity of actively cultivated areas, but to also grow crops in places that are identified as unsuitable (Godfray et al., 2010). Food security then becomes a challenge in small-island states, such as those in the Caribbean, which is already listed as a food-insecure region (Lobell et al., 2008). Another similar region is the Pacific, where land space, fresh water, and access to resources are already limited, thus highlighting the importance of land use efficiency (Nhan, Milstein, Verdegem, & Verreth, 2006). This issue of limited resources inherently leads to both the degradation of the natural environment, and scarcity of resources such as land and water (Nhan et al., 2006).

Sustainable intensification refers to increasing productivity of an area, while simultaneously reducing the environmental impacts, and has been proposed as the way forward in food security. It requires that the entire food production chain become more sustainable in practice, by increasing yield per area of food production, for example (Godfray et al., 2010; Tilman et al., 2011). The environmental cost of conventional food production is expected to increase with globalization, due to novel issues like emissions from transport. Despite the growth of globalization, individuals in most countries consume more locally grown food than imported food (Funk & Brown, 2009), regardless of cultural preferences (Brown & Funk, 2008). In developing countries, most rural citizens are involved to some extent in agriculture, however 30% of farmers are food insecure (Brown & Funk, 2008).

The main solution to food insecurity proposed by Godfray (2010), is an increase in local productivity combined with efforts to slow population growth/food demand. The use of agricultural land and water (both fresh and marine) for aquaculture and fisheries practices can be employed to reduce negative impacts on biodiversity. However, environmental impacts still exist through the release of organic effluents, as well as potential genetic contamination of wild populations (Godfray et al., 2010).

Fisheries

Global fisheries

Worldwide, fish is an important source of animal protein (Macaranas et al., 1997). However, wild stock harvestshave stagnated, with a reported increase in collapsed stocks coupled with a decline in the discovery of new stocks (Froese, Zeller, Kleisner, & Pauly, 2012). Meanwhile, demand continues to increase (Wik, Lindén, & Wramner, 2009). Global fisheries resources are being continuously threatened and overexploited (Macaranas et al., 1997). Since the 1950s, global fishing effort and technology has expanded (Kleisner, Zeller, Froese, & Pauly, 2013; McClanahan et al., 2015). There was a four-fold expansion in fishing area recorded in the North Atlantic, West Pacific, southern hemisphere and tropics, peaking in the period from 1980 to 1990, when expansion occurred at a rate of one latitudinal degree per annum (McClanahan et al., 2015). Unlike in agriculture, where a 10% increase in cultivated area resulted in the doubling of production, the five-fold increase of fisheries production during the past 60 years was the result of a 400% increase in fished areas (McClanahan et al., 2015).

By the mid-1990s, one third of the world's oceans and two thirds of the continental shelf fisheries had been fully exploited, resulting in a decline in the opening of new areas for utilization to meet growing food requirements (McClanahan et al., 2015). And yet, fishing effort continues to increase. Currently, the amount of fishing occurring globally has increased ten-fold since the 1950s, while the catch per unit effort is half of what it was. The rate at which marine fisheries are exploited has resulted in the collapse of the majority of the populations to below 10% of estimated original stock sizes (McClanahan et al., 2015). Currently, only California and New Zealand fisheries have sustainable exploitation rates (Worm et al., 2009). Additionally, the changes in global climate exacerbate the negative impacts of human activity on marine ecosystems, as well as independently depleting the remaining robust stocks.

Composite models suggest that there will be a 60% loss of present biodiversity by the year 2055, with extinctions in the sub-polar regions, tropics, and semi-enclosed bays. It is also expected that species invasions will increase in Polar Regions by 30-70%, and decrease in tropical regions by 40% (McClanahan et al., 2015). Fisheries in Northern European and Asian countries such as Norway, Greenland, Alaska and Russia are expected to benefit from climate change, while those in more equatorial countries such as Indonesia, Chile, China and the United States of America are expected to suffer losses amounting to USD 311 million, annually (McClanahan et al., 2015). The reduced productivity of tropical regions would result from a decline in coral cover, as well as changes in abiotic parameters such as dissolved oxygen, acidity and temperature, which will affect mixing in the water column and thus nutrient availability.

The decline of global fish stocks is a concern for food security. The actual importance of fisheries to food security globally should not be underestimated (Pomeroy, Parks, Courtney, & Mattich, 2016). Since most of the fisheries in the developed world have collapsed, their markets rely on fish stocks from developing tropical regions to meet demand. Fish trade from developing to developed countries is potentially beneficial to food security for both parties by promoting production and market development, thereby creating employment and encouraging economic growth. Senegal is an example of such success, where in the 1980s and 1990s, the value of exported fish matched the cost of their imported staples (McClanahan et al., 2015).

There have been efforts in North America and Europe to rebuild fish stocks, however effective control is still lacking. It is believed that reduced overexploitation of fisheries can be achieved by restricting types of fishing gear, to increase catch selectivity and reduce bycatch. Preservation of existing stocks can also be achieved by closing known nurseries and other biologically sensitive areas. Another control mechanism is reducing the Total Allowable Catch (TAC), which would directly reduce the amount of fish removed from wild stocks. In some regions, government fishing subsidies encourage overfishing and need to be reduced, even though reduced quotas result in the loss of jobs, which is not well received by individuals (Worm et al., 2009).

In small-scale fisheries, the most successful approach to management has been community based. This is the combination of traditional approaches, such as fishing quotas and community management, with strategic approaches, such as area closures, gear selection and economic incentives, that rely on cooperation between fisheries scientists, conservation biologists and the members of the community (Worm et al., 2009).

Despite the global decline in fisheries production, many countries depend on the industry as a primary source of income. Aquaculture is one avenue to increase fish production, which has been developed over the past 50 years and over the past 30 years has contributed to a global increase of per capita fish supply (McClanahan et al., 2015). Globally, fisheries and aquaculture collectively contribute on average 17 kg of safe animal protein per person, annually (McClanahan et al., 2015). Besides enhancing food security, aquaculture provides natural fish stocks with an opportunity to re-establish populations, by reducing fishing pressure placed on wild stocks (Shapawi & Shakeh, 2015).

Pacific Fisheries

Fishing forms a pivotal part of Pacific culture. Currently, despite the declines in global fisheries, many Pacific islands are net exporters of fish (Dey, Rosegrant, Gosh, Chen, & Valmonte-Santos, 2016). The coastal waters of southeast Asia are among the most productive and biodiverse in the world (Pomeroy et al., 2016). The Northwest Hawaiian Islands are home to some of the most pristine coral reefs globally (Vroom & Braun, 2010), which contribute to the health of the region's fisheries. The Pacific Island Countries are isolated archipelagos in a vast ocean, which is home to highly productive corals that support Pacific societies in a number of ways; including aesthetically, economically, culturally, and through subsistence fishing livelihoods (Albert, Tawake, Vave, Fisher, & Grinham, 2016).

Even with a fisheries industry more productive than most, the Pacific region is plagued with food insecurity (Valmonte-Santos, Rosegrant, & Dey, 2016). Stresses of land availability and the deterioration of coastal and marine biodiversity contribute to this issue, which is then further compounded by climate change (Valmonte-Santos et al., 2016). The islands of the Pacific are particularly vulnerable to climate change, with sea level rise being one of the most severe effects. Areas are rapidly becoming uninhabitable and slowly disappearing. Moreover, models suggest that the domestic demand of Pacific countries for food overall and fish specifically, is expected to rise, resulting in reduced exports and increased imports (Dey et al., 2016).

Traditionally in Vanuatu, inshore and offshore fishing is an important source of food and income, with over 70% of rural households practicing fishing (Rosegrant, Dey, Valmonte-Santos, & Chen, 2016). Food security in Vanuatu is threatened by climate change because of geographic location, the current socioeconomic condition and political instability. Many persons depend on subsistence agriculture and fish for food. The fisheries sector, (including aquaculture), plays a vital role in the economic development of a country, and the livelihood of its people (Rosegrant et al., 2016). Despite the growing domestic demands, particularly for freshwater fish, which is likely to exceed supply, the country is still a net exporter of ocean fish (Dey, Gosh, Valmonte-Santos, Rosegrant, & Chen, 2016). Aquaculture has been highlighted as a means of not only adapting to the impacts of climate change on local fisheries, but to also help meet the country's growing demand for fish protein (Rosegrant et al., 2016). Other suggestions to improve oceanic fisheries include implementation of Fish Aggregating Devices (FADs), Marine Protected Areas (MPAs), and legislation to control fishing gear.

Timor Leste is a Pacific country with a poorly developed fisheries sector, and is dependent on the rural interior to meet food security demands (Rosegrant et al., 2016). There have been efforts over the past decade to develop sustainable fisheries; however the country lacks a domestic commercial fleet. Instead, deep water fisheries are dominated by foreign fleets, forcing Timor Leste to act as a net importer of fish (Rosegrant et al., 2016). Freshwater fisheries systems are expected to help to meet the demand in the future however are not likely to replace the need for imports (Dey, Gosh, et al., 2016. Natural resource management and aquaculture have been suggested as adaptations to the anticipated impacts of climate change on the already strained fisheries, to help meet local demand. The implementation of the suggestions, however, is still heavily reliant on limited governmental resources (Rosegrant et al., 2016).

In the Solomon Islands, food is traditionally supplied primarily by subsistence farming, fishing, hunting and trading. However, with the recent change from an agriculture-based to a service-based local economy, food supply has shifted from local production, to a combination of local and imported supplies (Dey, Gosh, et al., 2016). The Solomon Islands' fisheries resources are important for human nutrition, employment and income, and foreign exchange. Fish provide up to 90% of animal protein in some areas (Dey, Gosh, et al., 2016). The Solomon Island fisheries are currently threatened by a lack of sustainable management policies, which have resulted in a decline in coastal fisheries resources, while offshore fisheries are dominated by foreign fleets for export (Dey, Gosh, et al., 2016). In order to help meet future demands for fish, suggested remedies include the implementation of natural resource management strategies, such as reserves and protected areas, to help control coastal fisheries. Another solution is supplementing local supply with aquaculture production and coastal invertebrates. Also, the deployment of Fish Aggregating Devices (FADs) contributes to an increase in the offshore fish supply (Dey, Gosh, et al., 2016; Valmonte-Santos et al., 2016). The efficiency of these techniques relies greatly on their combined application, rather than individual effort.

As regional populations continue to grow, so will demand for fish, thereby encouraging the exploitation of limited fisheries resources. This situation is worsened by the existing, inadequate governing systems (Pomeroy et al., 2016). There is a need for Pacific Island Countries and Territories (PICTs) to resolve social and political issues as they relate to fisheries resources (Valmonte-Santos et al., 2016). Collaborations exist between Pacific Island Countries and neighbouring Asian countries with which Pacific marine resources are shared; nevertheless there is a lack of regional policy and other strategies to properly manage the resources (Pomeroy et al., 2016). It is also important to sustainably address conflicts between overlapping economic sectors such as fisheries and tourism. It is the consensus of regional fisheries experts, however, that together with MPAs and FADs, aquaculture is a certain means of enhancing food security in the region (Valmonte-Santos et al., 2016).

The typical approach to fisheries management involves bans and restrictions on fishing of particular species. However, fish stocks are better managed with an ecosystem based approach, such as MPAs (Shapawi & Shakeh, 2015).

Fiji Fisheries

Like other Pacific island countries, Fiji relies on aquatic resources as an integral part of its economy and its citizens' livelihoods. Fiji is an archipelago comprising 332 islands, which lie between 10^0S and 25^0S, and 177^0E and 173^0W. The exclusive economic zone (EEZ) of Fiji has an area of 1.29 million km^2, 40% of which is bordered by water, and the rest, by islands (Albert et al., 2016).
Fisheries contribute to Fiji's rural development, to the GDP through income generation, and to the livelihoods of individuals. In 2014, fisheries contributed 73 million dollars (FJD) to the country's economy (Gillett, 2015). Fisheries also enhance food security in Fiji (Dey, Gosh, Valmonte-Santos, Rosegrant, & Chen, 2016), and have immeasurable social and cultural benefits. Approximately 40% of Fiji's animal protein is derived from the ocean(Selig et al., 2015).

Traditionally, coastal and marine resources in Fiji have been managed at the village level. Protected inshore areas, locally called *qoliqoli*, are controlled by village or clan chiefs and families, who manage their use in order to prevent overexploitation, especially by implementing bans. The knowledge used in making such decisions is referred to as Traditional Ecological Knowledge (TEK), which is passed down through generations and includes information about the timing and location of ecologically significant events related to all aspects of the environment, not just the marine habitats (Golden, Naisilsisili, Ligairi, & Drew, 2014). Recent generations have placed less importance on TEK and management practices. Of the 410 *qoliqoli* in Fiji, 250 have been developed to the maximum sustainable yield capacity, while 70 have been overexploited (Golden et al., 2014). Poor management is a downstream effect of western colonization, which resulted in the introduction of a market based economy to Fiji, as well as the devaluation of traditional methods and the imposition of colonial laws (Golden at al., 2014).

Like other Pacific countries, Fiji has embraced western management practices, such as the scientifically-basedMPAs, which incorporate top-down enforcement and formal management practices as well as community-based strategies and TEK(Golden et al., 2014; Selig et al., 2015). This is because, within the past forty years, scientists have accepted the importance of the integration of TEK in management strategies. However, the influence of the *qoliqoli* systems in Fiji makes top-down management strategies challenging. Additionally, the shift in management from indigenous institutions to national ministries is dependent on access to limited administrative and financial support, which also makes the implementation of regulations difficult. The stress of poor management on Fiji fisheries is being intensified by the impacts of climate change.

Fishing in Fiji was traditionally artisanal and subsistence-focused (Glaus, Adrian-Kalchhauser, Burkhardt-Holm, White, & Brunnschweiler, 2015). Following the Second World War, colonial pressure was placed on the country's resources and commercial fisheries were developed with the support of the Fiji Development Bank (Golden et al., 2014). Although remote parts of Fiji, such as Ono-i-Lau, maintained traditional practices and were able to utilize advancements in fishing equipment to improve efficiency and net volume of catch, generally, advancements in fishing gear exacerbated the situation and resulted in the overexploitation of both inshore and deep-sea fisheries such as tuna and shark (Glaus et al., 2015; Golden et al., 2014).

There is limited documentation on the status and production level of Fiji fisheries, or even the full range of involved species (Gillett, 2015; Glaus et al., 2015), however it is known to include finfish, invertebrates and plant species. Some of the invertebrate species, such assea cucumbers, are identified as vulnerable due to their easily accessible, inshore habitats (Hair et al., 2011). Fiji's reefs are also threatened by anthropogenic factors such as pollution and over-exploitation, with almost 85% of the reefs in the Coral Triangle being considered threatened (Albert et al., 2016; Selig et al., 2015). Therefore, coastal production is expected to decline, while local demand for fish is expected to increase, resulting in reduced exports and increased imports of fish (Dey, Gosh, et al., 2016. Species decline is expected since the current trends of local fisheries do not suggest that there exists the possibility of expansion (Gillett, 2015). Reductions in fishery resources would inevitably result in rising market prices, driving poorer persons to further exploit the threatened resources (Gillett, 2015).

The government of Fiji, like that of many other Pacific Islands, has introduced a National Adaptation Programme of Action against climate change, which involves two primary climate change adaptation strategies for fisheries: natural resource management through Locally Managed Marine Areas (LMMAs) and MPAs, and aquaculture (Dey, Gosh, et al., 2016). The LMMAs have allowed indigenous persons to share their traditional knowledge and tools in order to enhance management practices, and are currently present and effective in over 450 villages in Fiji. They can also be found in other member countries of the coral triangle (Albert et al., 2016).

Aquaculture has been identified as a means to enhance the economy and address food security concerns of Fiji and other Pacific Island Countries (Pickering, 2009; Pickering et al., 2011). However, like in other developing countries, the growth of aquaculture in Fiji has been more of a random as opposed to a systematically structured approach (Hurwood, Singh, Dammannagoda, Nandlal, & Mather, 2014; Pickering et al., 2011). Despite this, the importance of aquaculture in Fiji is increasing, with consumers showing a preference for tilapia and freshwater prawn (Dey et al., 2016). As the industry develops, it is expected to reduce the market price of freshwater fish and invertebrates (Dey, Gosh, et al., 2016). The use of tilapia as an aquaculture product in Fiji is encouraged, as it can grow to the desired market size of 200-400g within 6 months (Pickering et al., 2011).

The culture of local species is challenging, so tilapia was introduced to Fiji with great success in the 1950s, and giant freshwater prawn aquaculture was likewise introduced in the 1980s, (Hurwood et al., 2014; T. Pickering, 2009). Other species such as carp, milkfish, pearl oysters and seaweed have also been explored as aquaculture products (Rosegrant et al., 2016). Attempts have even been made to use existing *qoliqoli* areas as sea ranches for the production of sandfish (Hair et al., 2011). These efforts come at a time when the occurrence of non-communicable diseases is increasing, highlighting a shift in diet from fish and locally grown food to cheaper, unhealthy, imported options (Valmonte-Santos et al., 2016). This can be alleviated by increasing aquaculture outputs in order to provide persons with healthier aquatic protein sources at a cheaper price (Valmonte-Santos et al., 2016). The use of tilapia farming as an answer to food security concerns in Fiji and the Pacific region is proving fruitful, however means of reducing environmental impacts need to be explored.

Aquaculture

Aquaculture has been seen to have many negative impacts on the environment, especially through the discharge of waste water. The waste water contains a host of contaminants including particulate and dissolved organic material, suspended solids, dissolved nutrients and other inorganic and organic material (Piedrahita, 2003). The release of nutrients such as nitrogen and phosphorus into natural water bodies is known to cause eutrophication, which in turn results in severely depleted oxygen levels and threatens the health of the organisms naturally occurring in that area. In the late 1980s, there was an observed collapse in sea trout populations in Ireland in close proximity to coastal salmon rearing cages. This collapse is believed to be the result of a disruption in benthic communities in the area, resulting from over feeding in the salmon aquaculture cages (Emerson, 1999). Other similar situations have been observed. Additionally, antibiotics and supplements that are added to feed, upon entering the environment, have been seen to impact species for which they were not intended (Emerson, 1999).
Attempts have been made to address the issue of pollution from aquaculture, one of the most successful being aquaponics. Initiated in the 1970s (Love et al., 2014), aquaponics is an integrated culture system where crops are used to extract the nutrients from aquaculture discharge, optimizing the use of resources that would otherwise be deposited into the environment (Schuenhoff et al., 2003). The 'cleaned' water can then be returned to the fish tanks, reducing the need for freshwater input into the system.

Aquaponics systems maximize the use of land-space, while significantly reducing the impacts of both forms of culture on the environment through lower water and energy demands than traditional aquaculture (Frei & Becker, 2005; Mariscal-Lagarda et al., 2012; Nhan et al., 2006; Petrea et al., 2016). It contributes to sustainable agriculture and encourages food production in areas that are unsuitable for traditional agricultural practices, such as urban areas (Love et al., 2014; Petrea et al., 2016). This becomes especially relevant when considering the current cost and energy used to transport food globally.

In the U.S., the average meal travels roughly 2415 km from farm to plate. The fossil fuels used in the transportation of food contribute to greenhouse gas emission and, by extension, climate change. Additionally, the distance that food has to travel results in 25-40% of all agricultural products transported to the U.S. going bad before arriving at the intended destination (McIntosh & Pontius, 2017). The adaptability of aquaponics systems to urban areas makes it a suitable solution, as small units can be installed indoors in homes, or on rooftops and patios. There is growing interest in locally grown food in the U.S. and the rest of the world, the focus of which is aquaponics (Love et al., 2014). In Chicago, the 'FarmedHere' company operates an aquaponics system 15 minutes from the downtown area and is able to supply leafy green vegetables, basil and fish to nearby restaurants and markets (McIntosh & Pontius, 2017). In any culture system, species selection is important, especially for profitability. In aquaculture and aquaponics, the ability of a species to withstand crowded conditions and potential disease risks, and to breed in captivity, are all factors that need to be considered in species selection (Shapawi & Shakeh, 2015).

Aquaponics

Since the advent of aquaculture, tilapia has been farmed globally and has been accepted as a suitable substitute for marine fish species. It is also a sturdy fish that is relatively easy to culture, has favourable growth rates and seed production techniques are well established (Wohlfarth, 1994; Nandlal and Pickering, 2004). Many aquaculture farmers have explored the cultivation of fish alongside vegetable and other crops (Lightfoot, 1990).

The cost of setting up and running such a system is high, and thus deters potential entrepreneurs, particularly in small island states that lack the capital to invest in sophisticated installations (Love et al., 2014). The primary inputs in aquaponics systems are water, energy and fish feed, however, success in aquaponics also requires close and thorough monitoring systems and efficient production strategies (Petrea et al., 2016). The feed used for the fish remains as one of the most expensive inputs of the system (Kane, 1997), and by optimizing feed efficiency, cost can be reduced. It is important to make aquaponics more appealing by reducing the capital required.

The main input into an aquaponics systemis feed for the fish, since most other inputs are recycled. The fish feed is known to account for 30-60% of the operation cost of an aquaponics system (Pickering, 2009; Xavier et al., 2015), thus control of feed input leads to cost reduction in the operation (Xavier et al., 2015). Relevant decisions include the type and quantity of feed to best support the fish, as well as the crop being cultivated.

Water quality parameters and fluctuations in nutrient content of 'fish water' have been observed to impact crop growth rates, as well as the quality of the crop at harvest (Rakocy, Masser, & Losordo, 2006). The plant-essential nutrients in the water is derived from algae in the water, as well as the decomposition of fish waste and residual fish feed (Diver, 2000).Therefore, in order to successfully establish an efficient aquaponics system, it is necessary to understand the potential influences different fish feed regimes have on the overall output of the system.
Certain crops have been observed to thrive best in the presence (or absence) of particular nutrients; for example, lower concentrations of nitrates in substrate supports the growth of fruiting crops such as tomato, while lettuce and other leafy crops are most productive where nitrate levels are high (Trang, Schierup, & Brix, 2010). Control of nutrient concentrations highlights another key consideration in aquaponics systems: stocking density. Different plant species require varying amounts and composition of fish waste material, which determines the species and density of the crop to be used in the system (Lennard, 2004).

Another consideration in the cultivation of vegetables and small crops, whether using traditional media or soil-less techniques, is the importance of shelter for the crops. Greenhouses and other forms of shelter are known to protect crops from the elements, as well as from some pests (Myers, 2014). The incorporation of a greenhouse into an aquaponics system incurs an additional cost, so it is economically useful to determine whether it is in fact needed for a successful aquaponics system.

The plant and fish outputs from the aquaponics system also need to be monitored and understood. The crop component of an aquaponics system is potentially the most lucrative. Crops should be selected based on market demand, as well as productivity within such a system in order to optimize economic sustainability. Informed crop selection is now especially important, because the controlled environment created by an aquaponics system allows for the cultivation of an increasing number of species, including species of medicinal and cultural importance.

Similarly, fish species selection is important. The ability of a fish to be cultivated in a crowded pond or tank environment, with low infection and high growth rates is critical in its selection for aquaponics (Rakocy et al., 2006).

Overall, the risk associated with aquaponics is higher than that of traditional agriculture and aquaculture, and requires the attention of a diligent manager to make adjustments on a daily basis to avoid system collapse, and to be successful. There are many factors that influence the economic viability of an aquaponics system, including the design of the system, the feeding cycles, pest control and labour inputs (Petrea et al., 2016).

Science behind Aquaponics

The Nitrogen Cycle

The most important sub-system in successful aquaponics is the bio-filtration system (Tyson, Simonne, White, & Lamb, 2004), which treats and removes waste within the cultivation unit. Waste in aquaponics systems is mostly fish excrement. The primary composition of fish waste is urea, a form of ammonia (NH_3), but it also contains phosphorus and potassium (Llauradó et al., 2015). Ammonia is toxic to fish and therefore needs to be removed from the system in order for the fish to survive (Llauradó et al., 2015; Petrea et al., 2013; Tyson et al., 2004). In conventional aquaculture systems, a change of water would be required in order to deal with increasing levels of ammonia. However, in aquaponics, nitrifying bacteria associated with plant roots remove ammonia from the water before it is returned to the fish (Petrea et al., 2013; Tyson et al., 2004).

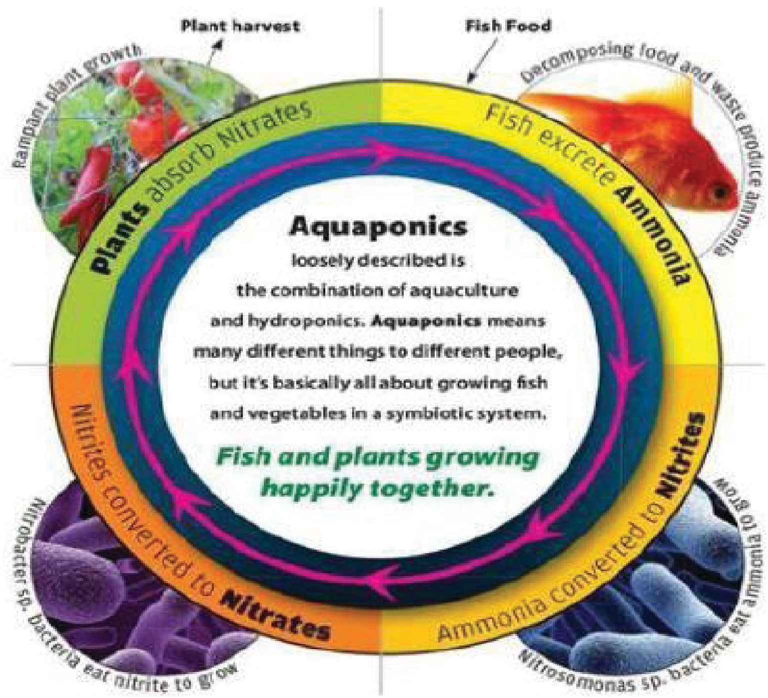

Figure 1. Nitrogen Cycle in Aquaponics

Source: (Llauradó et al., 2015)

The diagram above shows the nitrogen cycle within an aquaponics system. Fish, when fed, excrete ammonia-based waste, or urea. The concentration of ammonia in the waste depends heavily on the protein content of the feed provided to the fish. Bacteria from the genus *Nitrosomonas,* located in the water and on the media in the crop bed, convert the ammonia into nitrite (NO_2). The chemical formula of this conversion is:

$$55NH_4^+ + 5CO_2 + 76O_2 \longrightarrow C_5H_7NO_2 + 54NO_2^- + 52H_2O + 109H^+$$

Nitrites are also harmful to fish health and need to be converted into a form that is more easily absorbed by plants, namely nitrate (NO_3^-). This conversion is facilitated by bacteria known as Nitrobacter, which consume nitrites. The chemical formula of this conversion is:

$$400NO_2^- + 5CO_2 + NH_4^+ + 195O_2 + 2H_2O \rightarrow C_5H_7NO_2 + 400NO_3^- + H^+$$

The resulting nitrates are easily absorbed by plants and can also be tolerated by many species of fish at moderate concentrations, only becoming toxic when the concentration exceeds 400 ppm.

In total, nitrogen in the aquaponics cycle follows the Myers (2014) formula:

$$NH_3 + 1.5O_2 \rightarrow NO_2^- + H^+ + H_2O$$

$$NO_2^- + \frac{1}{2} O2 \rightarrow NO_3^-$$

$$\sum = NH_3 + 2O_2 \rightarrow NO_3^- + H^+ + H_2O$$

Ideal Parameters within Aquaponics

Although each crop and fish species used in aquaculture have their unique parameter preferences, there is a set range for each parameter within which the typical aquaponics system would function. It is important to keep each of the parameters within that range, not only because changes in these parameters affect the cultured species directly, but because changes in one parameter usually influence other parameters in the system, which then upset the balance and result in loss of fish and crops.

pH

pH is a measure of the ratio of hydrogen ions (H^+) to hydroxide ions (HO^-) present (Hancock, 2012). In aquaponics, it is important to maintain a pH of 6.8-7.2 (Kopsa, 2015), with 7.0 generally being ideal for plant nutrient uptake and nitrogen conversion (Hancock, 2012; Tyson et al., 2007). pH levels exceeding 7.0 in water can impact the conversion of nitrogen within the system, resulting in higher levels of ammonia, which is toxic to fish (Tyson et al., 2007).

Temperature

It is important to regulate temperature within a culture system, as sudden changes in temperature not only affect the metabolic and other cycles of the fish, but also the other physical parameters of the water in the system such as dissolved oxygen (Shapawi & Shakeh, 2015). The ideal temperature range for the typical aquaponics system is 18-30^{0}C, however the preferences of species varies (Shafeena, 2016). In the case of tilapia, temperature can range between 23-30^{0}C before the animals become stressed (Pickering et al., 2011).

Dissolved Oxygen (D.O)

Higher dissolved oxygen levels promote the health of all living components of aquaponics systems, however the typical aquaponics system should have a dissolved oxygen concentration of at least 5 mg/L (Shafeena, 2016). Bacterial activity is highest when dissolved oxygen levels are 67 mg/L (Rakocy et al., 2006).

Tilapia, due to their resilient nature, are able to survive in environments with dissolved oxygen levels as low as 0.1-0.5 mg/L for a limited time before they succumb to stress (Pickering et al., 2011), and can survive comfortably at dissolved oxygen levels >3 mg/L.

Nutrient levels

During the initial cycling of a typical tropical aquaponics system, which refers to the period during which the bacteria populations are allowed to populate the system, before the addition of fish or plants (Elia, Popa & Nicholae, 2014), the levels of ammonia (NH_4^+) and nitrites (NO_2^-) will be high, ranging from 2-4 ppm, and nitrate (NO_3^-) concentrations will be closer to zero (Kopsa, 2015). As bacterial populations in the system begin to establish, the ammonia and nitrite levels should drop and remain below 1 ppm, while nitrates should rise ideally to at least 80 ppm. In a mature system, ammonia or nitrite levels are <1 ppm (Shafeena, 2016). Higher values suggest that a problem exists in the system and that bacterial activity is low. Different fish species have variable tolerance for these nutrients. Tilapia is able to tolerate ammonia concentrations up to 4 ppm before becoming stressed.

Aquaponics Systems

System Design

There are three basic aquaponics system designs on which all models can be based. They are Deep Water Culture/ Floating Raft, Nutrient Film, and Media Bed systems (Kopsa, 2015; Llauradó et al., 2015). The Deep-Water Culture/ Floating Raft system is used widely in commercial or large-scale aquaponics systems (Llauradó et al., 2015), where crops are grown on a raft with their roots being continuously submerged in water pumped from the fish tanks, which contains nitrogenous waste (Fox et al., 2012). The Nutrient Film system, though used in aquaponics, is more popular in hydroponics systems, and tends to work well with leafy vegetative crops (Llauradó et al., 2015). This Nutrient Film design is similar to the Floating Raft system, where crops are grown in PVC pipes and a constant flow of 'fish water' submerges the roots. The Media Bed system requires a substrate for crop cultivation through which there may be a continuous flow of 'fish water,' or a flood-drain procedure (Fox, Howerton, & Tamaru, 2010; Llauradó et al., 2015). Of the three designs, the Continuous Flow or Nutrient Film system is known to be the simplest and most reliable system (Llauradó et al., 2015), and so will be used in this project.

Components of the Media Bed Aquaponics System

The diagram below illustrates a simple representation of a Media Bed aquaponics system.

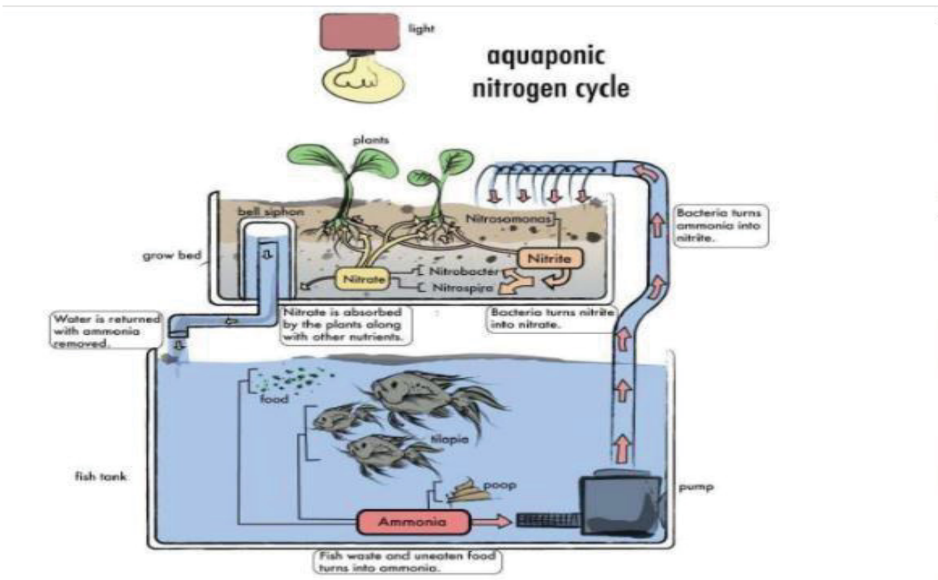

Figure 2. Basic illustration of Media Bed Aquaponics System

Source: (Llaurdo et al., 2015)

Light Source

For an aquaponics system to be efficient, all components need to be functioning optimally. Fish need to be fed in order to produce waste material to nourish crops, and bacterial colonies need to be thriving to break down the waste material from the fish into forms available for plant use. The crops also need to be healthy,to allow for adequate detoxifying of the water being returned to the fish tank. Healthy plant growth requires active photosynthesis, for which light is a key component.
This, therefore, makes adequate lighting a critical component of any aquaponics system. Light may be from natural (sun), or artificial sources. In this project, since the location is in on a tropical island, the sun provides an adequate and reliable light source.

Fish Tank

The fish tank is where the fish component of the aquaponics system is housed. This tank may take the form of an aquarium, a plastic water tank, or even a pond.

Water Pump

The water pump is used to supply the crops with water containing fish waste. It is an element in every type of aquaponics system. The size of the pump determines the rate at which water is pumped out of the fish tank. It is important to ensure that the water removed does not exceed the water being returned to the fish tank, so that water levels in the tank are not compromised, thereby threatening the health of the fish.

Substrate

The substrate in the media bed serves a dual purpose in providing support for the crops, as well as surface area for the proliferation of the essential bacteria required for successful aquaponics (Fox et al., 2010). The material can be either gravel, clay balls or cinder rock. This project will utilize gravel as a substrate, as it is locally the most readily available of the options.

The Bell Siphon

As previously mentioned in the description of Media Bed system, there may be either a continuous water flow or an ebb and flow water system employed. In the continuous water flow systems, 'fish water' is pumped continuously to the media grow-bed. This water flows through the grow bed and is returned to the fish tank. This is an ongoing process which requires the continuous use of pumps. In the ebb and flow system, also called the flood and drain system, the media bed is flooded with 'fish water' either continuously or at various intervals, and then the water is allowed to drain back to the fish tank before the next flooding occurs. In such a system, pumps may only be turned on during periods of flooding, resulting in more efficient energy use and lower costs.

As this project sought to find the most cost-effective means of aquaponics production, the ebb and flow method was used.

In ebb and flow aquaponics, the draining of the media bed can be controlled either by electronic timers, or by the use of non-electronic siphons. In order to minimize costs, a siphon component will be used in this project. Different types of siphons exist, but the simplest is known as a bell siphon (Fox et al., 2010), and was the type used in this project.

The bell siphon was developed by two scientists, Martinez and Hallam (Foskett, 2015). Siphons require the formation of a vacuum in order to initiate water flow, and thus activate when water levels drop and create the necessary low pressure.

Components of a Bell Siphon

The diagram below shows a bell siphon design.

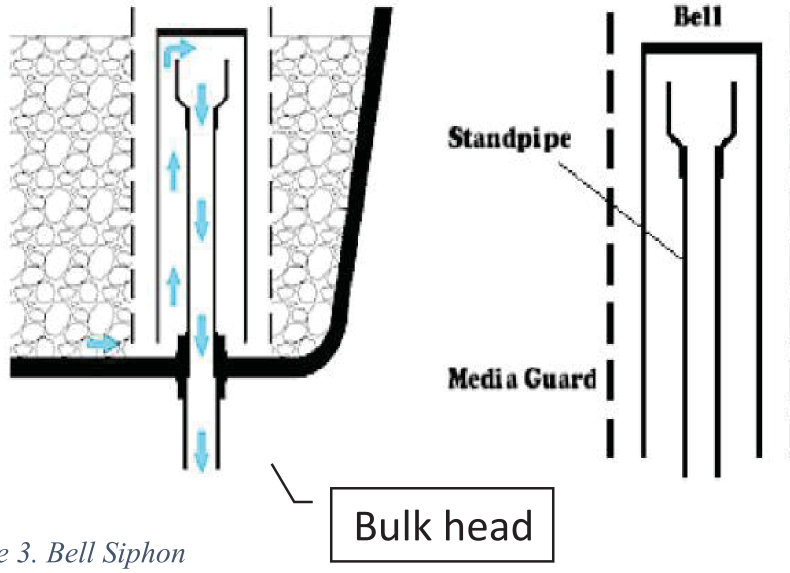

Figure 3. Bell Siphon

Source: (Hancock, 2012)

The bell siphon has four main components: a bulk head, a vertical stand pipe, a drain pipe and a bell pipe (Bruno et al.; Fox et al., 2010; Llauradó et al., 2015). The drain pipe is a horizontal attachment that allows water to flow from the media bed back to the fish tank. The bulkhead is a watertight fitting at the bottom of the media bed, to which the drain pipe and vertical stand pipe are attached. The vertical stand pipe regulates the level of water in the media bed by allowing water exceeding a stipulated height to overflow and return immediately to the fish tank via the drain pipe. The bell pipe is also a vertical pipe, generally twice the diameter of the vertical stand pipe, and has a sealed cap on the top end, to facilitate the siphon process. The bottom end of the bell pipe has notches cut into it and is placed over the stand pipe.

How the Bell Siphon Works

Water is pumped into the media bed from the fish tank. As the water level rises, water passes between the notches at the base of the bell pipe and fills the space between the bell and vertical stand pipes. When the water level exceeds the height of the stand pipe, water begins to drain and creates a vacuum in the empty space. The water drains back into the fish tank via the drain pipe until the water level drops below the notches in the bell pipe. At this point, air enters the pipes and interrupts the flow of water in the siphon, allowing the grow bed to be flooded again. This cycle can take hours to complete, allowing the roots of the crops to be exposed to air for adequate oxygen supply. The size of the siphon determines the rate at which water is returned to the fish tank, and so must be proportional to the size of the system as well as the desired flow rate of water (Bruno et al.; Fox et al., 2010; Kopsa, 2015).

Species Selection

Fish

Tilapia belongs to the cichlid family of fish from Africa, and originates from the Nile valley. Humans have expanded the species' distribution globally due to its suitability for aquaculture. Tilapia is a low maintenance fish, requiring little management and input, and is sometimes referred to as 'aquatic chicken' due to their hardiness as a species, broad diet range and ease of breeding (Nandlal & Pickering, 2004). In the wild, these fish feed on plankton, detritus, benthic organisms, small fish and aquatic plants. In captivity, acceptable diets include powdered mash or pellets.

Tilapia have a high reproductive rate, exhibit rapid growth and are resilient against diseases and infection. Due to their hardy nature, tilapia and other cichlids can be quite invasive when they enter the wild (Martin et al., 2010). Consequently, it is not recommended to introduce them into natural habitats, as they have now become problematic in many countries globally (Russel et al., 2012). Although their rapid reproductive rate is a selling point for the selection of tilapia as a culture species, it also spawns one of their less preferred traits: uncontrolled inbreeding. This can, however, be managed by proper stock control, for example harvesting entire ponds or tanks before restocking (Nandlal and Pickering, 2004b).

The Nile tilapia, *Oreochromis niloticus,* is commonly used in aquaculture (Ponia, 2010), and was also employed in this project. TheGenetically Improved Farmed Tilapia (GIFT) strain of the Nile tilapia can be identified by dark colour bands on the caudal fins and either grey or pink pigmentation on the throat of mature males. Generally, the males are larger than the females, and the sexes are easily distinguishable, with the males having two external genital openings, while the females have three (Nandlal and Pickering, 2004a). In Fiji, the commercial tilapia feed sold by Pacific Feeds Ltd contains roughly 20% protein. (Kane, 1997; Pickering et al., 2011).

Crop

Reports on aquaponics systems suggest that tilapia pairs well with many vegetable plants such as tomato, cucumber and lettuce, and culinary herbs such as basil (Knaus &Palm, 2017; Saha, Monroe, & Day, 2016). Culinary herbs have been identified as the best choice for aquaponics production, since they produce the highest income per unit area (Knaus &Palm, 2017). Basil is even reported to show better growth rates in soilless culture such as in aquaponics systems, than in conventional agriculture (Saha et al., 2016). This was considered in the crop selection for the project.

Lettuce is another popular crop used in aquaponics systems and was also selected for this project. The growth period for lettuce is 3 to 4 weeks, which makes it highly suitable for aquaponics, where crops with quick turn over rates are preferred (Rakocy et al., 2006). Also, the majority of the resulting plant is edible, while nutrient demand is low, making lettuce and other vegetative crops more desirable that fruiting plants for aquaponics production (Rakocy et al., 2006).

Pest Control

Pests pose a major threat to agricultural productivity around the world. In the tropics, 20-30% of damage to grains is a result of pests (Nakakita, Takahashi, Sugiyama, Shigyo, & Shinotsuka, 1998). Pests can be microorganisms (viruses, bacteria or fungi), nematodes (worms), arthropods (insects), and vertebrates (birds, rodents, etc.).

The varieties of pests that exist make their control particularly challenging. Among different control mechanisms currently implemented, synthetic chemical pesticides have proven to be among the most effective against their target pest. These pesticides, however, leave residues that enter the natural environment, especially water systems, and have severe implications (Ven & Jim, 2003). The residue also remains on the crop and is consumed. Many human illnesses have been associated with not only the consumption of pesticides, but also inhalation during the application by farmers (Kolankaya, 2009; Ven & Jim, 2003).

Strides have been made to develop natural means of pest control. Integrated pest management is a popular strategy where 'natural enemies' of pests are integrated into an agricultural system (Parolin et al., 2012; Song, Jiao, Tang, & Yao, 2014). These may take the form of companion plants that provide shelter, nitrogen fixing benefits, or biochemical pest suppressors or repellents. They can also be barrier plants that act as physical blockades between the crops and their associated pests (Parolin et al., 2012). The use of natural enemies is often transferable between regions, and has proven to be an effective agricultural technique in the Caribbean and southwest Nigeria (Browning, 1992; Okunlola, 2009).

Pests affect all crops, whether they are grown in soil or water. Aquaponics systems are possibly more vulnerable to pests than traditional agriculture, because synthetic chemical and even high concentrations of some natural pesticides are detrimental to the fish system,and so cannot be used. It is therefore important to have an understanding of safe, natural pest management strategies that will keep all aspects of the system healthy.

In Fiji, there is a host of agricultural pests. TheSPCas effectively created a database of existing pests, and the crops they target (Vernon, 2003) called the Pacific Islands Pest List Database (PLD). This database was created primarily for trade purposes, but also helps developing farmers to establish management strategies and be proactive in pest control and prevention, rather than post-infection treatment. This leads to higher yields and a more effective farm.

The crops of interest for cultivation in this project were lettuce (*Lactuca sativa*), sweet basil (*Ocimum basilicum*), and grosse lisse tomato (*Solanum lycopersicum).* According to the PLD the pests that have been associated with lettuce are fungi (*Sclerotina sclerotorium* and *Septoria lactucae*), nematodes (*Meloidogne incognita* and *Rotylenchus reniformis*) and arthropods (*Nezara viridula*) (Vernon, 2003). The same database lists insects as the major pests for tomato in Fiji: moths *Agrotis ipsilon, Eudocima fullonia,* and *Helicoverpa armigera* and bugs *Brachylybas variegatus* and *Howardia biclavis* (Vernon, 2003). There was no listing of pests for sweet basil in Fiji. Given the repellent properties of neem oil to microorganisms and general pests, it was applied as a treatment to protect the crops being cultivated, and to maximize the profitability of the aquaponics system.

Plant Shelter

Roofing or sheltering of crops has been seen to enhance agricultural production and is commonly found in traditional soil based production, as well as hydroponics and aquaponics. Farmers have reported shortening of growth cycles, and a reduction in water use when crops are grown in a sheltered area rather than being left exposed (Vollebregt, 2002). The lower demand for water is the result of the protection from wind that the shelter provides (Rogoyski, Pearson, Kelsey, & Wilhelm, 2004), limiting transpiration rates. Covering of crops has also been seen to increase the productivity due to light diffusion by roofing material (Hemming, Dueck, Janse, & van Noort, 2007). Additionally, sheltering is known to help control the incidence of pests, particularly arthropods, as the introduction of greenhouses to agricultural production has seen among its benefits, a reduction in pesticide use (Campen & Kempkes, 2009).

A notable disadvantage to the use of a shelter is the cost associated with construction (Rogoyski et al., 2004). Given that the primary objective of the system described in this study is to be low cost, the need for a shelter for effective operation of the prototype in Suva will be tested and reported.

RESEARCH METHODOLOGY

In keeping with the objectives of this project, the factors considered were:

- Fish growth: This refers to the rate at which the fish grow within a standard 6-month aquaculture fish cycle. This was determined by measuring the weight of the fish at the commencement and termination of a standard growth cycle, and standardizing the change by a given unit of time.

Values were then compared against the feed input to determine the Feed Conversion Ratio (FCR).

- Plant growth: This refers to the rate at which the crops grow on a weekly basis. The height of the individual plants was recorded and growth rates were determined. Alternatively, the weight of the plants was determined upon harvest. Comparisons were made based on crop treatments in a covered or uncovered system.
- Profit: This refers to the ability of the system to produce sufficient crops and fish to make up the capital invested into the system as well as cover the running costs, and further provide additional income that can either be re-invested into the system, or into other ventures.

This project is pre-experimental in nature. It entailed the development of new technology using the One-Shot Case Study sub-strategy, which has been described by DePoy and Gitlin (2009) as an experiment involving the introduction of an independent variable and the subsequent measuring of a dependent outcome.This project sought to compare the success of the aquaponics system with or without a roof over the grow bed areas. Consequently, the data collected was primarily observational, with detailed records kept for further statistical analysis.

Most parameters of the system were pre-determined by industry-standard recommendations (Rakocy, Masser and Losordo, 2006). The stocking density of the fish tank was determined based on feed requirements for the system, which is a function of the area of the plant grow bed, as well as the appropriate level of oxygen for the volume of the fish tank. The density of the crops in the grow bed was determined by the crop type and the standard planting density for that crop.

Low-Cost Aquaponics System

The system, as previously mentioned, was designed by Wilson Lennard (PhD), who provided schematics detailing its dimensions and layout. The uniqueness of this aquaponics unit lies in its simple design, which eliminates the components of typical aquaponics systems that are used to process fish waste, and reduces the cost of building the system.

Following standard recommendations published by Lennard (2004) (Appendix 1), the system used in this project was designed to culture 25-30kg of tilapia, which consume approximately 400-450g of feed daily, in order to support vegetable crops such as lettuce at a density of approximately 25 plants per m^2, with a feed to grow bed area ratio of 45g per square meter daily. Water is pumped at the rate of approximately 1000L per hour from the fish tank to the grow beds to optimize the bio-filtration process. A 'slow fill, rapid drain' mechanism was employed and facilitated by the use of a bell siphon. The system also required that there is constant aeration provided to the fish tank, ideally at 100% oxygen saturation of water via the installation of electrically-powered aerators.

Construction of an Aquaponics System

Site Selection and Preparation

Factors to be considered when selecting a site for this aquaponics system include:

- access to electricity and water supply.
- accessibility by vehicle to minimize labour.
- flat and level ground
- proximity to proper supervision, in case of system malfunction.

In the current study, an area of land large enough to accommodate the system was selected at Homes of Hope (located is Wailokua, Suva, Fiji), and was outfitted with an electrical outlet. In following the system design, a hole was dug in order to place the water tank at the lowest level of the system (Figure 4). The hole was approximately 1.5m deep.

Figure 4. Preparation of area for aquaponics system by digging a hole for the water tank and levelling the grow bed area.

The soil removed from the hole was used to level the area for the grow bed. Since the system is designed for the grow bed to drain by gravity into the fish tank, the grow bed area was angled at a 5° slope towards the tank. In order to achieve the slope, pegs were placed at the four corners of the grow bed area with string connecting the pegs, forming a rectangle at ground level.

A spirit level was then placed on the line in order to determine the slope of the string. Soil was added or removed by the use of shovels and then compacted using logs. This was done until the strings running along the length of the grow bed demonstrated a 5° downward slope towards the tank, while the strings running across the grow bed were level (Figure 3).

Building materials were obtained from Rotomould Fiji Ltd., RC Manubhai & Co. Ltd., Vinod Patel Co. Ltd., Kasabias Ltd., Marco Polo Holdings Ltd., and Suva Pet Shop (see Table 4 in Appendix 1 for quantities used and costs involved).

Construction of Aquaponics Components

Grow Bed Construction

Figure 5. Timber being cut to requisite lengths using power saw

The grow bed was built to parameters set by Lennard (2004), with a frame 300mm high, 1950mm wide and 4800mm long, and secured in place using 3-inch screws, with 3 screws being used per board in the four corners of the frame. Boards were first laid out in order, to finalize the positioning of the grow bed in situ (Figure 6). Then the boards were stacked and secured with nails.

Figure 6. Images highlighting the stages of constructing the frame for the grow bed

Installation of fish tank component

Once the frame for the grow bed was in place, a 5000L tank was placed in the previously prepared hole, and fitted firmly in place by filling in the space around the tank with previously extracted soil. On the top of the tank, one of the flat surfaces was cut to create a manhole to allow access to the tank during installation of plumbing, fish stocking and feeding, and to carry out general observations without leaving it entirely uncovered. The section that was cut out was used to make a door for the opening (Figure 7).

Figure 7. Door to access the tank with cable tie hinges

Once the frame for the grow bed was in its intended location, the position of the drain pipes from each of the two grow bed sections to the fish tank was determined. It was arbitrarily decided that the drain pipe in either grow bed section would be located approximately 305mm (1ft) from the centre dividing board, and the same distance from the edge of the grow bed closest to the fish tank. With those positions marked using pegs, the grow bed frame was removed, and trenches were dug from that location to the fish tank.

These drains were approximately 150mm deep, in order to accommodate PVC fittings under the grow bed. Once the trenches were complete, lengths of 50mm pressure pipes were cut to match the distance from the drain pipe outlet to a point approximately 6 inches inside the fish tank. A hole saw was used to make 50mm holes into the side of the fish tank, where the drain pipes would enter the tank based on the trenches prepared. The 50mm pressure elbow fittings were connected to the ends of these pipes and laid into the trenches (Figure 8).

Figure 8. Digging of trenches for drain pipes and subsequent installation of the drain pipes

After the plumbing was laid, the frame for the grow bed was returned to its position, maintaining the distances between the drain pipe outlets, and both the centre dividing board and the edge of the grow bed.

A woven plastic liner was then laid out over the frame to form the base of the grow bed, after ensuring that there were no sharp objects or stones which could puncture the plastic. Plastic is used to ensure that no water is able to seep into the environment and the system remains closed, thus reducing the need for continuous input of water. The plastic was carefully spread into all corners without being pulled too tightly on the sides, to ensure that it did not become strained when the gravel bed substrate was eventually added.

The plastic was secured by pressing the edges of the material between the frame and scraps of wood, which were then nailed onto the outside of the grow bed frame, in order to keep the liner in place. A sharp knife was used to cut a hole in the plastic over the drain pipe plumbing. A rubber washer was placed around the mouth of the 50mm elbow and the plastic liner was sealed on using silicone sealant.

Figure 9. Grow bed frame lined with plastic and secured with wood trimmings, with holes cut out at the drain pipe

A second rubber washer was placed on the upper surface of the plastic, and then a 25mm to 50mm converter PVC fitting was placed on the 50mm elbow connected to the drain pipes in both of the grow bed sections. These washers and silicone were used to secure the fitting, and to ensure that no water was able to leak from these openings in the plastic liner or the PVC connections. The 25mm PVC pressure pipe was then cut to a length of 177mm, as stipulated in the schematics provided by Lennard (Lennard & Leonard, 2004; Appendix I), and placed into the connectors in the drain pipes. The bell siphon was then constructed and placed over the 25mm stand pipe.

The bell siphon was made using 80mm PVC pressure pipe. The pipe was cut to 192mm and a drill was used to cut 20mm holes along one end of the pipe. On the other end of the pipe, an 80mm end cap was affixed using PVC glue. In order to support the siphon, a 5mm hole was drilled into the cap of the siphon and a small rubber hose of the same diameter was placed 2 inches inside the cap and sealed with silicone sealant. The end of the hose was fastened to the bottom of the bell using cable ties, just above the 20mm holes. This is to ensure that air gets into the siphon to stop water flow.

Figure 10. Bell siphon with rubber tubing to be places over standpipes

Once the bell siphons were in place, gravel guards were needed to keep the gravel from obstructing the flow of water up between the bell and the stand pipe. PVC pipes of 150mm diameter could be used, however, in an effort to reduce the cost of building material, the bases of two small plastic buckets were removed and 5mm diameter holes were drilled into them to allow the free flow of water. These were then placed around the bell siphon and drain pipe structures. Once all plumbing elements were in place, gravel was added to the grow bed.

Figure 11. Bell siphons and gravel guard in place and gravel being added to the grow bed

Other Plumbing

The grow bed water delivery pipes were then installed. Ideally, the system was designed to operate with one pump located at the entry of the fish tank, cycling water at a rate of 1000L/hr at a height of 1.5 metres to the grow bed, via a single delivery pipe. However, since large submersible pumps of that capacity were very costly, two smaller aquarium pumps with a flow rate of approximately 500L/hr at 1.5 metres height were substituted, and one was used per grow bed section. Therefore, two bed water delivery pipes were required from the fish tank. The pipes were installed to run along the right side of either grow bed. The drill was used to make 25mm holes in the tank at a height of 1.5 meters, and pipes were cut to match the distance from the furthermost edge of the grow bed, to the centre of the tank. Those lengths varied because of the positioning of the pipes. Inside the tank, 25mm elbows were placed on the ends of the pipes, and other pipes measuring approximately 1.5 metres were attached to the elbows. In order to connect the water pumps to the 25mm pipes, 25mm end caps were used. Holes were drilled into the end caps to match the diameter of the outlet on the water pumps. The end caps were then secured to the water pumps using PVC glue before being attached to the delivery pipes.

Along the length of the delivery pipe, 6mm holes were drilled at 400mm intervals to evenly distribute water along the entire length of the grow bed. Since water pressure was not very high in the delivery pipes, clips were made to regulate the amount of flow through each of the holes to ensure that water reached the end of the pipe. These clips were made by cutting 25mm pipe into rings and cutting out portions of the ring in order to open the clip and secure it to the pipe, so that the clips could then be slid along the pipe and adjusted as needed. This is seen in the picture below.

Figure 12. Picture showing the cutting of clips from 25mm PVC

Shelter

To observe the importance of covering aquaponics crops, a roof was constructed over half of each grow bed, while the other half of each remained uncovered. The shelter consisted of clear woven plastic mounted on PVC pipes. Firstly, rebar was cut into 500mm lengths and placed at the grow bed corners closest to the tank, then 1.25

metres along the bed and finally at 2.5 metres. The roof was shaped as a semi-circle, with the diameter being the width of the two grow beds, which is approximately 2 metres, and a roof height of 1 metre. Three pieces of 15mm PVC pressure pipe were cut in 3 metre lengths and looped over the rebar across the grow bed. To install a lock channel (necessary to secure the roofing plastic), blocks of wood measuring approximately 60mm in width were nailed onto the side of the grow bed (Figure 13). One block was placed to the left of each of the PVC hoops and secured using flat headed nails measuring approximately 3inches in length.

Figure 13. Blocks of wood to be used to mount the lock channel

The lock channels were then screwed onto the wooden blocks on either side of the grow bed using a power drill.

Figure 14. Screwing of lock channel onto the wooden blocks along the grow bed

The plastic was then spread over the PVC hoops and secured using lock wire. PVC clips similar to those on the water delivery pipes held the plastic on the PVC hoops. Aphid mesh screen doors were also installed on either end of the roof. Large pieces of the aphid mesh were cut into semi-circles to fit the openings and were affixed to the PVC hoops on the end using the PVC clips made from the pipe. This can be seen in Figure 15 below.

Figure 15. Roof and aphid screen doors installed on lower half of the grow bed

Once all the system components were in place, a hose pipe was used to fill the tank up to a height of 1.5 metres, with approximately 2000L of water. In order to ensure that the water in the tank never exceeded the desired level, an overflow hole measuring 25mm was made using a hole drill just above the water line. The water pumps were then turned on and the system cycling began. Once the gravel dust settled to the bottom of the grow bed and the water became clear again, the system was ready for fish to be added.

Cycling of the Aquaponics System

Fish stocking

In order to commence cycling, the first step was to add fish to the tank. Extreme care was taken with the transport and transferral of fish in order to minimize death by stress. For this project, it was decided that fish of various sizes would be stocked in the system, in order to stagger fish harvests over the entire project duration. Fish were acquired from a fish pond located on the Homes of Hope compound using a seine net (Figure 16).

Two persons on either side of the pond dragged the net through the length of the pond, and a third person walked half way between to ensure that the net remained on the bottom surface of the pond to maximize fish catch. Fish were organized into size categories of under 50g, 50-100g, and 100-150g. Roughly 60 fish within each size class were selected and placed in waiting buckets of pond water as quickly and carefully as possible.

Approximately 200 fish, collectively 13 kg, were selected and placed into the buckets at a concentration of 20 to 25 fish per bucket. Although only 60 fish within each size class were needed, extra individuals were taken to cater for mortality, which was likely to occur as a result of transportation stress. Fish were then promptly transferred to the prototype system's fish tank, located about five minutes away, by vehicle.

Figure 16. The catching of fish from the Homes of Hope fish pond for the aquaponics system

At the project site, an acclimatization tank made up of 50% tank water and 50% pond water was prepared and electrical aerators were installed. The fish were transferred from the buckets to the acclimatization tank, where they were left for 30 minutes. After the acclimatization period, the fish were individually removed by using a scoop net, weighed and transferred to the fish tank, along with the electrical aerators at the project site. The fish were then observed closely over the next 48 hours and those that died were removed using a scoop net and discarded. The total biomass of fish stockedin the tank was 13kg. Using the same procedure, another 5kg of fish were added to the tank two weeks after this initial stocking.

Water Testing

Two days after the first fish were stocked, water testing commenced for pH, ammonia, nitrite and nitrate levels. This was done using the API Freshwater Master Test Kit (Mars Fishcare) according to the manufacturer's instructions. The water test kit uses a basic titration method, where a set number of drops of reagents are added to a predetermined amount of sample water from the system, and left for a period of time to develop a colour change. This was then compared against a colour scale chart in order to determine water parameter levels.

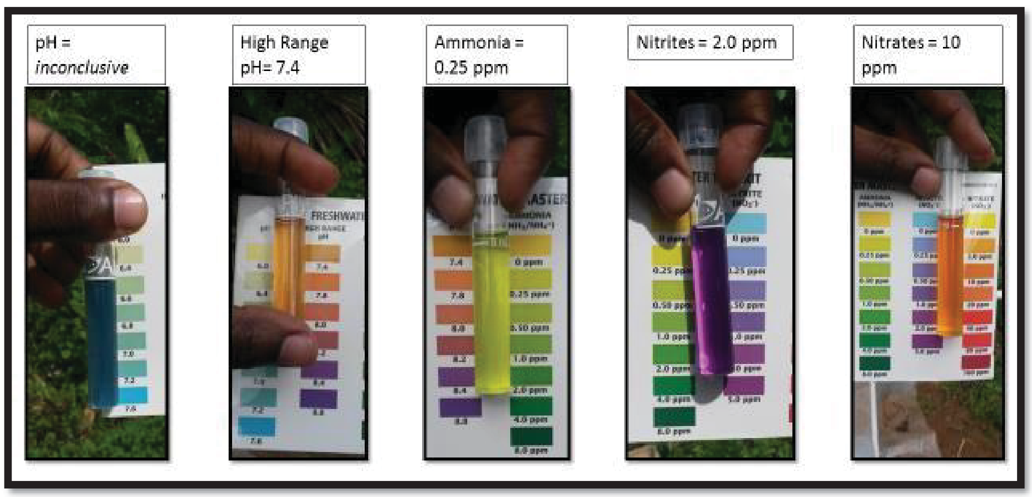

Figure 17. Tests conducted for the water quality parameters

When the nitrite and ammonia levels had dropped to zero, fish feed was slowly added to the system. The fish were initially fed an arbitrary amount of 50g daily for a week. The feed rations were increased by 50g weekly until fish were fed 400g daily, based on the system design specification. This feeding rate was then kept constant, while water quality was closely monitored every other day during the system cycling period. Dissolved oxygen and temperature were also monitored using a Yellow Springs Instrument (YSI) Pro20i Dissolved Oxygen meter and a Pentair Rainbow Sinking thermometer (Poolsmith Inc) respectively.

Plant Nursery

Seedling trays and potting mix were acquired from Hop Tiy & Co Ltd, in Suva. *Lactuca sativa* (Green Mignonette, Buttercrunch and Box Hill lettuce varieties), *Solanum lycopersicum* (Grosse Lisse tomato)and *Ocimum basilicum* (Sweet basil) Yates Australia seeds were planted and watered daily. After two months, once the fish had become settled, the seedlings were transferred to the grow beds (Figure 20). The height of the basil and weight of the lettuce seedlings were recorded before transplanting. The first seedlings transplanted in the system were two months old because of the cycling period of the system. Other seedlings were 3-4 weeks old at the time of transplanting. Tomato and chili seeds were also planted during the course of the project. Strawberry plants were obtained on site from another aquaponics unit for trial in the system.

Figure 18. Planting of seedling and subsequent transferring of seedling into the grow bed

Operation of Aquaponics System

Fish Component

In order to run the system, the fish were fed twice daily, in the morning and afternoon. Fish feed was obtained from the Pacific Feeds Limited, Laucala Beach, Fiji. The Pacific Tilapia Pellets, where were used in this project, is designed for tilapia at any stage in the grow-out cycle, containing 16.5% crude protein[1]. Fish behaviour was

[1]http://www.pacificfeeds.com/pacific-tilapia-pellets.html

observed to determine whether the conditions in the tank were suitable. If fish were observed to be gasping at the surface (hypoxia), feeding was ceased until the fish behaviour returned to normal.

Water quality parameters were monitored 2-3 times a week, and daily if fish behaviour suggested that there was a problem. If ammonia or nitrite levels increased above 2.0ppm, a fish tank water exchange was conducted, where 30-50% of the water in the fish tank was drained, and replaced by fresh water. If pH levels exceeded 7.2, NOW Calcium Carbonate buffer was added in the amount of 1 teaspoon dissolved in a litre of water per grow bed daily, until pH levels returned to within a 6.6-7.2 range. At the end of a 6-month growth cycle, the fish were removed from the tank using a cast net and transferred to a smaller tank filled with tank water. They were then individually weighed and returned to the fish tank. In a typical production setting, the fish would have been harvested for sale at this point and replaced with a new cohort. However, for this project, the same fish were used, and their growth rates monitored for the duration of two cycles.

Plant Component

Once transplanted, 3 to 4-week-oldseedlings were expected to spend approximately 4 weeks in the grow bed. In order to efficiently replace plants in the grow beds after harvest, new seeds were planted in the trays promptly after out-planting.
All seedlings in the grow bed were closely monitored. The seedlings were sprayed weekly with a mixture of neem oil and water in order to deter pests. If signs of pests were observed, such as holes in leaves, the plants were then treated with a mixture of liquid detergent, water and neem oil. Yellowing in the leaves was treated with the topical application ofYates iron chelate solution via a spray bottle. Once the crops had grown to market size and were ready for harvest, garden shears were used to cut basil stalks, lettuce heads were uprooted from the grow bed, and tomatoes were picked from the plants. The harvested crops were then weighed using a kitchen scale.

In addition to the crops, general maintenance in the grow bed area was required. With respect to plumbing, the holes in the water delivery pipes would become clogged with sludge from the fish tank and had to be cleaned periodically. Also, weeds that managed to take root in the system were removed on a weekly basis.

Where pest control was concerned, this experiment contained four treatments, numbered 1-4. Treatment 1 was where plants were both sheltered and treated with neem solution. Treatment 2 was there sheltered plants were not treated with neem. Treatment 3 was the treatment where plants were not sheltered, but were treated with neem. Treatment 4 was the control group where crops were neither sheltered nor treated with neem solution. The neem solution used in this project was made by combining equal parts of neem oil and water in a spray bottle, and applying topically to leaves.

Data Collection

From the start of the construction process, proper documentation was required in order to compile a simple guide for building and running the system. The cost of all items used in the system was noted. Pictures were also taken where possible, in order to illustrate the construction procedure.

When the initial nutrient cycling of the system commenced, water quality parameters were measured and noted. The project site was visited at least twice weekly, and observations as well as maintenance procedures were noted. When conditions were not ideal, and fish needed to be monitored more closely, the project site was visited daily until the crisis was averted. Fish weights were noted when stocked and when subsequently sampled. The quantity and weight of all crops harvested from the grow bed were noted and the market price at the time of harvest was also recorded. The heights of plants were measured and noted during the grow-out period, where possible. Special attention was also paid to the differences that existed between the two grow beds in the system, such as the rate at which water flowed into each bed. As it relates to pest control, signs of pest or disease were observed and noted. These signs included holes in leaves, shrivelled or abnormal leaves and discoloration or spots on leaves. The number of infected plants under each of the pre-described treatments was noted for basil and lettuce plants, as those were the only two crops under the 4 pest control treatments. Plants were also observed for influences from the weather (wind, rain, etc.) in the form of leaning in grow bed. As with all other observations, there were noted for further analysis.

Data Analysis

Microsoft Excel

Firstly, the construction materials and their costs were compiled in an Excel spreadsheet, as a reliable way to keep track of the expenses during system set-up. Once the system was constructed, the materials needed to operate the system for the duration of the project were also noted in Excel. These spreadsheets were then used to monitor the economic status of the system by totalling costs incurred, as well as the revenue that could be earned if products were sold.

The data collected throughout the project, such as water quality parameters, plant height and weight, and fish weights were all also recorded in Excel spreadsheets. Once the data were compiled, it was possible to calculate yield averages, growth rates of each species, and to also observe trends in the data. Trends in water quality parameters and other physical measurements were then compared against growth rates, and further analyses conducted to determine whether water quality parameters had direct impacts on the productivity of the crops.

Microsoft Excel was also used to develop a model to assess the aquaponics system. The model took into account the fish tank and grow bed area and stocking density, the yield from the two components, the capital and running costs, the market prices of the produce obtained and an overall assessment of the economic productivity of the system.

IBM SPSS

More comprehensive statistical analyses of certain test variables were successfully investigated using IBM SPSS Statistics version 23 (George & Mallery, 2016).

Independent –samples t-tests were conducted to compare:

1. Plant harvest weights in the grow bed with the higher water flow rate and the grow bed with the lower water flow rate.

H_0: There is no significant difference in the harvest weight of crops in the two growbeds.

2. Basil harvests in rainy and dry season.

H_0: There is no significant difference in the harvest weight of basil in the wet and dry season.

3. Lettuce (sp.) harvests in rainy and dry season.

H_0: There is no significant difference in the harvest weight of lettuce in the wet and dry season.

4. Lettuce harvests in sheltered and unsheltered portions of the growbeds.

H_0: There is no significant difference in the harvest of lettuce in the sheltered and unsheltered portions of the grow bed.

5. Basil harvests in sheltered and unsheltered portions of the grow beds.

H_0: There is no significant difference in the harvest of basil in the sheltered and unsheltered portions of the grow bed.

6. Effects of weather (rainfall and wind) on crops that were sheltered and unsheltered.

H_0: There is no significant difference in the impact of weather on crops.

One-way between-subjectsANOVA tests wereconducted to compare

1. The harvest weights of three varieties of lettuce (sp.) in the aquaponics system.

H_0: There is no significant difference in the harvest weights of the three varieties of lettuce sp.

2. The biomass of tilapia at three time intervals: the start of the study period, after 5 months and at the end of the study period.

H_0: There is no significant difference in the biomass of fish at the three time intervals.

3. The effects of neem treatments on plants in sheltered and unsheltered portions of the grow beds.

H_0: There is no significant difference in the occurrence of pests on plants under different treatments.

A Pearson correlation coefficient was computed to assess the relationship between the levels or nitrates and dissolved oxygen in the fish tank.
H_0: There is no significant relationship between dissolved oxygen and nitrate levels in the aquaponics system.

RESULTS

System Construction

The first objective of this project was to effectively construct the low-budget system as designed by Wilson Lennard, who was a co-supervisor on this project. This project ran from May 2016 to May 2017, with the first 3 months used for acquiring building material and constructing the prototype. The system without the roof component was constructed within a month of acquiring the building materials. Operation of the system was commenced by turning on the water pumps and allowing the water to cycle through the system, and observations were made. After a week, fish were stocked in the tank and plants in the grow bed. Roughly four months after the system had been constructed and operation commenced, the roof component was installed over a 2- day period. The performance of the system was observed until the end of the study period. The pictures below show the components of the constructed aquaponics system.

Figure 19. Grow bed area after the roof was installed, showing crops under the shade

Figure 20. The entire grow bed area of the aquaponics system, showing both the shaded and unshaded sections

Figure 21. The fish tank and the plumbing connecting it to the grow bed area.

System Productivity

The second objective was to test the ability of the system to grow the desired crops, and fine-tune it as necessary. Firstly, the water quality parameters measured during the study period were assessed.

Water Quality Parameters

pH

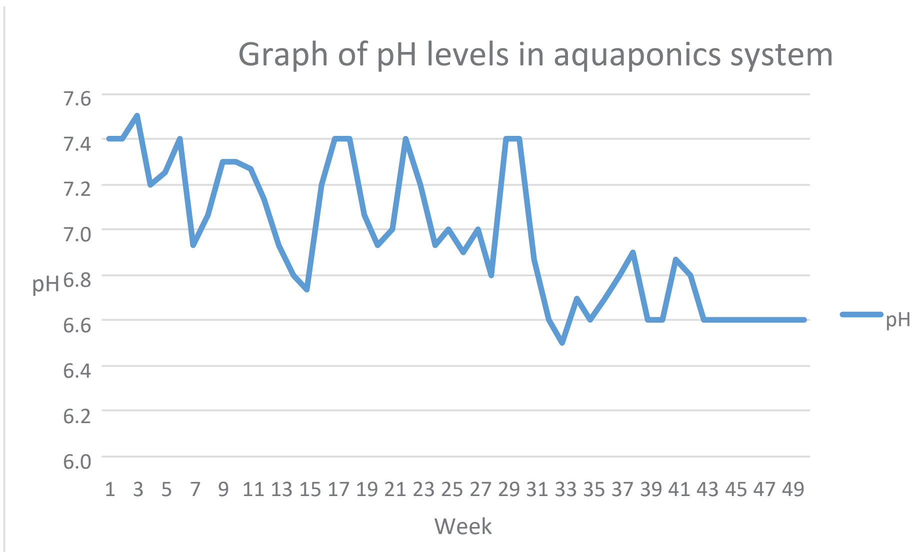

Figure 22. Graph of pH levels in aquaponics unit

In the first 2 weeks of the cycling of the system, the pH was at its highest of 7.5. Between weeks 3 and 33 the pH levels of the system fluctuated greatly, ranging from 6.5 to 7.4, before eventually settling at approximately 6.6 to 6.8, which are ideal aquaponics pH levels.

Nitrites and Ammonia

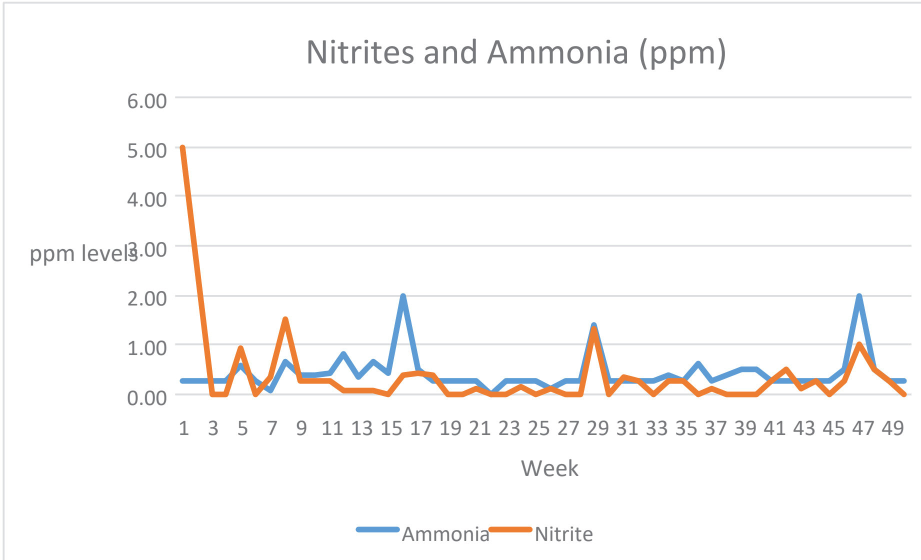

Figure 23. Graph of ammonia and nitrite levels in aquaponics unit

In the first week of the cycling of the system, a spike in nitrites of 5.0 ppm was observed. By the third week the nitrite levels had dropped to zero and fluctuated between 0 and 0.5 for the majority of the study period. There were, however four instances of nitrite levels were above or equal to 1.0 ppm, which were in weeks 5, 8, 29 and 47. The closer the levels of nitrites and ammonia levels come to zero, the healthier the aquaponics system.Ammonia levels remained below 1.0 ppm for most of the study period, much like nitrites. There were two major spikes of up to 2.0 ppm observed in weeks 16 and 47, and a spike of 1.5 ppm being observed in week 29. Generally, nitrite and ammonia levels seemed to follow similar patterns, with spikes occurring almost simultaneously for both parameters. The extent of the spikes, however, varied, with nitrites showing more volatility.

Nitrates

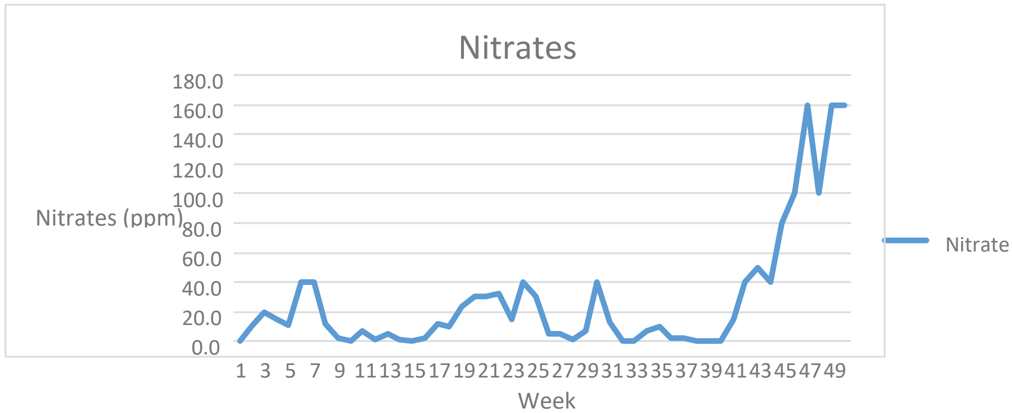

Figure 24. Graph of nitrate levels of aquaponics unit

Plants in aquaponics systems absorb nitrogen most readily in the form of nitrates. Thus, higher nitrate levels are encouraged to promote plant growth. At the start of the study period, the nitrate levels were 0 ppm. Values then steadily increased to 40 ppm over the next 8 weeks before dropping back to 0 ppm in week 9. They then fluctuated between 0 and 10 ppm for the next 6 weeks before gradually increasing to 40 ppm by week 25. In week 26, there was another fall to 0 ppm, after which concentrations remained below 20 ppm until week 40, with a brief spike to 40 ppm in week 30. From week 41 until the end of the study period, there was a continuous increase in nitrate levels to as high as 160 ppm.

Dissolved Oxygen

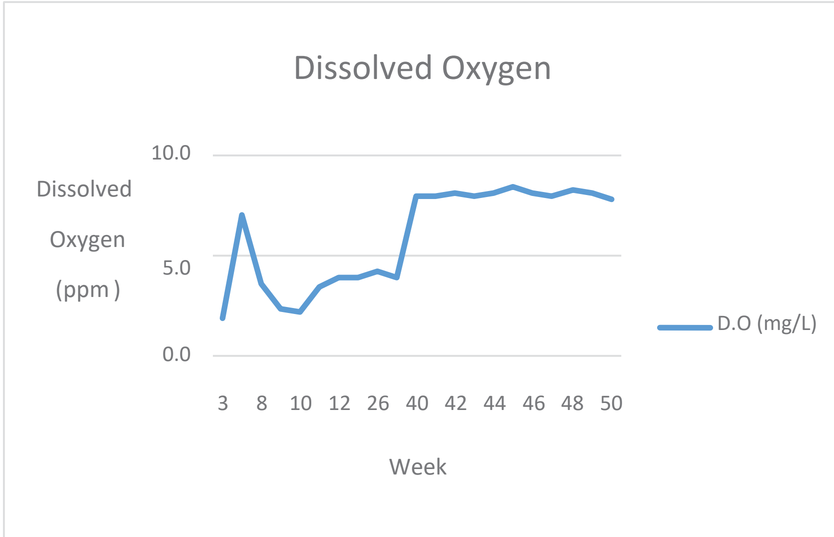

Figure 25. Graph on Dissolved Oxygen levels of aquaponics unit

Dissolved oxygen was not consistently measured throughout the study period, however still displayed an increasing trend. It can be seen that in the initial stages of the study period, the dissolved oxygen levels were approximately 2 mg/L. For the majority of the study period, the dissolved oxygen levels remained between 3 and 5 mg/L, however the last 10 weeks of the study period recorded dissolved oxygen levels of roughly 8.0 mg/L.

Of all the interactions between water quality parameters, the most noticeable was that of oxygen and nitrates. It was observed that when oxygen levels increased, nitrate levels also showed an increase, peaking at 160 ppm. Similarly, when oxygen levels dropped below 3ppm, nitrate levels varied between 40 ppm and 0. A Pearson correlation coefficient was computed to assess the relationship between the levels or nitrates and dissolved oxygen in the fish tank. There was a positive correlation between the two variables, $r = 0.597$, $n = 29$, $p = 0.001$.
Overall, there was a positive correlation between dissolved oxygen and nitrates. Increases in dissolved oxygen were correlated with increases in nitrates.

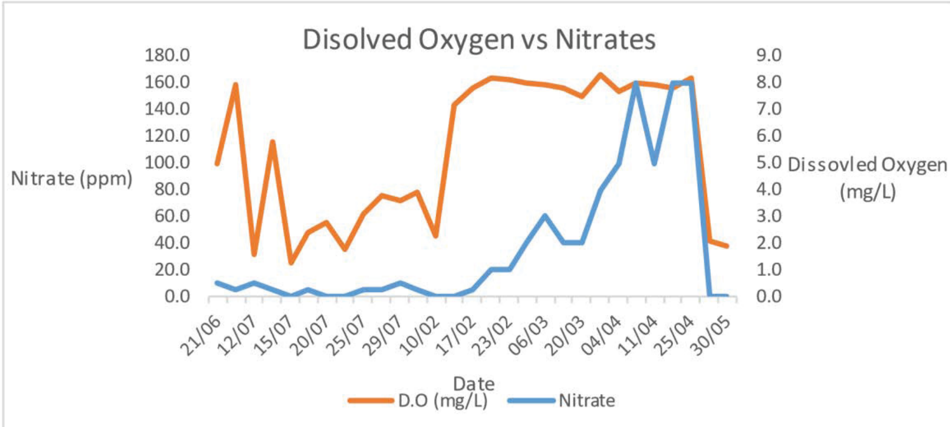

Figure 26. Graph showing correlation between Dissolved Oxygen and Nitrates in aquaponics unit

Temperature and Rainfall

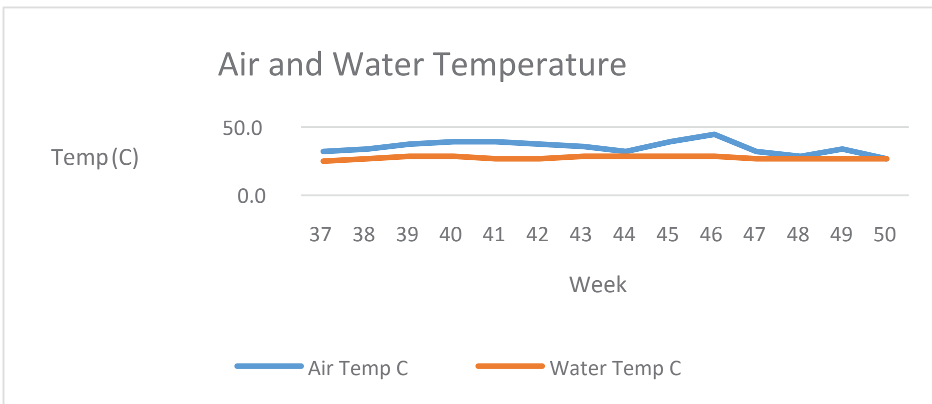

Figure 27. Graph showing water temperature in the fish tank and air temperature inside the shelter of the aquaponics unit

Similar to dissolved oxygen, temperature readings were not made throughout the entirety of the study period. Temperature readings were recorded in the last 14 weeks of the study period, due to concerns about environmental stress during the warmer season in Suva. During this time, air temperatures inside the shaded grow bed areas ranged from 28°C to 44°C, while water temperatures remained fairly constant at about 25°C to 28°C.

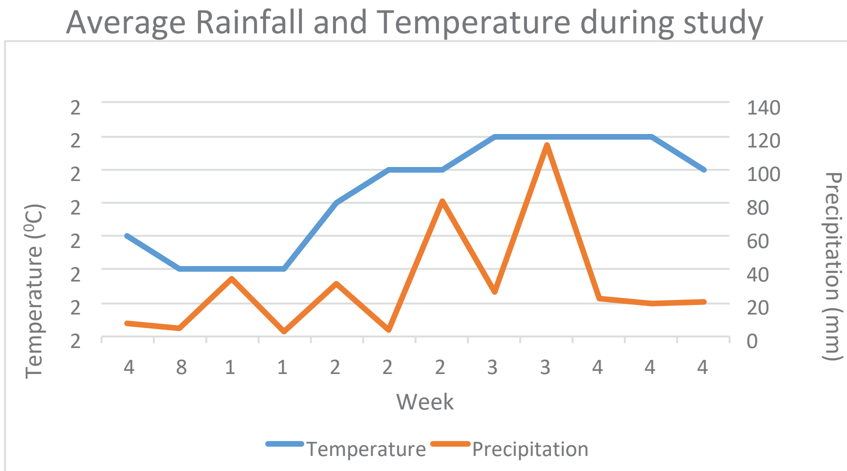

Figure 28. Graph showing the average monthly rainfall and temperature in Suva during the study period

The graph above shows the rainfall and temperature patterns for the entirety of the study period, obtained from the 'AccuWeather' website [1]. Average annual temperatures ranged from 23°C to 27°C, while rainfall ranged from 25 mm to 1145mm (AccuWeather, 2016).

[1] http://www.accuweather.com/en/fj/suva/127517/month/127517?monyr=7/01/2016

Other observations

Flow rate

It was observed that, although the same pumps were used to feed each grow bed, perhaps due to a factory manufacturing fault, one pump had a lower flow rate than the other, resulting in one grow bed flooding more rapidly than the other. It was observed that the grow bed with the longer flood time produced faster growing crops than the grow bed with the more rapid flood rate. Table 13 in Appendix 2 shows these observations.An independent –samples t-tests was conducted to compare plant harvest weights in the grow bed with the higher water flow rate and the grow bed with the lower water flow rate for the two test crops.

There was not a significant difference in the lettuce harvest weights in grow bed 1 (M=2102.00, SD= 1833.49) and grow bed 2 (M=2559.75, SD=2298.183) conditions; t(6)= -0.311, p = 0.766. There was not a significant difference in the basil harvest weights in grow bed 1 (M=1537.25, SD=1224.08) and grow bed 2 (M=1095.25, SD=224.83) conditions; t(14)=1.005, p = 0.332

Crop and Fish Performance

Two main crops were tested in the grow bed of the system. These were *Ocimum basilicum* (sweet basil) and *Lactuca sativa* (lettuce). Other crops such as *Solanum lycopersicum* (tomato), *Fragaria ananassa* (strawberry) and *Capsicum sp.* (local chilies) were also planted in the system, to determine whether the aquaponics system could support fruiting vegetable crops. The fish species in the fish tank was *Oreochromis niloticus,* or the Nile tilapia.

Basil

Basil was the most prolific crop grown in the system during the study period. For the duration of the study period, a total of 21.6 kg of basil was harvested at a stocking density of 5 plants/m^2 with the average plant harvest weight being 192g. An independent –samples t-tests was conducted to compare basil harvests in rainy and dry season. There was a not a significant difference in the basil harvest weights in the wet season (M=2015.75, SD= 208.593) and the dry season (M=3249.25, SD=1555.245) conditions; $t(6) = -1.572$, $p = 0.167$.This result suggests that seasonality did not affect basil productivity in the system.

Figure 29. Basil growing in the grow bed under the shade

The graph below shows the cumulative production of basil throughout the study period.

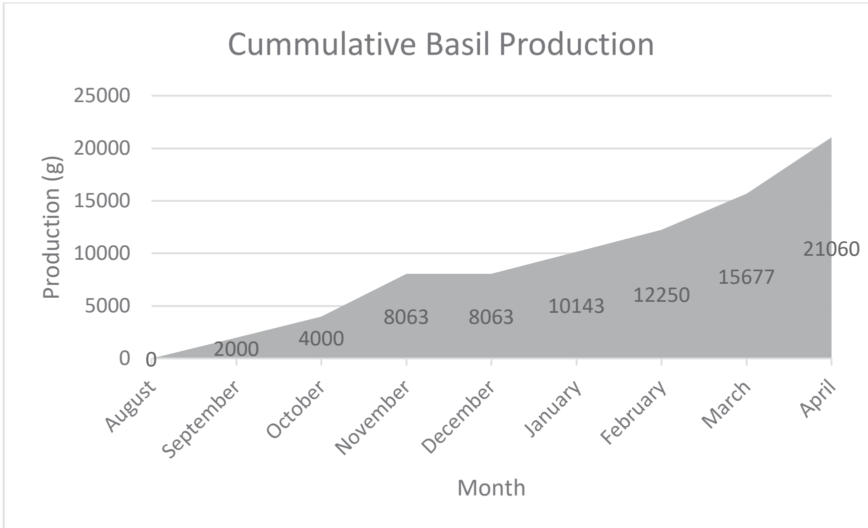

Figure 30. Basil production shown cumulatively throughout the study period

Lettuce

During the study period, a total of 18.4 kg of lettuce was harvested from the grow beds with a density of approximately 1.5kg/m^2 and an average of 71g/plant. It was observed that, as the weather got warmer, the productivity of lettuce in the system declined. Statistical tests supported this claim. An independent –samples t-tests was conducted to compare lettuce (sp.) harvests in rainy and dry season.There was a significant difference in the lettuce harvest weights in the wet season (M=4099.5, SD= 1670.43) and the dry season (M=526.25, SD=216.25) conditions; t(3)= 10.024, p = 0.002.

Three different varieties of lettuce were used: Green Mignonette, Buttercrunch and Box Hill. This was to determine whether any one variety performed better in the system than the others.A one-way between-subjects' ANOVA test was conducted to compare the harvest weights of three varieties of lettuce (sp.) in the aquaponics system.There was no significant difference in the harvest weight at the $p<.05$ level for the three varieties of lettuce used [F (2, 21) = 1.516, p = 0.243]. This result states that there was no significant difference in the yield of the three varieties in the aquaponics system, making them all viable options for cultivation.

Figure 31. Lettuce harvest from the system

Below is a graph showing the cumulative production of lettuce during the study period.

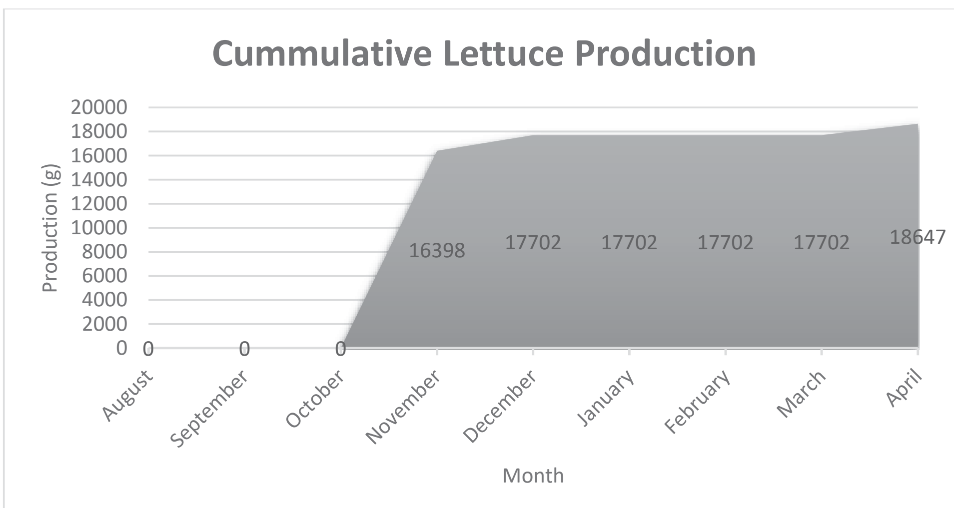

Figure 32. Cumulative lettuce production throughout the study period

Tomato

The harvest period for tomato was only 3 weeks, because a tropical depression in the second week of December destroyed all the plants. However, during this time a total of 2.6 kg of tomato were harvested from the system with an average of 2.6kg/m^2

production and approximately 890g/plant being produced. Due to growth cycle of tomato, it was not possible to conduct a comparison between seasons. The fruiting of the crops commenced after the weather became warmer at the end of November, despite the crops being in the grow bed from the end of August.

Figure 33. Fruiting tomato plant in the grow bed and tomatoes harvested

The graph below shows the cumulative tomato production observed during the study period.

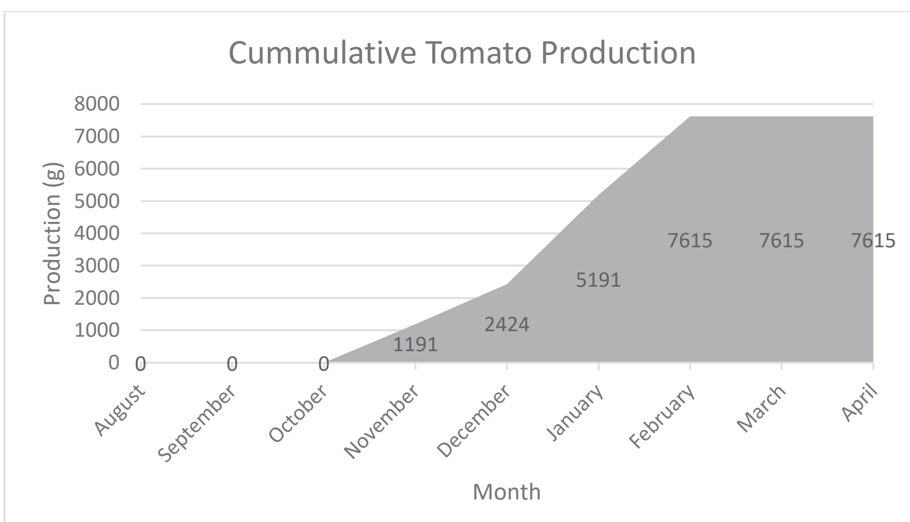

Figure 34. Cumulative tomato production during the study period

Strawberry

The strawberry plants thrived during the cooler months in the shaded portions of the grow bed. There were 2 plants in the system, which collectively produced 0.7 kg of fruit before the weather changed and the fruiting season ended.

Figure 35. Fruiting strawberry plant in grow bed

Below is a graph showing the cumulative strawberry production recorded during this study.

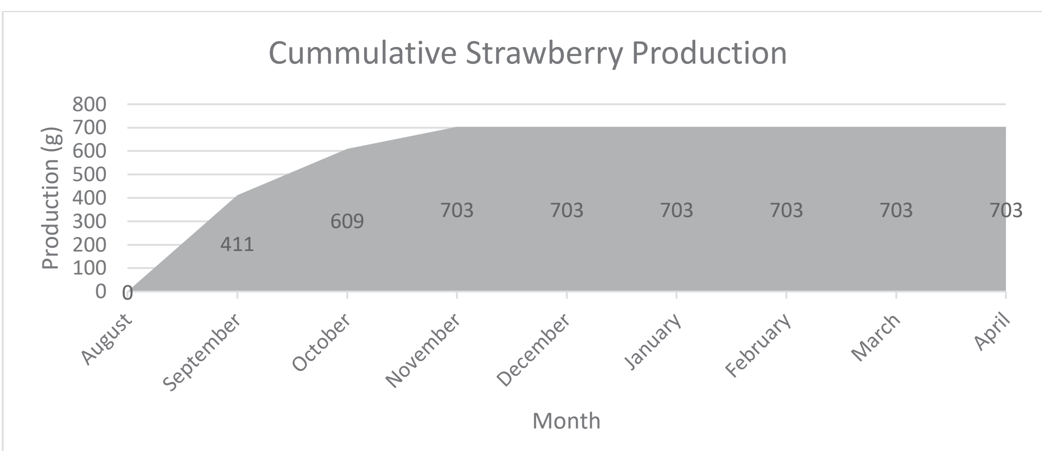

Figure 36. Cumulative strawberry production throughout study period

Chilies

As the weather became warmer, the chili plant began fruiting. A total of 2 kg of chilies were harvested from the system from January to April from the single, experimental plant. The graph below shows the cumulative production of chillies observed during this study period.

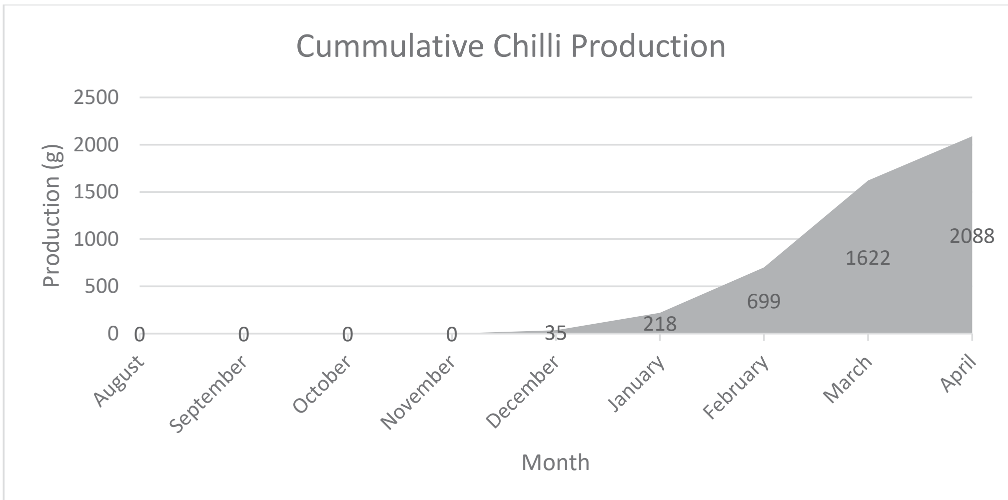

Figure 37. Cumulative chili production during the study period

Tilapia

A total of 21.999 kg of fish were harvested from the tank at the end of the study period. Due to logistics, fish sampling was only conducted twice during the study period, once after the first 5-month growth period, and again after the second 5-month growth cycle. The results are displayed in the table below.

Table 1. Biomass of fish in tank

Tank Biomass (kg)	
17-Jun	18.1
2-Dec	9.9
16-May	22.0

The biomass indicates the weight of all the fish placed into the tank. The initial stocking took place over a 2-week period, with roughly 150 fish weighing 13 kg being added. An additional 60 fish, weighing a total of 5 kg, were added shortly thereafter. The biomass of 9.9 kg observed in December was the result of two mass mortalities that occurred during the early cycling of the aquaponics system.

A one-way between-subjects' ANOVA test was conducted to compare the biomass of tilapia at three time intervals: the start of the study period, after 5 months and at the end of the study period.There was a significant difference in fish biomass at the $p<.05$ level for the three time periods [$F(2, 371) = 211.157$, $p = 0.000$]. Post hoc comparisons using the Tukey HSD test indicated that the mean starting biomass ($M = 84.5$, $SD = 50.37$) was significantly different from December biomass ($M = 126.35$, $SD = 57.89$) and also the end biomass ($M = 268.28$, $SD = 109.14$). These results suggest that over the study period, there was a significant increase in the biomass of tilapia in the fish tank.

Figure 38. Tilapia harvested from aquaponics system in May 2017

The FCR for the first 5-month period was calculated as -6.2, while FCR for the second 5-month period was calculated as 4.2. This was obtained by comparing the feed used during the study period and the biomass of the fish, with both parameters being recorded in kilograms.

Economic Analysis of System

An economic model for the system was designed using Microsoft Excel. The following tablesdisplay extracts from the model, summarizing the costs and revenue from the system.

The operating costs incurred by the aquaponics system for the duration of the project are listed below.

Table 2. Break down of operating costs (in FJD) for the aquaponics system for the study period

Item	Quantity	Unit cost	Total Cost
Water Test Kits	2	$89.30	$178.60
Potting mix	4	$10.30	$41.20
Seedling Trays	2	$3.00	$6.00
Sweet Basil Seeds	2	$1.50	$3.00
Lettuce Seeds	4	$2.50	$10.00
Tilapia Pellets	4	$31.00	$124.00
Tomato seeds	1	$2.50	$2.50
Yates Iron Chelate	1	$20.00	$20.00
Neem Oil	1	$2.00	$2.00
Chilli seeds	4	$3.00	$12.00
Electricity (kw)	198.8	$0.33	$65.80
Total			$465.10

The most expensive components of operation were water test kits and tilapia feed. Electricity costs amounted to 14% of the total operating cost incurred over the study period

Below is a summary of the capital cost of constructing the aquaponics system. A more complete table showing all line items can be found in Table 19 of Appendix 4.

Table 3. Cost (in FJD) to construct the aquaponics system

Component	Cost
Labour	300
Fish Component	1383.4
PVC	252.14
Roof	105.33
Plant Component	551.38
Misc.	571.67
Total	3163.92

Table 6. Potential revenue earned form the system for the study period

Product	Price per kg (FJD)	Number of cycles in study period	Revenue during study (FJD)	Projected Annual Revenue (FJD)
Lettuce	5.74	5	$105.36	$972.59
Basil	20	9	$414.72	$11,520.00
Tomato	3.74	1	$9.56	$1,147.13
Chili	5.86	4	$11.72	$1,054.80
Strawberry	29	1	$8.70	$4,350.00
Tilapia	10	1	$215.20	$1,076.00
Total			$765.26	

The potential earning from the system during the 10-month study period are listed in the table above, with the entire model attached in Appendix 4 Table 22.

The projected earnings for each of the crops was calculated by using the potential stocking density for each crop in a monoculture situation, and determining the total potential yield of each crop from the system in a given year. The yield (in kilograms) was then multiplied by the market price in order to provide an approximate figure. Based on these projections, it was possible to determine the pay-back period of the system, given that any one crop is cultured together with tilapia on an annual basis. This is illustrated in Figure 39 below.

It can be seen that for basil and strawberry, by the second year of production, a profit can be realised, while the other crops break even in the third year of operation, and show profits in the fourth year. This profit is calculated by determining potential revenue and removing capital cost and annual operation costs. Basil shows the highest potential for profit, with earnings in the second year being just under $10,000. The least profitable crop is lettuce. It should be noted that projected strawberry earnings are based on the price of imported strawberries in the supermarket. Other crops were projected based on the market value during the study period.

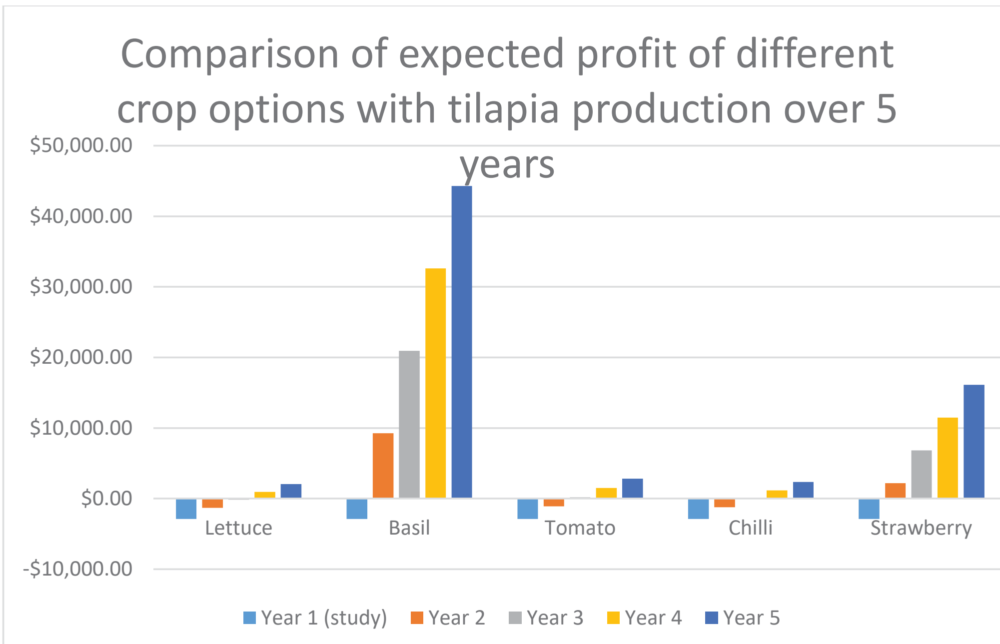

Figure 39. Graph showing the potential collective earning from the system over a 5-year period

Shelter for crops

The third objective was to test whether shelter for crops is necessary to optimize production in this aquaponics system. For this objective, three factors were considered in the determination of whether the shelter for the crops was necessary. These were harvest size of the crops, as well as the impact weather, and of pests. The two test crops, basil and lettuce, were used to collect data in order to determine whether the roof was necessary.

Independent –samples t-tests were conducted to compare lettuce and basil harvests in sheltered and unsheltered portions of the grow beds.

There was a not a significant difference in the basil harvest weights in the sheltered portion of the grow bed (M=1462.00, SD= 661.29) and the unsheltered portion of the grow bed (M=1170.5, SD=573.92) conditions; $t(14)= 0.942$, $p = 0.362$. Similarly, there was a not a significant difference in the lettuce harvest weights in the sheltered portion of the grow bed (M=3015.00, SD= 2790.669) and the unsheltered portion of the grow bed (M=1556.75, SD=1338.901) conditions; $t(6)= 1.000$, $p = 0.356$. These results suggest that having a roof over the crops did not affect lettuce or basil productivity in the system.

Any physical sign of pests was noted during the study period. In addition to the shelter for crops, a natural pesticide was applied to crops in order to control the occurrence of pests. This pesticide was a solution of neem oil and water applied topically to the plants via a spray bottle. The pesticide was applied to a selection of crops, both sheltered and unsheltered, in order to determine the best means of pest control in an aquaponics system while maintaining a low cost and organic system.

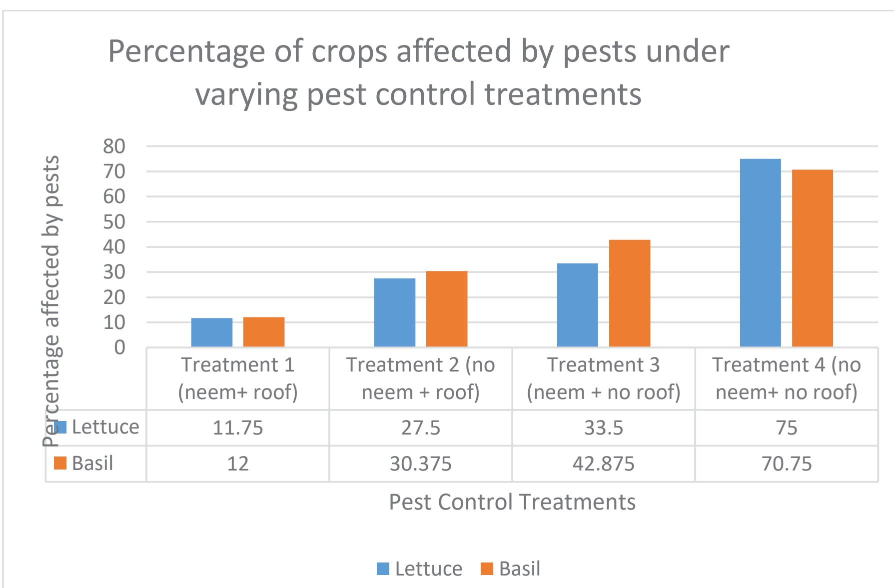

Figure 40. Graph showing the percentage of crops affected by pests under pest control treatments 1-4

A one-way between-subjects' ANOVA test was conducted to compare the effects of neem treatments on plants in sheltered and unsheltered portions of the grow beds.

There was a significant difference in fish biomass at the $p<.05$ level for the four pest control treatments [$F(3, 44) = 88.05$, $p = 0.000$].

Post hoc comparisons using the Tukey HSD test indicated that percentage of plants affected in Treatment 1 (M = 11.92, SD = 2.39) was significantly different from all the other treatments. Similarly, the number of plants affected in Treatment 4 (M = 72.17, SD = 12.27) was significantly different from all the other treatments. The percentage of plants affected by pests in Treatments 2 (M = 29.42, SD = 8.14) and Treatment 3 (M = 39.75, SD =11.27) were closer in value yet also statistically significantly different from each other. The mean difference between Treatments 1 and 4 was the largest (60.25%). The difference between Treatments 1 and 3 was less (27.83%) and even less between Treatments 1 and 2 (17.5%).

These results state that Treatment 1 (neem +roof) was the best treatment against pests in this project, while Treatment 4 (no neem + no roof) was the least effective against pests. When comparing the roof and the neem treatments in isolation, Treatment 2 (neem+ no roof) proved to be more effective than Treatment 3 (no neem + roof), which suggests that the use of neem treatments on crops is a more effective means of pest control that sheltering.

The effects of the weather were considered by either the mortality of crops, or damage suffered by crops following a heavy rainfall event, and also the observed slanting of crops in the grow bed resulting from the effects of winds. There was one observed rainfall incident in December which led to the death of 3 tomato plants in the system. However, other crops remained unaffected by the rain. As it relates to effects by wind, the number of crops observed to be slanting in the grow bed was noted, and a t test was conducted to determine if there was a significant difference in the number of unsheltered crops affected by the wind, as opposed to the sheltered crops.There was a significant difference in the percentage of crops damaged by weather in the sheltered portion of the grow bed (M=0, SD=0) and the unsheltered portion of the grow bed

(M=11, SD=6.5) conditions; $t(8)= -3.73$, $p = 0.005$. This result suggests that having a roof over the crops protected them from the effect of weather.

DISCUSSION

This study was aimed at constructing and testing a prototype of the Developing World Aquaponics System designed by Lennard Wilson, a specialist in the field of aquaponics. Obtaining a site for the system was relatively simple, as the director of Homes of Hope, Mark Roche, has shown interest in aquaponics for some time, and was eager to assist with this project. The acquisition of materials for construction was also effortless since, as part of the driving ideology behind the system, they could all be found at general hardware, garden and pet stores around Suva.

The system was constructed successfully, with half of the grow bed area sheltered with a woven plastic roof and an aphid screen door. Based on the observations made during the project, it can be concluded that, with the right choice of crop, the system can be very profitable in Suva. However, the system design specifications must be adhered to closely.

The Developing World Aquaponics System Design

The system was built to the specifications of the designs provided by Wilson Lennard (Lennard & Leonard, 2004), which were developed to be a low-cost aquaponics system built from material that can be primarily obtained locally. While keeping cost minimal is the main objective of this system, the materials used should also not compromise the quality of the harvested fish and plants.

The selected materials, although cheap, should also be durable (Rakocy, 2012), so that costs are reduced both initially and in the long run, by minimizing the need for regular repairs or maintenance. Some materials, such as the fish tank, the waterproof liner and the timber for the frame of the grow bed used in this project, could have been replaced by cheaper materials, however the quality and durability of these products could not be guaranteed.

The water tank was selected for the fish component of the system because its circular shape encourages the efficient removal of solid waste material suspended in water

(Malone, 2013). Waste management was also supported by placing water pumps in the centre of the tank, and angling the drain pipes from the grow bed to the sides of the tank, to create a swirling water current inside the fish tank that encouraged the settling of solid material in itscentre (Malone, 2013). The fish tank was kept covered to limit the amount of sunlight, thereby limiting the growth of microalgae (Ako & Baker, 2009), that can cause blockages in the water pumps and plumbing. The water delivery pipes in the grow bed had 6mm holes drilled at intervals along the length to distribute water evenly to the grow beds. The holes were sized at 6mm so that they were large enough to allow the flow of water and solids with minimal clogging, while being small enough to help maintain the pressure gradient within the delivery pipe, despite the small size of the water pumps and their low pumping capacity.

This system is designed so that the hydroponic or plant growing component also acts as a biofilter for the system (Rakocy, 2012). Biofilters are used to remove the ammonia waste excreted by the fish from the water in the system (Rakocy, 2012). If left unchecked, the ammonia can accumulate in the water and become toxic to the fish (Blidariu & Grozea, 2011). The gravel used as a growth medium in the grow beds provided a substrate on which the nitrifying bacteria, responsible for converting ammonia to nitrates, proliferate (Rakocy, 2012).

As with most things, there are drawbacks to the use of a gravel medium, particularly when the growth medium doubles as a biofilter. It is prone to clogging with solid waste material from the fish tank (Rakocy, 2012). The process of washing the gravel to remove solids is tedious, and threatens the integrity of the plastic liner used to keep water from escaping the system. Also, because gravel drains easily, if the water supply is hindered, (such as by power outages, which occurred on a few occasions during this project), water stress and wilting of plants occurs at a much quicker rate than in other plant cultivation techniques (Rakocy, 2012).

Ideally, the specific dimensions of an aquaponics system are set to manage the amount of solid material produced by the fish in the system; therefore, by determining the biomass of fish that should be produced in the system, the other parameters can be determined (Rakocy, 2012). This is to ensure that ammonia is adequately nitrified and does not become problematic. It is important to keep the amount of solids entering the hydroponic component low enough so that it does not clog the roots of the plant, but high enough to encourage microbial activity around the plant roots in order to release essential minerals close to the root systems (Rakocy et al., 2006).

Another important factor in determining the dimensions of the system is the ratio of fish tank:grow bed area, particularly factoring in the amount of feed being used daily (Rakocy et al., 2006). It is important to obtain an equilibrium because if the ratio is too high, there will be an accumulation of nutrients in the system that would affect the water quality; and if the ratio is too low, the resulting plants would be deficient and stunted (Rakocy et al., 2006). The traditional ratio used in aquaponics is a 1:2 ratio of fish tank volume:grow bed area in a system with a gravel medium (Rakocy, 2012; Rakocy et al., 2006).

The system built in this project had a grow bed to fish tank volume ratio of approximately 1:2, which is consistent with modern aquaponics system designs (Diver, 2000). It is often seen in aquaponics systems, after the calculation of dimensions, that some extra allowance in grow bed area is made as a safety measure (Rakocy et al., 2006), to allow for complete nutrient decomposition within the system itself, with no demand for additional components specifically for solid removal. Tillage of the gravel and introduction of worms to the system to aid in the breakdown of solids is also recommended to avoid clogging. However, the operation of the system with periodic flooding and draining of the gravel bed encourages oxygen from the air to enter the gravel, and promotes the decomposition of solids and mineralization of the system (Rakocy et al., 2006).

The size of the gravel also becomes important so that adequate moisture is retained for the crops, while solids are able to move from the surface to the bottom of the grow bed with ease and not cause clogging in the root zone (Rakocy et al., 2006). To support this process, the gravel size used in this project was 12mm in diameter, while the average recommended diameter of gravel for most aquaponics systems is 6mm (Rakocy et al., 2006).

Another factor used to determine the ratio between system components is the feeding rate, as measured by the ratio of feed to the grow bed area. In gravel systems, the recommended daily feed to grow bed ratio is roughly 25g of feed per square meter of grow bed area (Rakocy et al., 2006), which computed to a recommended daily feeding rate of 250g for the system used in this project. The system in this study, however, was operated at 40g of feed per square meter of grow bed area, with an average feeding rate of 400 g daily for the duration of the project. This is because the need for additional nutrient supplements for fish and plants in aquaponics is eliminated, if the amount of feed added to the system is increased beyond the typically recommended quantity (Rakocy et al., 2006).

The 'Developing World Aquaponics System' built in this project favoured this ratio between feeding rates and grow bed dimensions. The system was built to utilize 400-450g of tilapia pellet feed daily (W. Lennard, personal communication, April 26 2016). Using this feeding rate, the biomass of fish to be stocked was calculated based on the size of fish, which influences their feed requirements; for instance, tilapia fry with an average weight of 0.016g require approximately 30% of their body weight in feed daily (El_Sayed, 2002), while fish averaging 150g require only 2% of their body weight in feed daily (J. E. Rakocy & Brunson, 1989). Therefore, for this project, since the sizes of fish selected ranged from 50 to 150g, the tank was ultimately stocked with approximately 200 fish with a collective biomass of 15 kg. Additionally, using a feeding rate of 400-450g of tilapia feed daily, the grow bed area was then able to support the growth of lettuce, for example, at a higher than standard density of 30 plants per square meter (W. Lennard, personal communication, July 19, 2016).

As with the other components of the system, the materials selected for the shelter constructed over half of the system were based on the consideration of durability and cost. The shelter comprised a woven plastic roof and aphid screen net doors mounted on PVC hoops. The aphid netting used to make doors on either end of the shelter helped to keep pests out, while allowing the flow of air through the shelter.

Water quality parameters

Biofiltration of ammonia in an aquaponics system occurs best when temperature is kept between 25 and 30^{0}C, pH is kept between 7.0 and 9.0, and dissolved oxygen is at saturation (Rakocy, 2012). The saturation point of oxygen in water is considered to be approximately 10 ppm (Malone, 2013). The average system operates well at dissolved oxygen levels above 5 ppm, with colder water systems often being operated at 8 ppm (Malone, 2013). Fish and bacteria in an aquaponics system have high oxygen consumption, and so it is necessary to replace dissolved oxygen to the water at a rapid and consistent rate (Malone, 2013). The aeration method of choice used in smaller systems like the one in this project is diaphragm air pumps, as they are simpler and cheaper than other methods, and also provide the combined effect of increasing oxygen supply and removing carbon dioxide (Malone, 2013). Due to the unavailability of supply locally, aquarium air pumps were used but proved to be inadequate. They were designed only for use in small aquariums, so multiple air blowers were required to provide even the minimum requirement of 3-4 ppm of dissolved oxygen to the fish tank.

When possible, a larger air blower was used in order to observe system response. There was a marked difference in performance of the system under different dissolved oxygen regimes. This was shown in the t tests, which indicated that higher dissolved oxygen rates resulted in higher levels of nitrates, while oxygen rates below 2 ppm resulted in nitrate levels dropping to zero. This suggests that nitrifying bacterial activity was optimal at higher oxygen levels. (Rakocy, 2007). Dissolved oxygen levels below 2 ppm also results in the impairment of tilapia growth and metabolism (Popma & Lovshin, 1996).

Similarly, obtaining submersible water pumps to provide the recommended pump rate of 500L per hour proved difficult during the construction phase of the project, so aquarium substitutes were acquired instead. Two pumps providing 400L per hour each were used, providing a total water supply of 800L per hour, which exceeded the recommended amounts. A slower water exchange rate in the system reduces energy costs related to power consumption by water pumps, and increases removal of dissolved waste by the plants in the system (Rakocy et al., 2006).

The pH level in the system ranged between 6.5 and 7.5 during the study period. At the beginning of the study period, pH levels were 7.5, the highest recorded across the study. It is typical for new aquaponics systems in the cycling phase to record higher pH values, before bacterial colonies are established (Elia, Popa, & Nicolae, 2014). This is because a by-product of the nitrification process is the release of hydrogen ions, which cause pH levels to drop (Elia et al., 2014). The pH levels then dropped and fluctuated between 6.5 and 7.2 for the duration of the first 5 months of the study period. This was the result of instability in the system resulting from low oxygen concentrations and accumulations of ammonia, resulting in two major fish mortality events during that time. The pH levels rose above 7.1 during such events, until buffers were used to restore it to a preferred level. Both potassium hydroxide and calcium hydroxide were used. The hydrogen ions provided by these two chemicals reduce the pH, and also provide potassium and calcium to the system, since they are plant and fish essential nutrients (Treadwell, Taber, Tyson, & Simonne, 2010). After five months of the study period, the operation of the system had stabilized and the pH levels remained consistent at 6.6. Although this is not the ideal pH for aquaponics systems of 6.8 -7.0 (Bernstein, 2011; Treadwell et al., 2010), the system thrived during this portion of the study.

To commence the cycling of the system, approximately 20L of water from an existing aquaponics system was spread over the two grow beds. This was done to shorten the initial cycling of the prototype system by expediting the colonization of nitrifying bacteria. As a result of this, the typically 6 week cycling period for an aquaponics system (Bernstein, 2011) was shortened to two.

Un-ionized ammonia is produced as a waste product of fish respiration, as well as through decomposition of uneaten feed in the fish tank. Ammonia is toxic to fish, resulting in damage to gills, susceptibility to disease, and infection and death in extreme cases (Blidariu & Grozea, 2011). Typically, the ammonia concentration rises as the fish respire in the system, but reduce once bacteria colonies are established

(Bernstein, 2011). This system, however, recorded low ammonia levels, ranging between 0.25 and 0.5 ppm, for the majority of the study period. This is because nitrifying bacteria had been introduced into the system and so the spike in ammonia which would have occurred prior to the formation of a bacteria colony was not experienced. There were three observed instances of ammonia levels exceeding 1.0 ppm, and getting as high as 2.0 ppm on two occasions. These spikes were the result of bacterial inactivity in the system due to oxygen deficiency in the water, resulting from over feeding of fish.

In the first event, the decomposition of the excess feed in the system increased the oxygen demand in the fish tank while increasing the amount ammonia produced. The second peak in ammonia occurred in week 29 of the study and coincided with a 1°C increase in average temperature. This was because the toxicity of ammonia increases with temperature (Popma & Lovshin, 1996). On these occasions, mass mortality of fish was observed. While the high ammonia levels can be naturally reduced by the reestablishment of bacteria colonies, in order to minimize the loss of fish, a 50% water exchange was required to promptly bring the ammonia down to a more tolerable level. At a prolonged scale, tilapia can tolerate ammonia levels exceeding 1 ppm for up to a week before mortalities occur, while in the short term, tilapia can tolerate ammonia levels up to 4 ppm (Popma & Lovshin, 1996). However, ammonia concentration levels should ideally be kept as close to zero as possible, as concentration levels of 0.08 ppm can cause appetite depression (Popma & Lovshin, 1996).

Like ammonia, nitrites pose a threat to fish if present in high concentrations in water. Nitrite is produced as a transitional product in the decomposition of ammonia to nitrate in the nitrification process. Nitrites are known to cause anoxia in fish, which impairs in the ability of the blood to transfer oxygen (Lewis& Morris, 1986). Fish are able to tolerate nitrite concentrations up to 2 ppm before it is considered toxic, however, similar to ammonia, function best when nitrite levels are maintained close to zero (Lewis& Morris, 1986).

Other water quality parameters such as lower temperature and reduced dissolved oxygen concentration are known to increase the toxicity of nitrites in fish water (Lewis& Morris, 1986; Sifa, Chenhong, Dey, Gagalac, & Dunham, 2002), while the presence of certain nutrients such as calcium can reduce the toxicity of nitrites in fish water (Lewis Jr & Morris, 1986). Nitrites and ammonia recorded similar patterns, peaking and falling at similar intervals during the study period. The observed peaks coincided with previously mentioned fish crises resulting from low dissolved oxygen levels.

Nitrate concentration started off at zero in the system, but under stable system operation, was able to rise to 160 ppm. Nitrate levels exceeding 100 ppm are considered good for plant production in aquaponics, while levels of 500 ppm become lethal (Kotzen & Appelbaum, 2010). Nitrates in fish water are generally harmless to fish, and promote plant growth (Rakocy et al., 2006). Since plants readily absorb nitrates in aquaponics systems, providing that grow beds are continuously utilized, nitrates do not reach levels that would be toxic to fish (Blidariu & Grozea, 2011). It was observed that there is a direct positive relationship between dissolved oxygen and nitrate levels. The process of nitrification is an aerobic one, therefore requiring ample and consistent supplies of oxygen in order to proceed optimally (Rakocy, 2012). During periods of fish mortality, the nitrate levels also responded to the bacterial inactivity by dropping to zero.

Temperature ranged from 23^0C to 27^0C, which is typical for Suva throughout the year. During this time, the temperature had more of an influence on the seasonality and production of crops than it did on the fish component of the system. In one instance, in week 29 of the project, the temperature levels rose, and this coupled with limited oxygen has been attributed for the cause of a fish mortality event. Rainfall ranged from 20 mm to 1200 mm per month, throughout the year, which is also typical for Suva. Due to the open layout of the grow bed, rain water was able to enter the system. This helped with maintaining water levels, as evapotranspiration resulted in daily water loss from the system.

System Productivity

Crop and Fish Performance

Basil

Basil is referred to as an annual crop, meaning that it will continue to thrive year-round, once the right conditions are met (Cook, 1990). Basil is seen to thrive well between air temperatures of 17°C and 35°C, with the optimum temperature for seed germination being 22°C (Nicolae et al., 2015). Since the temperature in Suva fell well within that range throughout the entire study period, it explains why the basil did not demonstrate any significant seasonal preference. Basil plants, upon reaching maturity, begin to blossom and produce seeds. As an herb, the blossoms are undesirable; therefore ideally, basil should be harvested for market prior to the blossom stage (Cook, 1990). During this project it was noticed that, although a standard plant grow-out period of 4 weeks was used before crops were harvested, because of the rapid rate of growth in the system, and potentially induced maturity due to the shelter of the plant, blossoming and seed production commenced within 3 weeks of transplanting the basil into the grow bed. It was possible, therefore, to have increased the basil productivity of the system by reducing the grow-out period, and increasing the number of harvests within a given timeframe.

Typically, in an aquaponics system, basil can be produced at a density of 2 kg per square meter of grow bed area (Rakocy, Shultz, Bailey, & Thoman, 2003), with plants being ideally spaced 20 cm apart (MacMaster, Murphy, & Burton, 2014). Since at any given time during this project the grow beds were populated with multiple crops, it was not possible to produce basil at that density. However, if basil was the only crop cultivated in this aquaponics system, and cultivated at maximum density, the potential yield from the system would be approximately 48 kg of basil every 3-4 weeks. There was no local market data available for basil from the Ministry of Agriculture; however the prices obtained from market visits indicate that basil is the most lucrative choice for production in an aquaponics unit of this size in Suva, providing that the proper market can be obtained (Nicolae et al., 2015). Basil was not a very common herb in the Suva market, however, the principal researcher observed on social media during the study period that members of the expat community in Suva consistently inquired about local availability of the herb.

Lettuce

Lettuce seeds are known to germinate only when temperature is optimal, and temperatures that exceed 30°C would result in inhibition of the germination process (Borthwick & Robbins, 1928). The optimal air temperature for lettuce production is 24°C (Thompson, Langhans, Both, & Albright, 1998). This explains why lettuce thrived well during the cooler months and produced smaller crops during the warmer season, when given the same 4-week grow out period. The mean weight of lettuce during the project was 74 g, while lettuce has been recorded to reach up to 150 g within the same grow out period (Both, Albright, Langhans, Reiser, & Vinzant, 1994). The smaller sizes of lettuce can also be attributed to the low amounts of nitrates in the system during an extended period of the project, as rapid plant growth is generally attributed to high levels of dissolved nutrients in the system (Rakocy et al., 2006). Lettuce plants can be harvested in 3 to 4 weeks of being transplanted into the grow bed, depending on the variety, and once seedlings are produced at an optimal rate it is possible to operate a sustainable and continuously producing system (Rakocy et al., 2006).

In a commercial aquaponics system of tilapia and lettuce production, revenue from lettuce is double the revenue from tilapia (Bailey, Rakocy, Cole, Shultz, & St Croix, 1997), thereby making aquaponics a profitable venture providing that the right crop is selected for production. Lettuce is usually grown at a density of 16 plants per square meter in aquaponics (Rakocy et al., 2006) and can be grown at up to 20 plants per square meter. A similar density was used in this project, however the entire grow bed area was not fully populated with lettuce, and therefore, the true potential of lettuce production was not observed. Over the past 5 years, the average local market price of lettuce has remained fairly consistent at approximately $5 per kg, however the monthly data shows that lettuce production is usually highest in the cooler months of the year, indicated by lower market prices (Fiji Agtrade Unit, 2017).

Tomato

Tomato is an annual plant, which suggests that the plant can live for a number of years; however, its peak performance is observed in warmer months (Peet & Welles, 2005). Optimal tomato cultivation requires a temperature of 25°C for germination and an average day-time temperature of 27°C for growth (Peet & Welles, 2005). This suggests that tomato would thrive in the warmer season in Suva, when average day-time temperatures are 27-29°C. Market price surveys show that tomato prices generally peak between the months of March and May, which indicates a scarcity in the market (Unit, 2017). Over the past 5 years, the months which recorded the lowest tomato prices are October to February, which coincides with the onset of the warmer season in Fiji. Tomato plants require supporting, trimming and pruning throughout their life, making them a more labourdemanding crop (Peet & Welles, 2005). When compared to leafy, non-fruiting plants, tomato plants in aquaponics have a higher nitrate demand and uptake (Hu et al., 2015). The high root surface area of tomato, compared to other leafy plants, encouraged the proliferation of nitrifying bacteria within a system (Hu et al., 2015). While many factors such as light intensity would determine the output from tomato, it is possible to harvest 28 to 60 kg of tomato per square meter in traditional greenhouse agriculture and hydroponics (Peet & Welles, 2005). However, even at optimal production levels, operating this aquaponics system with tomato as the crop of choice would not be highly profitable, as the breakeven point is projected to be achieved in the fourth year of optimal operation.

Chili

Chili peppers are highly valued crops that are rich in vitamins (Ayodele, Ajewole, & Alabi, 2016), and thrive in tropical and semi tropical regions with high annual rainfall (Inusah et al., 2015). In areas with short rainy seasons and limited access to irrigation, the production period for chili plants is 3-4 months annually (Inusah et al., 2015). However, in an aquaponics system with continuous water supply and sunlight, production can be recorded all year (Atlason et al., 2017). Temperatures of approximately 26°C yielded larger plants, than lower temperatures of approximately 18°C (Dorland & Went, 1947). The temperatures observed during the second half of the study period, when the chili plants were present in the system, were near 26°C, which explains the productivity of the plants during that time.

Furthermore, the annual temperature in Suva ranges from 23 to 27°C, making it an ideal location for cultivation of chili. Chili plants are known to be productive in freshwater aquaponics systems (Kotzen & Appelbaum, 2010), however not as productive as the same plants grown using traditional cultivation (Goada, Essa, Hassaan, & Sharawy, 2015). Locally, the market price of chili has declined over the past 5 years from an average price of $9.16 in 2011 to $5.86 in 2016 (Fiji Agtrade Unit, 2017). The average monthly price in any given year does not vary significantly; however, market prices are usually lower in the earlier months of the year, suggesting abundant supply. Similar to tomatoes in this system, in Suva, chili is not an ideal crop for cultivation in a monocrop system, as a small profit can only be realized in the fifth year of optimal operation of the system.

Strawberry

Strawberries have shallow roots and thrive well in kitchen gardens and grow beds (Pramanick, Kishore, & Sharma, 2005), much like those present in aquaponics systems. Strawberries produced in hydroponics are reported to have a better taste than commercial strawberries (Bob, 2010). Being a temperate crop originally, strawberry plants tend to remain vegetative at temperatures exceeding 24°C, while the ideal flowering temperature is at 18^0C (Heide, 1977). However, tropical varieties have been developed that have an optimal temperature of 22°C during the day and 13°C at night for maximum production (Kumar & Ahad, 2012). These temperatures are experienced in Suva during the cooler months of the year, with July 2016 recording a low of 15°C (AccuWeather, 2016). The use of a plastic roof cover over strawberry plants helped induce the fruiting cycle and increased the annual productivity (Kumar & Ahad, 2012; Pramanick et al., 2005). Due to the temperature requirements for strawberry, production can only be guaranteed for a 2 to 3-month period of the year, when temperatures are significantly lower than the yearly average. Therefore, strawberries would not be an ideal crop for use in this aquaponics system in Suva, despite the high market price that exists.

Generally, in aquaponics, herbs and leafy vegetables such as basil and lettuce are more profitable than fruiting vegetable crops such as tomato (Rakocy et al., 2006). This is because they produce a higher yield per unit time and area (Knaus & H. Palm, 2017). Also, fruiting crops are not preferred because the grow-out period is longer than that of leafy vegetables and herbs, and the prolonged time spent in the grow bed increases the likelihood of and susceptibility to pests (Corsin, 2014). Since aquaponics does not allow for the use of pesticides on crops that would harm fish, reducing the incidence of pests is advised. Additionally, fruiting plants have a higher nutrient demand (Rakocy et al., 2006), requiring additional fish feed and nutrient supplements into the system for optimal production, thereby making their production costlierthan leafy vegetables and herbs.

Recommendations by Wilson Lennard (W. Lennard, personal communication, 10 August, 2015) to apply iron chelate to the plants were heeded when evidence of chlorosis, indicated by yellowing of leaves due to iron deficiency, was observed. This practice is commonly seen in aquaponics systems, as macro and micronutrients such as iron, which are typically obtained from the soil, become deficient in soilless culture systems (Kotzen & Appelbaum, 2010).

Tilapia

Providing that the optimal aquaponics water quality parameter levels are met, tilapia culture requires minimal labour input, due to their sturdy nature. Average growth in mature tilapia was observed to be 149g during a 101-day grow-out period, which computes to 1.45g daily (Kotzen & Appelbaum, 2010). Due to fish deaths in the first half of the study period, fish biomass decreased in the fish tank from 15kg to 10 kg. However, in the second half of the study period, biomass in the tank was seen to increase from 9.8 kg to 21.52 kg.

The second half of the study period was approximately 182 days, resulting in a 0.8 g daily growth rate of tilapia being recorded in the aquaponics unit. The average weight of tilapia at market size is 450g (J. E. Rakocy & McGinty, 1989). If the feeding rate used in the system is maintained, it would be possible to grow tilapia to a market size within 6 months. In the local market, tilapia is sold at an even smaller weight, averaging 200g, which can be achieved within 4-5 months, thereby increasing the potential annual output from the system.

Economic Evaluation

These estimations were made based on the observed performances of the various crops but also taking into consideration the fruiting seasons of the crops given the weather conditions in Suva.

Crops

Basil proved to be the most lucrative crop option in the aquaponics system, earning a total of $414.72 during the project. Annually, at maximum stocking density and optimal operation, basil can earn up to $11,000. Lettuce earned $105.36 during the study period and is projected to earn $972.59 annually. Tomato earned $9.56 during the project and can earn approximately $1,147.00 a year. Chili peppers earned $11.72 during the project, however over a year can earn up to $1,054.80. Strawberry was the lowest earning crop used during this project, with a total of $8.70 earned, but if cultured optimally, can earn $4,350.00 annually.

Tilapia

Feed was the most expensive component of tilapia cultivation, accounting for approximately 27% of the annual operating cost of the aquaponics system. This is typical in aquaculture and aquaponics, with feed sometimes accounting for up to 60% of the total operating cost (Gabriel, Akinrotimi, Bekibele, Onunkwo, & Anyanwu, 2007). The FCR refers to ratio of feed consumed by fish and the weight gained during the study period. In this project, particularly the second 5-month period when no fish deaths occurred, the FCR for tilapia was 4.2 kg eaten/kg grown. Tilapia FCR is known to range between 1 and 4 kg/kg in aquaculture, depending on the feed used (Chou & Shiau, 1996). Other fish species such as carp and salmon, in aquaculture settings, have FCRs of 1.5 and 1.3 kg/kg, respectively (Corsin, 2014). The high FCR seen in this study is due to the understocking of the fish tank, while maintaining a constant feed rate. Although the resource investment is less efficient than that of other aquaculture fish species, tilapia production remains a better alternative than most meat sources, with beef production recording an average FCR of 12.7 kg/kg (Corsin, 2014).

In aquaponics, the primary revenue source is the crop component (Rakocy, 2012). This was observed during this project, where the entire system earned a total of $765.26, of which $215.20 came from tilapia (at a market price of $10/kg). The annual operating cost of the system was $465.10. In a year, at optimal production of individual crops in a monocrop system with tilapia, it is projected that basil would be the most profitable option, with potential net profit exceeding $12,000. Strawberry is the next highest potential earner, with projected annual aquaponics income of $5,000. The other crops, lettuce, tomato and chili pepper all have potential annual earnings of approximately $1,500, $1,700 and $1,600, respectively. However, during the study period, with capital and operating costs included, the aquaponics system suffered a loss of $2,863.76. If basil and tilapia are cultured for the following year, a profit will be realized within the first quarter. Strawberry also is projected to reach the pay-back point within the first year of optimal operation by the start of the second half of the year. Selecting the other crops will result in a longer pay-back period for the system, of approximately 3 to 4 years.

Shelter

Agriculture is primarily dependent on climate and weather. The use of shelters in agricultural production increases the ability to withstand the effects of weather, and consequently improves yield (Wittwer & Castilla, 1995). Weather and climate are seen to affect not only the quantity but the quality of agricultural products (Wittwer & Castilla, 1995). Having shelter in crop production is known to reduce wind speed and its effect on crops, as well as soil erosion in traditional agriculture (Bird et al., 1992). Wind has been seen to affect plants not only anatomically, but also increases evapotranspiration and reduces their photosynthetic rate (Wittwer & Castilla, 1995).

Some of the plants, and particularly the basil, were affected by the winds during the study period. A number of plants that were not under the shelter were slanted by the winds and grew leaning towards the wind direction. Leaning of crops was not observed in the crops under the shelter, and statistical tests concluded that the effects of weather were significantly influenced by the presence of a shelter for the crops.

Greenhouses are also seen to induce precocity of crops, thereby increasing their productivity (Wittwer & Castilla, 1995). While the crop yield of basil and lettuce was not seen to vary significantly with shelter, literature, states that greenhouses can be used to produce crops even out of their typical season, and produce better quality crops overall (Wittwer & Castilla, 1995).

Greenhouses and plastic shelters help prevent water loss in crop production (Wittwer & Castilla, 1995). Although the shelter on the system would help limit water lost through evapotranspiration, it would also limit the amount of water entering the system from the rain, which would lead to dilution or even loss of the nutrients in the system. For this project, rain water was able to compensate for water loss. A fully sheltered aquaponics system would require manual addition of to compensate for water loss, which can be as high as 1% daily (Al_Hafedh, Alam, & Beltagi, 2008; Liang & Chien, 2013).

Pest control

Azadirachta indica, commonly known as neem, is very popular for its use in agriculture as a means of pest control. The bioactive properties of neem are responsible for its reputation of being antimicrobial, insecticidal, nematicidal, and effective for many other similar applications (Ogbuewu et al., 2011). Its medicinal properties have been used in Indian; ayurveda is a commonly used in traditional medicine and is currently under study for use in livestock tick and worm control (Ogbuewu et al., 2011). As a pesticide, the use of neem and neem-based products eliminated the risk of poisoning typically associated with synthetic pesticides, and in many cases, has been seen to outperform synthetic pesticide treatments (Ogbuewu et al., 2011). The pesticidal properties of neem are effective against a broad spectrum of economically relevant pests (Ahmed & Grainge, 1986).

Neem can also be used as a plant fertilizer and animal feed component (Ogbuewu et al., 2011). In this project, neem oil was obtained cheaply from a local pharmacy and applied topically to plants in a 1:1 neem and water solution. The neem treatment was observed to significantly reduce the effects of pests on the plants when compared to plants that were untreated. In the unsheltered part of the grow bed, the average percentage of plants affected by pests was 72.2% for untreated and 29.4% for treated plants. In the sheltered portion of the grow bed area, although the level of pest impacts was already significantly less that in the unsheltered parts, the application of neem was still observed to reduce the impact of pests on plants, with only 11.9% of plants treated with neem showing signs of pests, compared to 29.4% of the untreated plants under the shelter.

Based on the outcome of this project, as a singular pest control mechanism, the installation of a shelter over the grow bed proved more effective than neem treatment. However, the combined use of the two treatments resulted in the best form of safe organic pest control for an aquaponics system in Suva. In addition to protection from pests, the shelter was also seen to protect the crops from the effects of the weather, and, in the case of lettuce, considerably improved the yield. Although incurring additional cost, the addition of the roof would be strongly recommended.

CONCLUSIONS

The primary aim of this project was to test the low-cost aquaponics system designed by Wilson Lennard (PhD) and to determine the optimal protocols for fish and crop production under Fijian conditions using a prototype.

The low-cost Developing World Aquaponics System is capable of functioning profitably under Fijian conditions. The system was able to be constructed using locally available material at a cost of FJD 3,200.00 inclusive of labour costs, with an annual operating cost of FJD 465.00. This is significantly cheaper than other aquaponics units of a similar size. The use of this system by persons in Fiji and the wider south Pacific is highly recommended, as it is an efficient means of food and income for households and communities.

This primary aim was further divided into three key components. The first was to effectively construct a prototype, low-budget system aquaponics as designed by Wilson Lennard. The construction spanned a 2-month period during which key activities such as land preparation and material acquisition was done. Once land preparation and material acquisition was completed, the assembling of the materials into a working prototype was accomplished within a week.

The second key component of the project was to test the ability of the system to grow the desired crops, and fine-tune it as necessary. A total of five crops were selected for cultivation in the system in order to determine its versatility. While all the crops selected were successful, to guarantee profitability, crops which can be harvested all year outweigh seasonal crops in profitability, which was seen during the study period. Basil and lettuce proved more productive than chili, tomato and strawberry. Basil particularly outperformed all other crops, showing fast and continuous growth throughout the study period both in the sheltered and unsheltered sections of the system. This outstanding performance is overshadowed by the low market demand for basil, thereby making lettuce a superior choice for aquaponics production in Suva, unless a reliable market for basil can be found.

The third key component was to test whether shelter for crops is necessary to optimize production in this aquaponics system. The shelter proved to be a more effective pest control measure when compare to neem solution application if used in isolation. Also, the roof provided protection to the crops against elements of the weather. Although recommended, the addition of a shelter remains optional. When present, there was a reduction in the incidence of pests and weather damage. However, by not installing a roof, capital costs can be reduced, while the system still remains productive and pests can be controlled through the use of neem oil.

The prototype for the low-cost Developing World Aquaponics System was satisfactorily built and operated and allowed for the production of a user manual which is attached in Appendix 5.

RECOMMENDATIONS

General Recommendations

The learning opportunities during this project were numerous and a few observations were made as the system was being operated. These can be applied to any aquaponics operation.

1. Aeration in the fish tank was one of the biggest challenges faced in this project. Sourcing an aerator from outside of Fiji may prove beneficial in the long run, and improve overall performance of the system. This was not done for this project, as the system was intended to be constructed and operated from locally available items, only. Under regular operation with the two aquarium air pumps, the flow rate of air into the system was 7 L/minute. This proved inadequate, as the recorded dissolved oxygen levels remained at 3 mg/L. The resulting operating conditions contributed to crisis events, which mandated the use of a larger aerator capable of maintaining 8 mg/L dissolved oxygen.

2. Time should be spent researching the local market in order to decide the best crops for use in the aquaponics systems. When selecting crops, their seasonality should be considered in order to maximize use of the system and resulting earnings. In the event that the crops are seasonal, preparations should be in place to switch crops during off seasons, so that the grow bed never remains vacant. Not only does this maximize earnings, but it is also crucial to the nutrient balance of the system when the grow bed is constantly occupied.

3. Basil proved to be the most lucrative option for aquaponics production; however the demand in the Suva market for basil was low. If the demand for fresh basil does not meet the potential supply, small amounts of processing, such as drying, can be applied in order to increase the marketability of the product. Exploration into other basil-based products such as pesto may also prove useful, providing proper certification and permissions are granted.

4. Although not recommended if the nursery is incorporated into the grow bed, close monitoring of the trays should be carried out. Ideally, keeping seedling trays in a separate, well protected area out of direct rain and sunwould be recommended. If basil is selected as a crop, it should be ensured that the growth medium used to germinate the seeds is not too wet, which promotes seed rot (Nicolae et al., 2015). This also applies to most crops.

5. If installing a shelter over the system, when building a roof consider middle support pipe along the hoops for structural stability. It may also be useful to consider either a taller roof, or mounting PVC hoops on a wooden frame that can be hinged to one side of the grow bed, and can be lifted from the opposite end to make access to plants easier. This is because in the current set-up, planting and harvesting requires crawling under the shelter, and may not be preferred by all users. This is illustrated in the picture below sourced from the ‘Flickr’ website.

Figure 41. Grow bed with hinged shelter.

Source: (EatYourGarden, 2009)

Another alternative would be to construct a roof with a vertical pole to support the curved roof, with plastic on the top and aphid mesh walls and doors. This would help increase the ventilation in grow beds and promote healthier plant growth.

6. Cost could be reduced further by introducing airlift pumps into the system, which only require the use of air pumps and not water pumps. An airlift pump is obtained by the difference in density of a water column versus the density of a column of an air and water mixture (Malone, 2013). Typically, an air blower is used to create the air/water mixture within a vertical stand pipe and can move water through an outlet located at any level on the stand pipe, depending on the quantity of air being pumped (Malone, 2013). This option may be limited by the scarcity of powerful aerators in Fiji; however, airlift pumps have been seen to reduce the cost of aquaponics systems by up to 75% (Olafs, 2014).

7. Another means of cost reduction could be to seek cheaper alternatives to building materials such as the fish tank and the grow bed frame. One such substitute could be the use of sand bags in place of wooden boards for the frame of the grow bed. This would help reduce the cost of the system and increase its profitability.

8. According to standard aquaponics calculations, not only was the grow bed area undersized when compared to the size of the fish tank component of the system, but the daily feed rations were high and the fish biomass was significantly lower than for typical recirculating systems (Malone, 2013; Rakocy, 2012; Rakocy et al., 2006). This suggests that the biomass of fish produced during this project was an understatement of the potential capacity of the system, provided that adequate oxygen can be made available.

9. As it relates to the fish cultivation, a means of further reducing the cost of aquaponics in Fiji would be to source a cheaper feed alternative.

For this system in particular:

The system built at Homes of Hope in Wailoku was a prototype of the aquaponics system designed by Wilson Lennard. The schematics provided were followed and the system was successfully constructed and operated for a total of 10 months. Having tested the system, there are some recommendations to be made to the make operation of the system more efficient and potentially more energy and cost effective.

1. The system should have been allowed to mature for a longer time period before the initial stocking was commenced in order to ensure a stable colony of bacteria in the system for nitrogen conversion.

2. Given that the two aquarium air pumps used on the system were at times inadequate, adding two more to the current set up would provide more oxygen to the fish tank to meet the minimum dissolved oxygen requirement of 5 mg/L.

3. A potential flaw in the design was noticed whichwas the lack of an outlet from the grow bed area. This would prove useful in the periodic cleaning of the gravel, to prevent accumulation of solids and associated anoxic conditions. While the gravel can be removed from the grow bed, washed and returned, this process would be labour intensive and could result in damage to the plastic liner used inside the grow beds. Additionally, the project site for this aquaponics system did not have adequate space on the side of the grow beds to facilitate the removal of gravel for washing.

4. The safest and cheapest location for an outlet in the current system would be on the grow bed drain pipe to the fish tank, via the installation of a removable joint on the drain pipe, rather than one continuous pipe. The removable component would be located half way between the grow bed and the fish tank and could be detached to prevent water from re-entering the fish tank when necessary. While the cleaning of the system is only required once every 12 to 18 months, having an easier means of doing so would make operation of the system more efficient.

5. For the system in Wailoku, filling the hole around the tank with soil and levelling the entire area would allow for easier and safer access to the various components of the system, in order to carry out regular tasks such as feeding and water testing.

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Appendix 1

System Design for Developing World Aquaponics System provided by Wilson Lennard

Note: all dimensions are quoted in mm.

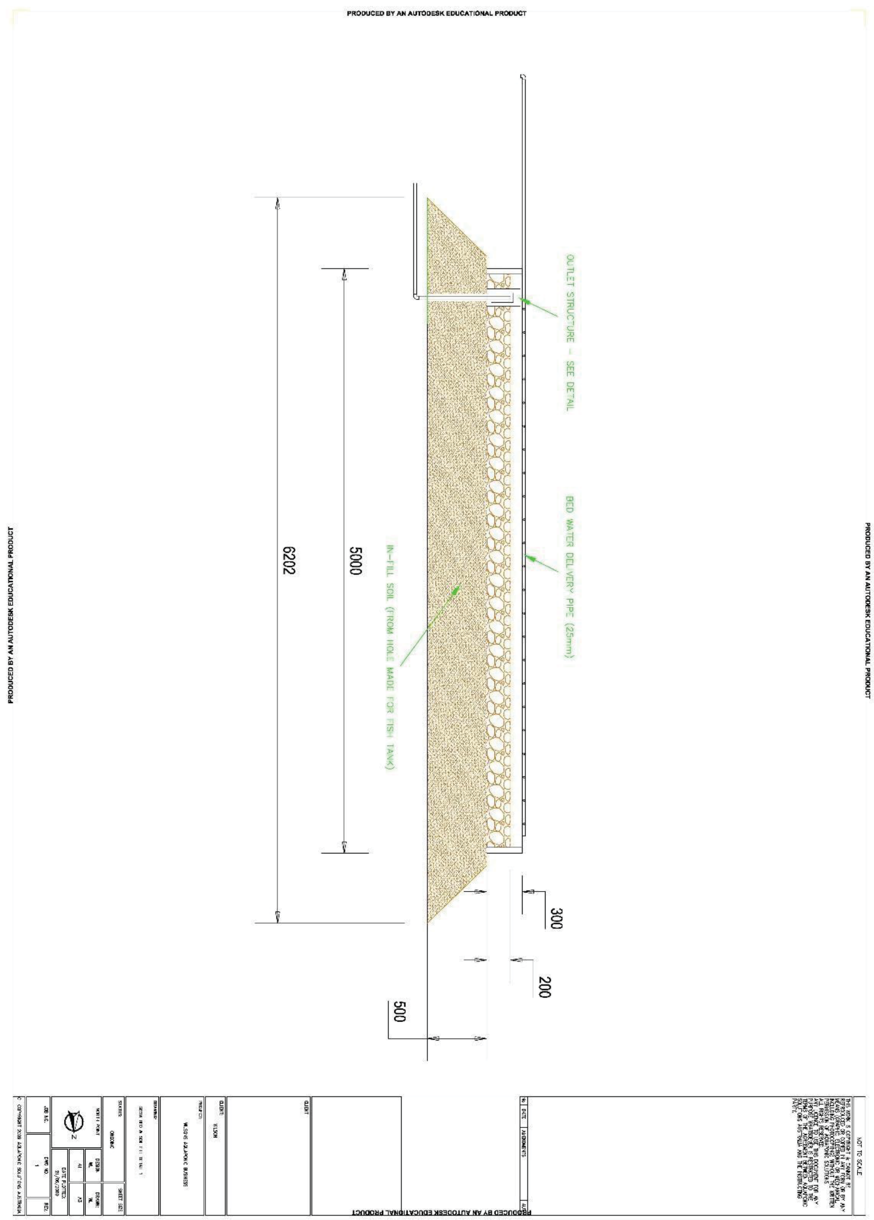


Figure 42. Elevation of grow bed component of system.

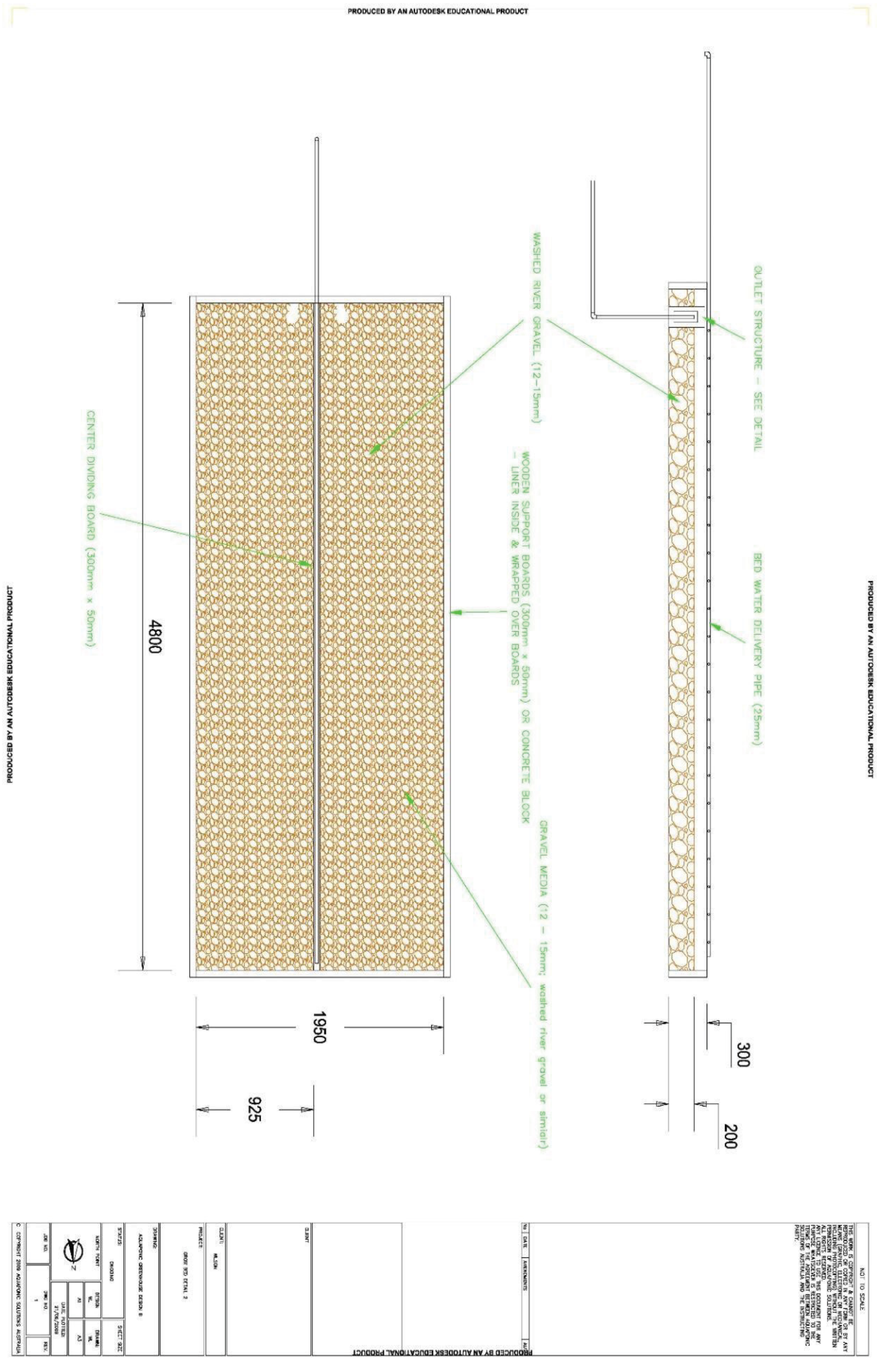


Figure 43. Grow bed details for the system

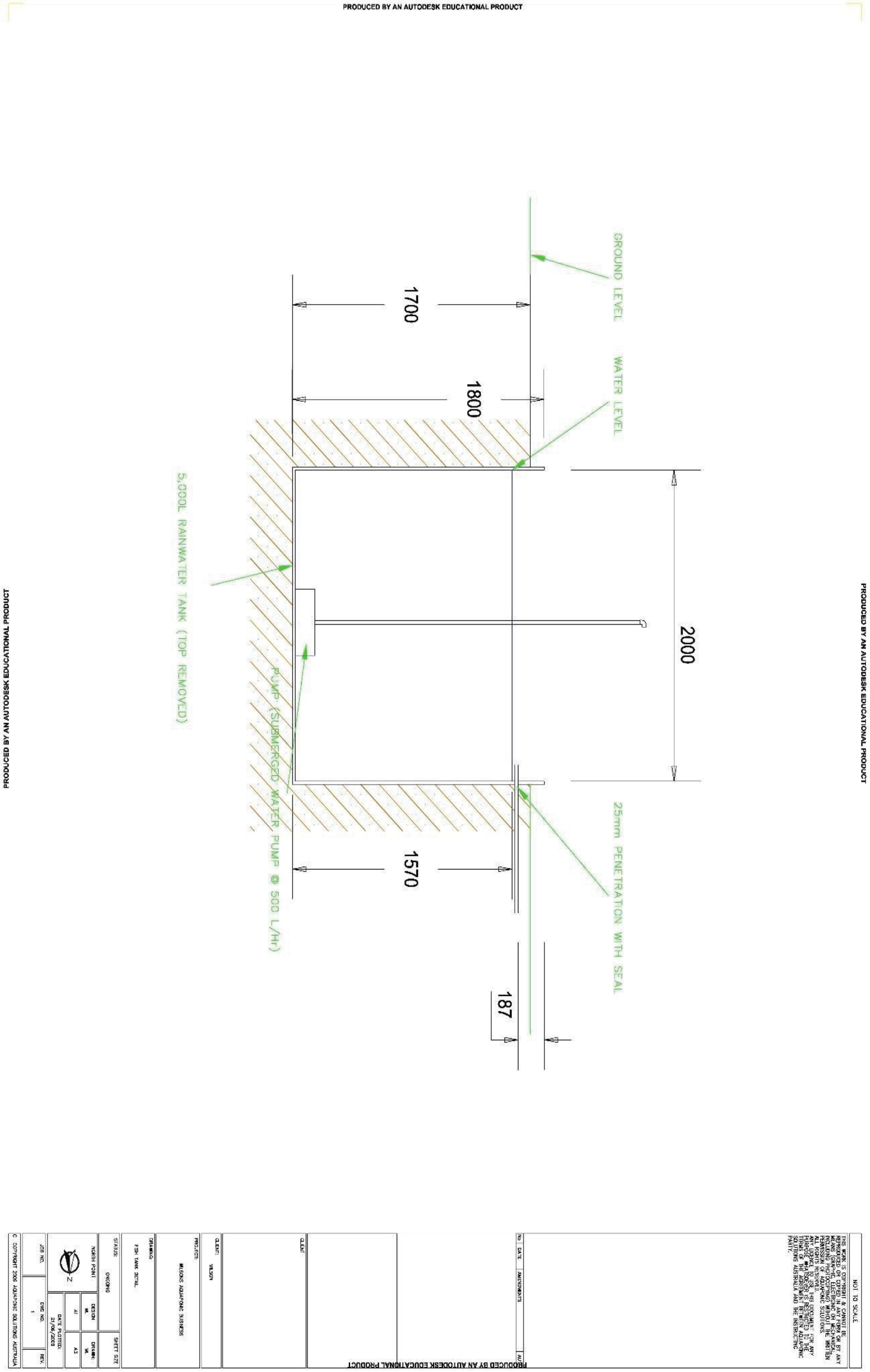


Figure 44. Fish tank detail for the system.

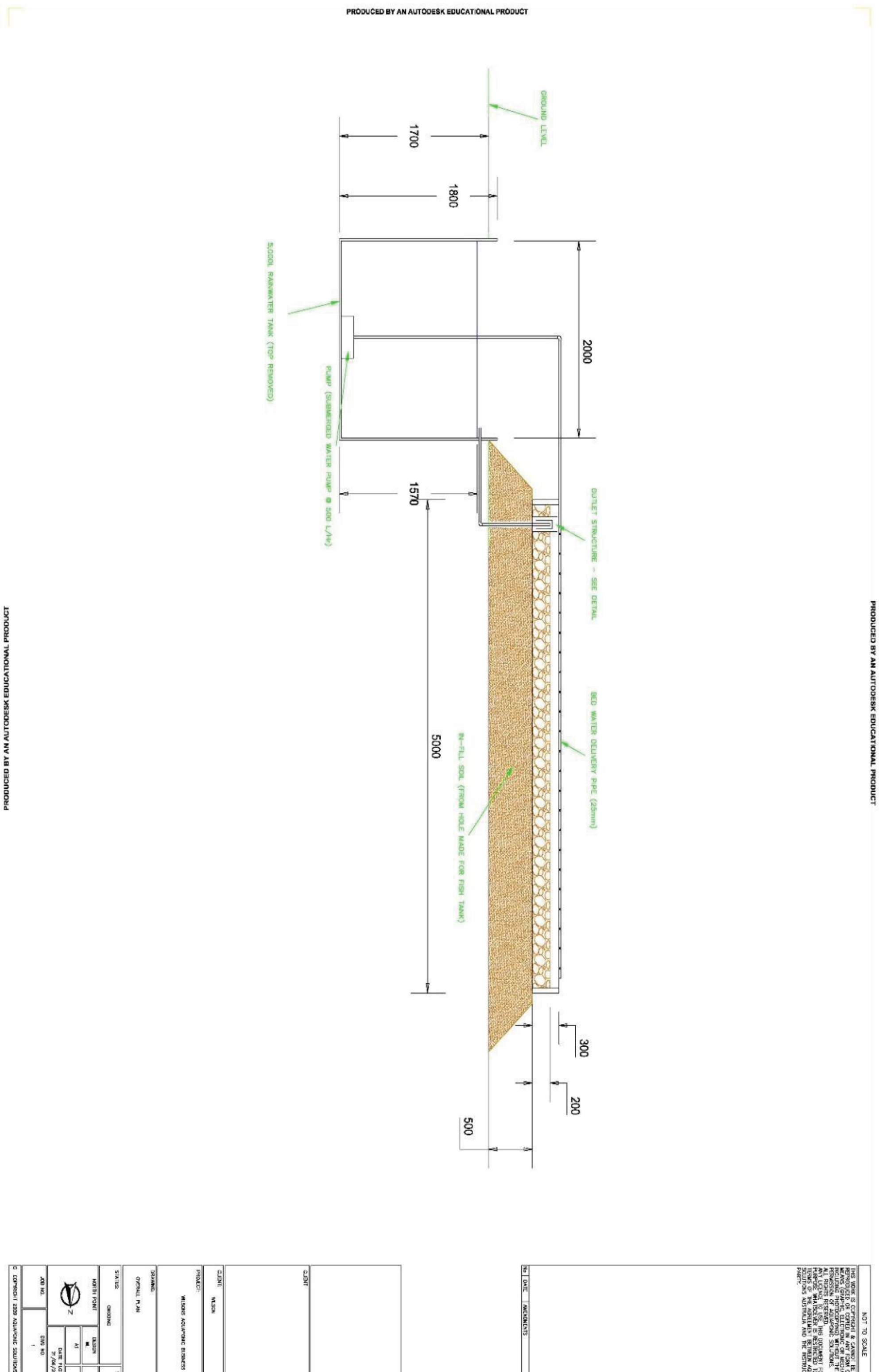


Figure 45. Elevation for all the components of the system.

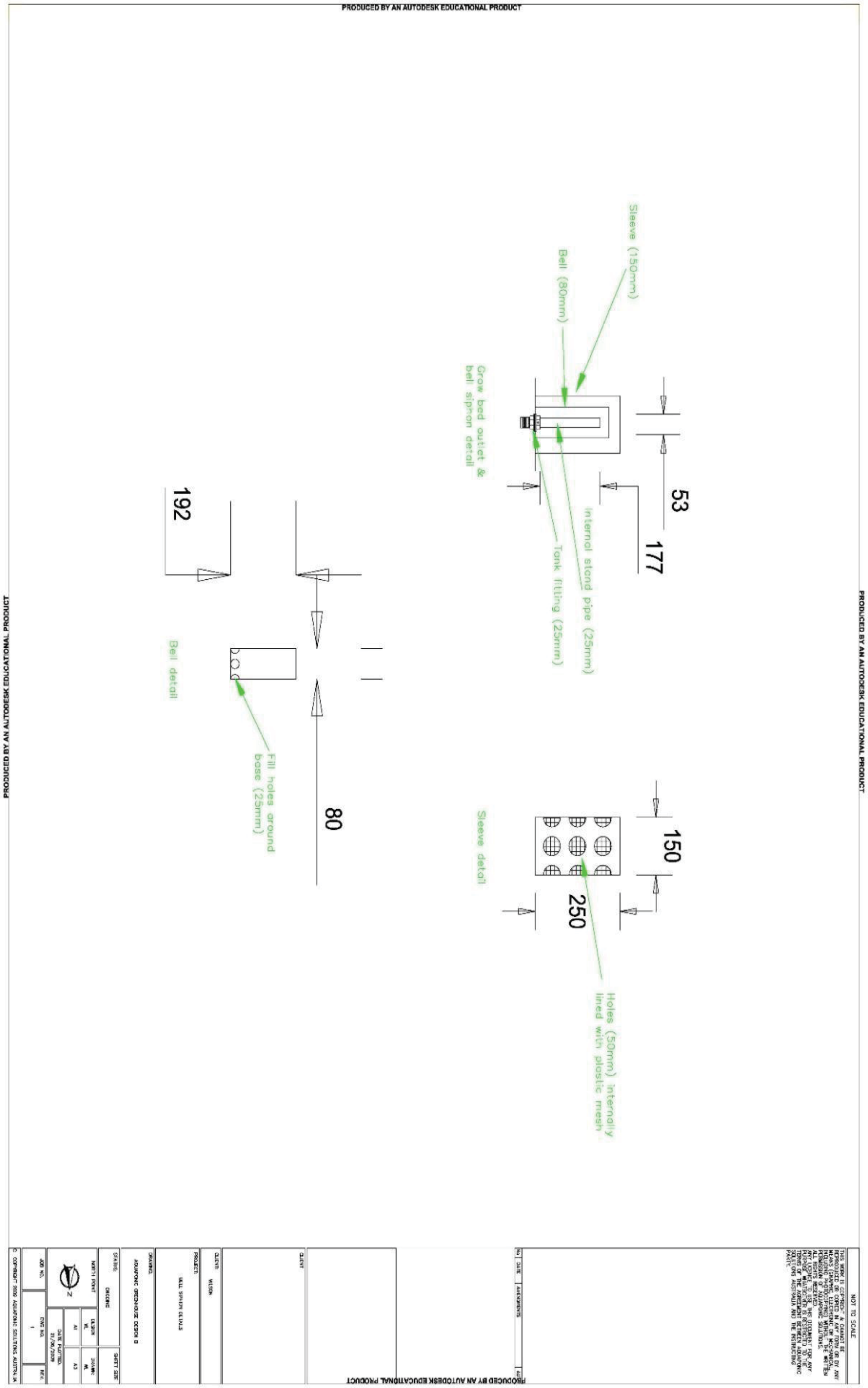


Figure 46. Bell siphon detail.

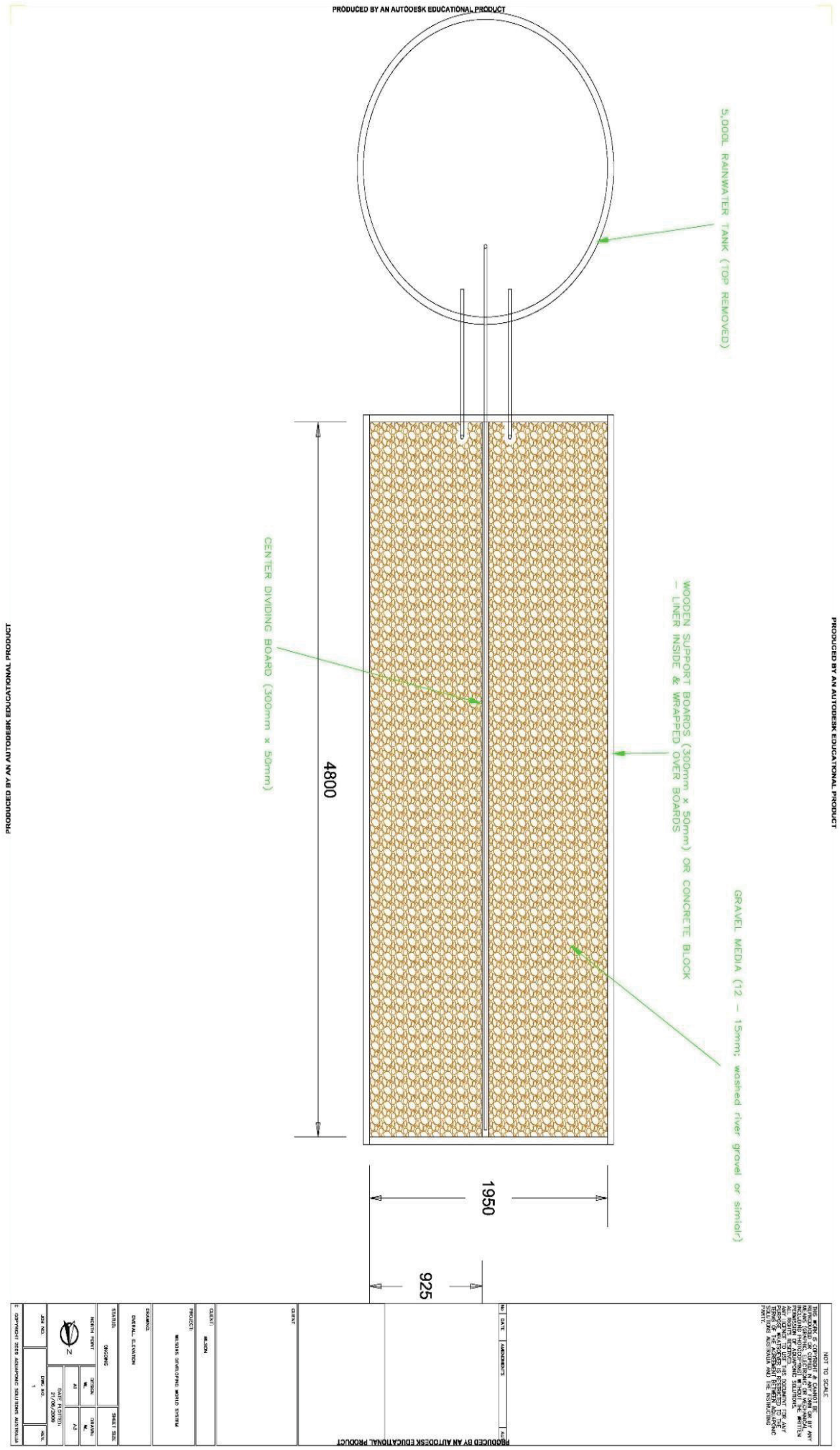


Figure 47. System Plan.

Material List

Table 4. List of all materials required for constructing the prototype of the aquaponics system

	Item	Description	Quantity	Cost (FJD)
FISH COMPONENT	Water Tank	5000L	1	1137.4
	Submersible Water pump	700L/Hr	2	156
	Air bubblers		3	90
PVC	Pressure pipe	25mm	16m	29.06
		50mm	6m	28.9
		80mm	1m	99.12
	End caps	25mm	2	3.6
		80mm	2	30.4
	Elbow	25mm	2	2.46
		50mm	4	21.6
	Pressure Socket	50mm	2	22.6
	Pressure Valve	50mm	2	4.7
	Rubber Washer	50mm	2	0.5
	Pressure R/Bush 50x25mm	50mm	2	9.2
ROOF	Plastic Liner	Woven	3m	66
	Rebar	15mm	3m	4.08
	PVC	15mm	9m	11.25
	Lock channel	6m	1	12
	Lock wire	2m	3	12
PLANT COMPONENT	Timber (treated Pine)	50mmx150mm (2x6 inches)	8 lengths of 5m	180
	Screws (metal)	3inch long; 100mm wide	36	19.99
	Plastic liner	Woven	7mx10m	154
	Gravel	15mm diameter	2m3 (half load)	186
	Nails	Flat head 1 inch long	32	5.54
	Waste paper bin		2	5.6
	Rubber Tube	5mm diameter	1m	0.25
	Cable Ties	Pack of 100	1	9.55
MISC	Silicone	Tube	1	10.9
	PVC tape	Roll	1	0.45
	Measuring Tape	8m	1	13.14
	PVC glue	Bottle	1	1.73
	Electrical work at Homes of Hope	1	390	390
	Bin for Feed storage	1	15	15

	Ag Lime	1	20	20
	Extension cords	2	19.5	39
	Gloves	1	1.9	1.9
	CaCO3	1	70	70
	Water (L)	2000		0
TOTAL				2863.92

Appendix 2

Water quality parameters recorded during project

Table 5. Water quality parameters and other notes made during project

D ate	H	Am monia (ppm)	N itrite (ppm)	N itrate (ppm)	D .O (mg/L)	A ir Temp C	W ater Temp C	eed (g)	Notes
3 0/05	.4	0.2 5	5	1 0					
6 -Jan	.2	0.2 5	5	1 0					
6 -Mar	.6	0.2 5	0	1 0					
6 -Jun	.6	0.2 5	0	2 0					
6 -Aug	.4	0.2 5	0	2 0					
6 -Oct	.2	0.2 5	0	1 0					
1 3/06	.2	0.2 5	0	2 0				35	Feed commenced
1 7/06	.2	0.5	1	2 0					Fish stock #2
2 0/06	.2	0.5	0 .5	1 0				35	7 dead fish
2 1/06	.2	0.2 5	2	1 0	5				17 dead fish. ~50% water exchange. Install aerator
2 2/06	.4	1	0 .25	5	7 .9				3 dead fish. Water cloudy; pumps off. Transplant 29 basil; 33 lettuce
2 3/06					8 .1				2 dead fish
2 7/06	.4	0.2 5	0	4 0				00	
2 9/06	.4	0.2 5	0	4 0				00	
7 -Apr	.2	0.2 5	0	4 0				00	
7 -Jun	.8	0	0	4 0				00	
7 -Aug	.8	0	1	4 0				00	
7 -Nov	.8	0.5	2	2 0				00	
7 -Dec		0.5	2	1 0	1 .6			00	
1 3/07	.4	1	0 .5	5	5 .8			00	
1 5/07	.4	0.5	0 .25	0	1 .3			00	
1 8/07	.2	0.2 5	0 .25	5	3 .4			50	Fish active. Water clear
2 0/07	.4	0.2 5	0 .25	0	2 .8			50	
2 2/07	.2	0.5	0 .25	0	1 .8			50	Extend growbed delivery pipes and make holes bigger. Install overflow hole.
2 5/07	.2	0.2 5	0 .25	5	3 .1			50	Add 2 more air stones
2 7/07	.4	0.5	0 .25	5	3 .8			50	
2 9/07	.2	0.5	0 .25	1 0	3 .58			50	
8 -Feb	.8	0.5	0	0					Water cloudy, fish piping. Cut off feed.
8 -Mar	.2	1	0	0					No observed piping. Water still cloudy.
8 -May	.4	1	0 .25	5	3 .9				1 dead fish.
8 -Aug	.8	0.2 5	0	5				00	
8 -Oct	.8	0.5	0	5				00	Water clear
8 -Dec	.2	0.2 5	0 .25	5				00	
1		0.5	0	5					Power outage. System fared well.

5/08	.8							00	
1 7/08	.8	0.5	0	0				00	
1 9/08	.8	1	0 .25	0				00	Delivery pipe detached from pump.
2 3/08	.8	0.5	0	0				00	
2 4/08	.8	0.5	0	0				00	plant lettuce (BC) seeds in tray 1. Transplant 24|20
2 6/08	.6	0.2 5	0	0				00	Pump disconnected from delivery pipe. Water turbid; a bit of surface gasping
2 8/08								00	Sunday crisis. 41 dead fish. 50% water exchange. Surface piping.
2 9/08									Big SPC aerator installed with 5 air stones. 20 dead fish removed. No more surface breathing after aerator installation.
3 0/08	.2	2	0 .25	0					Water change. Ammonia reduced to 1.0ppm
3 1/08	.2	2	0 .5	5					
9 -Jan	.4	1	0 .5	1 0					1 water pump not working.
9 -Mar	.4	0.2 5	0 .5	1 5					Transplant strawberry plant from Mark
9 -May	.4	0.2 5	0 .25	1 0				00	Resume feed (200g)
9 -Jun	.4	0.2 5	0 .5	1 0				00	Feed ~100g. Low response
9 -Aug	.4	0.2 5	0 .25	1 0				00	Feed ~100g. High response. Plant lettuce seeds (boxhill)
9 -Oct								00	Feed ~100g. High response.
9 -Dec	.4	0.2 5	0	3 0				00	Feed ~100g. High response. Revert to smaller aerators (pet shop sourced)
1 4/09	.8	0.2 5	0	2 0				00	Feed ~150g. HR. Water tea coloured. Strawberry (1 ripe, 2 green)
1 5/09		0.2 5	0	2 0				50	Feed ~150g. MR. Water tea coloured.
1 7/09								00	Feed ~100g. HR.
1 9/09	.8	0.2 5	0	3 0				50	Feed ~150g. HR. Harvest Strawberry.
2 1/09	.2	0.2 5	0	3 0				00	Feed ~200g. HR. Transplant lettuce. Harvest basil. Harvest strawberry.
2 2/09	.8	0.2 5	0	3 0				50	Feed ~250g. MR.
2 4/09								50	All well.
2 6/09	.8	0.2 5	0	3 0				50	Feed ~250g. HR. Plant seeds. Apply homemade pesticide to basil.
2 8/09	.2	0.2 5	0 .25	3 0				50	Feed 250g. Build frame for shade on lower half of growbeds
1 0-Mar	.4	0	0	4				50	Feed 250g. HR. Finish shade roof. Plant capsicum along edge of grow bed in unshaded portion. Apply iron chelate to all plants.
1 0-May	.4	0	0	6 0				00	Feed 300g. HR. Transplant lettuce. Plant mexican pepper seeds in tray 1.
1 0-Nov	.4	0.2 5	0	1 0				300	Feed 300g. HR. Start regular feeding.
1 3/10		0.2 5	0	2 0				00	Water clear.
1 7/10	.2	0.2 5	0 .25	4 0				00	Water clear.
1 9/10	.8	0.2 5	0	4 0				00	Water clear. Transplant lettuce. Plant Spinach seeds in tray 2 (summer supreme)
2 1/10	.8	0.2 5	0 .25	4 0				00	All well.
2 4/10	.8	0.2 5	0	3 0				00	strawberry and tomato fruiting. Tomato need support.
2 6/10		0.2 5	0	3 0				00	Basil harvested. Strawberry Harvest.
2 8/10	.2	0.2 5	0	3 0				00	All well.
1 1-Jan		0	0	5				00	Strawberry Harvest.
1 1-Apr	.8	0.2 5	0 .25	5				00	Lettuce harvest. Basil harvest
1 1-Sep		0.2 5	0	5				00	All well.

14/11		0.25	0	0				00	Lettuce black spot on leaf. Suspected fungus
16/11	.8	0.25	0	5				00	Tomato leaf yellowing
18/11	.6	0.25	0	0				00	Water cloudy. Fish piping at surface. Apply 5ml KOH. Put on big aerator. Lettuce harvest
21/11	.2	4	0	0				00	Water clearing. Piping observed. Tomato harvest.
23/11	.6	0	2	0				00	Prune tomato. Harvest basil and tomato. Plant seeds: Tray 1: lettuce. Tray 2: tomato (15), basil (15), lettuce(15), spinach
25/11	.4	0.25	2	20				00	Harvest tomato
30/11	.4	0.25	0	40				00	
12-Feb								00	Fish sampling. Install second water pump.
12-May	.8	0.25	0.25	20				00	Tomato harvest
12-Jul	.8	0.25	0.25	10				00	lettuce harvest
12-Sep		0.25	0.5	10				00	Tomato harvest
13/12	.6	0.25	0.25	0				00	Tomato harvest
19/12	.4	0.25	0	0				00	Tropical depression; excessive rains; destroy crops
23/12	.6	0.25	0	0				00	
28/12	.6	0.5	0.5	5				00	
30/12	.8	0.25	0	10				00	Harvest chili
1-May	.6	0.25	0.25	10				00	
1-Oct	.6	1	0	0				00	harvest basil. Harvest chili
1-Dec	.8	0.25	0	5				00	
17/01	.8	0.25	0.25	5				00	install pump sleeve. 1 pump not working. Harvest Chili
22/01	.8	0.25	0	0		32	24	00	plant basil seeds in tray 1
27/01	.8	0.25	0	0				00	Harvest Chili
2-Feb		0.5	0	0		34	26	00	spray neem oil on plants
2-Apr								00	basil seedlings 4 leaf stage. Spray iron chelate. Harvest chili
2-Jul	.6	0.5	0	0		38	28	00	harvest basil
2-Oct	.6	0.5	0	0	2.3	40	30	00	put on big aerator to monitor bacteria activity. Harvest Chili.
15/02	.6	0.5	0	0	8	38	28	00	aerator unplugged. Pump in bed 1 not working.
17/02		0.25	0.25	5	8	48	30	00	Harvest chili
20/02	.8	0.25	0.25	20	8	32	22	00	
23/02	.8	0.25	0.25	20	8	40	30	00	plant lettuce seeds (20). Harvest chili
27/02	.8	0.25	0.5	40	8	37	27	00	apply iron chelate. Install second water pump
3-Jun	.6	0.25	0.25	60	8	28	26	00	Harvest chili
3-Sep	.6	0.25	0	40	8	44	30	00	
13/03	.6	0.25	0.25	40	8	32	28	00	harvest chili
20/03	.6	0.25	0	80	8	40	28	00	Flow rate: bed 1- 55mins. Bed 2: 32 mins; harvest basil; plant lettuce
27/03	.6	0.5	0.25	100	8	44	28	00	Power outage; Harvest chilli
4-Apr					8			00	Power outage
4-Jun	.6	2	1	160	8	32	27	00	
4-Nov	.6	0.5	0.5	100	8	29	27	00	Harvest chilli

1 8/04	.6	0.2 5	0 .25	1 60	8	3 4	2 7	00	spray neem oil on plants; harvest lettuce
2 5/04	.6	0.2 5	0	1 60	8	2 7	2 7	00	Harvest Basil
2 6/05	.6	0.2 5	0	0	2 .1				
3 0/05	.6	0.2 5	0	0	1 .9				

The following tables show the harvests for each crop during the study period. The date of harvest, as well as the weight of the harvests. In some crops, the weight from shaded and unshaded portions were noted separately.

Table 6. Lettuce production during study period

Date	Covered	Uncovered	Total Weight (g)
04/11	4891	2701	7592
18/11	6077	2729	8806
07/12	830	474	1304
18/04	622	323	945

Table 7. three varieties of lettuce tested in the system

Harvest Weight (g)	Variety
71	1
104	1
79	1
87	1
57	1
133	1
59	1
89	1
95	1
115	2
63	2
67	2
79	2
98	3
66	3
100	3
117	3
38	3
43	3
73	3
28	3
77	3
42	3
40	3

KEY	
Variety	1=GM
	2=BC
	3=BH

Table 8. Basil production during study period

Date	Shaded	Unshaded	Total Weight (g)
21/09	1199	801	2000
26/10	1150	850	2000
04/11	1287	999	2286
23/11	947	830	1777
10/01	1190	890	2080
07/02	1225	882	2107
20/03	1680	1747	3427
25/04	3018	2365	5383

Table 9. Tomato production during study period

Date	Weight (g)
21/11	244
23/11	455
28/11	492
05/12	890
13/12	343

Table 10. Chili harvested during study period

Date	Weight (g)
30/12	35
17/01	77
27/01	106
04/02	89
10/02	128
17/02	97
23/02	167
06/03	286
13/03	308
27/03	329
11/04	209
25/04	257

Table 11. Strawberry harvest during study period

Date	Weight (g)
14/09	79
19/09	147
21/09	185
26/10	198
01/11	94

The following tables show the data used to compare harvests based on grow bed, roof cover and pest control.

Table 12. The weight of harvests in grams of basil and lettuce in shaded and unshaded grow bed areas

Crop	Weight (g)	Roof	Season
Basil	1199	1	1
Basil	1150	1	1
Basil	1287	1	1
Basil	947	1	1
Basil	1190	1	2
Basil	1225	1	2
Basil	1680	1	2
Basil	3018	1	2
Basil	801	2	1
Basil	850	2	1
Basil	999	2	1
Basil	830	2	1
Basil	890	2	2
Basil	882	2	2
Basil	1747	2	2
Basil	2365	2	2
Lettuce	4891	1	1
Lettuce	6077	1	1
Lettuce	830	1	2
Lettuce	622	1	2
Lettuce	2701	2	1
Lettuce	2729	2	1
Lettuce	474	2	2
Lettuce	323	2	2

Key	
Roof	1=Present
	2=Absent
Season	1=Dry
	2=Wet

Table 13. The harvest weight in grams of various crops from each grow bed

Crop	Growbed 1	Growbed 2
Lettuce	3624	3968
Lettuce	3750	5056
Lettuce	636	668
Lettuce	398	547
Basil	979	1021
Basil	970	1030
Basil	1062	1224
Basil	862	915
Basil	1030	1050
Basil	1090	1017
Basil	1830	1597
Basil	4475	908
Tomato	98	146
Tomato	305	150
Tomato	222	270
Tomato	537	353
Tomato	188	155
Strawberry	0	79
Strawberry	147	0

Strawberry	150	35
Strawberry	53	145
Strawberry	94	0

Table 14. Percentage crop infection by pests and diseases based on pest control treatment

	Treatment			
Crop	*1*	*2*	*3*	*4*
Lettuce	12	20	30	75
Lettuce	15	25	34	81
Lettuce	10	30	30	60
Lettuce	10	35	40	84
Basil	12	38	65	80
Basil	15	40	48	87
Basil	14	27	45	76
Basil	12	32	50	82
Basil	10	30	40	65
Basil	15	40	37	70
Basil	10	21	36	60
Basil	8	15	22	46

Weather Data

Table 15. Suva average monthly rainfall and temperature data during the study period

Year	Month	Week	Temperature ^{0}C	Precipitation (mm)
2016	June	4	24	82
	July	8	23	47
	August	12	23	346
	September	16	23	25
	October	20	25	311
	November	24	26	38
	December	28	26	809
2017	January	32	27	267
	February	36	27	1145
	March	40	27	230
	April	44	27	192
	May	48	26	208

Source: AccuWeather (http://www.accuweather.com/en/fj/suva/127517/weather-forecast/127517)

Fish Weight Data

Table 16. Fish Weights during project

WEIGHT (g)	<50	50-100	100-200	200-300	300-400	400-500	>500
FIRST BATCH	19	50	100				
	20	50	103				
	21	51	103				
	22	51	104				
	23	51	105				
	23	51	106				
	24	52	107				
	24	52	107				
	26	53	109				
	26	54	109				
	27	55	110				
	28	56	111				
	28	56	111				
	28	56	113				
	28	57	114				
	29	58	114				
	29	58	114				
	30	59	115				
	30	61	115				
	30	62	119				
	31	62	120				
	31	62	120				
	32	64	123				
	33	68	129				
	33	69	136				
	33	70	136				
	33	71	140				
	34	77	140				
	34	78	140				
	35	84	140				
	35	86	145				
	35	86	151				
	37	86	157				
	37	87	157				
	37	88	158				
	39	88	159				
	40	88	163				
	40	89	163				
	41	89	164				
	42	91	164				
	43	91	164				
	44	95	164				
	44	95	166				
	44	97	167				
	45	97	169				
	47	97	178				
	48	99	179				
	48	99	180				
	49		199				
	49		204				

			213				
			214				
			232				
			254				
17-Jun	27	51	100				
	31	53	103				
	33	54	114				
	34	54	115				
	35	54	115				
	38	55	120				
	40	55	127				
	44	56	127				
	44	56	128				
	45	57	144				
	45	62	146				
	45	64	161				
	48	65	166				
	48	65	166				
	49	67	184				
		67	189				
		69	194				
		69	196				
		70					
		71					
		72					
		75					
		80					
		80					
		81					
		90					
		90					
		94					
		96					
O2 DEC STOCK		63	100	223	312		
		66	100	240	326		
		68	100	260			
		70	101	262			
		72	102	288			
		72	103	288			
		72	103				
		72	104				
		76	104				
		77	104				
		81	108				
		83	109				
		84	110				
		85	110				
		86	116				
		88	118				
		89	120				
		91	120				
		91	120				
		91	121				
		92	121				

		93	122				
		93	123				
		93	125				
		96	125				
		98	126				
		99	126				
			127				
			127				
			129				
			139				
			145				
			147				
			147				
			147				
			148				
			151				
			152				
			152				
			153				
			153				
			159				
			198				
16-May		82	103	203	300	405	503
		86	103	205	300	433	511
			137	206	307	445	532
			139	207	310	455	618
			144	209	318	464	
			145	209	329	483	
			156	211	330		
			157	212	341		
			157	212	349		
			160	217	353		
			171	222	359		
			175	223	363		
			178	224	365		
			180	225	365		
			187	228	377		
			189	228	388		
			196	229	393		
			199	232			
				233			
				235			
				235			
				237			
				240			
				244			
				245			
				250			
				250			
				255			
				266			
				267			
				272			
				275			

				275			
				287			
				291			

Table 17. Capital cost of system

	Item	Description	Quantity	Cost
Labour		$30/day	10	300
Fish Component	Water Tank	5000L	1	1137.4
	Submersible Water pump	700L/Hr	2	156
	Air bubblers		3	90
PVC	Pressure pipe	25mm	16m	29.06
		50mm	6m	28.9
		80mm	1m	99.12
	End caps	25mm	2	3.6
		80mm	2	30.4
	Elbow	25mm	2	2.46
		50mm	4	21.6
	Pressure Socket	50mm	2	22.6
	Pressure Valve	50mm	2	4.7
	Rubber Washer	50mm	2	0.5
	Pressure R/Bush (50x25mm)	50mm	2	9.2
Roof	Plastic Liner	Woven	3m	66
	Rebar	15mm	3m	4.08
	PVC	15mm	9m	11.25
	Lock channel	6m	1	12
	Lock wire	2m	3	12
	Timber (treated Pine)	50mmx150m m (2x6 inches)	8 lengths of 5m	180
	Screws (metal)	3inch long; 100mm wide	36	19.99
	Plastic liner	Woven	7mx10m	154
	Gravel	15mm diameter	2m3(half load)	186
	Nails	Flat head 1 inch long	32	5.54
	Waste paper bin		2	5.6
	Rubber Tube	5mm diameter	1m	0.25
Misc	Cable Ties	Pack of 100	1	9.55
	Silicone	Tube	1	10.9

	PVC tape	Roll	1	0.45
	Measuring Tape	8m	1	13.14
	PVC glue	Bottle	1	1.73
	Electrical work at Homes ofHope	1	390	390
	Bin for Feed storage	1	15	15
	Arg Lime	1	20	20
	Extension cords	2	19.5	39
	Gloves	1	1.9	1.9
	$CaCO_3$	1	70	70
	Water (L)	2000		0
Total				3163.92

Appendix 3

SPSS Output

PEST CONTROL TREATMENTS

Descriptives

Percentage Infected

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound
Treatment 1 (neem+roof)	12	11.92	2.392	.690	10.40
Treatment 2 (neem+no roof)	12	29.42	8.140	2.350	24.24
Treatment 3 (no neem+roof)	12	39.75	11.274	3.255	32.59
Treatment 4 (no neem+no roof)	12	72.17	12.268	3.542	64.37
Total	48	38.31	23.939	3.455	31.36

ANOVA

Percentage Infected

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	23088.562	3	7696.188	88.054	.000
Within Groups	3845.750	44	87.403		
Total	26934.312	47			

Post Hoc Tests

Multiple Comparisons

Dependent Variable: Percentage Infected

Tukey HSD

(I) Pest Control Treatment	(J) Pest Control Treatment	Mean Difference (I-J)	Std. Error	Sig.
Treatment 1 (neem+roof)	Treatment 2 (neem+no roof)	-17.500*	3.817	.000
	Treatment 3 (no neem+roof)	-27.833*	3.817	.000
	Treatment 4 (no neem+no roof)	-60.250*	3.817	.000
Treatment 2 (neem+no roof)	Treatment 1 (neem+roof)	17.500*	3.817	.000
	Treatment 3 (no neem+roof)	-10.333*	3.817	.046
	Treatment 4 (no neem+no roof)	-42.750*	3.817	.000
Treatment 3 (no	Treatment 1 (neem+roof)	27.833*	3.817	.000

neem+roof)	Treatment 2 (neem+no roof)	10.333*	3.817	.046
	Treatment 4 (no neem+no roof)	-32.417*	3.817	.000
Treatment 4 (no neem+no roof)	Treatment 1 (neem+roof)	60.250*	3.817	.000
	Treatment 2 (neem+no roof)	42.750*	3.817	.000
	Treatment 3 (no neem+roof)	32.417*	3.817	.000

*. The mean difference is significant at the 0.05 level.

Homogeneous Subsets

Percentage Infected

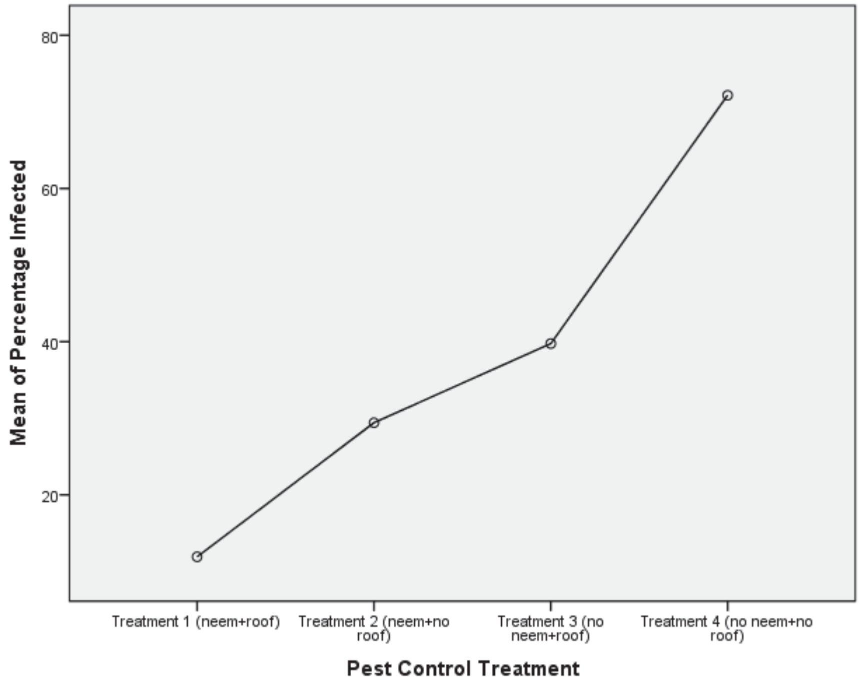
Tukey HSD[a]

Pest Control Treatment	N	Subset for alpha = 0.05			
		1	2	3	4
Treatment 1 (neem+roof)	12	11.92			
Treatment 2 (neem+no roof)	12		29.42		
Treatment 3 (no neem+roof)	12			39.75	
Treatment 4 (no neem+no roof)	12				72.17
Sig.		1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 12.000.

Means Plots



LETTUCE VARIETIES

Harvest Weight

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Green Mignonette	9	86.00	23.633	7.878	67.83	104.17
Buttercrunch	4	81.00	23.664	11.832	43.34	118.66
Box Hill	11	65.64	29.931	9.024	45.53	85.74
Total	24	75.83	27.416	5.596	64.26	87.41

ANOVA

Harvest Weight

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2180.788	2	1090.394	1.516	.243
Within Groups	15106.545	21	719.359		
Total	17287.333	23			

Post Hoc Tests

Multiple Comparisons

Dependent Variable: Harvest Weight

(I) Variety	(J) Variety	Mean Difference	Std. Error	Sig.

			(I-J)		
Tukey HSD	Green Mignonette	Buttercrunch	5.000	16.117	.948
		Box Hill	20.364	12.055	.233
	Buttercrunch	Green Mignonette	-5.000	16.117	.948
		Box Hill	15.364	15.660	.597
	Box Hill	Green Mignonette	-20.364	12.055	.233
		Buttercrunch	-15.364	15.660	.597
LSD	Green Mignonette	Buttercrunch	5.000	16.117	.759
		Box Hill	20.364	12.055	.106
	Buttercrunch	Green Mignonette	-5.000	16.117	.759
		Box Hill	15.364	15.660	.338
	Box Hill	Green Mignonette	-20.364	12.055	.106
		Buttercrunch	-15.364	15.660	.338

Homogeneous Subsets

Harvest Weight

	Variety	N	Subset for alpha = 0.05 1
Tukey HSD[a,b]	Box Hill	11	65.64
	Buttercrunch	4	81.00
	Green Mignonette	9	86.00
	Sig.		.367
Tukey B[a,b]	Box Hill	11	65.64
	Buttercrunch	4	81.00
	Green Mignonette	9	86.00

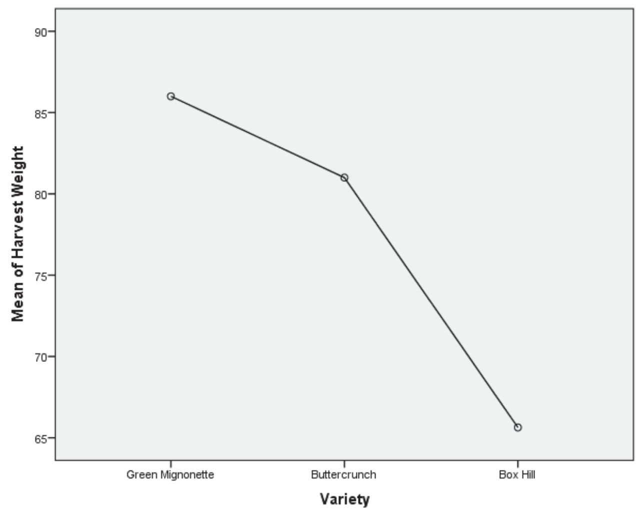
Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 6.637.

b. The group sizes are unequal. The harmonic mean of the group sizes is used.

Type I error levels are not guaranteed.

Means Plots



LETTUCE AND SHELTER

Group Statistics

	Roof	N	Mean	Std. Deviation	Std. Error Mean
Lettuce Weight (g)	Roof Present	4	3105.00	2790.669	1395.334
	Roof Absent	4	1556.75	1338.901	669.450

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Lettuce Weight (g)	Equal variances assumed	24.273	.003	1.000	6
	Equal variances not assumed			1.000	4.312

Independent Samples Test

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
Lettuce Weight (g)	Equal variances assumed	.356	1548.250	1547.618
	Equal variances not assumed	.370	1548.250	1547.618

BASIL AND SHELTER

T-Test

Group Statistics

	Roof	N	Mean	Std. Deviation	Std. Error Mean
Basil Weight (g)	Roof Present	8	1462.00	661.295	233.803
	Roof Absent	8	1170.50	573.921	202.912

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df

Basil Weight (g)	Equal variances assumed	.000	.997	.942	14
	Equal variances not assumed			.942	13.728

Independent Samples Test

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
Basil Weight (g)	Equal variances assumed	.362	291.500	309.576
	Equal variances not assumed	.363	291.500	309.576

LETTUCE SEASONALITY

Descriptives

Mean Weight (g)

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound
Green Mignonette	1	90.166666670000000	.	.	.
Buttercrunch	1	86.000000000000000	.	.	.
Box Hill	1	73.708333330000000	.	.	.
Total	3	83.291666670000000	8.556896991000000	4.940326781000000	62.035156160000000

Independent Samples Test

	Levene's Test for Equality of Variances		t-test for Equality of Means						
								95% Confidence Interval of the Difference	
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Weight Equal variances assumed	.008	.933	10.024	3	.002	999.667	99.723	682.304	1317.029

Equal variances not assumed				9.882	2.168	.008	999.667	101.160	595.159	1404.174

BASIL SEASONALITY

Group Statistics

	Season	N	Mean	Std. Deviation	Std. Error Mean
Total Weight (g)	Wet	4	2015.75	208.593	104.296
	Dry	4	3249.25	1555.245	777.623

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Total Weight (g)	Equal variances assumed	6.343	.045	-1.572	6
	Equal variances not assumed			-1.572	3.108

Independent Samples Test

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
Total Weight (g)	Equal variances assumed	.167	-1233.500	784.586
	Equal variances not assumed	.211	-1233.500	784.586

FISH WEIGHT

Descriptives

Weight (g)

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean Lower Bound	95% Confidence Interval for Mean Upper Bound
Start Weight	214	84.50	50.376	3.444	77.72	91.29
December Weight	78	126.35	57.894	6.555	113.29	139.40
End Weight	82	268.28	109.137	12.052	244.30	292.26
Total	374	133.52	100.544	5.199	123.30	143.75

ANOVA

Weight (g)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2007301.585	2	1003650.793	211.157	.000
Within Groups	1763401.698	371	4753.104		
Total	3770703.283	373			

Post Hoc Tests

Multiple Comparisons

Dependent Variable: Weight (g)

	(I) Time Period	(J) Time Period	Mean Difference (I-J)	Std. Error	Sig.
Tukey HSD	Start Weight	December Weight	-41.841*	9.119	.000
		End Weight	-183.776*	8.954	.000
	December Weight	Start Weight	41.841*	9.119	.000
		End Weight	-141.934*	10.904	.000
	End Weight	Start Weight	183.776*	8.954	.000
		December Weight	141.934*	10.904	.000

*. The mean difference is significant at the 0.05 level.

Homogeneous Subsets

Weight (g)

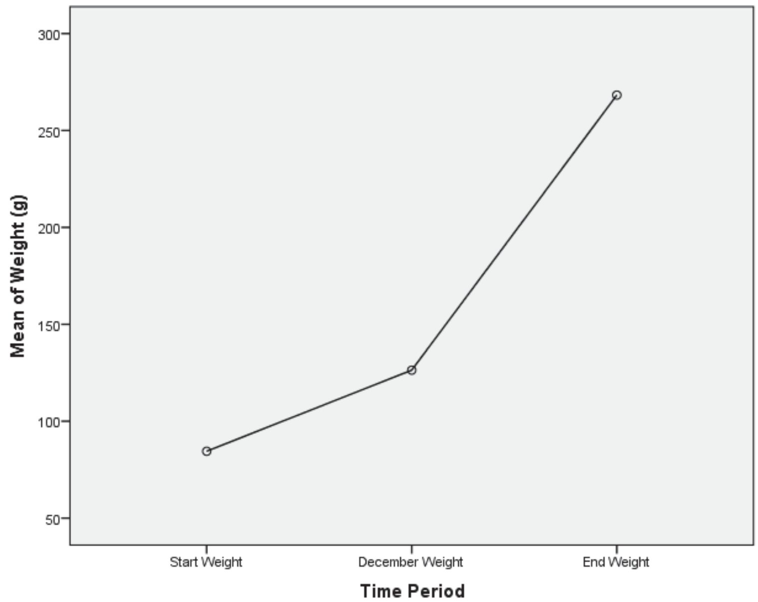
	Time Period	N	Subset for alpha = 0.05		
			1	2	3
Tukey B[a,b]	Start Weight	214	84.50		
	December Weight	78		126.35	
	End Weight	82			268.28

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 101.049.

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Means Plots



NITRATES AND DISSOLVED OXYGEN

Descriptive Statistics

	Mean	Std. Deviation	N
D.O (mg/L)	5.5062	2.67258	29
Nitrate	36.034	51.8304	29

Correlations

		D.O (mg/L)	Nitrate
D.O (mg/L)	Pearson Correlation	1	.597**
	Sig. (2-tailed)		.001
	N	29	29
Nitrate	Pearson Correlation	.597**	1
	Sig. (2-tailed)	.001	
	N	29	29

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.597[a]	.357	.333	42.3253	.357	14.988	1	27	.001

a. Predictors: (Constant), D.O (mg/L)

b. Dependent Variable: Nitrate

WEATHER
T-Test

Group Statistics

	Roof	N	Mean	Std. Deviation	Std. Error Mean
Percentage affected	Roof	5	.00	.000	.000
	No roof	5	11.00	6.519	2.915

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Percentage affected	Equal variances assumed	15.540	.004	-3.773	8
	Equal variances not assumed			-3.773	4.000

Independent Samples Test

		t-test for Equality of Means		
		Sig. (2-tailed)	Mean Difference	Std. Error Difference
Percentage affected	Equal variances assumed	.005	-11.000	2.915
	Equal variances not assumed	.020	-11.000	2.915

Appendix 4

Aquaponics Economic Model

The model was developed using Microsoft Excel, with a total of 7 worksheets within one spreadsheet document. The 7 worksheets will be displayed below.

Table 18. Physical description of the system

Physical Description			
Grow beds			
	Number of grow beds	2	
	Length of grow bed	5	metres
	Width of grow bed	1	metres
	Grow bed surface area	5	metres
Fish Tanks			
	Number of fish tanks	1	
	Volume of fish tank	2000	litres
		20	square meters

Table 19. Capital cost of the system

	Item	Description	Quantity	Cost
Labour		$30/day	10	300
Fish Component	Water Tank	5000L	1	1137.4
	Submersible Water pump	700L/Hr	2	156
	Air bubblers		3	90
PVC	Pressure pipe	25mm	16m	29.06
		50mm	6m	28.9
		80mm	1m	99.12
	End caps	25mm	2	3.6
		80mm	2	30.4
	Elbow	25mm	2	2.46
		50mm	4	21.6
	Pressure Socket	50mm	2	22.6
	Pressure Valve	50mm	2	4.7
	Rubber Washer	50mm	2	0.5
	Pressure R/Bush 50x25mm	50mm	2	9.2
Roof	Plastic Liner	Woven	3m	66
	Rebar	15mm	3m	4.08
	PVC	15mm	9m	11.25
	Lock channel	6m	1	12

	Lock wire	2m	3	12
Plant Component				
	Timber (treated Pine)	50mmx150mm (2x6 inches)	8 lengths of 5m	180
	Screws (metal)	3inch long; 100mm wide	36	19.99
	Plastic liner	Woven	7mx10m	154
	Gravel	15mm diameter	2m3 (half load)	186
	Nails	Flat head 1 inch long	32	5.54
	Waste paper bin		2	5.6
	Rubber Tube	5mm diameter	1m	0.25
Misc	Cable Ties	Pack of 100	1	9.55
	Silicone	Tube	1	10.9
	PVC tape	Roll	1	0.45
	Measuring Tape	8m	1	13.14
	PVC glue	Bottle	1	1.73
	Electrical work at Homes of Hope	1	390	390
	Bin for Feed storage	1	15	15
	Arg Lime	1	20	20
	Extension cords	2	19.5	39
	Gloves	1	1.9	1.9
	CaCO3	1	70	70
	Water (L)	2000		0
Total				3163.92

Table 20. Breakdown of operating costs of the system for one year

Item	Quantity	Unit cost	Total Cost
Water Test Kits	2	$89.30	$178.60
Potting mix	4	$10.30	$41.20
Seedling Trays	2	$3.00	$6.00
Sweet Basil Seeds	2	$1.50	$3.00
Lettuce Seeds	4	$2.50	$10.00
Tilapia Pellets	4	$31.00	$124.00
Tomato seeds	1	$2.50	$2.50
Iron Chelate	1	$20.00	$20.00
Neem Oil	1	$2.00	$2.00
Chili seeds	4	$3.00	$12.00
Electricity (kw)	198.8	$0.33	$65.80
Total			$465.10

Table 21. The grow out parameters for the system

Lettuce Production Targets			
	Actual number of plants sowed per crop	52	
	Potential number of plants at the end of crop	200	
Lettuce Growout Parameters			
	Growout period	1	Months
	Actual Stocking density	20	per square meter
	Potential Stocking density	20	per square meter
	Mean weight at harvest	70.6	Grams
Lettuce Harvest			
	Production per crop	3.6712	Kilograms
	Potential production per crop	14.12	Kilograms
Basil Production Targets			
	Actual number of plants sowed per crop	12	
	Potential number of plants at the end of crop	250	
Basil Growout Parameters			
	Growout period	1	Months
	Actual Stocking density	10	per square meter
	Potential Stocking density	25	per square meter
	Mean weight at harvest	192	Grams
Basil Harvest			
	Production per crop	2.304	Kilograms
	Potential production per crop	48	Kilograms
Tomato Production Targets			
	Actual number of plants per crop	3	
	Potential number of plants per crop	60	
Tomato Growout Parameters			
	Growout period	1	Months
	Actual Stocking density	3	per square meter
	Potential Stocking density	6	per square meter
	Mean weight of harvest per plant	852	Grams
Tomato Harvest			
	Production per crop	2.556	kilograms
	Potential production per crop	51.12	kilograms
Chilli Production Targets			
	Actual number of plants sowed per crop	2	
	Potential number of plants per crop	120	
Chilli Growout Parameters			
	Growout period	1	months
	Actual Stocking density	2	per square meter
	Potential Stocking density	12	per square meter
	Mean weight of harvest per plant	250	grams
Chilli Harvest			
	Production per crop	0.5	kilograms
	Potential production per crop	30	kilograms
Strawberry Production Targets			
	Actual number of plants sowed per crop	2	
	Potential number of plants at the end of crop	200	

Strawberry Growout Parameters		
Growout period	1	months
Actual Stocking density	2	per square meter
Potential Stocking density	20	per square meter
Mean weight of harvest per plant	150	grams
Strawberry Harvest		
Production per crop	0.3	kilograms
Potential production per crop	30	kilograms
Tilapia Production Targets		
Number of Tilapia stocked	80	
Number of Tilapia at the end of cycle	80	
Final Density of Tilapia	4	per square meter
Tilapia Growout Parameters		
Growout period	10	months
Actual Stocking density	4	per square meter
Potential stocking density	10	per square meter
Death rate during growout	1	%
Mean weight at harvest	269	grams
Tilapia Harvest		
Production per cycle	21.52	kilograms
Potential production per cycle	53.8	kilograms
Tilapia Feed Conversion Ratio		
Mean stocking weight	0.08	kilograms
Average daily feed	0.34	kilograms
Feed per cycle	102	kilograms
FCR	6.75	kg/kg
Daily Growth Rate	0.785714	grams per day

Table 22. The revenue earned and projected annual revenue of products in the system

Product	Price per kg	Number of cycles in study period	Revenue during study	Projected Annual Revenue
Lettuce	5.74	5	$105.36	$972.59
Basil	20	9	$414.72	$11,520.00
Tomato	3.74	1	$9.56	$1,147.13
Chilli	5.86	4	$11.72	$1,054.80
Strawberry	29	1	$8.70	$4,350.00
Tilapia	10	1	$215.20	$1,076.00
Total			$765.26	

Output Summary					Economic Indicators		
Annual Production							
	Lettuce	169.44	kilograms		Projected Annual return		$
	Basil	576	kilograms			Lettuce + Tilapia	$ 2,048.59

	Tomato	306.72	kilograms		Basil + Talapia	$12,596.00
	Chilli	180	kilograms		Tomato + Tilapia	$2,223.13
	Strawberry	150	kilograms		Chilli + Tilapia	$2,130.80
	Tilapia	107.6	kilograms		Strawberry + Tilapia	$5,426.00
Annual Gross Revenue				Projected Net Value		
	Lettuce	$972.59			Lettuce + Tilapia	$1,581.24
	Basil	$11,520.00			Basil + Talapia	$12,135.66
	Tomato	$1,147.13			Tomato + Tilapia	$1,763.29
	Chilli	$1,054.80			Chilli + Tilapia	$1,661.46
	Strawberry	$4,350.00			Strawberry + Tilapia	$5,037.86
	Tilapia	$1,076.00				
				Current Net Value	Crops + Tilapia	($2,863.76)
		Annual	Per kg			
Production Cost						
	Lettuce	$79.20	$0.47			
	Basil	$72.20	$0.13			
	Tomato	$71.70	$0.23			
	Chilli	$81.20	$0.45			
	Strawberry	$0.00	$0.00			
	Tilapia	$388.14	$3.61			
Cost structure summary						
		Annual	per kg			
	Feed	$124.00	1.152416			
	Electricity	$65.80				
	Tilapia Operating Cost	$388.14				
	Crop Operating Cost	$60.86				
	Aquaponics Capital Cost	$3,163.92				

Note:

Net Value refers to the potential profits made if the system is cultivated at maximum capacity using the specified selection of crops after operating costs are removed. Positive values suggest a profit.

Table 23. Cash flow

	Year 1 (study)	Year 2	Year 3	Year 4	Year 5
Lettuce	-$2,863.76	-$1,282.52	-$168.62	$945.28	$2,059.18
Basil	-$2,863.76	$9,271.90	$20,947.21	$32,622.52	$44,297.83
Tomato	-$2,863.76	-$1,100.47	$202.97	$1,506.42	$2,809.87
Chilli	-$2,863.76	-$1,202.30	-$10.19	$1,181.92	$2,374.03
Strawberry	-$2,863.76	$2,174.10	$6,823.81	$11,473.52	$16,123.23

Appendix 5

User Manual

Low-Cost Aquaponics System

User Manual

January 2018

This manual was compiled by Mia Avril after building a prototype of the system and testing for several months. Under the supervision of Timothy Pickering (PhD) (SPC), Wilson Lennard (PhD) (Aquaponics Solution) and Professor Ciro Rico (USP).

TABLE OF CONTENTS

GENERAL INFORMATION

Aquaponics has been identified as a means to help countries, communities or persons meet their food security demands. Its closed system approach to cultivation of fish and vegetables is safe for the environment as it eliminates the contamination experienced with other traditional forms of crop and fish cultivation. Since it is not possible to use plant fertilizers or pesticides in aquaponics it is possible to produce fish and vegetables through the use of fish feed, thereby producing organic and chemical free food. Aquaponics can vary from backyard to commercial size, however the system presented in this manual is for personal or community use. Although the system does not occupy much land space, its potential productivity makes it a profitable venture for an individual or community.

1.1 System Overview

The *Developing World Aquaponics System* was designed by Dr. Wilson Lennard. Dr. Lennard has spent almost 2 decades researching and working with aquaponics systems and is the director of Aquaponics Solutions, an Australian based aquaponics consultancy company. This system is intended specifically for use in the developing world, where financial resources are limited. It is designed to be built at minimal cost from locally available material, requiring small amounts energy for operation, thereby incurring minimal operating cost.

The system was tested in Suva over a 10-month period, from July 2016 to May 2017 and is made up of one fish tank and two plant grow beds.

1.2 Project References

The testing of the system and production of a User Manual was conducted by Mia Avril under the supervision of Timothy Pickering (SPC), Ciro Rico (USP) and Wilson Lennard (Aquaponics Solutions).

1.3 Organization of the Manual

This manual will first briefly describe the system. Then list of materials and potential sources will be stated. This will be followed by instructions on assembling the system and details on daily operation and maintenance of the aquaponics system. Finally, the manual will provide some tips and recommendations for optimizing the success of the system.

1.4 Acronyms, Abbreviations and Definitions

Cycling: This refers to the starting period of the system operation, when bacterial colonies are allowed to populate the system in order to ensure efficient nutrient conversion. This period can take anywhere from 2 to 8 weeks.

SYSTEM SUMMARY

How aquaponics works

Every aquaponics system regardless of size, is home to three groups of organisms: fish, plants and bacteria. Fish in the tank excrete ammonia. Ammonia is also the result of the decomposition of fish waste and uneaten feed in the tank. If left unchecked, this ammonia becomes toxic to the fish and can result in a host of problems including death. Bacteria in the system is then able to break down this ammonia into nitrates, which are not toxic to fish, and also the preferred form of nitrogen for plants. The plants are then able to grow from the nitrates in the water, thereby making the water clean for the fish.
Achieving the right balance of water quality and environmental conditions to support all three groups is the key to successful aquaponics. Regular and careful supervision is required to maintain and operate a profitable aquaponics unit.

2.1 System Configuration

Dr. Wilson Lennard designed the system very specifically, outlining the dimensions of every component, as well as the size of pumps and quantity of feed to be used. The fish tank to be used in the system is a water tank. Since the system is designed for minimal automation, the fish tank is meant to be at the lowest point of the system. A hole is needed in the ground to place the fish tank so that the water level is below the grow beds, which will be placed on the ground directly. From the fish tank, water is then pumped to the grow beds via a water pump placed at the center of the fish tank. PVC pipes will be used to transfer the water to the grow beds via the central pump. The grow beds will be made of a wooden frame, lined with plastic to keep water from leaking out of the system. This will be placed directly on the ground. Inside the grow bed, gravel will be used as the substrate for the plants. This gravel will also provide surface area for the bacteria colonies to grow. When the grow beds are filled to a certain level, determined by a standpipe, the water that has been cleaned by the plants will be returned to the fish tank via a drain pipe. This drain pipe will be attached to the standpipe on the end of the grow beds closer to the tank and allow water to drain at a fairly rapid rate back into the tank controlled by a bell siphon. A bell siphon is a device made up of PVC pipes placed over the standpipe which works on the establishment of a vacuum inside the standpipe. This was selected so that another pump would not be needed to return water to the fish tank. In order to keep the flow of water unobstructed, a gravel guard was placed over the bell siphon.
An optional, but recommended roof was then constructed over the grow beds. This roof is not part of the system design by Dr. Lennard, but given the weather patterns in Suva, where torrential downpours occur on occasion, the use of a roof is advised. The roof also proved useful in controlling pests.

Below are some of the schematics provided by Dr. Lennard.

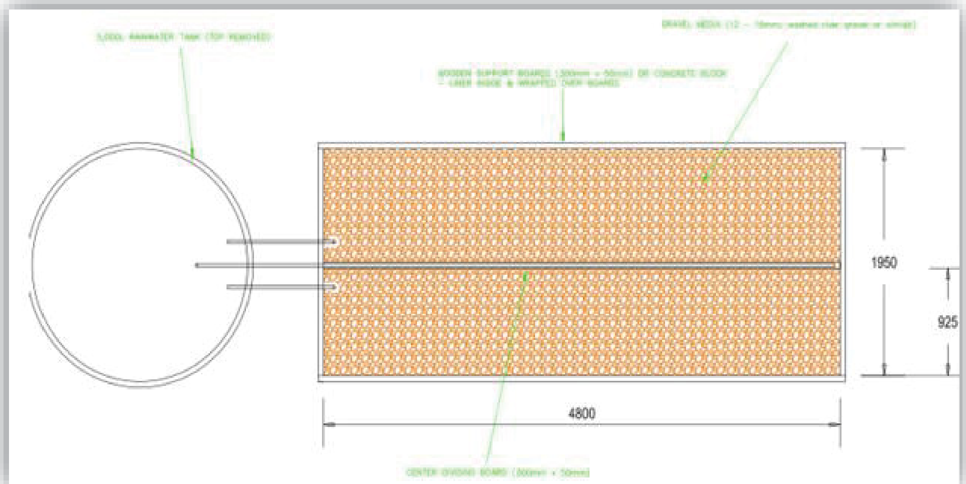


Figure 48. This figure shows an aerial view of the system, with the fish tank, the grow beds and some of the plumbing. Dimensions (in mm) for the grow bed can be seen in the diagram.

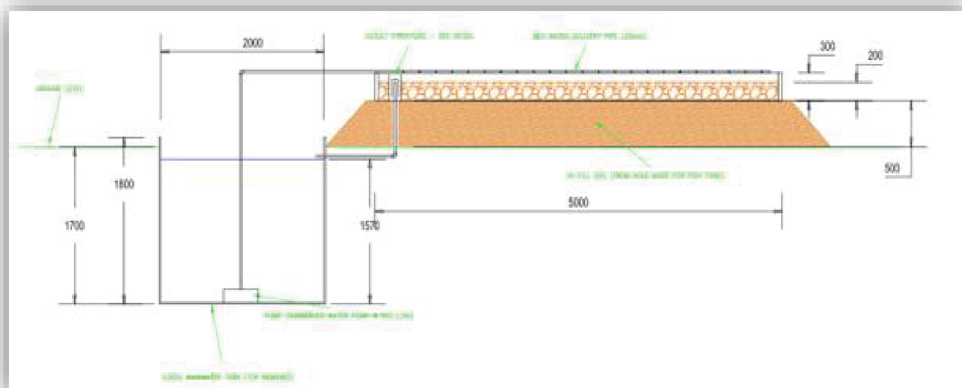


Figure 49. This figure is a side view of the system, showing the depth of the hole required for the tank, the dimensions of the tank, the height of water inside the tank, the location of the water pump in the tank and the depth of the grow beds. It also shows the location and dimensions of the drain pipes and the water delivery pipes.

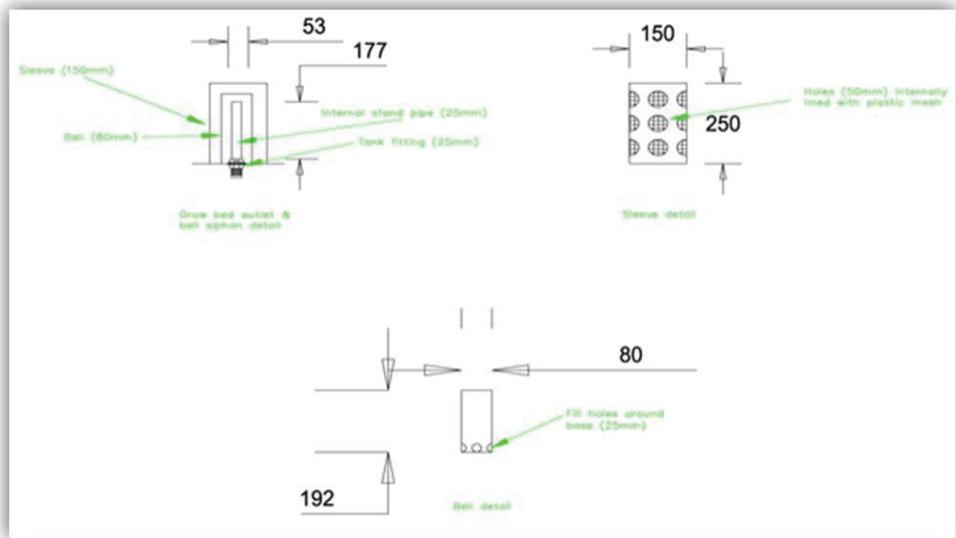


Figure 3. This figure shows the details of the bell siphon and stand pipe.

GETTING STARTED

The first thing to consider when undertaking this project is the intended location. The entire project requires an approximate land area of 12m by 4m.

Factors to be considered when selecting a site for this aquaponics system are:

- Ensure that the selected site has easy access to electricity and water supply.
- It is helpful if the site is easily accessible by vehicle to minimize labour.
- An area that is as flat and level as possible reduces the amount of preparation needed before construction can commence.
- If not at the owner's place of residence, then a location that is as close as possible with proper supervision in order to reduce the event of malfunction, and the extent of damage resulting from unavoidable issues.

Secondly, the materials to build the system should be obtained. Below is the list of materials, where they were obtained for the test system, and an approximate cost. Additionally, if hiring labourers, a minimum of 2 would be best in order to efficiently complete construction. At an average labour cost of $40 per person daily, approximately $400 should be allocated to labour costs.

Note: all costs are quoted in Fijian Dollars.

	Item	Description	Quantity	Cost
Labour		$30/day	10	300
Fish Component	Water Tank	5000L	1	1137.4
	Submersible Water pump	700L/Hr	2	156
	Air bubblers		3	90
PVC	Pressure pipe	25mm	16m	29.06
		50mm	6m	28.9
		80mm	1m	99.12
	End caps	25mm	2	3.6
		80mm	2	30.4
	Elbow	25mm	2	2.46
		50mm	4	21.6
	Pressure Socket	50mm	2	22.6
	Pressure Valve	50mm	2	4.7
	Rubber Washer	50mm	2	0.5
	Pressure R/Bush 50x25mm	50mm	2	9.2
Roof	Plastic Liner	Woven	3m	66
	Rebar	15mm	3m	4.08
	PVC	15mm	9m	11.25
	Lock channel	6m	1	12
	Lock wire	2m	3	12
Plant Component				
	Timber (treated Pine)	50mmx150mm (2x6 inches)	8 lengths of 5m	180
	Screws (metal)	3inch long; 100mm wide	36	19.99
	Plastic liner	Woven	7mx10m	154
	Gravel	15mm diameter	2m3 (half load)	186
	Nails	Flat head 1 inch long	32	5.54
	Waste paper bin		2	5.6
	Rubber Tube	5mm diameter	1m	0.25
Misc	Cable Ties	Pack of 100	1	9.55
	Silicone	Tube	1	10.9
	PVC tape	Roll	1	0.45
	Measuring Tape	8m	1	13.14
	PVC glue	Bottle	1	1.73
	Electrical work at Homes of Hope	1	390	390
	Bin for Feed storage	1	15	15
	Arg Lime	1	20	20
	Extension cords	2	19.5	39
	Gloves	1	1.9	1.9
	CaCO3	1	70	70
	Water (L)	2000		0
Total				**3163.92**

*The additional length of timber here would be needed to pin the two 150mm wide boards together in order to obtain a height of 300mm.

If constructing yourself, below is a list of tools that you will need. If a contractor will be hired, verify that they have the following tools available.

List of Tools Needed for Construction
Shovels
Tape Measure
Spirit Level & string
Power Saw
Power Drill with different sized bits
Hole Saw
Hand Saw
Knife

The construction of the system can be completed within a week, once all material is available. The dimensions are all obtained from the system designs provided by Dr. Lennard.

3.1 Land Preparation

The land preparation process requires the digging of a hole for the fish tank as well as the preparation of the grow bed area. Firstly, a hole that is at least 2m wide and exactly 1.7m deep. Once the hole is dug, some soil that was removed from the hole can be used to prepare the grow bed area.
Preparation of the grow bed area requires the levelling of an area 6m long and 4m wide. The levelled area should start 2m from the edge of the hole for the water tank and extend for 6 meters. The 4m width should cover the tank in the middle and a meter on either side. Ideally the grow bed area should be 500mm higher than ground level and slope slightly towards the water tank. The recommended slope angle is 5^0. Pegs should be placed at the four corners or the leveled area and string run along the ground level. The spirit level should then be used to obtain the desired angle, adding or removing soil where necessary.

It is important when preparing the grow bed area to remove any rocks, stones or debris present in the soil that could potentially damage the plastic liner to be used in the grow bed later on. (Sand can even be used to line the bottom of the grow bed area for this reason.)

Allow the soil to settle for a day or two before proceeding with the construction of the grow bed. During this time, the water tank can be placed in the hole, and the remaining soil that was removed from the hole can be used to fill in the spaces around the tank up to ground level.

Before placing the tank in the hole, since the tank used is a water tank with an outlet at the bottom, an endcap would be needed to seal off that hole to prevent water loss from the system.


3.2 Grow Bed Preparation

The frame for the grow bed is made up of two side boards, two end boards and a center dividing board. According to the schematics, the frame is 300mm in height.

If you can obtain timber that is 300mm wide that would be ideal. In this case, cut the timber to the desired lengths. These are:

2 Side boards at 4.8 m each
2 End boards at 1.95m each
1 Center board at 4.8m

Once the timber is cut, lay it out on the ground into the frame of the grow bed. Using the power drill, secure the boards in place using the 3 inch screws, with 6 screws being used per board in the four corners of the frame. Another 6 screws should be used on either of the end boards to secure the center dividing board in place.

If 300mm wide timber is not available, utilize two lengths of timber of 150mm width each and stack them in order to achieve the required height. The additional length of 100mmx200mm timber will also be utilized to pin the side boards together. The timber will then be measured using a tape measure and cut to the requisite lengths of:
2 side boards requiring 4 lengths at 4.8m each
2 end boards requiring 4 lengths at 1.95m each
1 center board requiring 2 lengths at 4.8m each
8 Pieces of wood (100mmx200mm) to pin the side boards at 200mm each

Once the timber is cut, lay it out on the ground into the frame of the grow bed. Lay the two lengths of timber forming 1 sideboard side by side, and place one of the short pieces of wood across the two boards 1m from the end. Using a power drill, use three of the 3 inch screws in a triangular pattern to secure one end of the piece of wood to one of the lengths of timber for the side board. Do the same on the other end of the piece of wood on the other length of timber. Repeat this at 1 m intervals along the length of the sideboard, using a total of 4 pieces. This is shown in the picture below.

To facilitate this process, the holes can be pre-drilled into the short pieces of wood, before attempting to affix them to the lengths of timber. This is shown in the picture below.

The picture below shows the completed size boards.

Once the sideboards were completed, the frame for the grow bed was laid out and assembled using 6 screws per corner to secure the side boards to the end boards. 6 screws were also used on either end board to secure the center boards in place. This is shown in the picture below.

Once the frame for the grow bed is finished, place it in line with the fish tank with approximately 2m between them.

With the frame for the grow bed in place, mark out the locations for the drain pipes. A distance of 305mm (1 foot) from the center board and 305mm (1 foot) from the end board can be used. Once those positions are clearly marked using pegs, remove the frame for the grow bed from its location to allow for drainpipe construction.

Once the frame is removed, begin digging a trench from the location of the drainpipe to the tank. The trench should be approximately 500mm deep in the elevated grow bed area, and continue at ground level to the tank.

Once the trenches are dug, the distance from the peg marking the location of the drain pipe to approximately 6 inches inside the fish tank should be measured and lengths of 50mm pressure pipes cut. A hole saw should then be used to make 50mm holes into the side of the fish tank where the drain pipes would enter the tank based on the trenches prepared. The 50mm pressure elbow fittings should then be connected to the end of these pipes and laid into the trenches. This is shown in the figure below.

**This was not included in the initial design of the system but may prove effective: half way along the drain pipe to the tank, cut the pipe and use a 50mm connector to join the two parts. This way, the end in the tank can be easily disconnected in the event that the gravel bed needs to be drained outside the system, for instance, if it needs to be cleaned.*

After the plumbing is laid, the frame for the grow bed can now be returned to its position, being careful to ensure the distances from the center dividing board and the edge of the grow bed is maintained (305mm or 1 foot).

The woven plastic liner can be laid out over the frame to form the base of the grow bed after ensuring that there are no sharp objects or stones which could puncture the plastic.

Sand can also be used to line the base of the grow bed to protect the plastic.

The plastic should be carefully spread into all corners without being pulled too tightly on the sides to ensure that it does not become strained when the gravel was eventually added.
Batons, cut to length of each side of the grow bed using a power saw is then nailed onto the outside of the grow bed frame in order to keep the plastic liner in place. This can be seen in the picture below.

The next step is to use a sharp knife to cut a hole in the plastic over the drain pipe plumbing.
Place one of the rubber washers around the mouth of the 50mm elbow under the plastic liner and seal on using silicone. Place a second rubber washer was placed on the upper surface of the plastic liner and seal with silicone.

These washers and silicone are used to secure the fitting and to ensure that no water was able to leak at these openings in the plastic liner or the PVC connections.

The standpipe can now be cut from the 25mm PVC pressure pipe was then cut to a length of 190mm. The stipulated lengths in the schematics is 177mm which will be demarked by the placement of the 25mm to 50mm converter. Cut a short piece of the 25mm pipe, approximately 1-inch long and slit along the length in order for it to be squeezed. The shorter piece of pipe should now be placed inside the bottom of the standpipe to create a sleeve. This sleeve was inserted to help encourage the build-up of water in the standpipe to encourage the water siphon to form. This can be seen in the picture below.

Once this is done, mark the 177mm point from the top of the standpipe and place the 25mm to 50mm converter at that point from the top of the standpipe. This is showin in the picture below.

The converter should then be placed into the drain pipe with the extra length containing the sleeve going into the elbow of the drain pipe.

The extra length of pipe and sleeve were used to help the bell siphon to form by encouraging water to build up in the standpipe.

Next, the bell syphon will be constructed and placed over the 25mm stand pipe.

The bell syphon is made using 80mm PVC pressure pipe. The pipe should be cut to 192mm (according to the schematics) and a hole drill can be used to cut 20mm holes along one end of the pipe. On the other end of the pipe, an 80mm end cap should be affixed using PVC glue. Next, drill a 5mm hole into the end cap of the siphon and attach a length of 200mm rubber tubing of the same diameter so that one end of the tube is 2 inches inside the cap and sealed with silicone. The end of the tube should be fastened using cable ties to the bottom of the bell, just above the 20mm holes. This is shown in the picture below.

This is to ensure that air gets into the siphon to stop water flow.

Once the bell siphons are in place, gravel guard will be needed to keep the gravel from obstructing the flow of water up between the bell and the stand pipe. According to the design, PVC pipes of 150mm diameter could be used, however in an effort to reduce the cost of building material, two small plastic buckets which were purchased from a local household store (Rups Big Bear) can be used.

To build gravel guards from plastic buckets, first use a knife and remove the base of the bucket. Then use a power drill and drill 5mm diameter holes to allow the free flow of water. Place the bucket around the bell siphon and drain pipe structures. Repeat the drainpipe, standpipe, bell siphon and gravel guard instructions for the other grow bed.

Once those are in place, then gravel can now be added to the grow bed. The gravel should be divided between the grow beds and spread as evenly and carefully as possible. The picture below shows the adding of gravel to the grow beds.

3.3 Fish Tank Preparation

On the top of the tank, one of the flat surfaces should be cut using a hole saw in a rounded triangular shape in order to create a manhole for accessing the tank for the installation of plumbing, fish stocking and feeding, and general observation without leaving it entirely uncovered. The part that is cut out will be used to make a door by drilling 5mm holes along the edge of the 'door' and the tank near to where the 'door' was removed from using a power drill and a 5mm bit. Plastic cable ties were then used as hinges to attach the door back to the tank.

Once this hatch is in place, the other plumbing can be installed for the grow bed water delivery pipe.

The system was designed to operate with one pump located at the center of the fish tank pumping water at a rate of 500L/hr. at a height of 1.5 meters to the grow bed via a single delivery pipe.

If a pump meeting that capacity can be obtained proceed as follows:

Run a 3m length of 25mm PVC from the edge of the center board of the grow bed towards the fish tank. At the point where the pipe encounters the tank, using the hole saw, cut a hole of 25mm diameter in the side of the tank. The pipe should then extend approximately 1 meter into the tank, near the center. A 25mm elbow should be placed on the end of the delivery pipe inside the tank. Measure the distance from the 25mm elbow to the pump at the center of the base of the tank (approximately 1.5m).

A drill bit matching the size of the outlet of the pump should be used to drill a hole into a 25mm endcap. The endcap should then be secured to the pump using silicone, and then attached to the delivery pipe on to the pump using the ~1.5m length of pipe previously cut.

At the center board, place a 25mm T connection on the pipe coming from the tank and 25mm PVC pipe should be cut to the length of each grow bed ~0.9m. Then 25mm elbows should be placed on each pipe before a length of 25mm pipe extending along the length of the grow bed can be attached to it to form the bed water delivery pipes.

The delivery pipes along the grow beds should be drilled using the 6mm drill bit to create holes at 0.5m intervals for water to be evenly distributed along the grow bed from the fish tank.

If a pump meeting that capacity cannot be obtained and two smaller pumps need to be utilized:

Two bed water delivery pipes will be required from the fish tank from each pump to one grow bed. The pipes can be installed to run along the right side of either grow bed (that is the center dividing board for the first grow bed and the right sideboard for the second grow bed). The hole drill was used to make 25mm holes in the tank at a height of approximately 1.5 meters, where the pipes would encounter the tank and pipes were cut measuring the distance from the furthermost edge of the grow bed to the center of the tank. Those lengths varied because of the positioning of the pipes. Inside the tank, 25mm elbows should be placed on the ends of the pipes and pipe measuring approximately 1.5 meters will be attached to the elbows. In order to connect the water pumps to the 25mm pipes, 25mm end caps will be used as described above. Similarly, the delivery pipes along the grow beds should be drilled using the 6mm drill bit to create holes at 0.5m intervals for water to be evenly distributed along the grow bed from the fish tank.

3.4 Shelter *(optional)*

If it is decided that a roof will be included on the system, then proceed as follows:

The height of the roof will be 1m.
Cut rebar into 0.5m lengths, giving 12 pieces. Starting at one corner, at 1 meter intervals place rebar along the length of the grow bed, on either side, using 6 pieces per side. These rods of steel should be placed as close to the grow bed frame as possible.
Six pieces of 15mm PVC pressure pipe should now be cut in 3 meter lengths and looped over the rebar across the grow beds.

The lock channel now needs to be installed along the length of the grow bed. The PVC hoops for the roof would prevent the installation of the lock channel directly on to the outside of the grow bed, blocks of wood left over from the grow bed frame boards measuring approximately 60mm in width were nailed onto the side of the grow bed. One block was placed to the left of each of the PVC hoops and secured using flat headed nails measuring approximately 3inches in length. This is shown in the picture below.

Once all the blocks were in place, the lock channel can now be screwed onto the side of the grow beds. This was done using the power drill and 3 inch screws and can be seen in the picture below.

The woven plastic can then be placed over the hoops and secured in place by the lock cable. In order to further secure the plastic on the hoops, clips can be made from leftover 15mm PVC pipe. The pipe can be cut used a saw into 2-inch long pieces. A notch can then be removed from each length of pipe in order to form a clip. The clip can then be placed over the plastic onto the pipe hoop frame of the roof. The picture below shows the roof partially constructed with the clip holding the plastic in place.

Once the plastic is in place, the aphid screen doors can be installed. Each door measures of 1m x 2m. Place the mesh under the plastic on the end hoops of the roof and use the clips made previously to secure the doors in place. Using a knife, the screen doors can be cut open to provide access into the grow beds.

OPERATING THE SYSTEM

4.1 Material list for System Operation

Material needed for operating the system
Water Test Kits (for testing pH, ammonia, nitrites and nitrates)
Potting mix
Seedling Trays
Seeds for crop(s) of choice
Ag Lime (water buffer)
Calcium carbonate (water buffer)
Tilapia Pellets
Bin for Feed storage
Iron Chelate (plant supplement)
Neem Oil (pest control)
Extension cords (if needed for water pumps and aerators)
Hand shovel
Gloves

4.2 System Cycling

Now that all the system components are in place it is time to add water. The design states that the water level should be at 1.57m (approximately 2000L), so that point should be marked and the tank should be filled to that level. Turn on the water pump and allow the grow beds filled with gravel to fill up and drain for approximately 24 hours until all the dust and sediments in the water settle, and the water runs clear. Aerators with air stones connected via rubber tubing approximately 5m long should be added to the fish tank. In Suva, only aquarium air pumps were available, so 4 of those should suffice.

Next, fish can be stocked into the system. Being as careful and as gentle as possible, transfer a total biomass of 15 kg of fish into the system.

For proper record keeping, fish should be individually weighed in order to determine growth rates if desired.

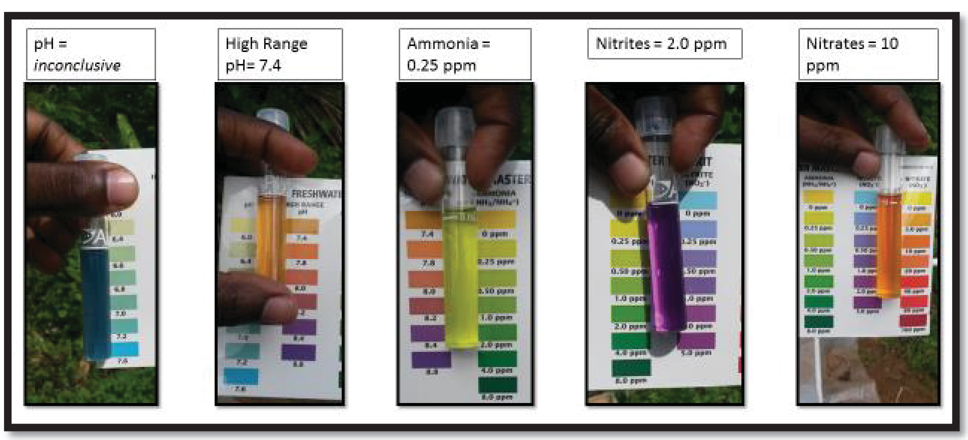
Tips for handling fish:

- Ensure that you provide lots of oxygen to the fish during the transfer.
- Minimize shaking of the turbulence in the containers during transportation
- Try not to handle fish in direct sunlight- shaded areas or working on cloudy days is recommended
- Use gloves to minimize damage to fish scales and to your hands from the fins

- Ensure fish are acclimatized before being introduced into the system. Acclimatization tanks should be prepared with 50% tank water and 50% source water, where fish should be placed for a minimum of half an hour before being placed inside the tank.
- Do not feed fish for the first two days after being transported. Fish are easily stressed and do not eat well when stressed. Any feed added to the system at this point would be wasted and cause the water to become cloudy, which would further stress fish.

Note: it is common to experience a few fish deaths within 24 hours of a transfer due to stress.

For the initial cycling period of the system, fish should not be fed. Fish gill respiration results in the excretion of ammonia into the system. This ammonia promotes the growth of nitrifying bacteria, which is needed in the system to convert the ammonia into plant-essential nitrates. 24 hours after stocking fish, being daily water tests using the Water Test Kit. Each kit will have different instructions, but ensure that the kit obtained can be used to test pH, ammonia, nitrites and nitrates levels in the system. Sample water can be obtained from the grow bed delivery pipes. Until bacteria colonies are established, it is expected that the ammonia levels will be above 2.0ppm. During this time pH is expected to be high, ranging between 7.2 and 7.4. Within a week, these levels should begin to drop, and nitrite should be present in the system, at about 2.0ppm as well. In the following week, nitrates should begin appearing in the system, while ammonia and nitrite levels should fall steadily below 0.5 ppm. By this time, pH levels should also have settled between 6.8 and 7.0. The picture below demonstrates a water test kit results.



This period is referred to as the cycling of the aquaponics system, and can take anywhere from 2 weeks to 2 months.

For more information on fish cycling, please consult the *'Small-scale aquaponics food pr*oduction' report published by the United Nations Food and Agriculture Organization. It can be accessed via the link below.
http://www.fao.org/3/a-i4021e/index.html

4.3 Regular Fish Operation

Once nitrates begin to appear in the system, it means that the necessary bacteria is present and so feeding can commence.
Ultimately, 400-450g of feed should be used daily. However, feeding at this rate from the beginning will cause ammonia poisoning in the system. In the first week of feeding, start with 50g daily, with 25g being fed in the morning and 25g in the evening. The following week, providing that fish response to food was good and no food appeared to be wasted, increase the daily rations to 100g daily, with 50g in the morning and 50 in the afternoon. In the following week, raise the rations to 150g daily, with 75g in the morning and 75g in the evening.
Continue to increase the rations by 50g weekly until the required rate of 400-450g daily is achieved.
Tips for feeding fish:

- *Always observe fish response to the feed. If fish appear to be attacking feed, then this is a good sign. If they show little to no interest in food, then stop feeding.*
- *When feeding fish, do not just pour the entire ration all at once in one location. Rather, sprinkle small amounts around the area of the fish tank slowly and monitor fish response. If response begins to slow before all of the ration is fed, do not supply the full ration.*
- *If fish water appears to be cloudy, refrain from feeding the fish until the water clears up.*

Fish water in a healthy aquaponics system should be tea coloured. If water appears cloudy, there is a problem and an immediate response would be to cease all feeding until the water clears up.

4.4 Plant Nursery and Grow Bed Operation

From the start of the cycling period, the nursery should be commenced as well. Using the seedling trays and potting mix, seeds of the desired crop for the system should be germinated and grown for approximately 4 weeks. The seed trays should be watered once to twice daily, depending on the weather, preferably with nutrient rich water from the aquaponics system.

Note: it is not recommended to include the nursery component of the system into the grow bed, as too much moisture in the potting mix can lead to seed rot.

Once seedlings are approximately 4 weeks old, they should be transplanted into the gravel bed. Gloves and hand shovels should be used to protect fingers. If leafy crops such as basil and lettuce are selected, the recommended grow out period in the grow bed is 3-4 weeks. By this time the plant would have grown to market size. Plants such as lettuce and basil can be stocked at 20-25/m^2.

On a weekly basis, iron chelate was applied topically via a spray bottle to the plants according to the instructions on the bottle to prevent the leaves from yellowing from lack of iron in the system. This is recommended if leafy crops are being grown in the system.

Once seedling trays are emptied, seeds should be immediately replanted, so as to ensure a continuous supply of seedlings for the grow bed.
The grow beds may either be populated entirely at the same time, or a staggered plant cycle can be established where crops are planted so that harvests can occur on a weekly or fortnightly basis, rather than monthly.
Whatever cycle is decided; it is important to ensure that the nursery is able to supply seedlings in a timely manner.

General maintenance requires that the holes in the delivery pipes are kept clear. Sludge from the fish tank sometimes accumulates and causes some of the holes to become clogged.

4.5 Pest Control

If a shelter was constructed as part of the system, this may not be necessary as a roof proved highly effective against pests. However, a small amount of pest presence was still observed inside the shelter.
If signs of pests are noticed (such as holes in leaves, etc.), or just to be proactive to prevent pests, the recommended means of pest control is the use of *neem oil*. A basic solution of 50% water and 50% neem oil is placed in a spray bottle and applied topically to the plants every week. This method proved effective against most pests.

4.6 Summary of Tasks

Daily:

Check that pumps are all working well
Check that water is flowing well and that water is at the desired level
Check water temp if possible
Monitor fish behavior during feeding
Remove dead fish, sick or dead plants

Weekly:

Water quality tests for pH, ammonia, nitrites and nitrates
If needed use buffer to fix pH irregularities
Apply neem to plants
If on a weekly harvest cycle, harvest crops
Apply iron supplements (fortnightly)

Monthly

Harvest if necessary

Annually

Clean gravel bed

4.7 Vegetable growing guide

Basil:

Germination takes ~1 week
Transfer to grow bed when plant has at least 4 leaves approximately 2 weeks after germination
Space plants ~ 20cm apart giving roughly 25 plants per meter
Harvest when plant is at least 15cm in height, roughly 2 – 3 weeks after transplanting.
Spray with neem oil solution weekly, and iron chelate fortnightly.

Lettuce:
Germination: roughly 7 days
Transfer to grow bed approximately 3 weeks after germination.
Space plants at ~20cm; 25 plants per meter.
Harvest after 3-4 weeks
Spray with neem solution weekly; and iron chelate fortnightly

HARVESTING

5.1 Plant Harvesting

After the 3 to 4-week plant grow out period, plants were removed gently from the system by uprooting. The use of gravel 12mm in diameter makes the harvesting of plants easy. The roots are then cut from the rest of the plant, and the marketable portion of the plant is weighed.

Since the gravel bed should never be left vacant, plants should be replaced soon after harvest.

5.2 Fish Harvesting

If an entire stock harvest is expected, replacement stock should be sourced in order to maintain the balance in the system. The average grow-out period for tilapia is 6 months.

Note: To make the harvest a bit more successful, allow the grow beds to fill to capacity with water and stop the siphon that allows the water to return to the fish tank by removing the bell siphon from the stand pipe. This would lower the water level in the tank and make it easier to capture the fish.

Using a cast net if available or hand nets, remove the fish from the fish tank and place in buckets containing water. The fish should be weighed in order to calculate growth rates and earnings if going to market. In Suva, the average cost of tilapia is $10/kg. If fingerlings were stocked, they would be expected to have achieved market size of 300-400g after 6 months at the feeding rates used in this system.

When restocking fish, remember to take all necessary precaution previously mentioned so as to minimize loss.

RECOMMENDATIONS

Key note: Aquaponics management does not require large amounts of time and effort. Well-functioning systems require under 30 minutes daily. However, this maintenance needs to be routine.

Keep the system and its surrounds clean. This includes materials used in building, as well as weeds that may grow in and around the system. Weeds around the system may encourage pests in the system, which is not desirable.

Pay attention to the seasons and how they may affect the crops selected for the system.

Pay attention to the weather. Conveniently, the plastic roof on the system can be easily dismounted in the event of a storm to prevent damage and loss of material. If winds become too strong and the roof becomes threatened, the lock wire and be removed from the lock channel, freeing the plastic for safe storage until the weather improves.

Due to the unavailability of powerful aerators locally, the small aquarium aerators available from the pet shops are not very effective in the system. Therefore, in the event of power outages, refrain from feeding or stressing fish as the lack of oxygen in the tank would lead to further stressing and potential death.

It is recommended that in a new system, for the first 3 months to grow low nutrient demanding crops such as leafy vegetables. Fruiting crops can be introduced after that time.

Ensure electronic connections are secure.

Ensure feed is kept in a secure airtight container to prevent contamination.

Contact Fiji Ministry of Fisheries and Forests, and SPC Fisheries, Aquaculture and Marine Ecosystem (FAME) Division for advice on sourcing tilapia fingerlings and equipment such as field Water Test Kits and powerful air pumps which are more easily sourced abroad.

Notes