A HOLISTIC MANAGEMENT APPROACH: ASSESSING THE SUSTAINABILITY OF AQUAPONICS SYSTEMS USING BIODIGESTATE AS PARTIAL ALTERNATIVE NUTRIENT SOURCE

Thesis presented in partial fulfilment of the requirements for the degree of Master of Science in Sustainable Agriculture in the Faculty of AgriSciences Stellenbosch University

Robert Andrews

SUPERVISORS: DR. ELMI LÖTZE
CO-SUPERVISOR DR. ESTELLE KEMPEN
TECHNINAL ADIVISOR: MR. HENK STANDER

Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third-party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

March 2018

Acknowledgement

This study was funded by the DST-NRF Centre of Excellence in Food Security.

Table of Contents

SUMMARY

One of the hurdles facing sustainable agricultural practice is the declining soil fertility that results from consistently cropping the same parcel of land and the demand of plants on especially mineral elements, which are often not sufficient for sustaining yields. In rural areas, this is exacerbated by the lack of various resources like knowledge, skills, infrastructure and equipment, limiting yield, quality or sustainability. In a water scarce country, the availability and use of this resource to optimize food production is another key point as varying climatic conditions have a greater impact on smallholder farmers that lack the resources, infrastructure, skills and knowledge to provide sustainable yields year upon year. The cost of fertilizers for higher production coupled to the cost to the environment by using only inorganic fertilisers is mounting. The search for alternative sources for nutrient supplementation in crops is a critical one that has not to date yielded a solution that is both environmentally and economically sustainable. The current project addresses the use of an alternative nutrient source, the by-product of anaerobic digestion of fruit and dairy feedlot waste in an aquaponics system compared to a conventional system which will utilize a conventional inorganic nutrient solution and municipal water, as a model to address the declining soil fertility and yield reduction as well as food security under conventional agricultural land based production.

Objectives

The overall objective of this study was to:

1) Identify an anaerobic digester facility as a source for nutrient rich digestate for plant growth in RAS aquaponics. It was also imperative to as well as a source of recycled water.

2) Quantify water quality parameters and selectively manipulate it accordingly to allow plants and fish to survive and grow. Plant species must be selected for the adaptability thereof in hydroponic culture conditions. The latter with specific dissolved nutrient availability and constitution to be identified. The plant species must also function acceptably as a source produce.

3) Identify a biofilter for the remediation of recycled water. The selected fish species must have viable hardy enough to grow in this medium and with an economic potential and be

hardy enough to grow and consistently provide biofilter processed soluble nutrients for the aquaponic culture medium in the market.

4) Identify a plant species that can be grown hydroponically under these nutrient conditions and that could be used to evaluate the viability and function as a bio-filter to clean water for further use.

5) Lastly the best option for fish in this system that will allow marketing of the final product as well as be a bio-filter to purify water for recirculation was determined.

The hypotheses of the study were therefore that:

Digestate can be utilised as alternative nutrient source in an aquaponic system;

H_0: Digestate is not suitable as alternative nutrient source for aquaponic plants.

Biofilter

Biofilter digestate as a suitable medium for fish growth in an aquaponic system:

H_0: Digestate is not a suitable medium for the growth of plants and fish in an aquaponic system

CHAPTER 1

Literature Review

1.1 Overview

Food security infers that, "people should have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and preferences for an active and healthy life" (FAO, 2010). These basic rights frame the discussion around food security quite intently highlighting its exacting issues in relation to nutritional security, food safety and climate change. These aspects are of importance as they have probable bearing on efficiency and health of our nation's people. Though the right to food is the most basic of human needs, it is a universal observation especially in less developed countries that hunger is widespread with many food production systems being unsustainable (McDonald, 2010).

Variable climatic conditions have continued to challenge producers as greater seasonal ambiguities like water scarcity, land degradation and many more have become the mainstay impacts effecting current production systems (Karunasagar and Karunasagar, 2016). It is for this reason that the sustainability and environmental impacts of production systems whether conventional or small-scale agricultural systems are being highlighted.

Although various food production activities influence environmental change, widespread climatic variations have had a significant part in food production sectors from conventional agricultural practises to smaller niche and developing sectors. Impacts are becoming more pronounced across land and water mediums with variations becoming more apparent through medium quality, carbon footprints and production of greenhouse gases and consequent effect on bio-geochemical cycles.

Inputs because of both agricultural and aquaculture activities result in land, water and health concerns promoting degradation of the very resources that sustain current production systems (Karunasagar and Karunasagar, 2016). Mitigation through management of several key issues relating to sustainability and climate change going forward needs to be researched as it is continuously evolving.

The global condition of water security is directly related to the level at which sustainable development of our economies and ecosystems have taken place. Rapidly increasing water consumption, worsening water pollution and excessive extraction of water resources due to competition of different sectors aggravated by global water shortages and deteriorated water ecosystems threaten conventional food, agricultural and economic systems.

Before large scale privatisation and the development of pellet-fed aquaculture Asia provided a phenomenal case study for integrated aquaculture systems. Although not as prominent as was previously it is still of considerable importance in small scale rural practice. These integrated systems made use of indirect integration as most on farm inputs are limited. Similarly, waste water fed aquaculture like those in existence in East Kolkata wetland ponds provide both protein (fish) and supplementary vegetable crops (Mukherjee, 2006).

The implementation of recirculating aquaculture systems (RAS) mitigated many of the environmental concerns by providing closed systems with self-contained water treatment solutions that reduce the amount of environmental discharge (Klinger and Naylor, 2012).

Aquaponics is defined as the incorporation of RAS with hydroponics to grow crops within a "nutrient-rich solution using soil-less support medium with the plants fertilized with waste nutrients from the fish tank effluent" (Rakocy, 2007; Rakocy et al., 2006). This type of production system has been peeking the interest of agricultural practitioners and academics alike, but as few working commercial farms exist its viability is still in question (Hambrey Consulting, 2013).

A greater focus has been placed on the cropping aspects of Aquaponic systems proposed by Hambrey Consulting (2013), as many communities are already invested in some form of conventional fishery system. This is more evident in more developed and first world countries where much of the fishing industry is mechanised, but a large portion of the population is involved more intently within the economic structure of countries, working to earn a salary to purchase goods from larger stores or vendors.

Aquaponic systems have not been favoured in the past as the financial implications have seen countless projects fail or be shelved as the alternatives of both conventional vegetable and pond culture of fish has existed as cheaper options. Until recently, very few established commercial operations have been operated, a working pilot at University of the Virgin Islands has served as the basic design for subsequent systems to follow. The system currently employed at the University of Stellenbosch is geared towards subsistence, low capital and energy inputs and most importantly food security looking at providing good quality affordable produce available to the producer and his immediate circles.

The expectancy of aquaponics systems is that they will be able to be utilized in a variety of different climatic conditions with management being key to overcoming initial setbacks when compared to conventional site selection as well as provided key products to certain niche markets where water is especially scarce, and consumers are willing to pay a higher price for produce of a higher quality.

Hambrey Consulting (2013), noted the concentrations of nutrients and the ratios between them are significantly different in a stable aquaponic system compared to a hydroponic system, which may reduce vegetable growth. A recent study by a commercial hydroponic greenhouse in Belgium reported that the RAS water could only supply about 25% of the nitrogen, phosphorus and potassium needed by the plants (Beyers, 2014). Furthermore, reusing RAS wastewater to save on fertilizer costs in hydroponics was hardly an issue as the cost of artificial fertilizers only comprised 2% of the total production cost in hydroponics.

Aquaculture like other food producing sectors (e.g., agriculture and animal husbandry), must function inside ecological boundaries to diminish possible degradation as the environment provides services necessary to the prolonged survival of mankind globally (Millennium Ecosystem Assessment, 2003). The 'Blue Revolution' is a term frequently used to depict the development of global aquaculture, this 'Blue Revolution must go green' is a sentiment provided by Costa-Pierce (2002), which speaks to an 'alternative aquaculture development model', one which incorporates ecological principles.

The notion of production systems utilising ecological practices to closely replicate systems found in nature is not a new idea, but the focus at present is one that promotes sustainability and food security (Costa-Pierce, 2002), even though such systems lack conventional outputs, the input and longevity of such systems make them attractive to a new breed of producer.

As part of new producers is the search for new markets away from some the conventional systems which are dominated by large agro-business. Aquaculture itself may be adversely impacted by sources of pollution from the external environment, from agricultural, industrial and domestic effluents, especially cages installed in public water bodies (Beveridge et al., 1997).

A case study put forward by Merican (2013), speaks to instances like declining quality of the river water, temperature fluctuations, changing weather conditions that have adversely affected conventional production systems. Examples of more specific nutrient-related and potentially adverse impacts on aquaculture are increased upwelling of deoxygenated water in reservoirs, which would impact inland cage culture as well as damage relatively fragile infrastructure such as cages and ponds from increased frequency and severity of storms; and sea level rise impacting aquaculture in coastal areas and salinity intrusion into deltas which are major areas of freshwater aquaculture. Aquaponics is providing producers along with holistic management of systems the ability to mitigate many of the problems plaguing conventional aquaponics. These systems provide a sustainable way forward.

CHAPTER 2

Survey of the economic potential of the current tilapia industry

The definition of food security provided at the World Food Summit in 1996 describes the vision, but not necessarily the way to get there. Food Security is a complex issue that may be addressed from several entry points. Some of the key ideas surrounding food security is the availability of food in terms of quantity and quality, global access to food, nutritional security, stability and influence of production systems, food loss and wastage. Growing population, greater consumption of animal proteins and the growth of biofuels as an alternative to grains and other products are driving the need for greater production from conventional agro-industries as the demand of consumers increase (Koning et al. 2008). Conventional evaluations predict a production increase of 70 % within the next four decades to sustain global consumer demands; a conservative approach that has not made provision for biofuel production (Lobell et al. 2009). Previous production increases have not led to increased access to food for all, as implementation of new technologies, intensive farming practices and retailers all influence the cost to consumers.

Growing production volumes by 70% using antiquated strategies that were commonplace over the past 50 years is not feasible, as its principles are not aligned with a sustainable approach. This unsustainable approach promotes the use of finite resources beyond the proverbial tipping point (Foley et al. 2005). Attaining global food security while considering the stresses on the environment and its finite resources is the challenge faced by humankind today. Growing production while mitigating adverse environmental effects, as well as cultivating greater inputs toward natural capital and sustaining the contributions of environmental services is not sufficient to attain food security. Food security should enable populations to have diverse diets that provide all essential nutrients.

Numerous international fishing nations, including South Africa have highlighted the specific drawbacks relating to their specific fishing industries. South Africa's fishing industry can easily be categorized into two components; predominantly capture fisheries, comprising of commercial, recreational and subsistence fisheries, each of which requires specific research and management interventions. Aquaculture considered grossly underdeveloped at a global scale is has been prioritised as a sector in need of development to mitigate against issues, for instance the declining wild stocks as to maintain local economies.

Over the last three decades, global seafood markets have transformed considerably (Asche et al., 2015). This is as a result of the expansion of aquaculture and an observed decrease in the output from conventional fishing enterprises. Developments within this sector with regards to consumer demand has led to the globalization of products generating international markets for a variety of species, which previously dominated only local and regional markets (Grafton et al., 2009). It is for this reason that many species like tilapia has gained popularity and is at present a viable source of high-quality, low-cost protein.

With an increased demand seafood has become one of the more widely traded food products (Smith et al., 2010). In 2010, 39% of the seafood production was traded and an estimated 77% of production was exposed to trade competition (Tveterås et al., 2012). Currently, the bulk of traded seafood has seen a noticeable transformation in terms of production, moving away from the conventional capture fisheries to aquaculture products. This transformation in terms of production is due to the pressure exerted by the mismanaging of wild fish stocks and the subsequent implementation of fishing quotas and other conservation-guided protocols to provide longevity of current resources. China maintains an overriding role in the global fisheries sector as the largest producer, exporter and consumer of aquaculture and aquaculture related products (FAO, 2012). With both production and consumption predicted to increase so does the demand for greater quantities of aquaculture product. The latest available statistics show that, in 2010, China produced 63% of global aquaculture output in volume and over 61% of global farmed finfish output (FISHSTAT, 2013).

Over the last two decades China's aqua cultural production has increased by 400%, with *Oreochromis niloticus* forming part of the most demanded consumer-driven species currently under cultivation with regards to volume. FISHSTAT (2013) statistics has China producing 1 million metric tonnes (Mt) of tilapia (40% of global production). Apparently just more than half of this production makes its way into exports markets landing in most countries cheaper than local economies can produce these products for (Cui et al. 2011).

In approximately a 40-year period where most seafood traded globally was wild-harvested (97% in the 1970's), to present day where the balance of traded and consumed seafood globally appears to have surpassed capture fisheries even though capture fisheries continue to be greater as a result of non-food implementations such as the production of fishmeal (FAO, 2014). This shift from a system reliant on wild harvests to aquaculture can be attributed to the commercialisation of production systems as well as the globalization of many economies coupled to a global increase in the demand for seafood (Anderson, 2002). This increased global demand for seafood products has provided an opportunity for producers to meet protein and lifestyle demands servicing a growing global seafood market. "Global aquaculture production has increased from about 4 million T in 1970 to 66.6 million T in 2012 and predictions of future aquaculture production indicate a substantial increase in production in the coming decades" (Msangi et al., 2013).

Livestock and fish value chains support the livelihoods of millions of rural and urban poor, for whom they can act as pathways out of poverty (ILRI, 2011). For more than 30% of the world population particularly in developing countries, fish and other aquatic products provide at least 20% of protein intake (Béné et al., 2007). In the poorest countries of Africa and South Asia, small-scale fisheries are considered critical for food security, as they supply more than 50% of the protein and minerals for over 400 million people (Richardson et al., 2011). Fisheries and aquaculture also provide direct jobs for more than 36 million people worldwide (98% of them in developing countries), and indirect jobs for about half a billion people (Richardson et al., 2011).

The FAO (2013) named Egypt as Africa's largest aquaculture producer, producing close to 1 T. This sector is recognised by the government as a contributor in areas such as income generation, job creation and food security (Macfadyen et al., 2012). "As a rapidly growing sector, consumption in Egypt rose from 8.5 kg to 15.4 kg/person/year between 1996 and 2008" (Macfadyen et al., 2012). Egypt produces several different species like carp, catfish and mullet, but a recent value chain analysis of the industry revealed that aquaculture production is focused predominantly on tilapia (Macfadyen et al., 2012).

Commercial aquaculture involves various internal factors that influence production profitability. Among these, the most important are aspects related to growth and feed efficiency, since feeding costs can represent 40–50% of the total operating costs (El-Sayed, 2006). To mitigate this cost, manufacturers of balanced feed provide feeding tables that indicate the amount of feed to be supplied according to fish size (% body weight) and water temperature. However, in some cases producers rely only on observations of surface-feeding and do not use the above tables, providing fish with satiation rations without knowing the effect of this on feeding costs and the generation of nitrogenous waste (Silverstein, 2006).

South Africa has a well-established fishery sector and is a net exporter of fishery products. However, most of South African fisheries are considered to be fully used and high-value fisheries such as abalone, prawns and line-fish are largely overexploited. Aquaculture within South Africa, is still in its infancy in comparison to aquaculture on a global scale. Although aquaculture is being promoted nationally as an agenda, the sector is still in its infancy as much of the fisheries expertise, funding and infrastructure was previously earmarked for conventional fisheries. Historically, aquaculture in South Africa focused on high value species such as abalone, mussels and oysters, consequently the South African government has identified aquaculture as an area for expansion.

South Africa's, production could grow from 3.543 T (worth approx. ZAR 218m) to more than 90 000 T (worth approx. ZAR 2.4bn) over the next 10 to 20 years. The aquaculture industry even though viewed as secondary to capture fisheries has been earmarked for expansion through government funding and technical support schemes like Operation Phakisa. As such an extensive knowledge base pertaining to aquaculture is available globally bodes well for South African aquaculture sector which is emerging and could possibly provide sustainable solutions in terms of employment and a waning commercial fishing industry.

Current sub-sectors of aquaculture that have enjoyed success is the abalone and rainbow trout industries, the former being almost exclusively an export industry, but both being marketed quite successfully locally to high-end consumers that earn high salaries. There are several other emerging sub-sectors, including tilapia production that have technologies, which can be transferred into our local industry. Currently, this industry is based solely on imports as local producers are hampered in terms of legislation, demand of this industry on our country's freshwater resources and a perceived lack of buy-in from consumers. The factors pushing this industry towards localised production are a weakening currency, government backing (operation Phakisa, DTI, etc.), localised job creation and sustainability issues.

Legislation promotes the idea that fish be grown in bio-secure recirculating aquaculture systems that present minimal risks to the environment irrespective of the location where these farms are located. These systems should be designed to ensure that no effluent water can ever reach nearby rivers. This is easy: filter sediment flushes (which may contain fish escapees) must be channelled into containment tanks, which also provide a ready source of high quality fertiliser.

Such systems can be situated away from natural water courses, and all movement of live fish into or out of such systems restricted to permit holders. In other words, if you do not have a permit for Nile tilapia farming and your system has not been inspected to ensure bio-security, you cannot use this species. If this protocol is followed, the use of the species will stimulate a growing and highly desirable aquaculture industry. There is a lack in the market of skilled aquaculture staff as the focus was conventional capture fisheries and their export.

The absence of necessary technical skills and technical support or extension services coupled to the hefty cost of essentials such as feed, equipment and technology has hindered the expansion of this niche industry. Other factors adding to the slow uptake of entrepreneurs has been attributed to a veterinary service and disease management gear more towards more "conventionally adopted" agricultural industry. Poor governmental involvement at a grass-roots level in terms of restrictive legislative policies making species inaccessible. Start-up capital is not available through financial sector coupled to an inadequate support service structure which does not necessarily promote agricultural, but more so aqua cultural ventures. Lack of marketing services, marketing structures and market penetration. There is high demand for affordable protein and shortages in traditional fisheries products.

Aquaculture is becoming more attractive as a business idea as it has become a focal point on current government agendas. The focus is placed on aquaculture as a replacement for conventional fishing systems that rely on dwindling natural stocks. This idea needs to be supported in terms of revising strict legislation around natural resources, looking towards upgraded infrastructure, the potential of local and export opportunities.

In interviews conducted with current importers, retailers and distributors within the local and national fisheries sector their outlook regarding a tilapia fishery is positive across both higher and lower lsm's as well as informal markets.

Table 1: Current volumes, cost and type of processing for tilapia.

Institution	Weekly (T)	Monthly (T)	Annually (T)	Cost/ton (ZAR)	Market lsm	Processing
Fish and Egg	1	4	48	32000 retail	informal	Gilled and gutted
Woolworths	2 (processed)	8	96	270000 retail	7-10	Value added
Blue Atlantic	N/A	N/A	150	24633 wholesale	N/A	Gilled and gutted
Total	3	12	294			

Two hundred ninety-four T at wholesale value is equivalent to an annual net income of approximately 7.3 m ZAR excluding any value-adding post-harvest interventions. This is still a conservative estimation as it is based on interviews conducted with three resellers within the tilapia industry.

CHAPTER 3

Evaluation of the suitability of anaerobic digester digestate as mineral element supplement for aquaponic production of selected vegetables

3.1 Introduction

Production has always been a significant factor in terms of approximating existing as well as new production systems. Hydroponics refers to the system in which plants are propagated in a soil-less culture, using mineral nutrients dissolved in a water medium (Santos et al., 2013). Terrestrial plants may be grown with only their roots exposed to the mineral solution, or the roots may be supported by an inert medium, often coco peat. The nutrients in hydroponics can be from a conventional nutrient solution or from organic sources such as fish waste or duck manure.

The uptake of nutrients plays a key role in the development of crops. The nutrient uptake refers to the process of nutrient movement from an external environment into a plant. It is one of the fundamental demonstrations of plant's life which involves especially a qualitative change where an abiotic material becomes a component of a cell capable of further assimilation processes, resulting in production of new mass. Plants receive mostly carbon and oxygen in a form of CO_2 from air and partly hydrogen (Evans, 1972). These nutrients enter a plant in a molecular form. Thanks to leaves, stems, and eventually generative organs, most plants can also receive other nutrients, such as N, P, K, Ca, Mg and microelements, mostly in a form of soluble salts of certain concentration. Such way of nutrition is marked as folic nutrition.

Treadwell et al. (2010) states that inorganic nutrient applications are the most appropriate sources of micronutrients for aquaponics because they allow the amount of each nutrient to be controlled independently. By contrast, aquatic plant extracts and other products derived from biological sources will provide a variety of micronutrients and may not contain them in the correct ratio for an individual aquaponic system and may lead to toxicity issues rendering the medium used for fish culture and plant growth unsuitable for continued operation. Timmons and Ebeling (2002) looked at the management of pH within aquaponics critically stating that even though many of the micronutrients necessary for plant development are readily available at pH 5.5 – 6.5 the recommended pH for optimal running is a pH of 7. The management of pH is an integral task as many aspects like access to nutrients (both micro and macro) are critical to achieving a fish, plant and bacterial balance. At a pH of 6.0–6.5, all the nutrients are readily available, but outside of this range the nutrients become difficult for plants to access for example deficiencies of iron, phosphorus and manganese are prevalent at a pH of 7.5. Nitrifying bacteria have trouble below a pH of 6, and the bacteria's capacity to convert ammonia into nitrate reduces in acidic, low pH conditions. This can lead to reduction in efficiency and provide stress within the system. Fish have specific tolerance ranges for pH as well, but most fish used in aquaponics have a pH tolerance range of 6.0–8.5. However, the pH affects the toxicity of ammonia to fish, with higher pH leading to higher toxicity. The ideal aquaponic medium would be a solution that is managed regularly to remain more or less neutral which would provide an environment for a high functioning bacterial component, allow plants access to nutrients and an optimal pH to promote fish growth.

There were significant differences between crop fresh weights can also be explained by the high amount of sodium ions in the digestate medium (9958 mg. Kg^{-1}), affecting the uptake of essential nutrients needed for plant growth. This is representative of lower mean fresh end weights as high sodium levels can stunt growth and lead to toxicity of plants (Parvaiz and Satyawati, 2008).

The addition of fish production (aquaculture) to such a hydroponic system is then referred to as an aquaponics system where fish waste associated production provides the essential nutrients necessary for vegetable cropping. This is a closed system in which the nitrogenous compounds excreted in dissolved form by the fish, and transformed by the nitrifying bacteria (nitrogen cycle e.g. *Azotobater*), provide nitrogen in a usable form, nitrate for the plants by converting waste ammonia produce by fish.

Today many of the systems used in hydroponics have their origins reflected in the original water culture system (Harris, 1988). "This simple system was comprised of a tank, an air stone, a tubing system, an air pump, and a floating platform" (Hoagland and Arnon, 1950). With development of better methods aerate water sources, aerated culture water to maximise dissolved oxygen, the deep-water culture system was created so that plants can be cultivated with their roots-systems continuously suspended in the water medium. In comparison to other systems that are utilised today, the deep-water culture system produces crops more vigorously as the root-system is continuously submersed in the water medium (Saaid et al., 2013). To optimize growing conditions, it is essential to monitor the levels in the system of dissolved oxygen, concentrations of both macro and micro nutrients, salinity, temperature and pH (Table 2) (Domingues et al., 2012). Although all kinds of plants, especially leafy greens such as lettuce and herbs, grow well in this system, large or long-term crops may not, and algae and moulds can grow rapidly in the reservoir.

There are various benefits of hydroponic systems over soil culture systems such as performance, even in areas that are usually deemed as not fit for growing crops as a result of contaminants within the soil cultures (Jones, 1997). “Enclosed hydroponic systems provide a measure of control as growing conditions such as temperature, flow velocity and volume of water, nutrients, relative humidity, and duration of lighting can be manipulated to optimize crop production” (Norén et al., 2004). These enclosed systems are influenced minimally by climate change factors and therefore the possibility of perennial cultivation under a wide range of conditions exist (Manzocco et al., 2011). In lieu of the sustainability of such systems many of the practices related to degradation of agricultural land is alleviated, such as cultivating, weeding, watering, and tilling (Jovicich et al., 2003). Soil-based crops can be exposed and contaminated by many harmful biotic or abiotic compounds, some of which are hard to prevent. However, using hydroponics, most media and other materials can be sterilized by ultraviolet (UV) irradiation, chemical compounds (e.g., alkylating and oxidizing agents), steam, and/or high temperatures (Knutson, 2000). Furthermore, indoor hydroponics are not expected to be infected by diseases common to plants cultivated in soil, thereby reducing or eliminating the use of pesticides and their resulting toxicity (Fu et al., 1999). Delivering recycled or used water directly or indirectly to the root area provides a more effective utilization of resources, reduces water loss, and distributes nutrients evenly to each plant (Midmore and Resh, 2013). Finally, pH can be easily controlled, according to the plant’s requirements (Rolot and Seutin, 1999). Because of these advantages, many studies reports that hydroponic systems can increase the yield and quality of crops (Resh, 2013). However, there are also some limitations to hydroponic systems.

The main problem is the high initial setup cost, as the fundamental supplies are expensive (Domingues et al., 2012; Resh, 2013). Hydroponic systems are also vulnerable to power outages, as the electrical-driven machines in the systems cannot supply water or nutrient solution without power (Knutson, 2000).

3.2 Materials and methods

3.2.1 Experimental site and layout

The type of system employed in this experiment, is a deep-culture system that utilises two grow beds, reservoirs, submersible pumps, two 1500 L fish tanks, settler/skimmer, bio filter and top-flow inlets (see appendix Figures 5 and 7). Spinach, red lettuce, green lettuce, cabbage and broccoli plants were used in this trial. Plants were cultivated in the nursery on Welgevallen experimental farm (red lettuce, green lettuce, cherry tomato and spinach) as well as bought in from Kuikenvlei nursery in Firgrove (cabbage and broccoli). The plants that were cultivated from seeds were germinated in a coco peat medium and irrigated thrice daily using a nutrient solution which EC measured 1.6 $mS.cm^{-1}$. Coco peat was soaked and rinsed several times until the EC reading was 1 $mS.cm^{-1}$. Seeds were placed in the coco peat and germinated and once seedlings reached 10 cm in length they were transferred into the pre-cut isoboard rafts within the grow beds. The plants that were purchased from Kuikenvlei nursery were transferred into aquaponic pots that were filled with a coco peat medium. Both bought and cultivated plants were irrigated with a timed irrigation system providing 30 seconds of water twice a day (09:00 and 15:00). Planting layout was a randomized block design (see appendix Table 10). All plants were transferred to have at 12 plants (spinach, red lettuce, green lettuce, cabbage and later broccoli) per raft (1,5m^2) except for tomatoes which were plant at 8 plants per raft.

3.2.2 Trial management

The control grow bed utilised a municipal water source and a conventional nutrient solution (Pantenella *et* al., 2010) to which the EC was matched to that of the experimental grow bed, which the latter utilised liquid digestate effluent obtained as a by-product of anaerobic digestion of fruit waste and cow manure. A water analyses of both treatments was performed by the Western Cape department of Agriculture (Table 1).

Before the trial could commence a series of holistic management practices were used to obtain the desired pH required for nutrient uptake of the plants. These practises included twice per week monitoring of selected water parameters such as both water medium looking at temperature, pH, dissolved oxygen (DO) and electrical conductivity (EC), we used the Oxyguard® handy Polaris 2 meter was employed to measure both temperature (^{0}C) and DO (mg/L), pH/EC meter was used to measure pH and EC ($mS.cm^{-1}$). These measurements were recorded twice per week (Monday and Thursday) at the same time. To avoid any resolution deviances all measuring equipment was calibrated before use by accompanied calibrating solutions (Figure 1). The pH was adjusted by adding either an acid (H_2SO_4) or alkaline solutions (KOH) based on the bicarbonate concentration in the solution. Suspended organic material (SOM) was also regularly removed as many of the sources of particulate waste are uneaten feed and organisms (e.g., bacteria, fungi and algae) that grow and accumulate within the system depressing dissolved oxygen (DO) levels as it decays leading to the production of carbon dioxide and ammonia. This decay could eventually present as an anaerobically decomposing sludge which when produce methane and hydrogen sulphide create a toxic environment for the culture of fish (Rakocy *et al.*, 2006) Initially the tomato plants were trellised and once large enough smaller growth shoots pruned and dead/dying leaves removed. The rest of the other plants were pruned and dead/dying leaves removed. All plants were monitored for any signs of mould or pests which conventional mitigating approaches were utilised.

3.2.3 Data collected

The initial weights of randomly selected plants were measured and recorded and continually monitored on a fortnightly basis as to determine the change in weights over the length of the experiment. Once harvested, 13 individual broccolis and 7 cabbage plants were sent to the Western Cape department of Agriculture, Elsenburg, for chemical analysis (appendix Table 11) (Table 2). Unfortunately, not all crops were analysed and not equal numbers of plants per crop. Fruit weight at harvest for broccoli and cabbage were determined for 10 individual plants at harvest (Table 3). Total soluble solids (TSS) were also determined for an additional sample of 10 individual broccoli and cabbage plants from both treatments, using a hand held Atago refractometer (Table 4).

3.2.4 Stastical analyses

Statistical analyses were performed using a one-way ANOVA using SAS 9.3 for TSS and FW analyses in crops (broccoli and cabbage) and the mean with standard errors for nutrient uptake differences between crops.

3.3 Results and discussion

With the limited results available for mineral nutrient contents, only trends can be discussed for the cabbage and broccoli. All macro element concentrations were higher in the control than digestate for cabbage and broccoli. Apart from sodium (Na), iron (Fe) and boron (B), all micro nutrient concentrations were higher in the control than digestate treatments (Table 1) for both cabbage and broccoli. Sodium concentration was almost four times higher in the cabbage and broccoli from the digestate treatment compared to the control. This is contributed to the high concentration of Na in the digestate sourced (Table 1) and would have played an important role in plant performance, as Na ions inhibit the uptake of other essential ions for development and growth.

For cabbage, Fe levels in the plants fed the digestate treatment was higher than in the Fe levels of cabbage plants fed the control treatment, but in the case of the broccoli, the concentration was higher in the plants supplemented with digestate fed plants. This indicated an imbalance between the two treatments. Similarly, B assimilated in higher concentrations in cabbage from the digestate treatment than the control, with the opposite trend for broccoli. This indicated plant differences in mineral uptake and requirements.

The TSS for broccoli was higher than that of cabbage, but TSS was not significantly different between treatments for either crop (Table 3). Again, this indicates plant species differences in accumulation of sugars and photosynthesis.

For all five crops evaluated (Green and Red lettuce, broccoli, cabbage and spinach), the control treatment plants showed a significantly higher fresh weight than for the digestate treatment. This may partly be explained by the excessive Na concentration in the digestate treatment, in addition to the overall lower mineral nutrient content of both crops grown in the digestate treatment. This result was expected. However, the lack of sufficient levels of most nutrients is probably not due to the digestate Na concentrations only, as it was not meant to fully supply in the demand, but more related to management to sustain the required levels in the digestate treatment. Cabbage and spinach proved to be the most resilient plants in the digestate treatment and survived the longest in the evaluation.

3.4 Conclusion

The system at Welgevallen experimental farm is directed at small-scale producers or self-sufficiency providing a variety of vegetable crops as well as a low-cost protein source available to informal markets or consumption. When looking at the outcomes for this paper H0: Digestate is not suitable as an alternative nutrient source is accepted, though there is a significant higher concentration in the control for 10 of the 13 nutrients assessed. Moreover, in this case only 10 – 20 percent of digestate was used due to logistic challenges and the pH was not obtained at optimum levels during the trial, requiring a re-evaluation of this hypothesis with an alternative resource of digestate before finally accepting this hypothesis.

The higher macro nutrient concentrations in the control plants indicate a higher uptake efficiency under these conditions than in the digestate fed grow bed. This phenomenon was also echoed when looking at the micronutrient concentrations of the crops. Both mediums differ slightly. Mediums differed from one another, particularly with regards to conductivity, total dissolved solids (TDS) - with Na varying substantially as well as a marked imbalance in the availability of N. the lack of the availability of N in the digestive treatment is a contributing factor to growth and growth consistency issues experienced by plants that were cultivated using the digestive treatment. Conductivity was remedied by adding inorganic nutrient solution to the control to have both mediums mirror each other from a nutrient availability standpoint. However, despite these amendments, there was still variation in the pH between the treatments and this variation in pH played a major role in the lack of nutrients available to plants cultivated in the digestate medium.

Unfortunately, in this trial, the aim to create similar conditions (pH, EC and mineral composition) in two grow beds via two approaches by incorporating a natural/biological source of nutrients as an alternative to only inorganic nutrients, was not successful. Due to logistic challenges with the organic nutrient source (digestate), the variation between the grow beds was too much to compare plant reaction on a similar basis. Thus, variation in plant growth and nutrient uptake could not solely be attributed to the different nutrient sources, but was also due to differential uptake of nutrients due to differences in pH and EC. Acceptance of the H_0 would therefore be bias as the treatments were not applied correctly for this purpose. Similarly, rejecting the H_0 would also be inaccurate, as plant growth performance did indicate significant decreases in the digestate vs control treatments, but the reason for this change was not merely due to a difference in mineral nutrient sources as initially envisaged. The nitrogen deficiency in digestate should be rectified in future work and be balanced out with control value to ensure both systems are equal. This is further confirmed by lower N values in plants fed digestate than in control (Table 2). The efficiency on biofilters to convert ammonia to useable nitrates within the system should be monitored closely as well.

3.5 References

Beveridge, M.C.M., Phillips, M.J., MacIntosh, D.J., 1997. Aquaculture and the environment: the supply and demand for environmental goods and services by Asian aquaculture and the implications for sustainability. Aquaculture Research. 28, 797–807.

Beyers, T., 2014. Cost-benefit analysis of the integration of a RAS in a heated tomato greenhouse. Paper Presented at Aquaculture Europe 2014, October 14–17, Donostia-San Sebastian, Spain.

Costa-Pierce, B., 2002. Ecological Aquaculture: The Evolution of the Blue Revolution. Blackwell Science, Oxford.

Delgado, C., Wada, N., Rosengrant, M.W., Meijer, S., Ahmed, M. (2003). Fish to 2020: supply and demand in changing global markets, IFPRI, Washington.

Domingues, D.S., Takahashi, H.W., Camara, C.A.P., Nixdorf, S.L., 2012. Automated system developed to control pH and concentration of nutrient solution evaluated in hydroponic lettuce production. Computers and Electronics in Agriculture 84, 53–61.

Evans, G.C., 1972. The quantitative analysis of plant growth (Vol. 1). University of California Press.

FAO, 2010. Aquaculture Development, 4. Ecosystem Approach to Aquaculture. FAO Technical Guidelines for Responsible Fisheries Number 5, Supplement 4. FAO, Rome, p. 53.

FAO Fisheries Data Statistical Reporting Software.

Fu, T., Liu, J., Hammitt, J.K., 1999. Consumer willingness to pay for low-pesticide fresh produce in Taiwan. Journal of Agricultural Economics. 50, 220–233.

Hambrey Consulting, 2013. Aquaponics Research Project. The relevance of aquaponics to the New Zealand aid programme, particularly in the Pacific. Commissioned Report prepared for the New Zealand Aid Programme, Ministry of Foreign Affairs and Trade. Hambrey Consulting, Strathpeffer, Scotland (96 pp. http://www.aid.govt.nz/ webfm_send/553).

Harris, D., 1988. Hydroponics: The Complete Guide to Gardening without Soil: A Practical Handbook for Beginners, Hobbyists and Commercial Growers. New Holland Publishers, London, MA, pp. 8–210.

Hoagland, D.R., Arnon, D.I., 1950. The Water-culture Method for Growing Plants without Soil. California Agricultural Experiment Station, Calif. MA, pp. 7–95.

Jovicich, E., Cantliffe, D.J., Stoffella, P.J., 2003. SPANISH pepper trellis system and high plant density can increase fruit yield, fruit quality, and reduce labour in a hydroponic, passive-ventilated greenhouse. Acta Horticulturae.614, 255–262.

Karunasagar, I and Karunasagar, I. 2016. Challenges of Food Security – Need for Interdisciplinary Collaboration, Procedia Food Science, Volume 6: 31-33

Knutson, A., 2000. The Best of the Growing Edge 2: Popular Hydroponics and Gardening for Small-commercial Growers and Hobbyists. New Moon Pub, Corvallis, MA.

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop yield gaps: their importance, magnitudes, and causes. Annual Review of Environment and Resources, 34, 179–204.

Manzocco, L., Foschia, M., Tomasi, N., Maifreni, M., Costa, L.D., Marino, M., Cortella, G., Cesco, S., 2011. Influence of hydroponic and soil cultivation on quality and shelf life of ready-to-eat lamb's lettuce (Valerianella locusta L. Laterr). Journal of Science in Food Agriculture. 91, 1373–1380.

McDonald, Bryan. L. 2010. Food security. Cambridge: Polity press. Pinstrup-Andersen, Per. 2007. "Agricultural research and policy for better health and nutrition in developing countries: A food systems approach." Agricultural economics 37: 187-98

Merican, Z., 2013. Driving Barramundi in Thailand. AQUA Culture Asia Pacific Magazine pp. 15–17 (January/February).

Midmore, D., Deng-lin, W., 1999. Work that water! hydroponics made easy. Waterlines London 17, 28–30.

Millennium Ecosystem Assessment, 2003. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington D.C. (137 pp.).

Norén, H., Svensson, P., Andersson, B., 2004. A convenient and versatile hydroponic cultivation system for Arabidopsis thaliana. Physiology Plantae 121, 343–348.

Parvaiz, A. and Satyawati, S., 2008. Salt stress and phyto-biochemical responses of plants-a review. Plant Soil and Environment, 54(3), p.89.

Pantanella, E., Cardarelli, M., Colla, G., Rea, E. and Marcucci, A., 2010, August. Aquaponics vs. hydroponics: production and quality of lettuce crop. In XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): International Symposium on 927 (pp. 887-893).

Rakocy, J.E., Masser, M.P., Losordo, T.M., 2006. Recirculating Aquaculture Tank Production Systems: Aquaponics–Integrating fish and Plant Culture. SRAC Publication No. 454. Southern Regional Aquaculture Center, United States Department of Agriculture (16 pp.). Rakocy, J.E., 2007. Aquaponics: integrating fish and plant culture. In: Timms, M.B., Ebeling, J.M. (Eds.), Recirculating Aquaculture, North Eastern Regional Center Publication No. 01-007. United States Department of Agriculture, pp. 767–822.

Resh, H.M., 2013. Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower. CRC Press, Boca Raton, Fla.

Rolot, J.L., Seutin, H., 1999. Soilless production of potato mini-tubers using a hydroponic technique. Potato Research. 42, 457–469.

Saaid, M.F., Yahya, N.A.M., Noor, M.Z.H., Ali, M.S.A.M. 2013. A development of an automatic microcontroller system for deep water culture (DWC). Signal Processing and Its Applications, 2013 IEEE 9th International Colloquium.

Timmons, M. B., and Ebeling, J. M. 2002. Recirculating aquaculture systems. 2nd ed. Ithaca, NY: Cayuga Aqua Ventures.

Treadwell, D., Taber, S., Tyson, R. and Simonne, E., 2010. Foliar-applied micronutrients in aquaponics: A guide to use and sourcing. Horticultural Sciences Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, pp.1-8.

Tables and Figures

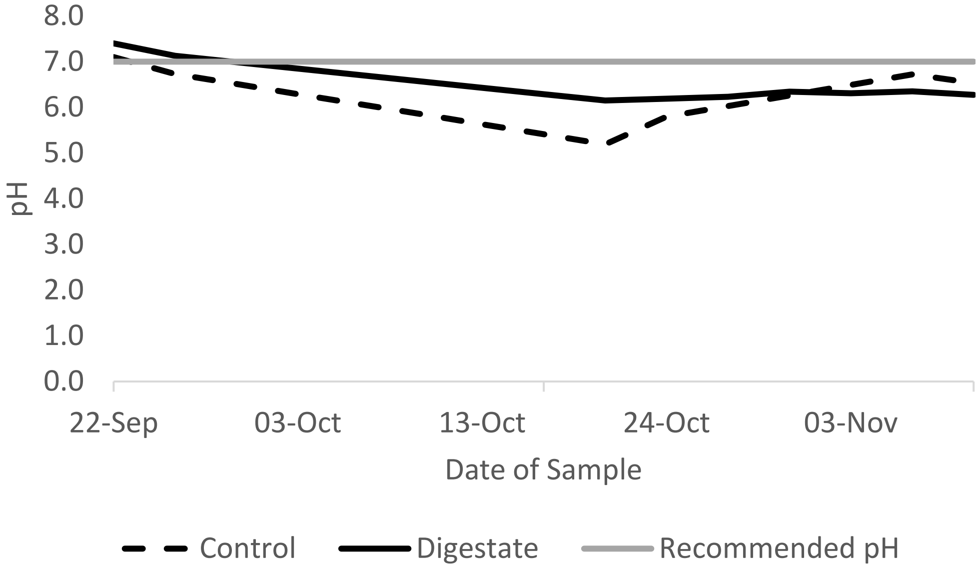

Figure 1. Levels of pH over the duration of the trial in accordance with Timmons and Eibling (2002).

Table 1. Water analysis of both mediums obtained from Western Cape Agricultural laboratories at the onset of the trial.

Parameter	Control	Digestate	Units
pH	7.9	8.3	
Conductivity	232	1087	mS/m
TDS	1508	7066	mg/l
Calcium	14	44	mg/l
Magnesium	12	34	mg/l
Potassium	249	1455	mg/l
Sodium	181	1003	mg/l
Sulphate	17	25	mg/l
Copper	0.01	0.01	mg/l
Manganese	0.01	0.03	mg/l
Zinc	0.01	0.01	mg/l
Boron	0.41	1.40	mg/l
Iron	0.07	0.17	mg/l
Hardness	84	250	mg/l
SAR	8.58	27.61	
Ammonium	26.47	4.53	mg/l
Phosphorus	10	15	mg/l

Table 2. Mineral analyses of cabbage (13) and broccoli (7) plants at harvest after being grown in either a standard nutrient solution (control) or biodigester effluent (digestate). N is given as a percentage (%) while all other nutrients are given as mg. Kg^{-1} accompanied by the respective standard error (SE).

Treatment	N	SE	P	SE	K	SE	Ca	SE	Mg	SE	Na	SE	Fe	SE
Cabbage														
Control	3.32	0.14	0.54	0.03	5.94	0.33	2.88	0.13	0.61	0.04	3458.88	562.10	69.75	4.50
Digestate	2.80	0.18	0.41	0.04	1.84	0.42	1.62	0.16	0.20	0.05	11764.00	711.01	95.59	5.69
Broccoli														
Control	4.02	0.15	0.61	0.02	5.15	0.07	3.02	0.16	0.72	0.05	3285.25	435.12	157.10	44.36
Digestate	2.49	0.18	0.35	0.03	1.41	0.08	1.37	0.19	0.15	0.06	10439.67	502.43	110.22	51.22

Treatment	Cu	SE	Zn	SE	Mn	SE	B	SE	Al	SE	S	SE
Cabbage												
Control	4.34	0.15	102.18	4.88	48.28	2.00	59.75	3.77	1.29	0.06	1.29	0.06
Digestate	1.23	0.20	22.79	6.18	33.62	2.52	83.60	4.76	0.83	0.07	0.83	0.07
Broccoli												
Control	4.61	0.31	266.58	21.24	75.75	5.46	53.03	1.82	128.75	33.27	1.53	0.09
Digestate	1.17	0.35	55.72	24.53	33.40	6.31	25.74	2.10	101.67	38.41	0.74	0.10

Table 3. Fresh weight at harvest for the different plants cultivated in a hydroponic grow bed to which either a standard nutrient solution (control) or biodigester effluent (digestate) was added as nutrient source. P< 0.05.

Treatment	Green Lettuce	Broccoli	Red Lettuce	Cabbage	Spinach
			Fresh Weight (g)		
Control	146.5a	256.8a	216.6a	489.8a	423.7a
Digestate	69.2b	163.6b	93.6b	211.5b	83.2b
P	<.0001	0.0337	0.0007	0.0019	<.0001

Letters showing significance at p < 0.05; ns = not significant at p>0.05.

Table 4. TSS results for individual broccoli and cabbage plants at harvest 2016.

Treatment	Broccoli	Cabbage
	%	
Control	5.4ns	3.5ns
Digestate	6.1	6.4
P	0.1062	0.7260

ns = *not* significant at p<0.05

CHAPTER 4

Evaluation of the suitability of anaerobic digester digestate as mineral element supplement for aquaponic production of tilapia

4.1 Introduction

Currently, in South Africa the focus of aquaculture funding has been geared to support larger commercial enterprises with the long-term goal of creating jobs and growing what is quite a niche industry into something that resembles commercial capture fisheries. This approach is aimed at industries like abalone and trout that have made lots of headway in both local and international markets. The drawback of this type of funding is that the scale of enterprises is of major concern (Hart et al., 2013), but also that parastatal funding has failed to see the value in funding small-scale and subsistence producers.

Informal markets that are indicative of rural areas and periphery of larger cities are not subject to the quality-control measures put in place by large retail business, but are more concerned with having access to good quality protein at a lower cost (Roitman, 1990, Anderson., 2006).

This project is aimed at small-scale and subsistence producers looking to provide for their families or access informal markets not regulated by the needs of the higher income bracket consumers. The culture of tilapia has grown phenomenally over the past half century from a relatively unknown species that was being cultivated for mainly subsistence to global commodity (Shelton, 2002). The fish is being farmed in about 85 countries worldwide and about 98% of tilapia produced in these countries is grown outside their original habitats (Shelton, 2002). At a national level however, we are net importers of this commodity as environmental constraints, permitting issues, cost of production and lack of funding has deterred investors from building this as a local industry. Table 1 refers to an annual import figure of 294 T by three retailers which presents an opportunity for an industry and legitimises the need for localised production/cultivation of this species.

The culture of this freshwater species raises some concerns with regards to physiology and growing conditions, but also climatic constraints as an end user of freshwater resources in a severely water constrained country. Aquaponics offers many solutions in this regard, the ability to use a waste water source in a recirculating system as well as provide alternative solutions using tunnels, polyurethane plastics and other solutions.

4.2 Material and methods

The details of this system are mentioned under materials and methods in chapter 2. The trial was completed over a 16-week period from 17 July 2016 till 10 November 2016. The initial 10 weeks the system was run completely as a hydroponic system using the two mediums (control and digestate) as the source of nutrients for the cultivation of plants, the last six weeks saw the introduction of Nile tilapia and was run as an aquaponics system. As individual fish were not able to be marked during the trial growth in terms of weight gain and total length were depicted using a series of graphs looking at the initial and harvest values for weight and total length.

4.2.1 Water Management

We received 5400 L of liquid digestate comprised completely of apple fruit waste obtained from Elgin Fruit Juices, in Grabouw which was pumped into grow bed 3 (see Appendix Fig 2.). The digestate that was pumped into grow bed 3 posed many problems as it appeared more slurry-like when compared to previous digestate applications. The digestate was then reduced to half the original volume (2700 L) to contend with consistency issues brought about by the amount of suspended organic material (SOM), dissolved organic material (DOM) and sediment contained within the sample. The amount of sediment that settled once in grow bed 3 created an anoxic environment, which utilised all available dissolved oxygen in the digestate medium creating an environment not suitable for crop production. The digestate was then agitated and pumped into a holding tank where it was allowed to settle for two days before being pumped back into grow bed 3 minimising to amount of SOM and DOM within the digestate medium. After which the entire line was filled with freshwater to a total of 9500L. 2700:9500 = a simplified ratio of 1:3.5 (28.42% digestate of total volume). We further removed another 1000L out of the system (2700L-284L= 2416L). This left the ratio at 1:3 or 25% digestate of total volume. We continued to struggle with decomposition in the water medium and proceeded to remove all the remaining sediment out of the water medium. The sediment amount to 750 L removed from the remaining digestate (2416 L-750 L= 1666 L) leaves us on a current ratio of 1:5.7 or 17.5% of total volume. The EC of both mediums vary quite a bit with the freshwater measuring 1.5 and the digestate solution measuring 2.94. Also, we were still struggling with managing DO (dissolved oxygen) to such an extent that fish added to this system would not survive. As we wanted both lines the experiment and the control to be equal we added more nutrient solution to the control to have both EC readings equal to 2.94. Once both readings were equivalent, samples were sent to Elsenburg laboratory for water analysis (see Appendix Fig 4 & 5) and Stellenbosch Biochemistry lab for *E. coli* levels (see Appendix Fig 6.). Once the water analysis was returned from the laboratory we focused on decreasing pH (8.3) in the experimental line as it was higher than the preferred pH of 6.5 which is the value at which most macro and micro nutrients are available to plants. To decrease the pH, we used a sulphuric acid which was added to experimental line (biofilter) in 500ml increments and then retested using a pH meter 24hours after the addition to compensate for the relatively low flow-rate within the system. Once both systems were running equivalent to each other in terms of temperature, pH, DO and EC; plants were then added to the system and their growth in terms of weight was monitored. As the experiment progressed both the control and the experimental lines were monitored in terms of temperature, pH, DO and EC (Table 9) and when necessary measures were taken to increase EC by adding digestate or nutrient solution, pH was managed with the use potassium hydroxide (KOH) or sulphuric acid and lastly the biofilter in both lines was inoculated with a 2 kg of healthy soil to promote microbial development.

4.2.2 Fish Management

The fish were obtained from Welgevallen experimental farm in Stellenbosch. Each tank, of which there were two per line, were filled with 20 kg fish per tank. The fish used in this experiment were Nile tilapia (*Oreochromus niloticus*) that were only added to the tanks once the both the control and digestate system water temperatures reached values greater than 16 ^{0}C. Fish were fed using a conventional fish feed until satiation, this occurred twice daily (morning and afternoon).

4.2.3 Data recorded

Each morning tanks were checked for mortalities which were logged. Fish were measured individually in terms of total length and weight at the beginning when added to the tanks, and at harvest. As it was not possible to mark individual fish for the trial, the total gain or loss in length (Table 8), as well as averages and frequency distributions (Figures 8, 9) of fish weight and length, were used to draw a comparison between performances in the different treatments.

4.3 Results

Table 6 shows the dissolved oxygen (DO), pH, EC and temperature conditions during the 42-day fish production cycle. The DO of both growth beds exceeded the ideal DO of 1 mg. L^{-1} during the whole period, with a steady state DO of 2 mg. L^{-1} that was reached on the 20th of October 2016. Similarly, the optimum temperature ranges between 31 °C – 36 °C required for optimum growth was never achieved during the 42 days. Average water temperatures were approximately 15 °C.

pH dynamics in the growth beds during the trial period were sub-optimal during (3 October-10 November 2016) the fish trial (Fig 3). EC was well below upper tolerance threshold for Nile tilapia, but the expectation that EC levels would be maintained during the fish trial were not met as EC levels declined steadily declined towards the completion of the trial.

Analysis of the fish growth data (Table 8) revealed a declining trend in both fish length and weight during the 42 days of monitoring for both treatments. This could possibly be due to mortalities, which indeed occurred. In the control treatment, 22 (17%) fish died in comparison with only 10 (10%) mortalities in the digestate treatment. This cannot be explained at present.

If the average values for length and weight are adapted, first to represent the initial (adapted for initial) records and then to expressed as an equal (adapted for 100 fish) number of fish in the system, the length of the surviving fish was higher in the digestate treatment (244.9 mm) than in the control (195.6 mm), indicating more growth in length (Table 8). Similarly, if adjustments are made for the difference in initial fish weight and mortalities and expressed for 100 fish, the final adjusted fresh weight of fish in the digestate treatment was higher (19458 g) than in the control treatment (15503 g), which indicated positive growth.

Population dynamics from beginning until harvest are presented in Figures 3 and 4. This shows a peak in length between 260 and 300 mm, in the beginning and end, but with a variation in number of fish in the smaller sizes (Figure 3). This distribution changed dramatically towards harvest, showing a bigger number of fish in the small size (200 – 210) and a second, smaller peak between 240 – 260 mm. This confirms the reduction of average fish length depicted in Table 4. A similar trend is observed when fish weight distribution is presented (Figure 4). Both presentations indicate that the main mortality occurred amongst the bigger fish in both treatments.

The rate of decline in fish length and fresh weight from day 0 (added to the system) towards day 42 (harvest date) is illustrated in Figures 6 and 7. The rate of decline is similar for both treatments and not very steep as expected for the parameter. For fresh weight (Fig 4), the declining slope seems steeper as with the length, also confirming the bigger change in fish weight during the trial. There was however a bigger variance in fish weight at harvest in the control than in the digestate treatment.

4.4 Discussion

Fish populations in both treatments showed a decrease in total length and weight, indicating sub-optimal growing conditions in the system for Nile tilapia. Rakocy *et al.* (2004) stated that the expected growth for Nile tilapia that is not managed intensely is 4.40 g.day^{-1} which would equate to an average approximate weight gain of 167.2 g for the 38-day trial. This confirms reports (Popma and Masser, 1999) about ideal requirements that contrasted the present conditions. Popma and Masser (1999) describe the culture conditions for Nile tilapia as having a lower lethal temperature of 11-12 °C and an optimum temperature range from 31 to 36 °C, a preferable tolerance for DO kept about 5 mg. L^{-1}, an optimal pH of 7. This contrasted with our sub-optimal values with regards to average temperature of the medium (Table 4) which fell well below the optimal considered temperature 24 °C, and that had knock-on/downstream effects in terms of DO availability throughout the system. The decreased temperature within both systems inversely effects feeding frequency and therefore did not promote weight gain. Furthermore, it did not allow for the maintenance of EC levels within the system, which could have adversely affected plant growth and impaired overall system synergy. The optimal prescribed pH for aquaponics systems is 7, which provides a compromise between the needs of the fish and plants. The pH throughout the remained below 7 through the duration of the study fell below 7, which is another stress factor in terms of fish production in both systems. The drop in DO with the control medium tapering off to just above 4 mg. L^{-1} and the digestate medium tapering off to just above 2 mg. L^{-1} (Figure 14) partly explains the lack of weight gain, as DO levels drop, less feed is consumed as consumption requires quite large amounts of oxygen which could have led to the mortalities in both treatments. One of the reasons that explain. A possible explanation for the decrease in average weight and size brought on through the mortality of larger fish within the system is regulatory mechanisms underlying the relationship between growth rate and temperature limited weight gain is experienced by fish that experience was exposed to temperatures close to their lower limit of 11 °C (where the average temperature of the fish trial is averaged at approx. 15 ^{0}C). Tilapia only grow significantly at temperatures above 15 °C), where the total increment in weight increases with temperatures moving toward optimal and upper thresholds.

According to (Buentello *et al.*, 1999) “temperature-dependent increases in growth rate reflects an increased appetite, greater foraging efficiency, and biochemical reaction rates within the thermal tolerance range of the fish”. Tran-Duy *et al*. (2007) explain the uptake of oxygen in fish as limited by the gill surface area. Energy dependent processes such as food processing, depend on their maximum oxygen uptake capacity. Maximum oxygen uptake capacity relative to body weight in bigger fish is smaller than in smaller fish because the gill surface area is allometrically related to body weight. This coupled with the organic loading in both systems due to two biofilter inoculation may explain the mortalities of larger fish due to being outcompeted by smaller fish within the system resulting in decreased weight gains and total length within the system. Although there is no marked difference for the temperature recorded for either medium, the relatively low temperatures recorded for both mediums coupled with the low levels of dissolved oxygen as well as mortalities added to the lack of weight gain and decrease in average total length as the environment does not allow for homeostasis.

4.5 Conclusion

In both treatments, the control and the digestate mediums, a decrease in fresh fish weight and length occurred during the 40 days of growth. However, as this was evident in both mediums, the hypothesis that bio digester effluent is not suitable as an additional nutrient source for fish growth in aquaponics systems has to be rejected. The digestate component of the experimental system was only 10% of the final water volume in the system and could not completely explain the observed retarded growth. However, it could have had a smaller influence in terms of feed availability. This addition of digestate provided a greater amount of suspended organic material (personal observation) as an additional feed source. The fact that the fish in the digestate treatment seemed bigger than the control may thus be partly due to this feed source.

The general mortality rate and lack of growth can also be contributed to the sub-optimal growing conditions of the mediums (pH, temperature, DO), more than the availability of food or the direct contribution of the digestate.

Recommendations for future research include an alternative source for the digestate with a much lower suspended organic content and higher DO, which must be determined beforehand

and if possible a separation of solids and liquid would be advisable. The medium temperature is more critical in the case of fish production and increasing the water temperature to fit the fish must be a priority. This system broaches the ideals of sustainability in many aspects: the use of waste water as nutrient addition and additional feed source, a system that provides several varying crops, a low energy demand and a system that can be tailored to suit the specific needs of the producer. However, to be practical, the quality of the bio-digestate should be monitored more closely to enable a substantial increase thereof to justify the contribution as a mineral nutrient substitute. It is also possible to try alternative fish species like catfish as a more robust model for this kind of experiment. The use of different digestate was as a result of the on-farm anaerobic biodigester leaking and having to be repaired. After the repair the system was not able to reach temperature to produce desired digestate. A batch of digestate was then acquired from a fruit farm which contained an excessive amount of tss and media which had to be manipulated to a point where the percentage of digestate to municipal water in the experiment was 17%. With a higher ratio of digestate that was envisaged a more balanced nutrient budget could have been achieved. The season in which the trial took place also adversely affected the trial as tilapia is a tropical species, even though we used a water heater, the average water temperatures fell below the optimal range.

4.6 References

Anderson, J. L. (2002). Aquaculture and the future: why fisheries economists should care. Marine Resource Economics, 133-151.

Asche, F., Bellemare, M. F., Roheim, C., Smith, M. D., & Tveteras, S. (2015). Fair Enough? Food Security and the International Seafood Trade. World Dev. 67, 151–160.

Béné, C., Macfadyen, G., & Allison, E. H. (2007). Increasing the contribution of small-scale fisheries to poverty alleviation and food security. Food and Agriculture Organization of the United Nations.

Buentello, J. A., Gatlin, D. M., & Neill, W. H. (2000). Effects of water temperature and dissolved oxygen on daily feed consumption, feed utilization and growth of channel catfish (*Ictalurus punctatus*). Aquaculture, 182, 339–352.

Cui, H., Zou, L., Clarke, S., Muldoon, G., Potts, J., & Zhang, H. (2011). Greening China's fish and fish products market supply chains. International Institute for Sustainable Development.

El-Sayed, A. F. M. (2006). Tilapia culture. CABI.

FAO, The state of world fisheries and aquaculture 2012, FAO, Rome, 2012.

FAO, The state of world fisheries and aquaculture 2014, FAO, Rome, 2014.FISHSTAT, P. (2013).

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., et al. (2005). Global consequences of land use. Science, 309, 570–574.

Grafton, R. Q., Hilborn, R., Squires, D., Tait, M., & Williams, M. (2009). Handbook of marine fisheries conservation and management. Oxford University Press.

Hart, E.R., Webb, J.B. and Danylchuk, A.J., 2013. Implementation of Aquaponics in Education: An Assessment of Challenges and Solutions. Science Education International, 24(4), pp.460-480.

Klinger, D. and Naylor, R., 2012. Searching for solutions in aquaculture: charting a sustainable course. Annual Review of Environment and Resources, 37, pp.247-276.

Koning, N. B. J., Van Ittersum, M. K., Becx, G. A., van Boekel, M. A. J. S., Brandenburg, W. A., van Den Broek, J. A., et al. (2008). Long term global availability of food: continued abundance or new scarcity? NJAS, 55(3), 229–292.

Macfadyen, G., Allah, A. M. N., Kenawy, D. A. R., Ahmed, M. F. M., Hebicha, H., Diab, A. & Naggar, G. E. (2012). Value-chain analysis of Egyptian aquaculture [in Arabic]. The World Fish Center Working Papers.

Msangi, S., Kobayashi, M., Batka, M., Vannuccini, S., Dey, M. M., & Anderson, J. L. (2013). Fish to 2030: Prospects for Fisheries and Aquaculture. World Bank Report, (83177-GLB).

Mukherjee, M. (2006). Waste-fed fisheries in peri-urban Kolkata. MACGREGOR, D. et al. The Peri-Urban Interface. Londres: Earthscan, pp.104-115.

Popma, T. and M. Masser. 1999. Tilapia: Life history and biology. Southern Regional Aquaculture Center Pub. SRAC-283 pp 4. Richardson, K., Steffen, W., & Liverman, D. (Eds.). (2011). Climate change: Global risks, challenges and decisions. Cambridge University Press.

Roitman, J.L., 1990. The politics of informal markets in sub-Saharan Africa. The Journal of Modern African Studies, 28(04), pp.671-696.

Silverstein, J. T. (2006). Relationships among feed intake, feed efficiency, and growth in juvenile rainbow trout. North American Journal of Aquaculture, 68(2), 168-175.

Shelton, W.L. 2002. Tilapia culture in the 21st century. p.1-20. In: Guerrero, R.D. III and M.R. Guerrero-del Castillo (eds.). Proceedings of the International Forum on Tilapia Farming in the 21st Century (Tilapia Forum 2002), 184p. Philippine Fisheries Association Inc. Los, Banos, Laguna, Philippines.

Smith, M. D., Roheim, C. A., Crowder, L. B., Halpern, B. S., Turnipseed, M., Anderson, J. L., & Liguori, L. A. (2010). Sustainability and global seafood. Science, 327(5967), 784-786.

Tran-Duy, A., Schrama, J. W., Van Dam, A. A., Verreth, J. A. J. (2008). Effects of oxygen concentration and body weight on maximum feed intake, growth and hematological parameters of Nile tilapia, *Oreochromis niloticus*. Aquaculture 275: 152-162

Tveterås, S., Asche, F., Bellemare, M. F., Smith, M. D., Guttormsen, A. G., Lem, A., & Vannuccini, S. (2012). Fish is food-the FAO's fish price index. PLoS One, 7(5).

Tables and figures

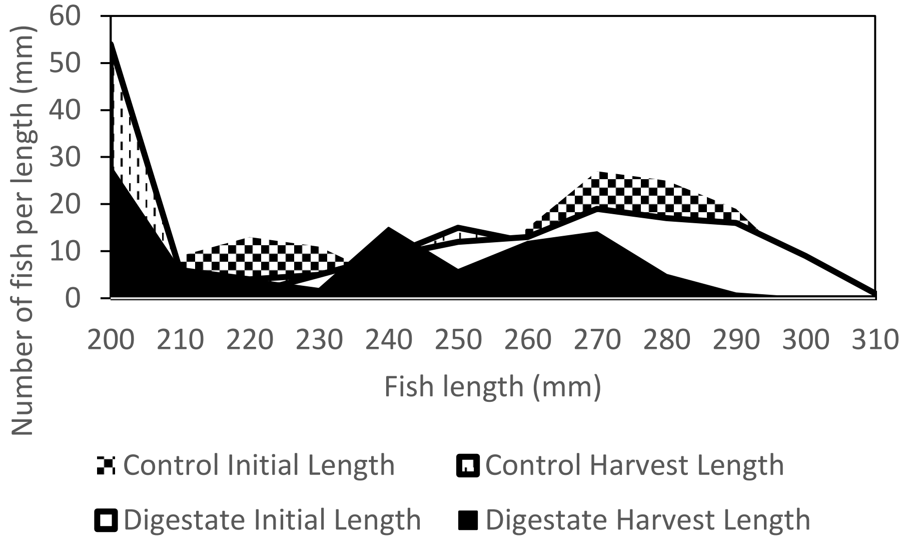

Fig.8 Frequency distribution of fish lengths comparing both initial and harvest total length as they are represented across both mediums (control and digestate).

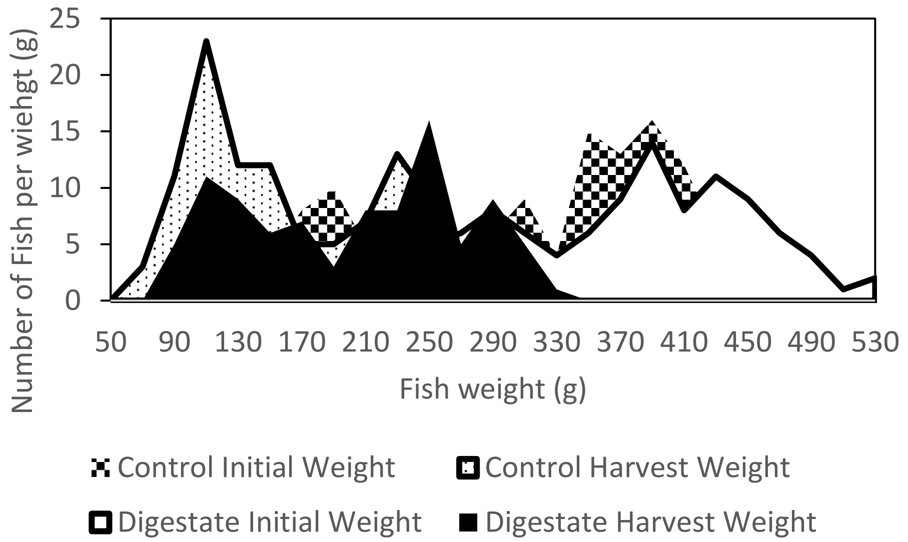

Fig. 9 The frequency distribution of fish weights comparing both the initial and harvest weights as they are represented across both mediums (control and digestate) at the Welgevallen Experimental Farm 2016.

.

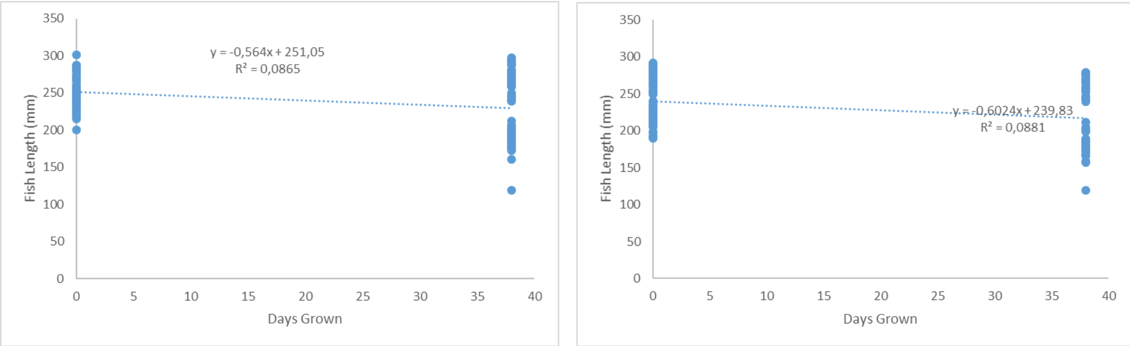

Fig. 10 Growth trends of fish grown in the (a) digestate and (b) the control medium from day 0 (added to the system) towards day 40 (harvest date) at the Welgevallen Experimental Farm 2016.

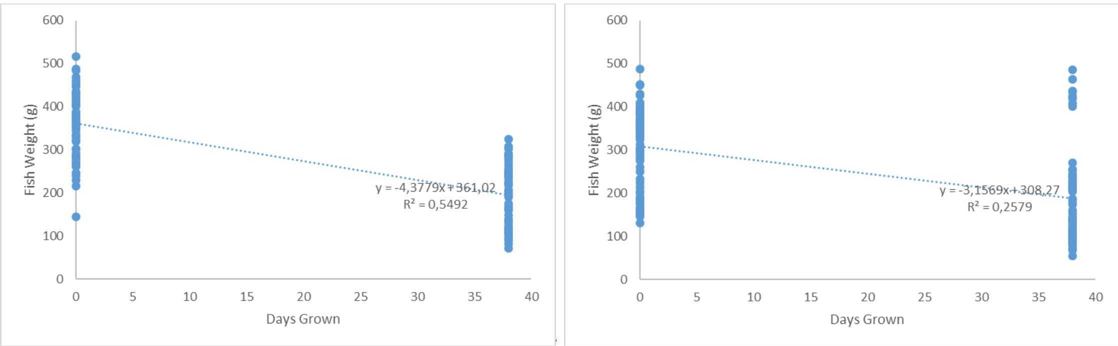

Fig. 12 Growth trends of fish grown in (a) the digestate and (b) the control medium at the Welgevallen Experimental Farm 2016.

Table 6. Change in total length (mm) and fresh weight (g) for tilapia grown in a control or digestate medium, also indicating the percentage mortalities over the same period during 2016.

	Avg Total length (mm)					Adjusted at Harvest to Initial number	Adjusted for 100 fish
Treatment	No of fish	Mortalities	% Mortality	Initial	Harvest		
Control	130	22	0.17	257.4	211.3	274.2	195.6
Digestate	103	10	0.10	264.7	227.8	234.0	244.9
Difference						40.2	-49.3

	Avg Total Weight (g)			Total fish Weight (g)			Adjusted for 100 fish
Treatment	Initial	Harvest	Adjusted	Initial	Harvest	Adjusted at Harvest	
Control	317.6	155.0	186.6	41283	16743	20154	15503
Digestate	363.2	194.6	217.6	37774	18096	20042	19458
Difference			-31.0			111.8	-3955.3

Table 7. The conditions under which the fish were cultured measuring for pH, Temperature, EC and DO at Welgevallen experimental farm, during 2016.

	Parameter	Week11		Week12		Week13		Week14		Week15		Week16	
		Mon	Thu	Mon	Thu	Mon	Thu	Mon	Thu	Mon	Thu	Mon	Thu
C	pH	6.29	6.07	5.85	5.63	5.41	5.19	5.80	6.03	6.26	6.49	6.72	6.53
	Temp	14.50	15.90	14.30	15.20	14.50	14.70	13.90	16.90	12.30	15.70	13.30	16.10
	DO	9.70	9.60	11.10	3.50	6.30	5.40	4.80	4.70	4.53	4.53	4.47	5.13
	EC	3.01	2.70	2.54	2.28	2.05	1.81	2.01	2.42	2.23	2.04	1.85	1.66
D	pH	6.85	6.71	6.57	6.43	6.29	6.15	6.19	6.23	6.34	6.31	6.35	6.27
	Temp	14.10	15.90	14.40	14.60	13.60	14.50	14.10	16.30	11.40	15.30	13.30	16.10
	DO	6.90	7.20	10.10	2.60	4.20	2.70	2.30	2.30	2.30	2.30	2.30	2.30
	EC	2.87	2.80	2.82	2.74	2.53	2.41	2.23	2.07	1.90	1.74	1.57	1.41

CHAPTER 5

5.1 Recommendations

Recommendations for future research include an alternative source for the biodigestate with a much lower suspended organic content and higher DO, which must be determined beforehand. The medium temperature is more critical in the case of fish production and increasing the water temperature to fit the fish must be a first priority. This system broaches the ideals of sustainability in many aspects: the use of waste water as nutrient addition and additional feed source, a system that provides several varying crops, a low energy demand and a system that can be tailored to suit the specific needs of the producer. However, to be practical, the quality of the bio-digestate should be monitored more closely to enable a substantial increase thereof to justify the contribution as a mineral nutrient substitute. It is also possible to try alternative fish species like catfish as a more robust model for this kind of experiment.

5.1.1 Overview

In today's economic climate most, small-scale farmers have become isolated from mainstream agricultural enterprises as major corporations rely on feedlots and other commercial operations to mitigate issues surrounding food security. Many of these commercial operations are fossil-fuel dependent activities that are nearing a threshold. The cost to the environment, our daily lives and related ecosystems services will soon be insurmountable. Unlike "the green revolution" that brought about agrarian change in the past century a new solution must be sought. The latest trends within agro-industry at large are looking forward with the sustainability of systems at the forefront of this revolution. As the global population has become more aware of concepts like food sovereignty, organic practices, free-range and grass-fed to name but a few, it has pushed large corporations to review their current models and make these products readily available. The drawback is that these niche demands are available at a cost which does not make them available to the everyday consumer. In the same way that they are not available to the everyday consumer, the capital outlay to produce such products makes it inaccessible to many farmers as well. It is for that reason that many production systems like aquaponics have gained notoriety as a system that can provide a variety of produce on both a commercial and small-scale level. One definition for sustainability is looking at an underutilised resource and redefining its purpose to create something new and novel that minimises waste and provides a new way forward. This was the premise of this pilot study, looking at bio digester effluent as an alternative nutrient source using it in an unconventional way. Although both null hypotheses were not rejected, circumstances were not ideal and with the following changes, this alternative approach renders demands another opportunity before it is discarded. The two most prominent factors that respectively affected the outcome in both the hydroponics and aquaponics sections of the trial was; (1) pH, which acted as a limiting factor in terms of both macro and micro-nutrient uptake, and (2) temperature acting as a limiting factor by providing a temperature-related stress to the system where fish growth was arrested or severely inhibited to provide a biological maintenance. (3) The nutrient imbalance that exists between the inorganic fertilizers and digestate used e.g. the imbalance of nitrogen provided into the system was much higher in the control. (4) Inconsistency in not using the same digestate in both trials providing a different nutrient composition and having to compensate therefore. As can be seen from Table 2 an abundance of nutrients was available in both treatments, but it was not possible for the plants or fish to benefit from this due to the suboptimal pH range. The marked difference in nitrogen availability between the control and experiment is one of the limiting factors affecting plant growth. In addition, the low DO and high organic matter in the digestate affected the plants and fish negatively, although in different ways. The drawback of this nutrient source is its quality. Initial adaptations to attempt a mitigation for the digestate quality had detrimental effects on the digestate system, as flowrate was constant and could not be adjusted as the systems relies on gravity to move water between components. These difficulties that arose made it quite difficult to have the two treatments mirror each other in terms of EC, pH and mineral composition.

The variation in plant growth and nutrient uptake efficiency could not solely be attributed to the different nutrient sources, but was also due to differential uptake of nutrients due to differences in pH and EC. Coupled to this buffering of aquaponics is a necessary tool in maintain an effective pH level where nutrient availability for plants is optimal. The most commonly used buffers are either potassium or calcium based as they are not prevalent in fish feeds and can be obtained calcium carbonate ($CaCO_3$) and potassium hydroxide (KOH). When these buffers are applied correctly to an aquaponic system an accumulation of the carrier portion of the buffer will not affect the system as it should be utilized by the hydroponic component of the system. Acceptance of the H_0 would therefore be bias as the treatments were not applied correctly for this purpose. Similarly, rejecting the H_0 would also be inaccurate, as plant performance did indicate significant decreases in the digestate vs control treatments, but the reason for this change was not merely due to a difference in mineral nutrient sources as initially envisaged.

Seasonal timing played a significant role in terms of the fish component which then provides several knock-on effects subsequently affecting the trial adversely for both fish and plants alike. The system temperature fell below the optimal range for the growth of Nile tilapia. Seemingly, this stressed the fish, which in turn led to low feed uptake and hence a low conversion of feed into nutrients to sustain nutrient levels in the digestate treatment. This means that the already low percentage of digestate would be unable to sustain nutrient levels throughout the digestate treatment. Mortalities in both treatments saw a decline in both TL and TW of fish, which could be explained by the mortality of larger fish within the system. It may be advisable to have the inlet at the fish tanks when water temperatures can be increased, before allowing the medium to flow to the plants. In the present trial, the fish seemed to have benefitted from the additional organic material, whereas the plants were not able to filter the digestate sufficiently as was originally anticipated.

The source of biodigestate influences the composition of the digestate and is thus a source of variation. It is possible that a different combination of organic waste may be more balanced, which could be more easily implemented into aquaponics to maximize nutrient availability.

Finally, a change from one, aquaponics, to two systems, hydroponics and aquaculture, running parallel can be considered as an interim approach. This will allow for time to determine the optimum management practices for both systems before connecting them again with a better understanding of the logistics when using a complex alternative mineral nutrient source such as biodigestate.

Appendix

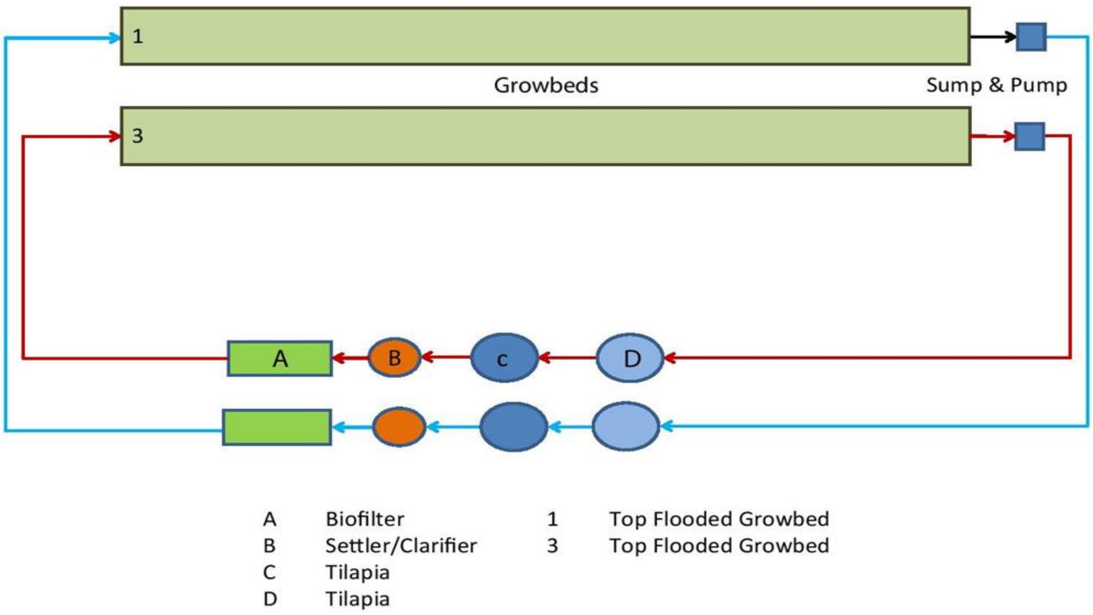

Fig.4 System layout of the aquaponic system at Welgevallen experimental farm

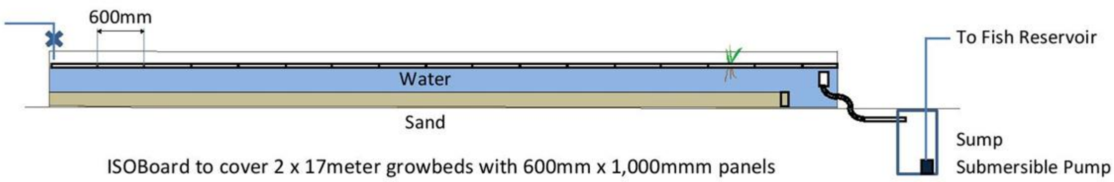

Fig. 5 Growbed layout of the deep-water culture system at Welgevallen experimental farm

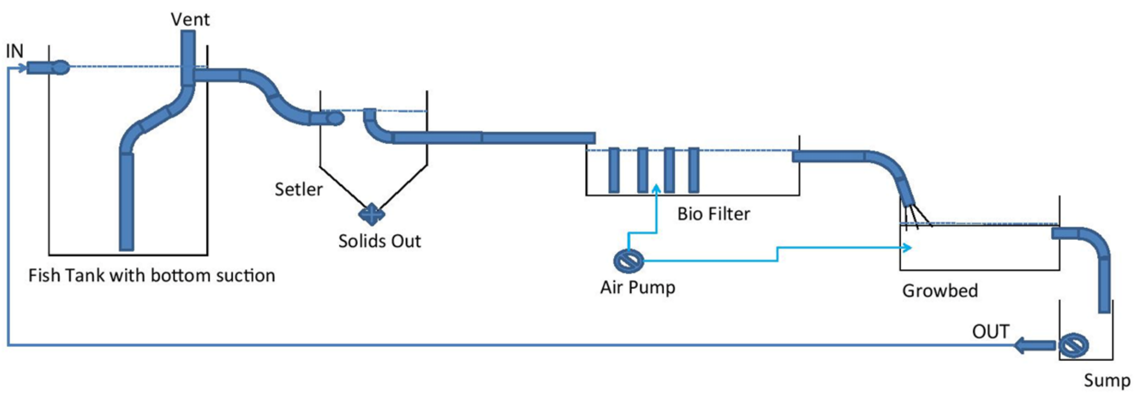

Fig. 6 Line components of the aquaculture system at Welgevallen experimental farm

WATERONTLEDINGSBESONDERHEDE / WATER ANALYSIS DETAILS :

Verslagverwysing / Report reference : PW-2016.06.007

Verslagdatum / Report date : 21/06/2016

Laboratoriumverwysingsnommer / Laboratory reference number PW/16/00191

Monsterverwysing / Sample reference Aquaponics before

pH	7.9	-
Konduktiwiteit / Conductivity	232	mS/m
TOS / TDS	1508	mg/l
Kalsium / Calcium	14	mg/l
Magnesium	12	mg/l
Kalium / Potassium	249	mg/l
Natrium / Sodium	181	mg/l
Sulfaat / Sulphate	17	mg/l
Koper / Copper	0.01	mg/l
Mangaan / Manganese	0.01	mg/l
Sink / Zinc	0.01	mg/l
Boor / Boron	0.41	mg/l
Yster / Iron	0.07	mg/l
Hardheid / Hardness	84	mg/l
NAV / SAR	8.58	-
Ammonium	26.47	mg/l
Fosfor / Phosphorus	10	mg/l

Fig. 7 Water analysis results obtained from Elsenburg laboratory

WATERONTLEDINGSBESONDERHEDE / WATER ANALYSIS DETAILS :

Verslagverwysing / Report reference : PW-2016.06.007

Verslagdatum / Report date : 21/06/2016

Laboratoriumverwysingsnommer / Laboratory reference number PW/16/00192

Monsterverwysing / Sample reference Aquaponics after

pH	8.3	-
Konduktiwiteit / Conductivity	1087	mS/m
TOS / TDS	7066	mg/l
Kalsium / Calcium	44	mg/l
Magnesium	34	mg/l
Kalium / Potassium	1455	mg/l
Natrium / Sodium	1003	mg/l
Sulfaat / Sulphate	25	mg/l
Koper / Copper	0.01	mg/l
Mangaan / Manganese	0.03	mg/l
Sink / Zinc	0.01	mg/l
Boor / Boron	1.40	mg/l
Yster / Iron	0.17	mg/l
Hardheid / Hardness	250	mg/l
NAV / SAR	27.61	-
Ammonium	4.53	mg/l
Fosfor / Phosphorus	15	mg/l

nms. Afdelings Hoof / pp Section Head ______________________

Fig. 8 Water analysis results obtained from Elsenburg laboratory continued

Table 10 Planting layout

A	System with biodigester effluent
B	System with nutrient solution
12 Plants per tray	lettuce, spinach, cabbage, brocolli
8 plants per tray	Tomatoes

Stoor

Tray	A	B
1	Tomatoes	Tomatoes
2	Green lettuce	Green lettuce
3	Red Lettuce	Red Lettuce
4	Cabbage	Cabbage
5	Spinach	Spinach
6		
7	Cabbage	Cabbage
8	Green lettuce	Green lettuce
9	Red Lettuce	Red Lettuce
10	Tomatoes	Tomatoes
11	Spinach	Spinach
12		
13	Spinach	Spinach
14	Cabbage	Cabbage
15	Red Lettuce	Red Lettuce
16	Tomatoes	Tomatoes
17	Green lettuce	Green lettuce
18		
19	Cabbage	Cabbage
20	Spinach	Spinach
21	Red Lettuce	Red Lettuce
22	Green lettuce	Green lettuce
23	Tomatoes	Tomatoes

Groei Kamers