# BIOECONOMIC FEASIBILITY OF AQUAPONICS IN SOUTH AFRICA: LEAPFROGGING FOR SUSTAINABLE DEVELOPMENT OF FRESHWATER AQUACULTURE

**by**

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## PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Marine Biology, School of Life Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Westville Campus, South Africa. The research was financially supported by NRF incentive fund (UID 112397)

The content of this work has not been submitted in any form to any other university except as stated in Declaration 2 and, where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate. Ethical approval to handle fish was approved by the University of KwaZulu-Natal's Animal Research Ethics Committee (AREC) with reference number AREC/069/017D.

## DECLARATION 1: PLAGIARISM

I, Babatunde Ayoade Adeleke, declare that:

(i) The research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

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## DECLARATION 2: CONFERENCES AND PUBLICATIONS

This work has been presented in the following formats. My role in each paper and presentation is indicated. The * indicates corresponding author.

1. Adeleke B. A*., Moodley G.K., Taylor S.M., Robertson-Andersson D.V. 2019. Quantitative swot analyses of key aquaculture players in Africa: a case study of Egypt, Nigeria and Uganda vis-à-vis South Africa. University of KwaZulu-Natal's School of Life Sciences Research Day, Westville, Durban, 14th October 2018, South Africa. This study applied quantitative SWOT analysis to determine the competitive strengths and aquaculture development opportunities of key aquaculture players in Africa as a benchmark for South Africa aspiring to rapidly develop its aquaculture sector **(Chapter 3)**. I designed the study, carried out the study, analyzed the data and did the oral presentation.
2. Adeleke B. A*., Moodley G.K., Taylor S.M., Robertson-Andersson D.V. 2020. Quantified SWOT analysis of major aquaculture species in South Africa. Aquaculture America, Honolulu, Hawaii, 9st – 12th February 2020, USA. This study analyzed the quantified SWOT analysis of key aquaculture species in South Africa to determine the competitive positions and aquaculture development potentials of these key species **(Chapter 4)**. I designed the study, carried out the study, analyzed the data and did the oral presentation.
3. Adeleke B. A*., Moodley G.K., Taylor S.M., Robertson-Andersson D.V. 2020. Aquaculture in Africa: A comparative review of Egypt, Nigeria and Uganda vis-à-vis South Africa. Accepted June 24th, 2020 and awaiting publication in *Reviews in Fisheries Science and Aquaculture* **(Chapter 2)**.
4. Adeleke B. A*., Moodley G.K., Taylor S.M., Robertson-Andersson D.V. 2020. Quantitative swot analyses of key aquaculture players in Africa: a case study of Egypt, Nigeria and Uganda vis-à-vis south Africa. Submitted and under review with the *Aquaculture International*. **(Chapter 3)**
5. Adeleke B. A*., Moodley G.K., Taylor S.M., Robertson-Andersson D.V. 2020. Quantitative SWOT analysis of major aquaculture species in South Africa. Submitted and under review with *Journal of the World Aquaculture Society.* **(Chapter 4)**

6. Adeleke B. A*., Moodley G.K., Taylor S.M., Robertson-Andersson D.V. 2020. Economic viability of low-cost aquaponic system in South Africa. Submitted and under review with *Journal of the World Aquaculture Society.* **(Chapter 5)**
7. Adeleke B. A*., Moodley G.K., Taylor S.M., Robertson-Andersson D.V. 2020. Bioeconomic yield of fish, tomato, sweet pepper and cucumber in a low-cost designed aquaponic system. Submitted and under review with the *Agricultural Systems.* **(Chapter 6)**
8. Adeleke B.A*., Robertson-Andersson D.V., Moodley G.K. and Mthethwa A.N. 2017. Bioeconomic feasibility of aquaponics for sustainable development of freshwater fin fish aquaculture in South Africa. World Aquaculture – South Africa (June 2017). Poster presentation. **(Chapter 1)**
9. Adeleke B. A*., Moodley G.K., Taylor S.M., Robertson-Andersson D.V. 2018. Standard operating procedure and ethical handling of Fish. Submitted to Animal Research Ethics Committee of UKZN, 2018. Revised by B.A. Adeleke. This work is based on ethical clearance requirement of Animal Research Ethics Committee for working and handling fish. I revised the holding, handling, transport, acclimatization, euthanasia and endpoint protocols (see Appendix BII.).

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## ABSTRACT

Food security is being threatened globally due to a combination of factors, such as climate change, anthropogenic pressures and burgeoning competition for limited water and land resources. The need to adopt environmentally and economically sound sustainable food production systems which are adaptable to the prevailing environmental stressors is imperative. Aquaponics sustainably converts aquaculture waste into nutrients for plant uptake resulting in an unconventional food production system which potentially provides an economically viable means of food production. Integrated recirculating aquaculture as adaptive technology is complex and capital intensive, thus, must be financially sustainable. This study, therefore, assessed the bioeconomic feasibility of aquaponics (a branch of aquaculture) in South Africa as a potential leapfrog technology for the rapid development of aquaculture, attainment of food security and local economic development. Quantitative and qualitative SWOT analyses, and key success factors of leading aquaculture players in Africa (Egypt, Nigeria and Uganda) were used as a benchmark to assess the South African aquaculture sector.

Qualitative analysis of South African aquaculture sector vis-à-vis the leading aquaculture players in Africa reveals a suboptimal environment that is not suitable to drive cost-effective and competitive conventional large-scale commercial aquaculture. Also, inadequate enabling environment due to bureaucratic hindrances towards the implementation of well-crafted aquaculture development policies and framework, and higher operating cost were identified.

The quantitative SWOT analysis of key aquaculture players in Africa revealed Egypt was having the highest aquaculture development competitive strengths, and Nigeria showed the highest aquaculture development and market opportunities. Quantitative SWOT analysis of key aquaculture species in South Africa showed trout and tilapia have the highest competitive strengths, while abalone, oyster and marron crayfish showed good market opportunities but weak in competitive strengths.

Growth performance of *Oreochromis mossambicus* and the yields from plants – tomato, pepper and cucumber due to the effects of plant density and stem pruning were assessed in a twin system designed, constructed and operationalized as a low-cost, small-scale aquaponic system. The economic viability of the aquaponic system was assessed using the price trend analysis of fresh produce in South Africa, biomass yield, cost inputs and revenue models using conventional aquaponic cultural methods. Financial performance was determined using financial metrics such as return on investment (ROI), net present value (NPV), internal rate of return (IRR) and profitability. Analyses were modelled to determine the financial performance of the aquaponic system.

The growth performance and yield of fish cultured in the aquaponic system showed excellent performance based on FCR (1.25 %), survival rate (97.5 %), LWR $r^2$ (0.945), regression coefficient b (3.1) and condition factor K (1.93). Total and marketable yield of vegetables (tomato, sweet pepper and cucumber) significantly increased ($p < 0.05$) with a higher plant density of 8 plants /m2 compared to 5 plants/m2. Plants with a higher stem pruning to two and three stems performed significantly better than those pruned to one stem ($p < 0.05$). The interactive effects of a higher plant density and stem pruning resulted in significant ($p < 0.05$) higher total and marketable yields with all the plants. Economic analysis of the small-scale aquaponic setup and operation did not present economic feasibility with the adoption of conventional cultural techniques (a revenue model of 59:

41 % fish to plant ratio) as a result of the higher operating cost associated with fish production. A fish to plant revenue model of 42 : 58 % ratio (achieved by adopting optimized cultural technique) however, showed marginal economic viability. Plant yield in aquaponics can be improved for higher economic returns through the synergistic optimization of plant density and stem pruning while adopting other optimal cultural management practices. A minimum revenue model of 30 : 70 % fish to plant ratio is recommended for aquaponic operations in South Africa to attain economic feasibility. Aquaponics thus presents optimistic potential to drive sustainable and feasible food production in South Africa with the adoption of viable production and marketing strategies.

Keywords: Aquaponics, bioeconomics, viability, biomass yield, SWOT analyses.

# DEDICATION

This Dissertation is dedicated to the blessed and loving memory of my mum,

Madam Christiana Olufunke Adeleke

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| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| AIS | Alien Invasive Species |
| ARAC | African Regional Aquaculture Centre |
| BTC | Belgian Technical Corporation |
| DAFF | Department of Agriculture, Forestry and Fisheries |
| DEFF | Department of Environment, Forestry and Fisheries |
| DFR | Department of Fisheries Resources |
| DWC | Deep Water Culture |
| EU | European Union |
| FAO | Food and Agricultural Organization |
| FDF | Federal Department of Fisheries |
| FFEs | Fish Farming Estates |
| FPMs | Fresh Produce Markets |
| GDP | Gross Domestic Production |
| GSM | Grand Strategy Matrix |
| IBC | Intermediate Bulk Container |
| IRR | Internal Rate of Return |
| LGA | Local Government Authorities |
| MAAIF | Ministry of Agriculture, Animal Industry and Fisheries |
| MADM | Multi-Attribute Decision Making method |
| NAPF | National Aquaculture Policy Framework |
| NASF | National Aquaculture Strategic Framework |
| NEMBA | National Environmental Management Biodiversity Act |
| NFPMs | National Fresh Produce Markets |
| NGO | Non-Governmental Organizations |
| NIFFR | National Institute for Freshwater Fisheries Research |
| NIOMR | Nigerian Institute for Oceanography and Marine Research |
| NPV | Net Present Value |
| PI | Profitability Index |
| RAS | Recirculatory Aquaculture System |
| ROI | Return on Investment |
| SDF | State Departments of Fisheries |
| SPADA | Special Programme for Aquaculture Development in Africa |
| SWOT | Strengths, Weaknesses, Opportunities and Threats |

# CHAPTER 1: INTRODUCTION

## 1.1 General Introduction

Demographic pressures, climate change, and the increasing competition for land and water are likely to increase vulnerability to food insecurity, particularly in Africa and Asia (FAO, 2011). FAO (2011) asserts that the challenge of providing sufficient food for everyone globally has never been greater, as this is accompanied by the human occupation of new lands and increasing use of natural resources, such as soil and water. Therefore, agriculture-dependent countries, especially developing countries that juggle food production with population growth, coupled with limited soil and water resources, need to adopt economically and environmentally sustainable production systems (Alexandratos & Bruinsma, 2012). In addition, adapting these systems under climate change scenarios is essential, as both land and water resources, which are the basis of food production are finite and already under heavy anthropogenic stress (Alexandratos & Bruinsma, 2012).

**Box 1: Definition of Agriculture, Aquaculture, Hydroponics and Aquaponics**

Agriculture involves the farming of both animals, *i.e.* animal husbandry and plants, *i.e.* agronomy, horticulture and forestry (Edwards & Demaine, 1997).
Aquaculture is the culture (involves levels of human interventions such as feeding, stocking, *etc*.) of aquatic organisms, which includes fish, molluscs, crustaceans and aquatic plants (Edwards & Demaine, 1997).
Hydroponics is a soilless culture method of cultivating plants either in an inert growing media (substrates) or by submerging the plants' bare roots in an aqueous medium connected with nutrient solution irrigation systems (Somerville *et al*., 2014). The inert growing media offer support for plant roots as well as retention of moisture (Somerville *et al*., 2014).
Aquaponics is the symbiotic integration of recirculating aquaculture and hydroponics as a single production system (Love *et al.*, 2015).

Aquaculture continues to be the fastest major food-producing sector globally (FAO, 2018) and accounted for 46.40 % of the total global fish landings in 2017 (Halwart *et al.*, 2019). Wild fish stocks are declining globally, while the demand for fish is constantly increasing, making the prospect of aquaculture increasingly attractive. Developing countries represent the biggest fish producers in the world, representing 92 % of overall aquaculture and 72 % of overall capture harvest (FAO, 2016). Asia-Pacific dominates in the global aquaculture market and represents the fastest growing regional market, with 89 % of global production in quantity and ~ 65 % of the global value (FAO, 2018). The global aquaculture production of aquatic animals recorded an average annual growth rate of 5.9 % from 2001 to 2010 and declined to 4.8 % per year from 2011 to 2017 (Halwart *et al.*, 2019).

Aquaponics incorporates hydroponic vegetable production and intensive aquaculture and has been flaunted as a sustainable food production technology (Tokunaga *et al.*, 2015). In aquaponic systems, nutrient-rich water is circulated from fish tanks to vegetable grow beds, while the vegetables act as a biofilter by assimilating the nutrients produced from fish feacal waste thereby purifying the water to be circulated back to the fish tank and thus conserving water (Diver, 2000). By absorbing the dissolved phosphorus and nitrogenous substances from the fish wastes in the water, plants grow faster thus, increasing the net revenue from both fish and crop production (Rakocy, 2012; Goada *et al.*, 2015).

Aquaponics has several advantages above aquaculture and hydroponics as stand-alone units;

I. It is a water-saving technology, as water is circulated between vegetable grow bed and fish tank.
II. Water is only added to compensate for the loss due to evaporation.
III. Aquaponics does not need soil to grow plants; therefore, marginal land can be utilized to produce both fish and vegetables.
IV. Reduces pests and soil-borne diseases affecting monoculture crops by avoiding the contact between plants and soil.
V. The system setup can easily be modulated depending on a farm's location and components availability.

It is in light of these advantages, that aquaponics is touted as a sustainable food production practice (Somerville *et al.*, 2014; Tokunaga *et al.*, 2015).

Aquaponics, although has several advantages, however, this system of food production is not without its major weaknesses (Somerville *et al.*, 2014). Some key disadvantages of aquaponics include but not limited to;

I. The initial setup cost is high thus expensive compared to either open field vegetable production or hydroponics.
II. It is energy demanding, as electricity is required to maintain and recycle water within the system.
III. Highly technical and complicated. Knowledge of fish, plant and bacteria is required for successful operation.
IV. Component failure can lead to catastrophic loss of both fish and plant.
V. Reliable access to inputs such as electricity, fish seed, fish feed and plant seedlings is required.

The selection of plant species that are well adapted to aquaponics culture is directly related to the stocking density of fish tanks and subsequent nutrient concentration of aquaculture effluent (Diver, 2000). For example, lettuce, herbs, and speciality greens (spinach, chives, basil, and watercress) have low to medium nutritional requirements and are well adapted to aquaponic systems (Schmautz *et al.*, 2016). Fruit yielding plants such as tomatoes, bell peppers, and cucumbers have higher nutritional demands and perform better in a heavily stocked and well-established aquaponic systems (Schmautz *et al.*, 2016). Therefore, the choice of plant species to be cultivated in the hydroponic component of greenhouse aquaponics is largely determined by the stocking density of fish tanks and subsequent nutrient concentration of the aquaculture effluent (Pardossi *et al.*, 2002; Buzby & Lin, 2014; Goddek *et al.*, 2015).

Many warm and cold-water fish species are adapted to recirculating aquaculture systems, including tilapia, catfish, carp, koi, trout, perch, arctic char, and bass (Diver, 2000). However, tilapia, catfish and common carp perform well in recirculating tank culture as they can tolerate fluctuating water quality parameters such as pH, temperature, oxygen, and dissolved solids (Diver, 2000). Tilapia are the most widely used fish species in aquaponics systems due to their ease of breeding, high availability, fast growth rates, hardiness and easy adaptation to culture systems thus allowing for high stocking densities (Hussain, 2004; Rakocy *et al.*, 2006; IDC, 2015). Tilapia has remarkable appeal to consumers globally with the USA accounting for the world's leading market (IDC, 2015). Africa is currently the fastest-growing market for tilapia as the continent has become a major target for Chinese exports of food fish (IDC, 2015).

Sampford (2002) defines leapfrog technology as an approach in which areas with poorly developed technology or economic bases are able to move forward at a rapid pace through the adoption of modern systems, without going through intermediary processes. In a broad sense, leapfrogging is not just limited to a particular technology or industry rather, it centers on the entire pathway that could be trailed by developing countries while avoiding, as much as possible, the "harmful" development pathways previously followed by many developed economies (Sauter & Watson, 2008). Therefore, this allows for the developing economies to attain accelerated growth with minimal environmental impacts (Gallagher, 2006). Major types of leapfrogging relate to the adoption of new technologies and industrial development. In both scenarios, technology adaption to the local environment is an indispensable condition for leapfrogging strategies to be successful (Sauter & Watson, 2008).

A major successful model of leapfrogging is the rapid adoption and proliferation of mobile phone technologies in developing countries. According to Kyem and LeMaire (2006), the African continent recorded the highest mobile phone growth rate globally between 1999 and 2004, with a 60 % average growth rate in mobile phone subscriptions yearly. Leapfrogging occurred in rural areas that skipped landline phones for mobile phones during the later stages due to proliferation from urban to rural areas (Kyem & LeMaire, 2006).

In the light of the mobile phone proliferation in Africa and other developing economies as an example of successful leapfrog technology model, aquaponics could potentially be leveraged as a leapfrog technology for the rapid development of the nascent aquaculture sector in South Africa. Aquaponics due to its numerous advantages over other aquaculture technologies as earlier highlighted in this section and its wide adaptability to different environmental conditions can accelerate the growth of both aquaculture and plant production sector in South Africa.

## 1.2 Global and Regional Aquaculture Production Synopsis

A total of 622 species items have been documented for aquaculture production globally from 1950 to 2018. The tilapias are the most widely farmed species globally, from South Africa to Poland, Latin America to Canada, cultured in varying water systems ranging from brackish ponds and coastal cages to heated ponds (Halwart *et al.*, 2019; Halwart, 2020). Production in earthen ponds still remains the most widely adopted culture system for aquatic animal production globally; however, the growth and distribution of cage and pen culture methods in lakes and reservoirs, have led to the emergence of many countries such as some African countries, India, Bangladesh and Saudi Arabia as key regional aquaculture players (Halwart *et al.*, 2019). The development of cage culture in the aforementioned regions has not been without challenges as farmers faced more stringent regulations in some countries (Halwart, 2020). The development and adoption of recirculating aquaculture systems (RAS) production technology have evolved at a rapid pace in the past decade, with the developed countries taking the lead, while some developing countries with favourable local conditions are also adopting RAS systems (Halwart *et al.*, 2019).

The total global aquaculture production output in 2017 was 111.9 million tons, valued at USD 249.6 billion for both aquatic animals and plants produced in 198 countries (Halwart *et al.*, 2019). Aquatic animal production accounted for 80.1 million tons valued at USD 237.5 billion, while aquatic plants represented 31.8 million tons with a market value of USD 11.8 billion and 2.2 thousand tons of nonfood products valued at USD 186 million (Halwart *et al.*, 2019). Farmed aquatic animal production categories and values include finfish (53.4 million tons; USD 139.7 billion), molluscs (17.4 million tons; USD 30.4 billion), crustaceans (8.4 million tons; USD 61.1 billion) and other aquatic animals (893 900 tons; USD 6.6 billion) (Halwart *et al.*, 2019). The inland aquaculture production of finfish species was the most significant sector in the global aquaculture production with a total production output of 45.6 million tons and represented 56.9 % of global aquaculture production of aquatic animals in 2017(Halwart *et al.*, 2019).

Asia was the global leader in aquaculture production, contributing 88.8 % (70.65 million tons) of total farmed aquatic animals in 2017, distantly followed by Americas (North and

South) with 4.5 % (3.60 million tons), Europe 3.8 % (3.01 million tons), Africa 2.6 % (2.09 million tons) and Oceania 0.26 % (0.205 million tons) (Halwart, 2020). China led the top ten global aquaculture producer with 46.8 million tons (57 %), India 6.2 million tons (7.6 %), Indonesia 6.2 million tons (7.6 %), Vietnam 3.8 million tons (4.6 %), Bangladesh 2.3 million tons (2.8 %), Egypt 1.5 million tons (1.8 %), Norway 1.3 million tons (1.6 %), Chile 1.2 million tons (1.5 %), Myanmar 1 million tons (1.2 %) and Thailand 0.89 million tons (1.1 %) (Halwart *et al.*, 2019). These top ten aquaculture producers collectively contributed 71.2 million tons of farmed aquatic animals, representing 88.9 % of the total global production output in 2017 (Halwart *et al.*, 2019).

Aquaculture as a means of livelihood and sustainable food production was introduced to Africa about a century ago with the first production of tilapia in static ponds recorded in Kenya in the 1920s (FAO, 2005-2020e). Egypt contributed 71 % of aquaculture production of aquatic animal in Africa in 2018, sustaining its position as the largest aquaculture producer in the continent, followed by Nigeria (13 %), Uganda (5 %), Ghana (3.5 %), Zambia (1 %) and Tunisia (1 %) (FAO, 2003-2020a, 2003-2020b, 2004-2020, 2005-2020a, 2005-2020b, 2007-2020). Egypt, Nigeria, Uganda and Ghana accounted for about 93 % of total aquaculture production in Africa.

## 1.3 Overview of Aquaculture in South Africa

Aquaculture in South Africa is comparatively recent and underexploited, mainly focused on high-value species such as abalone, mussels and oysters, albeit with meagre production output (DAFF, 2012). In 2018, the total South African aquaculture production output excluding ornamentals, koi carp and seaweed was 6,181 tons (0.3 % of aquaculture production in Africa) (FAO, 2010-2020a). Finfish production is an emerging sub-sector of the aquaculture sector in South Africa (DAFF, 2015, 2017a). The dusky kob *(Argyrosomus japonicus* - Temminck & Schlegel, 1844*)* is the only current commercial marine finfish being cultured although, some other species of finfish were piloted in the past years in order to assess aquaculture feasibility and market access. Dusky kob production recorded a total standing stock of 77.32 tons at the end of 2016 mostly from farms in Eastern Cape (DAFF, 2017a).

The freshwater aquaculture sector of South Africa is still at the infancy stage in with regards to production output and contribution to the economy, despite being introduced in the early 1800s (DAFF, 2015). The slow pace of development in this sector is largely due to the dearth of skill development, transformation and awareness of the aquaculture sector (DAFF, 2017b). The sub-sectors of freshwater aquaculture include trout (*Onchorynchus mykiss* – Walbaum 1792 *and Salmo trutta* – L. 1758), tilapia (*Oreochromis mossambicus* – W. K. H. Peters, 1852*, O. niloticus* – L. 1758 and *Coptodon rendalli* - Boulenger, 1897), African sharp tooth catfish *(Clarias gariepinus* – Burchell, 1822*)*, carp *(Cyprinus carpio* – L. 1758 and *Ctenopharyngodon idella* – Steindachner, 1866*)*, marron crayfish *(Cherax tenuimanus* – Smith, 1912*)*, and ornamental species (FAO, 2010-2020a). The most cultured freshwater species are trout with production sites spread across the Western Cape, Eastern Cape, Mpumalanga and KwaZulu-Natal provinces, while tilapia is the second-largest cultured freshwater species in fish farms located across the country (DAFF, 2015). Total freshwater aquaculture production in 2015***** was 1,827 tons with trout accounting for 1,497 tons recording a growth rate of 8.7

% between 2005 and 2015 (DAFF, 2017b). Trout production accounted for highest production in 2015, followed by abalone and mussels, while marine finfish, oyster, tilapia, catfish and marron are still developing sub-sectors (DAFF, 2015, 2017a).

The South African aquaculture sector value was estimated to be ~ R 696 million in 2013 and grew by 38.1 % from 2012 to 2013, as reported by DAFF (2015). The sector value was based on aquaculture products sales from both freshwater and marine aquaculture. Abalone production, worth about R529 million and accounting for 76 % of the total aquaculture market value, continued to dominate local aquaculture production in 2015 (DAFF, 2018). Production of trout represents the second-largest aquaculture market contributor valued at R113 million and representing 16.27 % of the total market value (DAFF, 2018). Other species like mussels were valued at R20 million, oysters R16.6 million, tilapia R9.9 million, dusky kob at R6 million and marron crayfish R1 million, representing 2.89, 2.39, 1.42, 0.88 and 0.14 percent respectively of the total value of South African aquaculture industry (DAFF, 2015).

As a result of insignificant aquaculture output from South Africa compared to key regional producers (Egypt, Nigeria, and Uganda) and key global players (China, Indonesia, India, Vietnam and Norway) (Cai *et al.*, 2017; FAO, 2018) coupled with the opportunities presented by aquaculture to address challenges such as sustainable utilization of aquatic resources, food security, economic inequality, unemployment and importation; the National Aquaculture Policy Framework (NAPF), was drafted to accelerate the development of aquaculture industry value chain (DAFF, 2013). The aim of the NAPF is to address several challenges such as overregulation of aquaculture sector, suitable aquaculture species, accessibility to land and water, climate change, skilled human resources, funding and marketing, all of which all have culminated in the stagnation and suboptimal development of the aquaculture sector in South Africa (DAFF, 2013).

## 1.4 Problem Statement

According to DAFF (2015), the South African aquaculture sector is in its nascent phase and characterized by very low production output and myriads of challenges that have contributed to the suboptimal development of this sector as compared to key regional and global players. South Africa is a dry country and currently confronted with water supply crisis due to combination of low rainfall, high evaporation rates, expanding economy and a growing population whose geographical demands for water do not conform to the distribution of exploitable water supplies (CSIR, 2010). As of 2005, over 95 % of the country's freshwater resources had already been apportioned, and the water quality of these resources has also deteriorated due to increased pollution from anthropogenic activities (Ashton *et al.*, 2008). Water utilization in South Africa is dominated by irrigation, accounting for 62 % of total water consumption, domestic and urban use account for 27 % while mining, large industries, and power generation account for eight percent. Commercial forestry plantations account for a little less than three per cent of water used by reducing runoff into rivers and streams (DWA, 2004).

Climate change is one of the major threats to water and food security globally (Misra, 2014). Projections show that increasing evaporation, evapotranspiration and associated soil moisture shortfalls will affect rain-fed agriculture, especially in Sub-Saharan Africa (Ludi, 2009). South Africa at the national level is currently food secure, but the food security situation at the household and intra-household level are not the same (Labadarios *et al.*, 2011). The South African Food Bank reported about 19 million South Africans as food insecure as a result of socioeconomic factors at various scales and environmental stressors (droughts and floods) leading to a decrease in production levels (Teka Tsegay *et al.*, 2014). Future threats to water supplies would threaten food security, and if food production in South Africa falls below domestic requirements, food insecurity will probably escalate especially among the poor (Labadarios *et al.*, 2011).

South Africa generally possess a suboptimal environment for aquaculture, due to temperature variations of summer highs and winter lows, thus is limited by a natural environment that is suitable to drive viable large-scale commercial aquaculture (Britz & Venter, 2016). The combined effects of the scarcity of inland water and overstretched demand for the available freshwater systems, therefore, limit the environmental suitability for commercial-scale freshwater aquaculture production using conventional aquaculture production systems. In addition, the vastly exposed shoreline of South Africa, plagued by high energy wave action from Indian Ocean cyclones and Southern Ocean frontal systems, severely limit the potential for commercial-scale mariculture systems such as sea cage aquaculture (FAO, 2010-2020b; Britz & Venter, 2016). These environmental constraints, coupled with other prevailing macroeconomic challenges, severely limit the aquaculture development potentials of South Africa, compared with the key global and regional aquaculture producers.

The challenge for South Africa with heavy utilization of the nation's water-scarce resources coupled with the suboptimal climatic conditions for commercial aquaculture, therefore, lies on sustainable and viable production systems such as aquaponics – an unconventional integrated food production system that needs to be developed to mitigate these impacts. Aquaponics and RAS technology are highly intensive with a high operating cost; however, they represent the most suitable and environmentally friendly technology for the development of aquaculture in South Africa. Aquaponics thus represents a viable and sustainable technology that South Africa may leverage to potentially leapfrog its budding aquaculture sector, especially the development of the finfish inland aquaculture. Sustainability in agriculture refers to a food production system that fairly integrates economic viability, environmental health and social justice (Brodt *et al.*, 2011).

The conventional assessment of aquaculture potential has been basic, one-sided and often based on market value rather than integrated approach (Allen *et al.*, 1984).

Bioeconomics is used to describe the dynamic and integrative interactions between the biological and economic attributes of a physical production system (Allen *et al.*, 1984). In the light of bioeconomics, aquaculture is assessed from three broad functional areas which according to Allen *et al*. (1984) are biological features of the (i) cultured species (ii) culture system design and (iii) economic performance of the culture system and marketing of the cultured species. Previous techno-economic feasibility of aquaponic operations in South Africa conducted by Lapere, (2010) showed that most of the aquaponic operations evaluated were not economically viable due to a myriad of factors. The identified factors include aquaponic system design, high operating cost, pricing and marketing, farming of slow-growing *O. mossambicus* compared to *O. niloticus* with better growth performance, management and cultural practices, inability to attain economies of scale and others (Lapere, 2010). This study is therefore designed to re-evaluate the feasibility of aquaponics in South Africa taking into cognizance the challenges identified from the study of Lapere, (2010), the success factors identified from the studies of Engle, (2016) and the critical aquaculture success factors of the regional key producers. The bioeconomic viability of the modelled aquaponic operation will be assessed using plant production optimization and yield, fish biomass yield, management practices, cost analysis, and financial performance.

### 1.5 Key Research Questions

The key questions are:

I. Is aquaponics economically feasible in South Africa?

II. Is the biomass yield from aquaponics sustainable?

III. What are the critical success factors for aquaculture development in South Africa?

## 1.6 Aim

Aquaponics as leapfrog technology has the potentials of addressing key challenges (i.e. climate change, water shortages, land and food security) confronting the growth of aquaculture in South Africa. Moreover, the accelerated national development strategy and implementation of "Operation Phakisa" give priority attention to the development of the aquaculture industry under the development of the ocean economy (Zuma, 2014). The implementation of "Operation Phakisa" is expected to significantly grow the aquaculture sector to a major GDP contributor within a short term with the adoption and propagation of aquaponics technology (Britz & Venter, 2016). Therefore, the aim of this study is to assess the prospects of technical, biological, and socioeconomic viability of sustainable freshwater aquaculture integrated with organic vegetable production in South Africa using aquaponics as a leapfrog technology.

## 1.7 Objectives

The main objective of this study is to conduct a bioeconomic feasibility study on aquaponics to determine its viability in South Africa. Specific objectives include the following:

1. Conduct a qualitative and quantitative analysis of aquaculture in Africa focusing on the key regional producers (Egypt, Nigeria and Uganda) compared to South Africa – an aspiring key aquaculture producer.
2. Conduct quantitative analysis of major aquaculture species in South Africa for aquaculture development.
3. Design, setup and operationalize a low-cost, small-scale commercial aquaponic system model.
4. Determine the growth performance, survival, environmental performance of *O. mossambicus* in the designed low-cost model aquaponic system.
5. Determine the aquaponic yield of tomato (*Solanum lycopersicum* – L. 1758), sweet pepper (*Capsicum annuum* – L. 1758) and cucumber (*Cucumis sativus* – L. 1758) due to the effect of plant density and stem pruning.
6. Assess the financial feasibility of the low-cost aquaponic model in South Africa using financial performance models.

## 1.8 Dissertation Structure

Each chapter is predominantly autonomous, covering an abstract, literature review, materials and methods, results, discussion, and conclusions. Chapter two is based on the first objective, chapter three is linked with the second objective, chapter four is linked with the third objective, chapter five is based on the sixth objective, and chapter six is linked with the fourth and fifth objectives,

Chapter 1. Discusses the introduction, overview of aquaculture in South Africa, problem statement and the structure of this research.

Chapter 2. Reviews the qualitative analysis of aquaculture in Africa with specific interest in the qualitative strengths, weaknesses, opportunities and threats (SWOT) and critical success factors of key players (Egypt, Nigeria and Uganda) compared with South Africa. Key aspects of this chapter were to establish qualitative factors driving the slow growth of aquaculture in South Africa compared with Egypt and Nigeria.

Chapter 3. Undertakes comparative quantitative SWOT analyses of aquaculture sector of Egypt, Nigeria and Uganda compared with South Africa to determine their competitive positions and opportunities for aquaculture development.

Chapter 4. Compares major aquaculture species in South Africa using quantitative SWOT method to determine their competitive positions and market development opportunities.

Chapter 5. Analyzed the economic viability of the setup and operationalization of the modelled low-cost aquaponics using fresh produce price trend analysis and financial performance indicators.

Chapter 6. Assessed the growth performance and yield of *O. mossambicus* using growth and environmental parameters. Fruit vegetable yield of tomato, sweet pepper and cucumber were determined due to the combined effects of plant density and stem pruning.

Chapter 7. Integrates the study and provides conclusions and recommendations of this research. Future teaching, learning and research gaps are also included.

** The lack of recent and updated aquaculture data poses a major constraint to country aquaculture research, and it will be further discussed in Section 3.0 and 4.0.*

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# CHAPTER 2: AQUACULTURE IN AFRICA: A COMPARATIVE REVIEW OF EGYPT, NIGERIA AND UGANDA VIS-À-VIS SOUTH AFRICA

## 2.1 Introduction

This chapter reviews the development and conventional qualitative analysis of aquaculture in Africa, specifically by reviewing the aquaculture sector of key players (Egypt, Nigeria and Uganda) as a reference for South Africa; an aspiring key aquaculture player in Africa based on the launch of Operation Phakisa – South African version of the blue economy initiative (Zuma, 2014). The key players were identified based on current annual production output and critical success factors, which were used as a benchmark for South Africa. Qualitative factors reviewed are critical success factors of the country's aquaculture sector that are widely germane to aquaculture development. These factors include production outputs (tons) and value ($); cultured species; prevalent aquaculture production systems; types of aquaculture, i.e. freshwater and mariculture; aquaculture development challenges related to fish seed, fish feed, land and water availability; aquaculture market and trade and provision of enabling environment through policies and frameworks. These factors were qualitatively reviewed and analyzed in ranking the aquaculture operations of the key players and South Africa to elucidate the critical success factors and challenges as well as form the basis for the quantitative analysis of these players in Chapter 3.

## 2.2 History and General Background of Aquaculture in Africa

Aquaculture was first introduced to many countries in Africa at the turn of the 20$^{th}$ century mainly to satisfy colonial recreational fishing needs (Hecht *et al.*, 2006). In the 1920s, tilapia were successfully produced in static water ponds in Kenya (FAO, 2005-2020e). Aquaculture as a means of sustainable food production was later introduced by the colonial governments across Africa between the 1940s and 1950s (Brummett *et al.*, 2008) with the objectives of improving nutrition in rural areas, supplementary income generation, diversification to reduce crop failure risks and employment creation in rural areas. As a result, many fish farming stations were built by the government in the 1950s (Fisheries, 2006), with about 300,000 active production ponds in the whole of Africa as at the end of 1950 (Satia, 1989).

The FAO, in partnership with governments, donor countries, national and international research bodies and Non-Governmental Organizations (NGOs) began to spearhead the development of aquaculture in the region since the 1960s (Hecht *et al.*, 2006). Efforts were focused on elementary research and development to understand practical techniques for a range of mostly indigenous species. The development of aquaculture in the region was expedited through increased financial and technical aids from bilateral and multilateral donors worth about US$ 500 million from the early 1970s to early 1990s (Hecht *et al.*, 2006). Subsequently, financial support for aquaculture in Africa significantly regressed due to donor priorities shifting towards other pressing challenges such as education, health, HIV/AIDS and good governance in Africa (Hecht *et al.*, 2006). The development of aquaculture in Africa can be broadly segmented into three phases (Table 2.1).

**Table 2.1: Evolution of Aquaculture in Africa.**

| Phase | Period | Description of Activities |
|---|---|---|
| I | 1950 - 1970 | ○ Introduction of aquaculture<br>○ Limited knowledge and understanding of aquaculture<br>○ Fish farms were built by governments |
| II | 1970 - 1995 | ○ Expansion of aquaculture<br>○ Significant donor support<br>○ Active R&D<br>○ Government involvement in seed supply and extension services<br>○ Commercialization of aquaculture in some countries such as Nigeria, Madagascar, Côte d'Ivoire, Zambia and South Africa |
| III | 1995 – till today | ○ Reduced donor support<br>○ Emergence of Commercial aquaculture<br>○ Re-orientation of public Support towards facilitation |

(adapted from Hecht *et al*., 2006)

## 2.3 Current Status of Aquaculture in Africa

The African contribution to world aquaculture production is still insignificant (~ 2.7 %) (Halwart, 2020) albeit significantly increasing with larger-scale investments in Egypt, Nigeria, Uganda and Ghana producing substantial quantities of fish (Cai *et al.*, 2017; FAO, 2018). The region recorded a twenty-fold production increase from 110,200 to 2,196,000 tons from 1995 to 2018 with a compound annual growth rate (CAGR) of 15.55 % (FAO, 2016; Halwart, 2020). The growth of aquaculture production was due to the advent and intensification of private sector controlled small and medium scale enterprises (SMEs) (Satia, 2011). Also, the development of big commercial enterprises mostly stimulated by the combination of burgeoning public support, expertise, foreign direct investment, interest in aquaculture, global awareness raised through the NEPAD Fish for All Summit of 2005 as well as the implementation of the FAO Special Program for Aquaculture Development in Africa (SPADA) contributed to aquaculture growth (Satia, 2011).

Most of the production (99 %) are from the inland freshwater systems and is mostly dominated by the culture of indigenous and abundant species of tilapia and African Sharptooth catfish (catfish) while mariculture only contributes a meagre 1 % to the total production quantity, although it is an emerging and promising subsector (FAO, 2016, 2018). New aquaculture production systems such as tanks and cages were introduced as well as the improvement of current production systems (Satia, 2017). The aquaculture sector employs about 6.2 million people in Africa, with a large share of the employees being women that are engaged in largescale commercial farms (Satia, 2016). Women are primarily involved in the downstream postharvest and marketing operations of the aquaculture value chain (Satia, 2016). The aquaculture sector, therefore, has the potential to significantly contribute to food security, reduce unemployment rates and economic development of Africa.

Many governments in Africa have started realizing the importance of creating an enabling business environment by taking steps such as expediting, coordinating and adopting policy reforms to create a conducive environment for business to thrive, with ripple effects on the aquaculture sector (Satia, 2011). Some countries have developed and adopted aquaculture-centered policies and strategic framework as a roadmap to guide development (Machena & Moehl, 2001). Few governments facilitated the provision of soft credits and incentives, however, access to affordable credit, sufficient quality and quantity of inputs and land ownership still constitute major constraints to the development and intensification of the aquaculture sector (Satia, 2011).

Generally, research activities in the region focused on the species characterization, selective breeding and low-cost diet production in some centres (Satia, 2011). On-farm participatory research approach using model farms and private enterprises are yielding fast aquaculture technologies transfer via farmer-to-farmer pathways in the target countries administered by SPADA (Cocker, 2014). Extension services are generally inadequate and weak; therefore, the pressing need to develop and strengthen the links between research and development (Satia, 2011).

Some countries have witnessed growing private sector-led participation in the production and delivery of major aquaculture inputs such as seed and feeds while other countries host the manufacturers and suppliers of aquaculture equipment (Koge *et al.*, 2018). Association of aquaculture products producers is located in many countries of Africa playing key roles such as information transfer, knowledge exchange and facilitation of aquaculture related activities (Satia, 2017). The formation of clusters of fish farmers has efficiently contributed to support services delivery, economies of scale, reduction of transaction costs and competitiveness (Satia, 2017).

The intra- and inter-distribution of aquaculture products within the region are hampered by dilapidated infrastructure and the dearth of facilities, however, the advent of fledging aquaculture marketing activities in some countries is contributing to aquaculture value chain improvement (Satia, 2011). In order to meet the demand for ready-to-prepare products by consumers, artisanal fish processing sub-sectors are emerging from farm gates and markets utilizing simple fish processing methods (Satia, 2017). Value addition is also carried out on the products by freezing, smoking, drying, as well as cold smoking of catfish fillets for export to European markets (Satia, 2017).

As the industry evolves and activities get intensified, aquaculture in some of the leading countries become confronted with challenges such as; the burgeoning demand for capital;

inadequate quantities and quality of seed and feeds; resource (land/water/feed) competition; requirement to reinforce aquaculture management and overall governance of the sector (Satia, 2016). The peak in both marine and inland capture fisheries yield, combined with growing markets and services, urbanization, private-sector development opportunities; make the prospects of aquaculture development huge (Satia, 2017).

The top aquaculture producers in Africa are Egypt, Nigeria, Uganda, Ghana, Tunisia, Kenya, Zambia, Madagascar, Malawi and South Africa (Satia, 2011; Satia, 2017). These key aquaculture producers experienced remarkable growth in the past decade as a result of several factors such as capacity building in critical subject areas, embracing good governance, research and development, access to credit facilities and largely due to the promotion of private sector-led aquaculture development (Satia, 2017). Private sector-led initiatives gave rise to investments in sound management, emerging production systems, the formulation and utilization of aqua-feeds and the emergence of strong and dynamic producer associations and service providers (Satia, 2010).

As the industry evolves and activities get intensified, aquaculture in some of the lead countries is currently being confronted with several challenges such as the burgeoning demand for capital; the need for adequate quantities and quality of seed and feeds; severe resource (land/water/feed) competition with other users, and the requirement to reinforce aquaculture management as well as the overall governance of the sector (Satia, 2016). However, with the peak in both marine and inland capture fisheries yield, combined with growing markets and services, urbanization, private-sector development opportunities, the prospects of aquaculture development are huge (Satia, 2017).

## 2.4 Comparative Analysis of Key Regional Players (Egypt, Nigeria and Uganda) vis-à-vis South Africa

The contribution of Africa to global aquaculture production in 2018 was estimated at 2,196 million tons representing an insignificant 2.67 % and dominated mainly by the production of freshwater finfish (Halwart, 2020). The leading producers - Egypt, Nigeria and Uganda, account for about 90 % of total aquaculture production from the region (Table 2.2). The aquaculture sector in Egypt experienced rapid development from 1998 due to the consistent and cumulative interventions by the Egyptian government over the past years, as well as growing private sector-driven investment (Soliman & Yacout, 2016). Aquaculture production in Egypt, therefore, grew from 139,389 tons in 1998 to 1,561,457 tons in 2018 (Figure 2.1), representing 71 % of total aquaculture production in Africa (FAO, 2003-2020b). Nigeria with a population of over 200 million (Pison, 2019), has the highest fish demand in Africa, resulting in the rapid development of peri-urban commercial aquaculture (Cai *et al.*, 2017). As a result of the market-driven development, aquaculture production grew from 20,458 tons in 1998 to 291,233 tons in 2018 (Figure 2.2). The Nigerian government is saddled with the responsibility of providing a conducive business environment, while the entire aquaculture value chain development is driven by the private sector initiatives (FDF, 2012). The development of aquaculture in Uganda gained momentum from 2000 due to the growing awareness of the potential of aquaculture to address malnutrition, food insecurity and unemployment (Cai *et al.*, 2017). As a result, aquaculture development received a boost through strategic interventions from the government and aids from developmental partners (Cai *et al.*, 2017). Aquaculture production increased from 2,360 tons in 2001 to 103,737 tons in 2018 (Figure 2.3). As a result of the significant leap in aquaculture production output of Egypt, Nigeria and Uganda in the past two decades, it is noteworthy to review the critical success factors of these key regional players. Out of the top ten aquaculture producers in Africa, Egypt, Nigeria, Uganda, and Ghana contribute about 93 % of total regional production output (Table 2.2).

**Table 2.2: Top Ten Aquaculture producers in Africa in 2018**

| No. | Country | Production (Metric tons) | Regional Share (%) | Global Share (%) |
|---|---|---|---|---|
| 1 | Egypt | 1,561,457 | 71.10 | 1.90 |
| 2 | Nigeria | 291,233 | 13.26 | 0.35 |
| 3 | Uganda | 103,737 | 4.72 | 0.13 |
| 4 | Ghana | 76,630 | 3.49 | 0.09 |
| 5 | Zambia | 24,300 | 1.11 | 0.03 |
| 6 | Tunisia | 21,756 | 0.99 | 0.03 |
| 7 | Kenya | 15,124 | 0.69 | 0.02 |
| 8 | Malawi | 9,014 | 0.41 | 0.01 |
| 9 | Madagascar | 7,421 | 0.34 | 0.01 |
| 10 | South Africa | 6,181 | 0.28 | 0.01 |

(FAO, 2003-2020a, 2003-2020b, 2004-2020, 2005-2020c, 2005-2020d, 2005-2020b, 2005-2020a, 2005-2020., 2007-2020, 2010-2020)

The subsequent sections of this chapter will review the aquaculture sector of the key regional players - Egypt, Nigeria and Uganda with reference to South Africa. The aim is to identify critical success factors responsible for the rapid aquaculture development amongst these major producers.

### 2.4.1 Aquaculture in Egypt

The practice of aquaculture in Egypt dates back several millennia, albeit modern management practices were only recently adopted to maximize production output (Shaalan *et al.*, 2018). In the past two decades, the Egyptian aquaculture sector has been experiencing rapid development due to paradigm shift from traditional extensive to semi-intensive aquaculture systems and modern intensive aquaculture systems (FAO, 2003-2020b). Also, factors such as the emergence of new technologies for the formulation and production of aquafeed (i.e. extruded feed), adoption of best farm management practices and prioritization of the aquaculture sector development by the government contributed immensely to the fast expansion of the sector (FAO, 2003-2020b; USDA, 2016).

#### 2.4.1.1 Aquaculture Production and Value

The annual production of Egypt exceeds one and a half million tons with a market value estimated at over USD 2 billion, ranking the country 6th amongst the leading aquaculture producing countries globally in 2018 (FAO, 2003-2020b; Shaalan *et al.*, 2018). The aquaculture sector in Egypt contributes 77 % of the total national fisheries production and employs more than 580,000 workers (El-Sayed *et al.*, 2015; FAO, 2016; Shaalan *et al.*, 2018). Assessment of fisheries stocks in the fishing areas of both Mediterranean and Red sea shows minimal potential for an increase in capture fisheries production (Soliman, 2017). Thus, the need for aquaculture production expansion to bridge the growing demand-supply gap for fisheries products (Nassr-Alla, 2008).

#### 2.4.1.2 Cultured Fish Species in Egypt

The aquaculture sector in Egypt is characterized by the culture of diverse species of finfish and shellfish (Table 2.3). Tilapia species are the most cultured aquaculture species in terms of production quantity and account for about 67 % of total cultured species in 2014 (Soliman & Yacout, 2016; Shaalan *et al.*, 2018). The other commonly cultured fish species are mullet, gilthead seabream, European seabass, penaeus shrimp, catfish and meagre (Soliman & Yacout, 2016; Shaalan *et al.*, 2018).

Commonly cultured tilapia species are - Nile tilapia (*Oreochromis niloticus*), blue tilapia (*O. aureus*) and the hybrid red tilapia (Sadek, 2011; Shaalan *et al.*, 2018). Before the 1990s, tilapia species were harvested as incidental catch from carp fishponds; however, production of cultured tilapia in Egypt currently ranks second globally after China (FAO, 2003-2020a; Norman-López & Bjørndal, 2009). The industry is characterized by the production of sex-reversed all-male tilapia fry for economic reasons, as they grow faster to attain market weights with better Feed Conversion Ratios (FCR) (Beardmore *et al.*, 2001; Shaalan *et al.*, 2018). Despite the enormous size of the Egyptian tilapia industry, they are highly restricted from exporting to the EU and USA due to inability to meet the stringent food safety standards of these markets; therefore, all the tilapia produced are currently consumed locally (Norman-López & Bjørndal, 2009; Soliman & Yacout, 2016; Shaalan *et al.*, 2018).

Carp production contributes about 17 % to total aquaculture production in Egypt and ranks second after tilapia. Commonly cultured species of carp are common carp (*Cyprinus carpio* – L. 1758), silver carp (*Hypophthalmichthys molitrix* – Valenciennes, 1844), and grass carp (*Ctenopharyngodon idella* – Steindachner, 1866) (Hagar Dighiesh, 2014; Shaalan *et al.*, 2018).

Production of mullet species account for about 10.5 % of total aquaculture production in Egypt and rank third after carp (GAFRD, 2014). Cultured species of mullet include flat-head grey mullet (*Mugil cephalus* – L. 1758), thin-lipped mullet (*Liza ramada* – Risso 1827), thick-lip grey mullet (*Chelon labrosus* – Risso 1827), black keeled mullet (*Liza carinata* – Valenciennes, 1836) golden grey mullet (*Liza aurata* – Risso 1827), leaping mullet (*Liza saliens* – Risso 1810) and bluespot mullet (*Valamugil seheli* – Forsskål, 1775) (Hagar Dighiesh, 2014; Sadek, 2016; Shaalan *et al.*, 2018). Egypt is the highest global producer of cultured flat-head grey mullet (Sadek, 2016), as they are the mullet species of choice for farmers because of their fast growth rate and large size (Saleh, 2008). Culture of mullets is mostly dependent on fry caught from the wild and subsequently stocked in lakes as monoculture species or polyculture with tilapia and carp (Sadek & Mires, 2000, Saleh, 2008; Shaalan *et al.*, 2018). The thin-lipped mullet accounts for the largest share of mullet production from farms due to greater fry availability as compared to the flat-head grey mullet (Sadek & Mires, 2000).

Marine fish species commonly cultured in Egypt are European sea bass (*Dicentrarchus labrax* – L. 1758) and gilthead seabream (*Sparus aurata* – L. 1758) which both account for about 3 % of total aquaculture production (GAFRD, 2014). The combined production of both species contributes about 2.8 % of the total fish farm production (GAFRD, 2014). Production of Meagre (*Argyrosomus regius* – Asso 1801) started in 2008 with nearly 2,000 tons and grew to almost 6,000 tons in 2014 (Rothuis *et al.*, 2013; Shaalan *et al.*, 2018).

Production of catfish (*Clarias gariepinus*) accounts for only 1 % of the total fish production in Egypt (GAFRD, 2014) as they are commonly polycultured with tilapia to increase fish yield from the same farm and to control the prolific reproduction of tilapia (Ibrahim & Naggar, 2010). Koi carp and molly are cultured; however, on a very small scale for the ornamental fish trade (Sadek, 2011).

Egypt produces cultured shellfish (*penaeid* shrimp and giant freshwater prawn) in semi-intensive systems with annual production above 7,000 tons and imports about 55,000 tons per year to bridge the local demand-supply gap for shrimps (Sadek, 2011; Rothuis *et al.*, 2013; GAFRD, 2014; Hagar Dighiesh, 2014; Shaalan *et al.*, 2018). The current production value of different aquaculture products, periodic growth in value and production quantity in Egypt are highlighted in Table 2.3, and Figure 2.1, respectively.

**Table 2.3: Aquaculture production quantity in Egypt in 2014**

| Fish species | Production quantity (Tonnes/year) |
|---|---|
| Nile tilapia | 759,601 |
| Carps | 198,829 |
| Mullets | 119,645 |
| Gilthead Seabream | 16,967 |
| European Seabass | 15,167 |
| Catfish | 14,109 |
| Penaeus shrimp | 7,235 |
| Meagre | 5,884 |
| Total | 1,137,437 |

(Shaalan *et al.*, 2018)

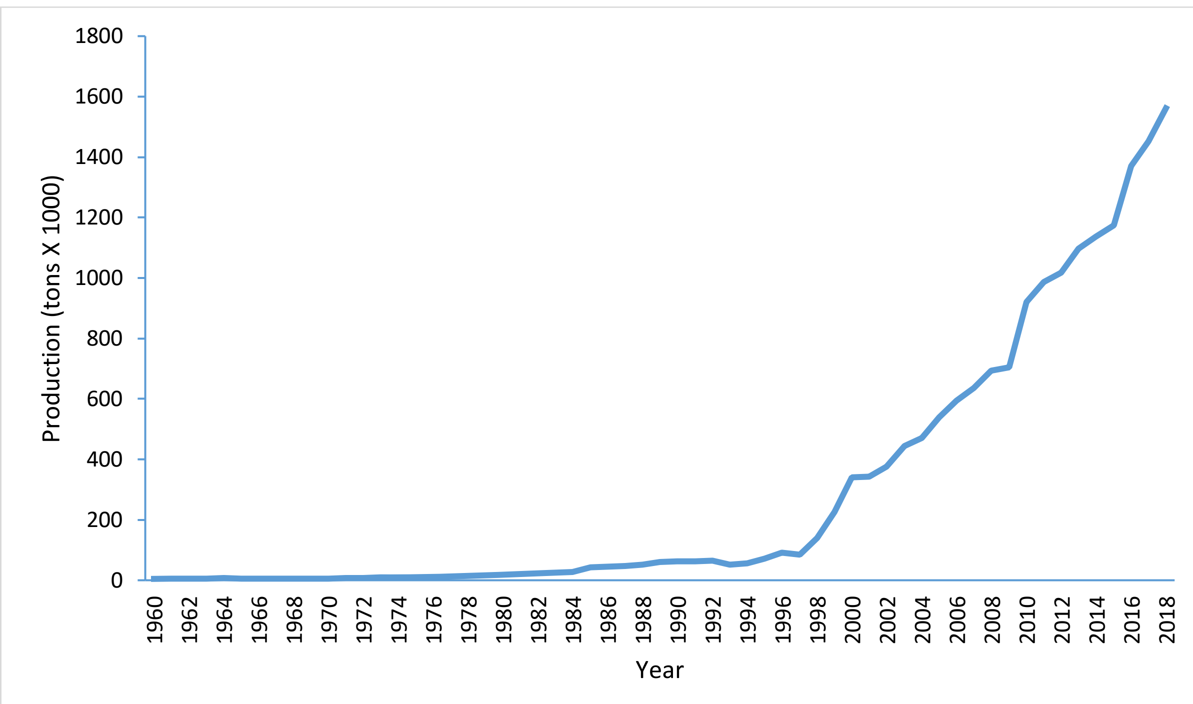


**Figure 2.1: Aquaculture production in Egypt (1960 - 2018 in Tons x1000)** *(FAO, 2003-2020c)*

#### 2.4.1.3 Aquaculture Production Systems in Egypt

The aquaculture sector in Egypt utilizes different production systems; however, most freshwater aquaculture production in the farms is carried out in semi-intensive earth ponds (El-Gayar, 2003; Kleih *et al.*, 2013). Both the intensive and extensive aquaculture production systems are also present and growing; however, semi-intensive and extensive systems are broadly adopted utilizing earth ponds, while concrete tanks are generally used under intensive production system (El-Gayar, 2003; Kleih *et al.*, 2013). In the early 1990s, cage aquaculture was introduced in the Nile river catchment for the production of Nile tilapia and silver carp (Cardia & Lovatelli, 2007) therefore; floating cages are important aquaculture production system with annual fish production of about 249,385 tons from over 37,000 operational cages across the country (Cardia & Lovatelli, 2007; GAFRD, 2012).

##### 2.4.1.3.1 Extensive Systems

Extensive aquaculture, in the form of net enclosures, has been in practice for many centuries and is still active in some regions in Egypt (Shaalan *et al.*, 2018). Extensive net aquaculture is the least economical, and yield from this system ranges from 0.25 – 0.75 tons $ha^{-1}$ $year^{-1}$ (El-Gayar, 2003; Shaheen *et al.*, 2013; Soliman & Yacout, 2016). Extensive culture system relies solely on naturally occurring food sources in the pond and does not utilize artificial aeration or feeding (Shaheen *et al.*, 2013).

#### 2.4.1.3.2 Semi-intensive Systems

The semi-intensive production systems are the most practiced aquaculture systems in Egypt contributing about 86 % to total aquaculture production with fish yields ranging from 5 – 20 tons $ha^{-1}$ $year^{-1}$ (Shaheen *et al.*, 2013; GAFRD, 2014). These systems require the supply of both aquafeed and fertilizers which are readily available in the market, with protein requirements of the feed ranging from 10 to 30 % (Soliman & Yacout, 2016). However, the development of intensive aquaculture systems resulted in ~ 50 % decline in fish production from semi-intensive systems in 2012 compared to 2011 production (GAFRD, 2014).

#### 2.4.1.3.3 Intensive Systems

Intensive systems are fast replacing many semi-intensive, and extensive production systems in Egypt to mitigate the dearth of suitable land, stretched water resources as well as economic factors (FAO, 2003-2020c). Intensive systems efficiently utilize water and land with yields ranging from 100 – 150 tons $ha^{-1}$ $year^{-1}$ (Shaheen *et al.*, 2013). Adoption of this system of aquaculture production is currently growing in Egypt particularly in the desert area with an annual production of the year 2012 tripling that 2011 (El-Sayed, 2007; Alexandratos & Bruinsma, 2012; GAFRD, 2012). This system requires diets containing high crude protein (> 30 %) to meet the nutritional demand for the high stocking density of fish, although only 5 % of aquafeed available in Egypt contains 30 % or more crude protein (El-Sayed *et al.*, 2015). Besides, artificial aeration and water pumps are required in intensive production systems (Soliman & Yacout, 2016).

#### 2.4.1.4 Integrated Aquaculture in Egypt

Integrated aquaculture systems refer to the utilization of effluent from fish farms to optimize production in other farming systems by maximizing the used water from the fish production system to cultivate crops and animal husbandry (Edwards, 1998; Rakocy *et al.*, 2003). Aquaponics and aquaculture cum rice-field farming are the two standard integrated aquaculture practices in Egypt (Shaalan *et al.*, 2018).

A model aquaponic farm was established in 2006 in Cairo by the National Institute of Oceanography and Fisheries (NIOF) to produce tilapia, vegetables and ornamental plants (Essa *et al.*, 2008). Studies conducted on the aquaponic farm showed that fish and crops produced from the farm were healthier, less prone to diseases and increased economic returns (Essa *et al.*, 2008). Aquaponic farms sited in Behira, Sharkia and North Sinai provinces utilize underground water and water from irrigation canals to produce tilapia, and the effluents are reused for vegetable and fruit farm irrigation (Van der Heijden, 2012). Aquaponics is developing and essential in Egypt due to a lack of water in the arid areas (Shaalan *et al.*, 2018).

The combination of fish and rice farming is a promising direction in maximizing the efficient utilization of land and water to optimize both fish and rice production and to attain food security, especially in rural areas (Suloma & Ogata, 2006). Egypt has the highest rice yield in Africa and the Middle East, with an annual production of about 6 million tons (Sadek, 2013; Shaalan *et al.*, 2018). This integrated aquaculture practice has been in existence in Egypt since 1984; however, a leap forward in aquaculture production from rice fields started in 2008 (FAO, 2003-2020c; GAFRD, 2012). The constraint of freshwater scarcity combined with the high water demands for rice cultivation necessitated the integration of fish production with rice farms. The government incentivized farmers with free supplies of common carp fingerlings to encourage this farming practice in Egypt (Sadek, 2013). Rice field aquaculture accounts for about 34,537 tons of fish production annually in Egypt with half of the production being tilapia, and the other half is made up of catfish and common carp (Sadek, 2013; GAFRD, 2014)

#### 2.4.1.4.3 Desert Aquaculture

Most of the land area in Egypt lies in the desert, although with a vast reservoir of underground water which accounts for about 20 % of freshwater sources nationally. The adoption of desert aquaculture practices, therefore, is an ideal model for the country (Allam *et al.*, 2003; Suloma & Ogata, 2006; Sadek, 2011; Rothuis *et al.*, 2013). There are about 120 farms established in the Egyptian desert, which contributes around 13,000 tons of aquaculture products annually (Sadek, 2011). Cultured species are mainly tilapia, especially the hybrid red tilapia, as they relatively tolerate higher salinity (Stickney, 1986; Watanabe *et al.*, 1989; Sadek, 2011). Other species cultured are catfish (*Clarias gariepinus*), carp, mullet, gilthead sea bream, European sea bass and ornamental fish such as koi carp and molly (Bakeer, 2006; Sadek, 2011). Desert aquaculture could be more sustainable by adopting the recirculating aquaculture system (RAS) to maximize the benefits of effluent water recycling (Martins *et al.*, 2010). Most of the farms in the desert area of Egypt, however, adopt flow-through system (FTS) using the effluent water from the fish farms to irrigate field crops, while only a few farms operate RAS system (Sadek, 2011).

### 2.4.1.5 Mariculture in Egypt

Egypt has a long coastline that stretches from the north bounded by the Mediterranean Sea (950 km) to the east bounded by the Red Sea (1,500 km) (Sadek, 2000; Bird, 2010) however, mariculture is still nascent and not as well developed as freshwater aquaculture (Rothuis *et al.*, 2013; Shaheen *et al.*, 2013). Mariculture operations are concentrated in the north of Egypt, and the Suez Canal with production focused on species such as flat-head grey mullet (*Mugil cephalus*), European sea bass (*Dicentrarchus labrax* – L. 1758) and gilthead seabream (*Sparus aurata*) (Rodger & Davies, 2000; Sadek, 2000; Rothuis *et al.*, 2013; GAFRD, 2014). Shrimp aquaculture is also present but on a limited scale; through extensive farming in Lake Qarun, semi-intensive ponds in commercial farms and recently around the Suez Canal (Megahed *et al.*, 2013; Rothuis *et al.*, 2013; GAFRD, 2014). Mariculture in Egypt contributes around 70 % of the total marine fish production in North Africa due to most North African countries relying on wild capture fisheries rather than aquaculture (Rodger & Davies, 2000; Shaalan *et al.*, 2018)

### 2.4.1.6 Challenges Confronting the Egyptian Aquaculture Sector

Despite the significant rapid development, the aquaculture sector in Egypt has experienced, there are still major challenges and constraints confronting the sustainable expansion of this sector (Soliman & Yacout, 2016). The future development of aquaculture industry in Egypt is critically dependent on tackling issues such as conflicts of resource utilization (water and land), energy, quality fish seed production, prices and availability of quality feed, product standardization, marketing and trade as well as provision of enabling environment (policies and framework) amongst others (Soliman, 2017).

#### 2.4.1.6.1 Fish Feed

The availability of quality and reasonably priced feed is a major constraint to the sustainable development of the aquaculture sector in Egypt. Cost of fish feed accounts for about 75 to 85 % operating expenses of fish production (Kleih *et al.*, 2013; Dickson *et al.*, 2016). The past few years have witnessed soaring fish feed costs (Macfadyen *et al.*, 2012) due to the importation of ingredients and fluctuations in foreign currency exchange rates (El-Sayed *et al.*, 2015). This has impacted the economic feasibility of production facilities due to farmers purchasing feed on credit, and the continuous increase in the price of feed without proportional increments in the price of fish products, (El-Sayed *et al.*, 2015; Eltholth *et al.*, 2015). Egypt currently has about 73 operational feed mills with an annual production capacity of about 1 million tons of aquafeed annually (Shaalan *et al.*, 2018). Private sector-controlled feed mills contribute about 90 % of the total production, while the outstanding 10 % comes from the government-owned feed mills (El-Sayed *et al.*, 2015; USDA, 2016). Skretting Nutreco with an annual production capacity of 150,000 tons of tilapia feed, besides catfish, sea bass and sea bream aquafeed production, is the largest feed producer in Egypt, followed by Aller Aqua Egypt which produces feed for both freshwater and marine fish (USDA, 2016).

#### 2.4.1.6.2 Fish Seed

Fish seed is sourced from two primary sources which are hatcheries and wild catch; however, the challenges of availability and price typically impact on marine fish production more than freshwater aquaculture (Sadek, 2000). The distribution of fry is controlled by GAFRD to prevent fraudulent practices; however, government legislation permits the establishment of hatcheries by farmers for the production of carp and sex-reversed all-male tilapia fry due to inability of government-owned hatcheries to keep up with the growing demands for fish seed from farmers (El-Gayar, 2003). The first privately-owned hatchery for the production of tilapia fry was established in 1992, and currently, there are over 600 operational hatcheries in Egypt allowing for rapid development of the aquaculture industry (Shaalan *et al.*, 2018). Freshwater fish hatcheries in Egypt have a combined annual production capacity of 411 million fries (GAFRD, 2014; Soliman & Yacout, 2016), while there are about 73 collection stations of wild-caught marine fry across seven states in Egypt (Rothuis *et al.*, 2013; GAFRD, 2014). The critical success factor for the sustainable operation of hatcheries include, but are not limited to, the capability to produce sex-reversed tilapia fingerlings at favourable sizes, different seasons and salinity tolerance (Stickney, 1986; El-Gayar, 2003).

Tilapia hatcheries are more functional in the summer due to favourable weather for spawning and fry production although some hatcheries adopt heating systems to be operational all year round albeit with increasing operational expenses (Nasr-Allah *et al.*, 2014). Hatcheries adopt different heating systems, including biogas; however, the most cost-effective method is the use of hapas covered by greenhouses (Sadek, 2011; Nasr-Allah *et al.*, 2014).

#### 2.4.1.6.3 Land and Water Availability

Government legislation permits the setup of fish farms on barren lands which are considered unsuitable for other activities such as agriculture and tourism, due to the competing demand for already scarce land and water resources in Egypt, (GAFRD, 2014). Also, the utilization of the River Nile for aquaculture activities is prohibited by the current laws, and the permit to set up a fish farm has to be issued by the Ministry of Agriculture (El-Gayar, 2003; Rothuis *et al.*, 2013; Hebisha & Fathi, 2014). Water problems caused by irrigation channels are usually subjected to agricultural seasons, water level variations all through the year and susceptibility to contamination with agricultural pesticides (Eltholth *et al.*, 2015). Lands that are unsustainable for crop production are often used for fish farming, to prevent competition between freshwater aquaculture and contemporary field agriculture (El-Gayar, 2003; Suloma & Ogata, 2006; Hebisha & Fathi, 2014). mariculture development is also confronted with the growth of tourism and urbanization along the coasts of the Mediterranean and Red Sea (El-Gayar, 2003). The desert aquaculture, therefore, could act as a promising substitute with minimal competition and the future of sustainable aquaculture due to the vast desert land of Egypt.

#### 2.4.1.6.4 Diseases

Fish diseases caused by parasites, bacteria, fungi and viruses are responsible for mortalities and substantial economic losses in aquaculture operations (Fathi *et al.*, 2017). Pathogenic conditions severely affect the FCR and final body weight of post-infection recovered fish asides mortalities. Fish mortalities linked with infectious diseases are prevalent in tilapia in the summer months of June to October yearly, resulting in about USD 100 million economic losses (Fathi *et al.*, 2017). Parasites are the most prevalent pathogens responsible for about 80 % fish disease condition in aquaculture farms (Shaheen *et al.*, 2013). Infectious diseases caused by different strains of bacteria also occur in fish with resultant mortalities as compared to parasitic infections were also reported in Egyptian farms (Al-Shamy, 2010; Aly, 2013; Shaheen *et al.*, 2013; Abdelsalam *et al.*, 2017). There is insufficient information about viral infections and spread in Egypt, probably due to the lack of established surveillance program for monitoring and controlling viral infections in fish.

#### 2.4.1.7 Aquaculture Marketing and Trade

The marketing of fish in Egypt is a simple and efficient system controlled by few big wholesalers who fix the market price for fish in response to forces of demand and supply (Soliman & Yacout, 2016). Farmers are usually at liberty to sell their fish directly to retailers or via wholesalers (Soliman & Yacout, 2016). There are approved wholesale markets, where farmers can bring and auction their fish daily in all major cities (El-Gayar, 2003). Aquaculture traders/wholesalers play a significant role as financiers in providing credits to many fish farmers and generating an income of ±3 - 6 % as sales commission on fish sales on behalf of the farmers (Soliman & Yacout, 2016). Annual farm production usually gets landed in the market within short periods and are mostly distributed and consumed in the fresh state as the fish processing sector in Egypt is still very nascent (Soliman & Yacout, 2016).

Egypt is yet to attain self-sufficiency and is a net importer of fish products, despite the significant growth in aquaculture production (GAFRD, 2014). Fish imports grew from 259,000 tons in 2007 to 335,000 tons in 2012 due to strong growth in annual per capita consumption of fish from 8.5 to 15.5 kg within the same period (GAFRD, 2012, 2014)Despite the significant growth in aquaculture production, Egypt is yet to attain self-sufficiency and is a net importer of fish products (GAFRD, 2014). Fish imports grew from 259,000 tons in 2007 to 335,000 tons in 2012 due to strong growth in annual per capita consumption of fish from 8.5 to 15.5 kg within the same period (GAFRD, 2012, 2014).

#### 2.4.1.8 Aquaculture Policies and Framework

The Ministry of Agriculture and Land Reclamation in Egypt is saddled with the task of managing the fisheries and aquaculture sector while management and policy implementation is assigned to the General Authority for Fish Resources Development (GAFRD) (GAFRD, 2014). GAFRD, which is a subsidiary of the Ministry of Agriculture and Land Reclamation, is the organization responsible for the planning and controlling of all activities that concern fish production (Macfadyen *et al.*, 2012). The current policy for the development of aquaculture and fisheries sectors as drafted by GAFRD aims at the following (Goulding & Kamel, 2013):

I. Increase the return on investment on fishery/aquaculture resources through environmentally compatible systems.
II. Attain annual production of 1.5 million tons (an annual per capita of local fish production, which amounts to 16.5 kg) in 2017 to maintain per capita of fish production as a result of the growing population.
III. Improve fish products from various sources that will meet the standard of international markets
IV. Support marine aquaculture.

The strategy of GAFRD aims to boost the productivity of freshwater fish production; however, the aquaculture policies of Egypt due to the limitation of freshwater resources are currently geared more towards promoting mariculture of species such as mullets, groupers, meagers, soles, perches and invertebrates such as shrimps, sea cucumbers and other shellfish species (Soliman & Yacout, 2016).

Fish farmers need approval from the Egyptian Environmental Affairs Agency (EEAA) and submit an Environmental Impact Assessment (EIA), to obtain a permit. In practice, EIA is, however, rarely conducted for aquaculture production, and not required before the commencement of aquaculture production, except for mariculture production, where inland waters rules are not applicable but EEAA laws (Nugent, 2009).

### 2.4.2 Aquaculture in Nigeria

Nigeria is the second-largest aquaculture producer in Africa with a production output of about 300, 000 tons annually and largely dominated by catfish culture (Ozigbo *et al.*, 2014; FAO, 2016, 2018). Aquaculture production began in Nigeria over five decades ago (Olagunju *et al.*, 2007); however, it has not been able to bridge the gap between domestic consumption and production output (Ozigbo *et al.*, 2014). Aquaculture development in Nigeria was primarily driven by socio-economic objectives such as supplementary income generation, improvement of nutrition in rural locations and employment creation, until recently when the perspective of aquaculture was changed and tailored to meet domestic shortfalls in fish supplies to reduce fish importations (Ozigbo *et al.*, 2014). Fish accounts for about 40 % of animal protein consumption, with a per capita fish consumption of 13.3 kg (WorldFish, 2018).

#### 2.4.2.1 Aquaculture Production and Value

According to Catfish Association of Nigeria (CAFAN), Nigeria produced 370,000 metric tons of fish from aquaculture systems in 2016 valued at over USD 1.3 billion (BusinessDay, 2017). Aquaculture production accounts for about 34 % of the total national fisheries production, employs about 475,000 people and contributes 4.5 % to GDP (BusinessDay, 2017; WorldFish, 2018).

#### 2.4.2.2 Cultured Fish Species in Nigeria

The Nigerian aquaculture sector is characterized by the culture of catfish, tilapia, carp and *Heterotis niloticus* G. Cuvier 1829 however, the catfish species (*Clarias spp*. and *Heterobranchus spp*.) (Table 2.4) are the most cultured species due to their hardiness, wide acceptability and high market value (Oyakhilomen & Zibah, 2013; Ozigbo *et al.*, 2014). These species are usually reared to acceptable market size within a culture period of 4 - 9 months, depending on the adopted production system (Adewumi, 2015). The success story of the aquaculture sector in Nigeria is primarily hinged on catfish farming (Adewumi & Olaleye, 2011) and accounts for over 80 % of aquaculture production in Nigeria (Anetekhai & Agenuma, 2010).

The production of catfish species in Nigeria has evolved rapidly over the years since 1985, with the advent of flow-through tank systems and recirculating aquaculture systems leading to a significant increase in production output of fish per unit area across the country (Adewumi, 2015). This study was restricted to present the total annual aquaculture production output and the estimated percentage production output of the dominant aquaculture species, due to lack of data on specific production outputs of each aquaculture species cultured in Nigeria.

**Table 2.4: Aquaculture production quantity in Nigeria by species in 2013.**

| Fish Species | Production Quantity (Tons/year) |
|---|---|
| Catfish | 233,605 |
| Tilapia | 21,680 |
| Carps | 23,421 |
| **Total** | **278,706** |

Adapted from (FAO, 2007-2020; Cai et al., 2017)

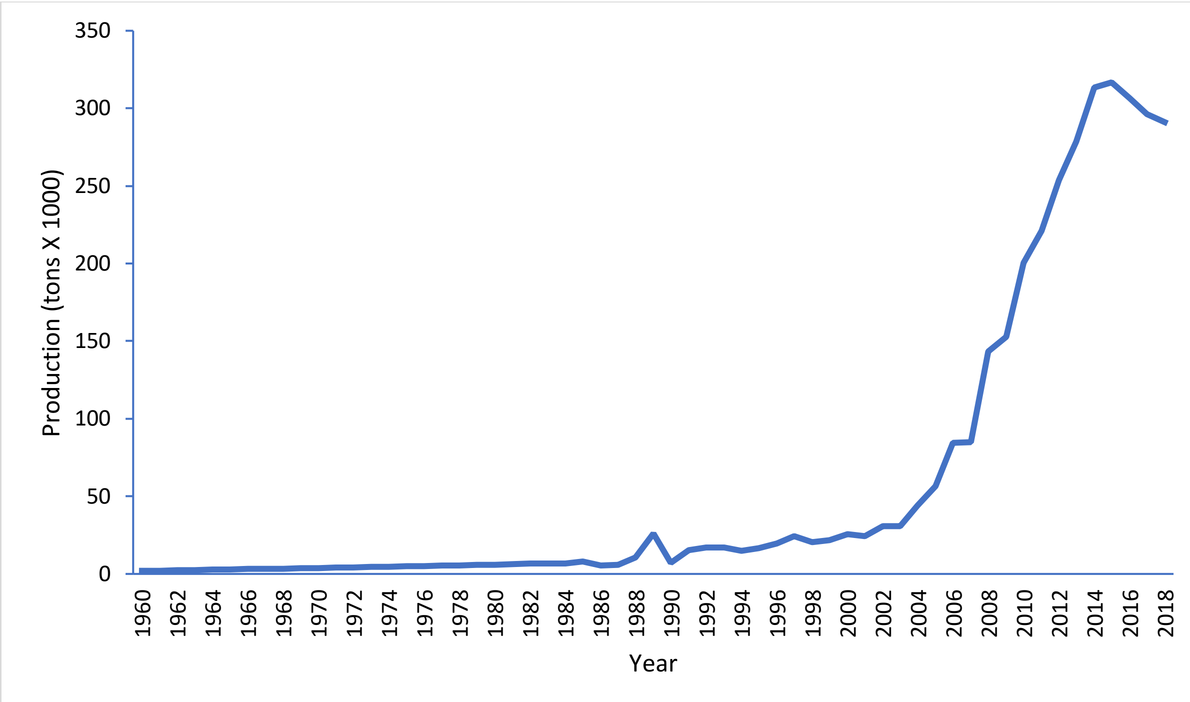


**Figure 2.2: Aquaculture production in Nigeria (1960 – 2018 in Tons x1000)** *(FAO, 2007-2020)*

### 2.4.2.3 Freshwater Aquaculture Production Systems in Nigeria

The advent and the development of hatchery technique for fingerlings (catfish seedlings) production of *Clarias* species and their hybrids resulted to catfish becoming the dominant aquaculture fish species produced by tonnage in Nigeria (Anetekhai & Agenuma, 2010). Aquaculture production involves two major stages of production:

1. Fish hatchery – production of fingerlings and juveniles.
2. Pond culture – earthen/dug-out, concrete tanks, cage/pen culture, fibre tanks, intensive recirculation and flow-through systems.

#### 2.4.2.3.1 Fish Hatchery

Fish hatchery setup in Nigeria typically is intensive systems comprising of overhead tanks, series of flow-through hatching troughs for incubation and hatching of fertilized eggs, and flow-through tanks for raising fry/hatchlings to fingerlings (Adewumi, 2015). Hatcheries in Nigeria are mainly flow-through systems which account for 99 %, while RAS account for 1 % of hatchery operations (Anetekhai & Agenuma, 2010). Hatchery operations entail series of breeding activities which include the collection, selection and manipulation of brood stocks for spawning or egg stripping, and from the rearing of hatchlings to fingerings stage which usually spans a minimum of four weeks (Akankali *et al.*, 2011).

#### 2.4.2.3.2 Grow-out Systems

This is the grow-out phase which entails rearing of fingerlings/juveniles to table size fish in different water holding systems (Adewumi & Olaleye, 2011). Pond aquaculture in Nigeria is usually carried out in systems such as earth ponds, concrete ponds, fibre tanks, cages and pens, RAS and other watertight containers that can hold sufficient water volume to sustain fish production (Anetekhai & Agenuma, 2010).

I. **Earthen Ponds:** These are excavated earth resulting in a water-holding depression, and it is a conventional aquaculture production system adopted in areas with a high water table (Anetekhai & Agenuma, 2010). Earthen ponds are usually impounded after preparatory processes (desilting, netting, liming, fertilizing) with water from underground seepage, reservoir, borehole and rainfall, after which fish are stocked and fed with pelletized or extruded feed from fingerlings/juveniles to table size (Anetekhai & Agenuma, 2010). Production period in earth ponds spans between 5 – 6 months with good feeding and water quality management (Anetekhai & Agenuma, 2010).

II. **Concrete Ponds:** Concrete ponds are similar to earth ponds except the walls and floor are made of concrete or building blocks filled with cement mix (Ozigbo *et al.*, 2014). Concrete ponds are mostly surface tanks and are well equipped with the water inlet and outlet drain for ease of operation (Anetekhai & Agenuma, 2010). Concrete ponds are intensive systems with higher stocking density than earth ponds and require good water exchange (Emmanuel *et al.*, 2014). Most concrete ponds in Nigeria are operated as a semi flow-through or flow-through ponds to improve water quality parameters during the culture period (Emmanuel *et al.*, 2014).

III. **Flow-through Systems:** This system is also referred to as a raceway, and it is one of the earliest systems utilized in inland aquaculture (Ozigbo *et al.*, 2014). The system generally has tanks made of concrete or plastic fitted with an inlet and outlet pipes that allow water to flow in and drain out without recirculation (Anetekhai & Agenuma, 2010; Ozigbo *et al.*, 2014). Continuous water flow is sustained within the system to maintain the required water quality parameters required to culture fish at high stocking density (Anetekhai & Agenuma, 2010). Flow-through systems are commonly used in Nigeria in hatcheries for the production of catfish fingerlings (Anetekhai & Agenuma, 2010).

IV. **Recirculating Aquaculture System (RAS):** This is a closed highly intensive system where water is pumped into the fish tank via mechanical and biological water filtration systems and reuse, thus capable of stocking about 200 to 400 catfish.$m^2$ (Anetekhai & Agenuma, 2010; Ozigbo *et al.*, 2014). Recirculating aquaculture system guarantees optimum rearing conditions as water is exchanged continuously (Anetekhai & Agenuma, 2010; Ozigbo *et al.*, 2014). Recirculating aquaculture system is highly technical and requires high-end management, equipment and constant power supply to maintain optimal operating conditions (Masser *et al.*, 1999). The setup and operating cost of RAS can be expensive; therefore, economically not feasible to grow low-value fish (Ozigbo *et al.*, 2014). Erratic power supply and high cost of operating power generators make the operation of RAS non-viable in Nigeria; however, there are a few farms that utilize RAS for fingerlings and table fish production of catfish (Anetekhai & Agenuma, 2010; Ozigbo *et al.*, 2014).

V. **Cage Culture:** These are enclosures made of synthetic netting and frames suspended in natural water bodies with the aid of buoys and anchors for table size fish production (Anetekhai & Agenuma, 2010). Cage culture is an emerging fish production system in Nigeria, and it is capable of significantly increasing the annual aquaculture production as more investments are being channeled towards cage culture (Obwanga *et al.*, 2018). Nigeria is well-endowed with natural water bodies such as rivers, lakes and estuaries, which are suitable for cage culture (Obwanga *et al.*, 2018). According to press statements released by commissioners of agriculture, Nigeria produced over 150 tons of fish from cage culture systems in 2017(Obwanga *et al.*, 2018).

#### 2.4.2.4 Aquaculture Production Models in Nigeria

The prevalent aquaculture production models practiced in Nigeria include, but are not limited to;

i. ***Backyard/Cottage Farming:*** This aquaculture production model was promoted to encourage families to be food sufficient and earn extra income by building and operating fishponds in their house using basic production systems that require minimal skills and low-cost materials such as waterproof materials (Anetekhai & Agenuma, 2010). Homestead catfish farming is prevalent in Nigeria and contributes significantly to the total yearly aquaculture output (Anetekhai & Agenuma, 2010).

ii. ***Integrated Farming***: This is usually the integration of fish rearing facilities with the poultry production system and crop production (Anetekhai & Agenuma, 2010). Maggots generated from poultry feacal droppings are channeled into catfish ponds as supplementary feed (Anetekhai & Agenuma, 2010). Also, effluent from catfish pond is channeled into leafy vegetables, plantain, pineapple, maize and rice field as organic fertilizer for good plant yield (Anetekhai & Agenuma, 2010).

iii. ***Hatcheries:*** Few farms in Nigeria run commercial fingerlings production solely and maintain viable brood-stock bank for all-year-round production of fingerlings/juveniles (Anetekhai & Agenuma, 2010). Sizes of catfish fingerlings range from 3 – 5 g per fish, while juveniles are from 8 – 10 g per fish and are reared intensively for 8 to 12 weeks from the point of hatching (Anetekhai & Agenuma, 2010). Hatchery operators generally supply production farms with fingerlings and juveniles (Anetekhai & Agenuma, 2010)

iv. ***Table Fish Production:*** This is a standard model of commercial fish production in Nigeria (Anetekhai & Agenuma, 2010). The farmers acquire either fingerlings/juveniles from a known hatchery and rear to table size in production ponds (Anetekhai & Agenuma, 2010).

v. ***Hatchery and Table Fish Production:*** Most big commercial fish farms in Nigeria operate a functional hatchery which produces the fingerlings or juveniles which are stocked and reared in earth or concrete production ponds for a period ranging from 4 to 6 months to attain acceptable market size while excess fingerlings/juveniles produced are sold to production farms (Anetekhai & Agenuma, 2010). The market size of frozen or live catfish in Nigeria varies according to the region; however, it ranges from 1 to 3 kg, while the size of wet fish to be smoked are between 0.35 to 1 kg (Anetekhai & Agenuma, 2010).

vi. ***Public/Private/Cooperative Partnership***: This farming model is based on setting up a central farm funded by the government, but managed by the private sector that services a network of satellite farms through the provision of fish production inputs such as juveniles and feed as a credit (Anetekhai & Agenuma, 2010). The satellite farms produced table size fish from the inputs supplied and payback with fish or cash after the production cycle (Anetekhai & Agenuma, 2010).

#### 2.4.2.5 Mariculture in Nigeria

Nigeria has a coastline stretch of 853 km from the south-west end of Badagry Lagoon to the southeastern tip of Cross River, near Calabar (Coche, 1982). It has an unexploited 729,000 hectares of land that is suitable for mariculture (Sylvanus & Gao, 2007; Amosu *et al.*, 2013); however, the culture of marine species in Nigeria is almost non-existent as freshwater catfish aquaculture dominates the industry (Anetekhai & Agenuma, 2010). Nearly all the aquaculture hatcheries in Nigeria are designed and situated to produce freshwater species, thereby, neglecting the development of numerous coastal and marine species with aquaculture potential (Anetekhai & Agenuma, 2010). The absence of mariculture has been linked to many factors which include; pollution due to densely distribution of anthropogenic activities (oil and gas exploration, sand mining, maritime activities and industrialization) in coastal areas; very shallow continental shelf; inadequate technical know-how on the hatchery management practices of the indigenous marine/coastal fish species and lack of political will due to preference for oil and gas exploration (Amosu *et al.*, 2013).

#### 2.4.2.6 Challenges Confronting the Aquaculture Sector in Nigeria

Nigeria has an estimated population of 201 million people according to the 2019 data of the United Nations with a projected annual fish demand of 3 million tons and local production of 1.1 million tons in 2017 (Vanguard, 2017). There is thus a huge gap of almost 2 million tons of fish demand which is partly bridged by importation (Vanguard, 2017). Despite the huge aquaculture potentials and development in freshwater aquaculture, Nigeria is yet to be able to bridge the gap between domestic fish production and consumption (Adedeji & Okocha, 2011) due to combination of prevailing challenges confronting the aquaculture sector. Some of the challenges are plaguing the aquaculture sector including but not limited to high-cost fish feed, the supply of quality breed of fingerlings from reliable hatcheries, availability of suitable land and reliable water source, disease management, creation of a favourable environment to drive accelerated development and marketing of aquaculture products (Adedeji & Okocha, 2011).

#### 2.4.2.6.1 Fish Feed

High and soaring cost of fish feed has been a major challenge confronting the economic viability of aquaculture development in Nigeria (Udoh & Dickson, 2017). The production of high-quality aquaculture feed has also been a major constraint hindering the growth of the aquaculture sector in Nigeria (Udoh & Dickson, 2017). Fagbenro & Adebayo, (2005) reported that feed account for about 60 % of operational cost in Nigeria. The cost of feed currently accounts for about 80 % of production cost due to currency devaluation, fluctuating exchange rate and inflation; thus increasing the cost of fish production (Udoh & Dickson, 2017). The aquaculture industry in Nigeria largely depends on the importation of both manufactured feeds and feed ingredients due to insufficient local production and competitive use of ingredients with other livestock feeds (Adedeji & Okocha, 2011). The importation of feeds and ingredients exposes the industry to increase in prices due to the rising exchange rate (Adedeji & Okocha, 2011).

Some interventions such as input subsidies, credit facilities, pricing policies and market liberalization were put in place, to meet the demand for aquafeed and increase the production output of the aquafeed industry, (Udoh & Dickson, 2017). The production output, however, is still very low and unable to meet the demand of the aquaculture industry (Udoh & Dickson, 2017).

Nigeria has the highest number of feed mills in Sub-Saharan Africa albeit, dominated by small-scale operators whose production capacity range from 0.5 – 3 tons per hour and account for about 60 % of local aquafeed production (Fagbenro & Adebayo, 2005).

#### 2.4.2.6.2 Fish Seed

The supply of fish seed is mostly sourced from hatchery production under a controlled environment, as fingerling collection from the wild is highly unreliable and unsustainable for aquaculture (Bondad-Reantaso, 2007). Numerous fish hatcheries have been established in Nigeria, with most of them located in the South-Western part of the Country (Bondad-Reantaso, 2007). Availability of quality fish seed produced from high-quality brood stock with known genetic composition and performance is required (Adewumi, 2015). The demand-supply gap for fish seed is considerably huge (Omoyinmi & Ezeri, 2011) as Nigeria currently requires at least 1 billion fingerlings/seeds annually to meet market demand for table size fish while it barely produces about 55 million fingerlings from all available sources (Atanda, 2007). There is, therefore, a pressing need to address the challenges of inadequate production of high-quality brood-stock and seed encountered by the aquaculture sector in Nigeria (Adewumi, 2015). Besides, there is a need for the Nigerian aquaculture sector to explore advanced technologies of breeding to develop improved strain and quantities of fish seed. Successful completion of ongoing research work on the cryopreservation and viability of the milt of Clarias is, therefore, expected to address the perennial shortage of male catfish brood-stock during the dry season, slaughtering of the male brooder for milt extraction and eventually boost commercial production and availability of fingerlings/seeds all-year-round (Adewumi, 2015). The lack of standardization of hatchery practices in Nigeria due to the nonexistence of institutionalized quality control processes results to sharp practices by hatchery operators in terms of seed quality, sizes and price which often affects farmers production output and profitability (Adewumi, 2015).

#### 2.4.2.6.3 Land and Water Availability

Land is an important resource which is readily available for production in Nigeria; however, land availability is a major constraint to aquaculture development in the southeastern part of Nigeria due to competitive use of land (Ugwumba & Chukwuji, 2010; Adedeji & Okocha, 2011). The location of available land often determines the utilization for aquaculture and production systems adopted by fish farmers (Adedeji & Okocha, 2011). Fish farms located in swampy areas with access to ample water usually adopt an earth pond system while other farmers convert available spaces in their homes into ponds (Adedeji & Okocha, 2011). Availability of land for aquaculture production in Nigeria involves the complexity of interactive factors such as land tenure system, population, technology level and competitive use of land, therefore, limiting the amount of land available for aquaculture (Ojo & Afolabi, 2003).

Water pollution as a result of dredging, oil exploration and discharge of toxic industrial effluents into water body has been responsible for mass fish mortality thus severely impacting fisheries production and aquaculture development especially in the southeastern and Niger-Delta region of Nigeria (Olowosegun *et al.*, 2005; Akanni & Akinwumi, 2007; Ugwumba & Chukwuji, 2010).

#### 2.4.2.6.4 Diseases

The awareness level of disease impacts on the aquaculture industry in Nigeria is currently low (Adedeji & Okocha, 2011). The economic importance of fish diseases largely remains a concern to the aquaculture industry (Adedeji *et al.*, 2003; Adeyemo *et al.*, 2003; Kolndadacha *et al.*, 2007). *Clarias gariepinus* is a highly resistant and valued freshwater fish species reared in Nigeria, thus the need for research on its vulnerable diseases and public health implications (Adedeji & Okocha, 2011).

The shortage of skilled and experienced aquatic veterinarians with knowledge of aquaculture disease prevention, treatment and control complicated by lack of fish diseases diagnostic laboratory has been a major limiting factor to aquaculture development in Nigeria due to inadequate teaching of fisheries and wildlife medicine in the veterinary medicine curriculum in Nigerian universities (Adedeji & Okocha, 2011).

High-level management practices which involve maintenance of good water quality, hygienic practices and disease-resistant species are, therefore, being employed by commercial farms to prevent or minimize the incidence of disease outbreaks (Adedeji & Okocha, 2011).

There has been a surge in the utilization of veterinary drugs, chemical and biological controls in the aquaculture sector due to the rapid development of aquaculture production in the past two decades, and increase in fish and shellfish diseases (Adewumi, 2015).

#### 2.4.2.7 Aquaculture Marketing and Trade in Nigeria

Catfish, which is the predominant aquaculture fish in Nigeria, is primarily traded and consumed fresh in the south (Veliu *et al.*, 2009). Smoked catfish is preferred in northern regions of the country, although there is also a growing production and demand for smoked catfish in the southern markets (Cocker, 2014). The supply chain of catfish in Nigeria is primarily controlled by wholesalers who determine the price per size range of fish in response to the prevailing macroeconomic conditions (Cocker, 2014). Catfish are commonly distributed and sold live from the farm gates to designated fish markets in most cities and towns nationwide, where the fish are sold to restaurants, processors and final consumers (Igoni-Egweke, 2018).

Several processing methods such as smoking, drying and freezing are used to increase the shelf life of catfish in Nigeria as a result of its high perishability. Smoking, the most feasible processing method and widely acceptable product form (Eyo, 1999), is very affordable, inhibits microbial spoilage and increases the organoleptic properties of the final product (Omobepade *et al.*, 2018). Smoked catfish are commonly packed in transparent plastic wrappers and are widely distributed across the country as well as exported to neighbouring countries and overseas (Igoni-Egweke, 2018).

#### 2.4.2.8 Nigerian Aquaculture Policies and framework

There is no specific legislation on aquaculture nationally in Nigeria; however, the Inland Fisheries Decree (1992) empowers the Minister in charge of fisheries matters to regulate the licensing of enclosures such as pens and cages (FAO, 2005-2020b).

Institutionally, the Federal Department of Fisheries (FDF) under the Federal Ministry of Agriculture and Natural Resources is the competent authority saddled with the responsibility of fisheries management, preparation of policies, development of fisheries programs and provision of technical support to State Departments of Fisheries (SDF). The SDFs, in turn, provide support to Local Government Authorities (Ayala-Tafoya *et al.*) on fisheries and aquaculture matters (FDF, 2012). The Nigerian Institute for Oceanography and Marine Research (NIOMR) and the National Institute for Freshwater Fisheries Research (NIFFR) are majorly responsible for fisheries and aquaculture research, while aquaculture training is certified by the African Regional Aquaculture Centre (ARAC) (FAO, 2005-2020b).

Aquaculture used to be a developmental program in which the government is directly involved in policy formulation, training, infrastructure development, inputs and products production (FAO, 2005-2020b). The current policy considers aquaculture as an industry in which production at all levels of the value chain is driven by the private sector, while the government creates enabling environments (Anetekhai & Agenuma, 2010).

### 2.4.3 Aquaculture in Uganda

Aquaculture started in Uganda in 1941 with the introduction of carp into the country by the colonial authorities (MAAIF, 2012). Aquaculture production grew from 15,000 to 118,000 tons from 2005 to 2015 due to interventions of government and developmental partners such as FAO (FAO, 2004-2020). Catfish (*Clarias gariepinus*) and Nile tilapia (*Oreochromis niloticus*) and are the two predominantly cultured fish species in Uganda with production mainly made up of catfish (60 %) while Nile tilapia accounts for 40 % (FAO, 2004-2020). Nile tilapia is widely cultured among the Ugandan fish farmers owing to its prolificacy and tasty appeal (Cai *et al.*, 2017). Catfish production has been growing and notably common among farmers in the Eastern region as a result of perfection in breeding technology among hatchery operators (Mwanja, 2007). Fish represents approximately 63 % of protein consumption in Uganda, with annual per capita consumption of fish estimated at 12.5 kg in 2013, higher than the African average of 10.1 kg (FAO, 2004-2020).

#### 2.4.3.1 Aquaculture Production and Value

Uganda is the third-largest aquaculture producer in Africa, after Egypt and Nigeria supplying fish and fishery products in the form of feed, fish seeds, aquaculture inputs and technical expertise to neighbouring countries mainly Kenya, Congo and Rwanda (FAO, 2004-2020; Namatovu Safina *et al.*, 2018). Uganda is the second largest aquaculture producer in Sub-Saharan Africa after Nigeria, with production increasing from about 800 tons in 2006 to 103 737 tons in 2018 (FAO, 2004-2020). The aquaculture industry in

Uganda directly employs about 24,434 people (FAO, 2004-2020). Fish is a high-value commodity and contributes 3 % to the national GDP of Uganda (Namatovu Safina *et al.*, 2018).

#### 2.4.3.2 Aquaculture Fish Species in Uganda

Nile tilapia (*Oreochromis niloticus*), until recently used to be the most cultured fish species across Uganda due to its taste, easy reproduction and growth performance, however, the catfish (*Clarias gariepinus*) production has recently surpassed the Nile tilapia production as common aquaculture species (FAO, 2004-2020). The characteristic rapid growth rate of catfish and ability to feed on the available organic matter available at household level makes it widely acceptable amongst Ugandan fish farmers (MAAIF, 2012). Catfish is predominant in all the water systems in Uganda, particularly water catchments linked with swamps (FAO, 2004-2020).

The common carp (*Cyprinus carpio*) is the third most cultured aquaculture species in Uganda; however, insufficient fingerlings production, inadequate extension services and unstable post-independence government policies hindered the growth of carp aquaculture. Carp culture is still currently abundant in some parts of Uganda, however, at a low scale of production (FAO, 2004-2020).

Other aquaculture species that were introduced and being cultured in the country are the giant river prawn (*Macrobrachium rosenbergii - De Man, 1879*) and the red swamp crayfish (*Procambarus clarkii*). The giant river prawn production in the country is mainly dependent on regular larvae importation while the red swamp crayfish population is well distributed in Lake Bunyonyi and at Kajjansi Aquaculture Research and Development Centre (FAO, 2004-2020). Due to limited available data on the current production outputs of each aquaculture species cultured in Uganda, this study presents the aquaculture production output of the dominant aquaculture species documented for 2013 (Table 2.5).

**Table 2. 5: Aquaculture production quantity in Uganda by species in 2013**.

| Fish Species | Production Quantity (Tons/year) |
|---|---|
| Catfish | 49,517 |
| Tilapia | 47,841 |
| Carps | 705 |
| **Total** | **98,063** |

Adapted from (FAO, 2004-2020; Cai et al., 2017)

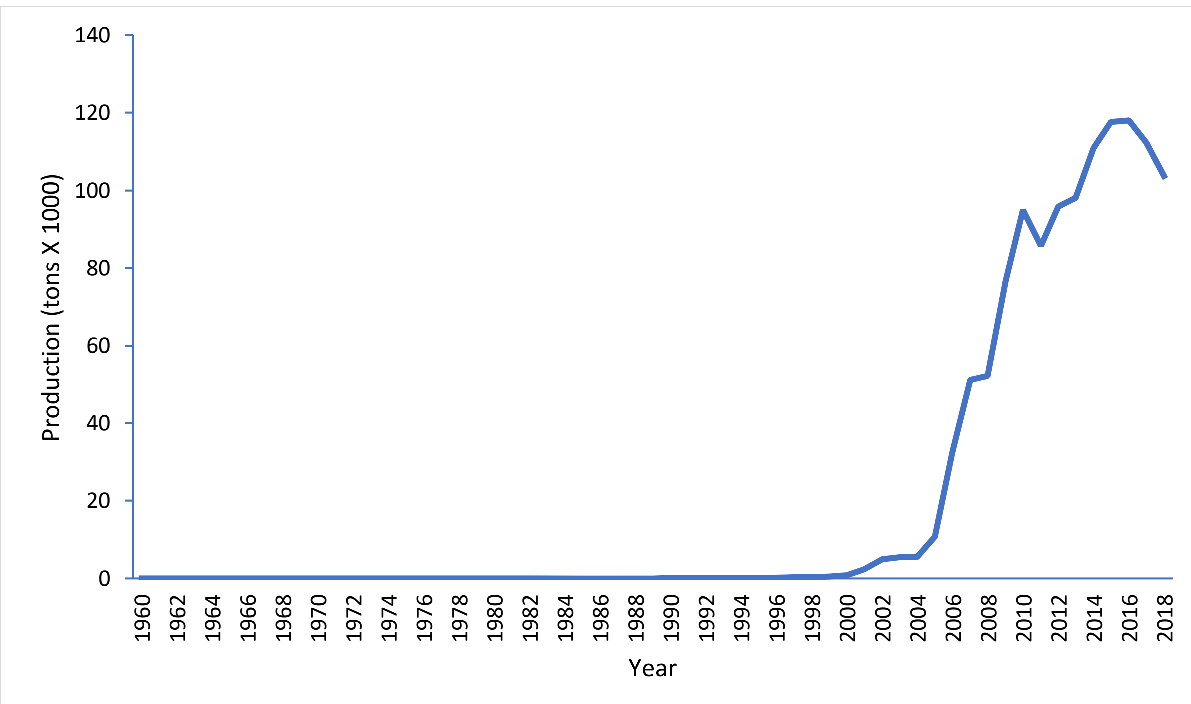


**Figure 2.3: Aquaculture production in Uganda (1960 – 2018 in Tons x1000)** *(FAO, 2004-2020)*

#### 2.4.3.3 Freshwater Aquaculture Production Systems in Uganda

Aquaculture productions in Uganda were carried out mainly using pond culture systems, until recently that other forms of fish production systems such as cage culture system are emerging due to the advent of commercial fish farms (FAO, 2004-2020).

##### 2.4.3.3.1 Pond Systems

Fish farmers mostly adopt intensive and semi-intensive pond culture systems in almost all districts of Uganda (Isyagi *et al.*, 2009). The intensive pond production system utilizes smaller and deeper earth ponds which are used mainly to culture sex-reversed Nile tilapia (Mbowa *et al.*, 2016b). Major factors that inform the decisions of fish farmers on the size of ponds are production costs, recommendations by extension personnel and land size (Isyagi, 2007). Due to the drive for the commercialization of aquaculture production in Uganda, average pond capacity has increased to 500 $m^2$ per fishpond (Rutaisire *et al.*, 2017).

##### 2.4.3.3.2 Tank Systems

Tank systems were first introduced in Uganda in the early 1990s to produce European eel (*Anguilla anguilla*) on private farms (Isyagi, 2001). Circular and rectangular tanks are currently being used for spawning and seed production by the catfish hatcheries (Rutaisire *et al.*, 2017). Aquaculture tanks of various designs are used generally in modern hatcheries for induced breeding of fish. Most of the hatchery setups typically are made up of breeding tanks, larvae rearing tanks and holding tanks (Rutaisire *et al.*, 2017). Tank systems are also employed for intensive Nile tilapia and catfish productions using underground freshwater system (Mbowa *et al.*, 2016b). Tank capacity is dependent on fish management practices, production cost, water quality maintenance and space utilization (Rutaisire *et al.*, 2017).

#### 2.4.3.3.3 Cage Systems

Cage culture system in Uganda emerged in 2006 in Lake Victoria and Kyoga as an alternate system to boost aquaculture production and still in its nascent phase (Blow & Leonard, 2007). The continuous decline in capture fisheries from Ugandan lakes and rivers have necessitated the development of cage aquaculture operations promoted by the Ugandan Government as a development priority and supported by development partners such as the Belgian Technical Corporation (BTC), European Union (EU), Non-governmental Organizations (NGOs), individual farmers, and youth groups (Kifuko, 2015). The most commonly adopted cage system is the low-volume high density (LVHD) cages of 8 $m^3$ with a stocking density of 200 – 400 fingerlings.$m^{-3}$ , depending on the depth and flow rate of water (Rutaisire *et al.*, 2017). Cage system is used predominantly in growing hatchery-produced fry of Nile tilapia (*Oreochromis niloticus*) using the pelleted aqua feed. Cage culture is adopted currently by the major stakeholders in the aquaculture sector such as research institutions, local governments, private investors and donor agencies (Mbowa *et al.*, 2016a; Rutaisire *et al.*, 2017).

The Nile River in Uganda provides favourable temperature and good water quality parameters; therefore, providing suitable opportunities for cage culture development and job creation (Blow & Leonard, 2007). The productivity of cage culture is substantially dependent on management practices, and ranges from 5 to 35 kg fish.$m^{-3}$ The government policy of restricting the number of cages has been a significant factor affecting operational cages in Uganda (Mbowa *et al.*, 2016a).

#### 2.4.3.4 Challenges Confronting the Aquaculture Sector in Uganda

Several challenges such as marketing, transaction costs, availability of feed, limited supply of fingerlings, limited availability of suitable land, fish diseases management, regulatory framework and policies amongst other factors of production, similar to those confronting the development of aquaculture in other Sub-Saharan African countries are the limiting factors challenging the growth of aquaculture in Uganda (Cai *et al.*, 2017).

##### 2.4.3.4.1 Fish Feed

The quality and quantity of aquafeed production level in Uganda are not sustainable to address the demand for fish feed (Olwo, 2009). The fish feed industry is solely driven by private producers whose uneven geographic distribution and production operations are grossly inadequate to meet the local aqua feed demand (Mbowa *et al.*, 2016a). Due to near absence of government regulation on fish feed quality assurance, the standard of locally manufactured fish feed constitutes a major limiting factor to the development of aquaculture as fish farmers are not guaranteed of the quality of feed being used (Rutaisire *et al.*, 2017).

#### 2.4.3.4.2 Fish Seed

One of the major constraining factors limiting the development of the aquaculture sector in Uganda is inadequate fry production due to a shortage of fish fry hatcheries in the country (Jagger & Pender, 2001). The government established fish hatcheries became moribund and non-operational due to poor management resulting in a dearth of fingerlings supply (Mbowa *et al.*, 2016a). The country continued to experience a deficit in the production of fish seed due to deficient production technologies used in hatcheries coupled with lack of standardization of production practices between research institutions and commercial hatcheries, (Mwanja *et al.*, 2015). The drive to develop the aquaculture sector coupled with diversification of aquaculture production systems resulted in a rapid increase in demand for fish seed. The supply of fingerlings, however, is greatly hindered by inadequate operational hatcheries and low productivity of existing hatcheries (Mwanja *et al.*, 2015).

#### 2.4.3.4.3 Land and Water Availability

Fragmentation of land and decreasing size of farms is a common occurrence in most parts of Uganda due to limited land availability and competitive demand for land (Jagger & Pender, 2001). The average farm size is about two hectares, whereas, in some densely populated upland regions such as Kabale, the average size of farms is smaller than two hectares (Kisamba-Mugerwa, 2001). Wasteland and other lands with a low cost or lack opportunity cost, including gullies and ditches that can support fishponds may be appropriate for fish farming (Jagger & Pender, 2001). The challenge facing aquaculture development in land constrained areas with a high opportunity cost may have been addressed by the development of aquaculture parks in areas including wetlands, lakes and rivers as proposed by the government. The attempts at creating enabling environment for the development of aquaculture sector, however, was met with weak governance capacity in securing site tenure, accountability and management (Jagger & Pender, 2001; Dickson *et al.*, 2012; Rutaisire *et al.*, 2017).

In trying to mitigate against the impact aquaculture activities on sustainability and biodiversity of wetland, the government opted to encourage small scale aquaculture as a sustainable means of wetland utilization; however, the permits fees for aquaculture activities in wetlands are beyond the affordability of many small-scale farmers (Jagger & Pender, 2001).

#### 2.4.3.4.4 Diseases

The policy instrument for the management and development of fisheries and aquaculture in Uganda gives limited attention to fish health management while the legal provisions for fish diseases control do not have management provisions for effective control and management (Akoll & Mwanja, 2012).

The emergence of medium and commercial scale aquaculture contributed to the outbreak of fish diseases resulting in mass mortalities being recorded in hatcheries and grow-out systems (William & Kim, 2015). Assessment of some fish farms and review of aquaculture regulatory frameworks of Uganda revealed significant lapses in biosecurity from the point of fish health management, farm management practices, inputs and products quality assurance, farmer organization and education, technical capacity, aquaculture environmental impact management, enforcement of aquaculture regulations and research (William & Kim, 2015). Previous studies on fish health mostly focused on wild fish parasites while very little information is available on pathogens and diseases of aquaculture species (William & Kim, 2015). Diagnostic facilities for fish are still very elementary with control and prevention plans existence barely in practice (William & Kim, 2015).

#### 2.4.3.4.5 Aquaculture Marketing and Trade in Uganda

The aquaculture sector in Uganda is grouped into three areas: smallholder fish farms, medium-scale commercial fish farms and large-scale commercial fish farms. The smallholder farmers target the local fish markets, while large-scale commercial farms focus on regional markets from neighbouring countries (Dickson *et al.*, 2012). The rapid decline in catches from the wild seems to portend a significant potential for the development of aquaculture products market in Uganda (FAO, 2004-2020). The current aquaculture production can barely sustain a steady market; however, the demands from various retail stores involved in the distribution of foodstuffs have considerably changed production patterns, supply and distribution of aquaculture products (Rutaisire *et al.*, 2017). Access to finance at an affordable interest rate is a major constraint hindering production capacity due to the high level of investments needed to meet the target market demands (Jagger & Pender, 2001).

### 2.4.3.5 Ugandan Aquaculture Policies and framework

The Department of Fisheries Resources (DFR) under the Ministry of Agriculture, Animal Industry and Fisheries (MAAIF) is the competent authority in Uganda saddled with the responsibility of inspection, certification and approval of aquaculture establishments and allied practices (FAO, 2004-2020). The overall strategic goal of the fisheries sector is to enhance sustainability in fish and fisheries products production and utilization through well-managed capture fisheries and the promotion of aquaculture (MAAIF, 2012). The DFR is mandated to promote, guide and support public and private sector partners involved in fisheries and aquaculture activities in sustainable development as well as responsible for setting and enforcing regulations and standard for practices on fisheries and aquaculture (MAAIF, 2012). The DFR also provides services such as technical back-up associated with fisheries and capacity building for Local Governments; information provided for all stakeholder groups; creation of funding strategies for sector development; ensure sustainable resource utilization through good fisheries policy and equitable legal basis for sustainable fisheries and aquaculture management (FAO, 2004-2020).

### 2.4.4 Aquaculture in South Africa

Aquaculture started in South Africa when attempts were made with mariculture of indigenous oysters in 1673 and 1676; however, commercial operations were not successful until 1948 (FAO, 2010-2020b). Abalone (*Haliotis midae* L. 1758.) aquaculture which started in the early 1990s is till date the leading mariculture sub-sector in South Africa, with most farms concentrated in the Overberg area of Western Cape Province (DAFF, 2018a).

Rainbow trout (*Oncorhynchus mykiss*) farming is the oldest freshwater aquaculture subsector in South Africa (DAFF, 2018b). The first batch of Rainbow trout seeds was imported into the country in 1896, while dry pelleted feeds were introduced in 1956 (Hecht & Britz, 1990). Rainbow trout are produced mainly in the Western Cape and Mpumalanga provinces with a production of about 1,000 tons recorded in 2010 (Hecht & Britz, 1990).

South Africa has conducive environmental conditions for the development of the aquaculture sector as well as enormous opportunities for the commercial production of various cultured species. The aquaculture sector has, however, underperformed compared to its potentials and therefore, minimally contributes to the fisheries products and GDP of the country (FAO, 2010-2020b). Aquaculture in South Africa compared to Egypt, Nigeria, Uganda and the rest of the world, relatively remains a small industry.

#### 2.4.4.1 Aquaculture Production and Value

South Africa occupies the tenth position amongst the top 10 aquaculture producing countries in Africa in 2018 and accounts for 0.28 % of total food fish aquaculture production in Africa (FAO, 2010-2020b; IDC, 2015). The aquaculture sector in South Africa recorded a total production (excluding seaweed) of 5,418 tons in 2015 valued at R 696 million (US$ 48.2 million), with mariculture subsector accounting for 3,592 tons (72 %), while the freshwater aquaculture subsector was recording 1,826 tons (DAFF, 2015a; Britz & Venter, 2016; DAFF, 2017a) (Table 2.6). Aquaculture production grew by 4 % (209 tons) compared to 2014 (DAFF, 2017a). Mussel farming recorded the most significant production in 2015, followed by abalone and trout production while the marine finfish, tilapia, catfish, oyster and marron are still in the new phase (DAFF, 2017a). The mariculture industry in 2015 only consisted of 37 operational farms as compared to 152 operational freshwater farms. It, however, recorded about 66 % of production volume and accounted for more than 80 % of production value, mainly due to the contribution of the well-established high-value abalone subsector (Britz & Venter, 2016; DAFF, 2017a).

**Table 2.6: Aquaculture production share and value by subsectors in RSA in 2013**

*(Britz & Venter, 2016)*

| Subsectors/Species | Production Share (%) | Production Share (Tons) | Value (%) | Value ($) |
|---|---|---|---|---|
| Trout | 31.7 | 1,568 | 16.3 | 7,856,600 |
| Abalone | 30.6 | 1,513 | 76 | 36,632,000 |
| Mussels | 23.2 | 1,147 | 2.9 | 1,397,800 |
| Others | 14.5 | 717 | 4.8 | 2,313,600 |
| Total Marine Species | 62.2 | 3,076 | 82.2 | 39,620,400 |
| Total Freshwater Species | 37.8 | 1,870 | 17.8 | 8,579,600 |

### 2.4.4.2 Aquaculture Species in South Africa

The mariculture species farmed in South Africa include abalone (*Haliotis midae*), Pacific oyster (*Crassostrea gigas*), mussels (*Mytilus galloprovincialis* and *Chromomytilus meridionalis*), dusky kob (*Argyrosomus japonicus*) and seaweed (*Ulva spp.* L. 1758 and *Gracilaria spp*. Greville, 1830) (DAFF, 2015a). Freshwater aquaculture species include trout (*Oncorhynchus mykiss* and *Salmo trutta*), tilapia (*Oreochromis mossambicus*, *Oreochromis niloticus* and *Oreochromis rendalli*), catfish (*Clarias gariepinus*), carp (*Cyprinus carpio*), marron crayfish (*Cherax tenuimanus*), as well as various ornamental species (DAFF, 2015a).

The culture of marine finfish in South Africa is an emerging subsector with dusky kob (*Argyrosomus japonicus*) as the only finfish being commercially grown. Ongoing studies, however, are currently being conducted on other species such as yellowtail (*Seriola lalandi*) for aquaculture potential while seaweeds are only grown for feeding abalone (Britz & Venter, 2016) (Table 2.7). Trout (*Oncorhynchus mykiss* and *Salmo trutta*) farming is the most established freshwater aquaculture in South Africa and accounts for the largest aquaculture production in terms of volume, slightly surpassing abalone production, but abalone far exceeds trout in value. Increasing focus and efforts are being channeled towards growing the emergent tilapia (*Oreochromis mossambicus*, *O. niloticus* and *Tilapia rendalli*), catfish (*Clarias gariepinus*) and marron crayfish (*Cherax tenuimanus*) freshwater aquaculture (Britz & Venter, 2016). Ornamental species, mostly koi and common carp (*Cyprinus carpio*) are also cultured, but on a small-scale for the aesthetic market.

**Table 2.7: Marine and Freshwater Aquaculture Species and Scale of Operations in South Africa**

| Marine Aquaculture Species | | | Freshwater Aquaculture Species | | |
|---|---|---|---|---|---|
| **Common Name** | **Scientific Name** | **Operational Scale** | **Common Name** | **Scientific Name** | **Operational Scale** |
| Abalone | *Haliotis midae* | Commercial | Rainbow trout | *Oncorhynchus mykiss* | Commercial |
| Pacific oyster | *Crassostrea gigas* | Commercial | Brown trout | *Salmo trutta* | Commercial |
| Mediterranean mussel | *Mytilus galloprovincialis* | Commercial | Mozambique tilapia | *Oreochromis mossambicus* | Commercial |
| Black mussel | *Choromytilus meridionalis* | Commercial | Nile tilapia | *Oreochromis niloticus* | Commercial |
| Seaweed | *Ulva spp* | Commercial | African Sharptooth catfish (catfish) | *Clarias gariepinus* | Pilot |
| Seaweed | *Gracilaria spp* | Commercial | Common carp | *Cyprinus carpio* | Commercial |
| Dusky kob | *Argyrosomus japonicus* | Commercial | Koi carp | *Cyprinus carpio* | Commercial |
| Yellowtail | *Seriola lalandi* | Research | Marron (Freshwater crayfish) | *Cherax tenuimanus* | Commercial |
| White stumpnose | *Rhabdosargus globiceps* | Research | | | |
| Spotted grunter | *Pomadasys commersonnii* | Pilot | | | |
| Salmon | *Salmo salar* | Pilot | | | |
| Yellowbelly rockcod | *Epinephelus marginatus* | Research | | | |
| Mangrove snapper | *Lutjanus argentimaculatus* | Research | | | |
| South Coast Sea Urchin | *Tripneustes gratilla* | Research | | | |
| South African Scallop | *Pecten sulcicostatus* | Research | | | |
| Bloodworm | *Arenicola loveni* | Research | | | |

(DAFF, 2015, 2017).

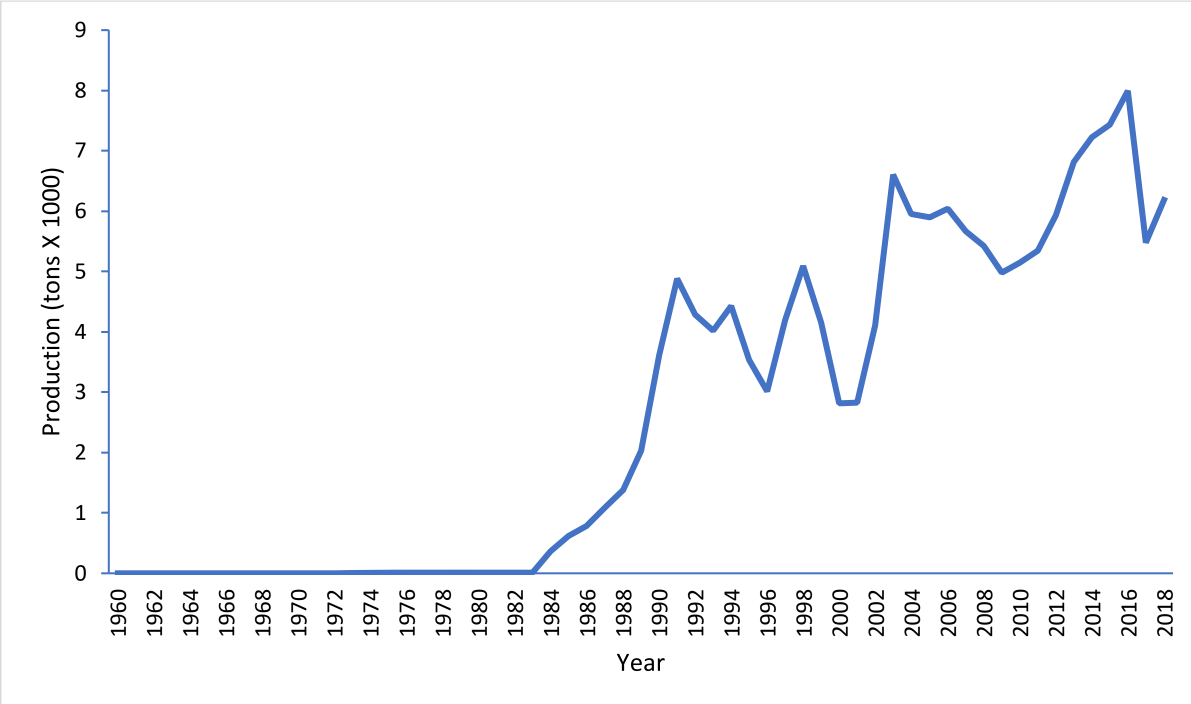


**Figure 2.4: Aquaculture production in South Africa (1960 – 2018 in Tons x1000)** *(FAO, 2010-2020b)*

#### 2.4.4.3 Aquaculture Production Systems in South Africa

The South African aquaculture sector involves the culture of a wide variety of unrelated farmed aquatic species whose biology requires specific aquaculture practices, hence the need to describe aquaculture production systems for each species (FAO, 2010-2020b).

**Raceway Systems**

Raceway systems are intensive aquaculture systems primarily used for trout grow-out production, koi carp, carp and catfish (FAO, 2010-2020b; DAFF, 2015a).

**Pond Systems**

Pond systems are used for semi-intensive to intensive grow-out production of trout, marron crayfish, dusky kob, catfish, tilapia, koi carp, carp and ornamental fish (FAO, 2010-2020b; DAFF, 2015a).

**Tank Systems**

Tanks are used mainly for the low-scale culture of ornamental fishes and carp, and primarily for the juvenile production of marron crayfish (FAO, 2010-2020b; DAFF, 2015a).

**Cage Systems**

Cage culture systems have been successfully used for the grow-out production of trout and piloted on the offshore production of salmon in South Africa (FAO, 2010-2020b; DAFF, 2015a)

**Recirculating Aquaculture Systems (RAS)**

Recirculating aquaculture system is a reasonably advanced production technology compared to the regular production technology adopted by the other African countries, used mainly for the production of tilapia (IDC, 2015). The RAS systems are used predominantly in South Africa as efficient techniques of controlling water temperatures, quality and conserving water usage as the control of water temperature is vital in tilapia production in South Africa due to prevalent climatic conditions in most parts of the country (IDC, 2015). Thermally regulated RAS systems have also been documented for the successful production of trout. Other aquaculture species cultured using RAS also include the catfish, koi carp, carp and ornamental species (FAO, 2010-2020b; DAFF, 2015a).

**Integrated Aquaculture Systems – Aquaponic Systems**

Aquaponics is an emerging and mainly practiced integrated aquaculture system in the Republic of South Africa (Mchunu N *et al.*, 2017). South Africa largely adopted RAS technology, a fairly advanced technique, when compared to average technology currently being utilized in other African countries for the production of tilapia. Aquaponics is a popular and well-established technology in developed countries; however, it is relatively new and rapidly developing in South Africa therefore, unlocking an innovative niche for sustainable food production (Mchunu N *et al.*, 2017).

**Longline Systems**

Longlines systems are used in mariculture operation for the grow-out production of oysters and mussels (FAO, 2010-2020b; DAFF, 2015a).

**Marine aquaculture**

***Abalone***

Abalone is predominantly cultured in onshore land-based tank systems in South Africa. These land-based facilities are sited proximately to the coastline due to access to an unlimited quantity of seawater which is usually pumped ashore and pre-treated in order to improve water quality (FAO, 2010-2020b). Most land-based tanks are operated as flow-through systems where effluents are directly released into the environment, while in some farms, land-based tanks are operated as RAS and water are recycled through suitable filtration and treatment systems to improve growth and survival. Small scale cage culture of abalone is also practiced in the Western Cape, which involves stocking of juveniles in submersible cages that are suspended off the seabed (FAO, 2010-2020b; DAFF, 2015a). Abalone ranching is another production method which involves raising cultured hatchery juveniles within an allocated area in the wild until they attain the market size and harvest by the permit holder.

***Oysters and Mussels***

Oysters are reared usually in submerged plastic mesh or nylon net cages suspended from longlines. Juvenile oysters are cultured on intertidal oyster racks before they are stocked out at sea off-bottom. Mussels are cultured using juveniles collected from a natural settlement on floating wooden raft or longlines with a series of suspended ropes (FAO, 2010-2020b; DAFF, 2015a).

***Marine finfish***

Intensive recirculating aquaculture systems are utilized in rearing Juveniles produced through induced spawning method and are subsequently moved to grow-out systems such as large land-based tank systems, flow-through saline earth ponds and offshore sea cages where juvenile fish are raised to market size. Offshore cage culture is still underdeveloped in South Africa, mainly due to high-energy shoreline and thus requires further considerations in technology (FAO, 2010-2020b).

***Ornamental marine species***

Ornamental marine species in South Africa are cultured intensively in systems such as fish rearing tanks, coral propagation tanks, grow out tanks, quarantine tanks and display tanks (FAO, 2010-2020b).

#### 2.4.4.4 Mariculture in South Africa

South Africa has a vast coastline stretching 2,798 km from the western desert border with Namibia on the Atlantic Ocean southwards around the tip of Africa and then northeast to the border with Mozambique on the Indian Ocean (FAO, 2010-2020a). South Africa mariculture industry, although it is still evolving and quite low in production output, it is the most developed in Africa. It, however, significantly lags in production volume as compared to other nations with similar coastline length (FAO, 2010-2020b).

South Africa recorded a total of 36 operational mariculture farms in 2013 (DAFF, 2015a). The Western Cape Province recorded the highest number of operational mariculture farms in 2013. The province has 24 marine aquaculture farms operating in four sub-sectors, i.e. abalone, finfish, oysters and mussels; however, abalone represents the key contributor (DAFF, 2015a). The Eastern Cape has six operational mariculture farms active in three sub-sectors which are abalone, oysters and finfish. The Northern Cape has five farms playing in the abalone and oysters subsectors, while KwaZulu-Natal has only one operational marine finfish farm (DAFF, 2015a).

#### 2.4.4.5 Challenges Confronting the South African Aquaculture Sector

South Africa is endowed with good infrastructure, business institutions, and supply chains, however, the high energy coastline coupled with a water-scarce inland area limit the potential of aquaculture production (Britz & Venter, 2016). Prevailing sub-optimal environmental conditions such as wide temperature variation, aridity combined with macroeconomic factors such as dearth of skilled human resources, fish prices, poorly developed value chain and complicated authorization procedures are mostly responsible for the challenges hindering the growth of aquaculture in South Africa (FAO, 2010-2020b; Britz & Venter, 2016).

Major difficulties experienced by potential investors include restricted access to suitable land and water. These difficulties include the rezoning process, onerous permitting requirements, and an obstructive bureaucracy in respect of compliance with environmental regulations (FAO, 2010-2020b; Britz & Venter, 2016). In terms of aquaculture technology, South Africa does possess a generally conducive infrastructure and supporting institutional environment for the development of large-scale commercial aquaculture (Britz & Venter, 2016). There is, however, a lack of sector-level institutional coordination and strategy and certain specific infrastructure and capacity requirements that individual firms cannot overcome (DAFF, 2015b). Before the release of the National Aquaculture Strategic Framework (NASF) and the National Aquaculture Policy Framework (NAPF) in 2012 and 2013 respectively, there has been a lack of a comprehensive set of national strategies and critical action plans for aquaculture (FAO, 2010-2020b; Britz & Venter, 2016).

#### 2.4.4.5.1 Environmental Conditions

South Africa has a limited conducive environment for the development of aquaculture due to strong ocean currents and heavy wave actions, as well as a shoreline having limited sheltered bays of adequate size thus limiting the potential for commercial-scale mariculture of sea-cage farming (Britz & Venter, 2016). South Africa, therefore, has successfully developed shore-based mariculture technology for the production of abalone (*Haliotis midae*) and dusky kob (*Argyrosomus japonicus*) however, production costs of pump-ashore are high, thus rendering shore-based mariculture technology suitable for only high-value aquaculture species (Britz & Venter, 2016).

Also, scarcity of fresh inland water coupled with vast temperature variations between summer highs and winter lows make most parts of the nation unsuitable for the production of either cold or warm water aquaculture species in open systems (Britz & Venter, 2016).

#### 2.4.4.5.2 Land and Water Availability

There is the dearth of suitable area inland, lakes, rivers, estuaries in addition to access to suitable water supply in South Africa due to competitive use of these sites for recreational, agricultural and residential activities thus, a major hindrance to the development of aquaculture (Mahieu, 2015). Also, accessing suitable land and water for aquaculture development is constrained by complications encountered by prospective investors which include but is not limited to rezoning process, arduous permit process and environmental regulations compliance (IDC, 2015).

#### 2.4.4.5.3 Complicated Regulation

The over-regulation of the aquaculture sector, when compared to other food production sectors, is one of the major anti-enabling environments constraining the growth of aquaculture in South Africa (DAFF, 2013). As a result of fragmented policies from different tiers of government departments, a prospective aquaculture venture will require at least thirteen different permits/licenses from different government departments to operate, which are issued in a cascading order thus needlessly prolonging the period of permit issuance (CSIR, 2017). The complicated and ambiguous regulatory environment, therefore, makes it difficult for potential aquaculture venture to attract investment.

#### 2.4.4.5.4 Other Macroeconomic Challenges

Other challenges that have stagnated the growth of aquaculture sector in South Africa include, but is not limited to, focus on a few but high-value species, scarce skilled resource persons and support services, the dearth of funds due to the reluctance of financial institution to fund aquaculture projects, high operating cost and weak marketing services (DAFF, 2013; CSIR, 2017).

### 2.4.4.6 Aquaculture Marketing and Trade

South African aquaculture products are sold both locally and internationally, depending on the species involved. The local aquaculture market is influenced typically by market price, species, consumer awareness and ease of accessibility. South Africa is not a traditional fish-eating country; however, the growing awareness of environmental sustainability and health concerns of consumers have led to the burgeoning demand for aquaculture products (DAFF, 2017a). The abalone industry with high-value species exports bulk of their product for sale in Asia due to higher returns while most of the trout produced are sold locally (DAFF, 2017b). South Africa exported almost 1,399 tons of aquaculture products valued at R487.80 million in 2015, with Hong Kong representing the leading aquaculture products importer, followed by Botswana and Taiwan (DAFF, 2017a). Approximately 325 tons of tilapia valued R3,5 million were exported from South Africa in 2015 with Botswana (196 tons), Democratic Republic of Congo (79 tons) and China (22 tons) being the three top destinations. The tilapia export market was growing and increased significantly by 323 % with ten destinations recorded in 2014, and 3 more destinations added in 2015 (DAFF, 2017a).

The primary processors developed the marketing system for aquaculture products in South Africa. These companies developed their cold storage facilities and supply network primarily to support their main aquaculture operations while there are also fully integrated marketing and merchandising firms that handle distribution to the retail sector (DAFF, 2017a).

#### 2.4.4.7 South African Aquaculture Policies and framework

The Department of Environment, Forestry and Fisheries (DEFF) formerly known as the Department of Agriculture, Forestry and Fisheries (DAFF) is the lead national agency tasked with the responsibility for aquaculture sector development in South Africa. The

National Aquaculture Strategic Framework (NASF) was developed in 2012 as a road map for the sustainable development of the aquaculture industry taken into consideration the current position of South Africa vis-à-vis global aquaculture production, challenges with creating enabling environment for aquaculture development, national food security as well as wealth and job creation (DAFF, 2013).

The current NASF policy of DEFF aims to achieve the following objectives:

I. Encourage responsible and sustainable aquaculture development that is globally competitive.
II. Facilitate and support the optimal growth of the aquaculture industry in order to foster economic growth, food security and wealth creation.
III. Encourage private sector participation through the provision of required support services.
IV. Investment in research and development to aid industry growth, diversification and sustainable production.
V. Promote sustainable aquaculture development from a macroeconomic perspective.
VI. Promote adaptive aquaculture management that can promote innovations, data collection and knowledge transfer.
VII. Promote good governance for the full development of the aquaculture industry under a supportive regulatory framework.

The aquaculture policy intends to support both commercial and small-scale emerging farmers and to adopt a value-chain approach for the development of the aquaculture sector.

## 2.5 Qualitative SWOT analysis and critical success factors of key players (Egypt, Nigeria and Uganda) vis-à-vis South Africa

This section compares the strengths, weaknesses, opportunities and threats (SWOT analyses) of the key players with South Africa (Table 2.8) and highlights the critical success factors responsible for the rapid evolution and positioning of Egypt, Nigeria and Uganda as key aquaculture players in Africa. The critical success factors identified amongst the key players are:

i. market demand

ii. Infrastructure

iii. environment

iv. technology

v. commercialization

vi. institutional support and

vii. skill development.

These identified factors formed the framework for both qualitative and quantitative (Chapter 3) SWOT analyses of this study.

### 2.5.1 Qualitative SWOT Analysis of Egypt, Nigeria, Uganda and South Africa

The key strengths of the Egyptian aquaculture sector are high production output and diversity of aquaculture species being produced (Table 2.8). The main weaknesses are due to overstretched water and land resources, as well as the prevalence of inefficient production systems (Table 2.8). High per capita fish consumption and prioritization of the aquaculture sector by the Egyptian government are the major opportunities; the sector is, however, currently being confronted by the threats of environmental and climate change impact; and lack of significant export of aquaculture products (Soliman, 2017).

Availability of suitable land and water resources, coupled with the emergence of intensive urban and peri-urban aquaculture clusters are the major strength driving the growth of aquaculture in Nigeria (Obwanga *et al.*, 2018). Soaring cost of feed, near absence of mariculture and focus on *Clarias spp.* are the major weaknesses of the Nigerian aquaculture sector (Obwanga *et al.*, 2018). Huge and widening demand-supply gap of fish, as well as the gradual ban of fish importation, are the key opportunities that can be leveraged by the aquaculture sector, unstable policies and poorly implemented framework are however major threats hindering the development of the sector (Table 2.8).

The key strengths of the aquaculture sector of Ugandan are the availability of suitable land and vast networks of inland water resources (Table 2.8). Growing adoption of cage culture is also contributing to the development of the sector (Table 2.8). Similar to Nigeria, the aquaculture sector of Uganda is focused mainly on tilapia and catfish; the sector is also plagued by the shortage of local commercial-scale aquafeed production (Rutaisire *et al.*, 2017). Uganda is a major supplier of fish to her neighbouring countries and potentially positioned as key fish processing hub in the East African region (Cai *et al.*, 2017). The sector is, however, threatened by a weak enabling environment (Mwanja, 2007).

The major strength of South Africa is its diversified environment, suitable for the production of both warm and cold-water aquaculture species (CSIR, 2017). The sector also boasts efficient production technology but focus on high-value species with low production output, and overstretched inland water resources are major weaknesses of the South African aquaculture sector (Table 2.8). Major opportunities in this sector are growing institutional support primarily driven by the government and established export markets (Table 2.8). Very low per capita consumption of fish (7.5 kg) compared to the global average of 17 kg and complicated authorization processes are the major threats confronting the growth of the sector (Table 2.8).

### 2.5.2 Critical success factors of key players (Egypt, Nigeria and Uganda) vis-à-vis South Africa

**Market Demand**

The domestic demands for fish driven by high per capita consumption of fish amongst the key players have been driving the growth of aquaculture production (Kawarazuka, 2010; Soliman & Yacout, 2016; Atanda & Fagbenro, 2017). The market for fish in Egypt is characterized by simple but efficient value chain and market systems; thus, fish is easily accessible in the markets within a short time (Table 2.8). Nigeria has a well-developed value chain for catfish (Obwanga *et al.*, 2018). A key emerging trend is the growth of peri-urban aquaculture and the establishment of Fish Farming Estates (FFEs) in large urban areas thus enabling access to large markets and reduction in post-harvest losses due to infrastructure challenges (Cocker, 2014; Obwanga *et al.*, 2018). Production in Uganda is dominated by tilapia and catfish aquaculture (Cocker, 2014). Catfish in Uganda is considered as a niche product in the market and commands higher prices than tilapia due short supply of both wild and farmed catfish (Cocker, 2014). The key players can leverage the opportunity of growing export markets regionally and globally through standardization of aquaculture products. South Africa in contrast, is typically not a fish-eating country as demonstrated by its low per capita (7.5 kg per person) compared to the global average of 17 kg per person (Britz & Venter, 2016). South African aquaculture is characterized by meagre and insignificant production output due to the myriads of challenges (Britz & Venter, 2016; DAFF, 2017a).

**Infrastructure**

The availability and accessibility to essential infrastructure are highly valuable to the development of aquaculture amongst the key producers (Cai *et al.*, 2017). The presence of many feed mills with high production capacity and proximity to the fish farm is a common success factor among the key players (Table 2.8). In addition to high feed milling capacity in Egypt, both the government and private sectors are actively involved in establishment and operations of hatcheries, as well as research, training and dissemination facilities (Cai *et al.*, 2017). As a result of the success recorded with the establishments of fish farm estates in Nigeria, the government became persuaded and involved with infrastructure improvement and provision to boost aquaculture production output (Ozigbo *et al.*, 2014; Atanda & Fagbenro, 2017). Aside from many privately-operated hatcheries which are responsible for the availability of fingerlings, the Ugandan government is developing aquaculture parks (a fish farm cluster with shared amenities) countrywide to lower cost and boost production output (Cocker, 2014). South Africa, on the hand, has infrastructure capability to support high feed and fish seed production output; however, there are only a few firms which are sited far away from many fish farms. The support from government is focused mainly on creating an enabling environment for aquaculture production through policies (DAFF, 2013).

**Environment**

Land and water availability, as well as favourable climatic conditions, are relevant factors for aquaculture development (Cocker, 2014). Egypt experiences warm temperatures for the most of the year, which is conducive for warm water fish aquaculture, however, due to the prevailing desert climate, it is limited by the availability of suitable land and water (Cai *et al.*, 2017; Soliman, 2017). Nigeria and Uganda are both endowed with arable land and water, as well as enjoy warm tropical climate suitable for aquaculture production (Ozigbo *et al.*, 2014; Adewumi, 2015; Rutaisire *et al.*, 2017). South Africa has a water-scarce inland area, highly exposed shoreline and sub-optimal climate; thus, limited by the availability of suitable natural environment for conventional aquaculture production (FAO, 2010-2020b; Britz & Venter, 2016).

### Technology

Adoption of improved technology has been identified as a key success factor and mitigant against environmental factors limiting the development of aquaculture (Soliman, 2017). Besides adopting efficient fish production systems, the key producers are also embracing cutting-edge technology in feed production, hatchery operations and fish processing (El-Sayed *et al.*, 2015; Soliman & Yacout, 2016; Atanda & Fagbenro, 2017; Rutaisire *et al.*, 2017). A paradigm shift in production technology to the adoption of efficient water systems such as desert aquaculture, intensive earthen pond production and development of integrated aquaculture systems immensely contributed to the rapid expansion of aquaculture production in Egypt (Soliman, 2017).

### Commercialization

Aquaculture development activities are concentrated often on production techniques at the expense of its business development, aquaculture will not be, however, sustainable, if not managed and promoted as a business (Muir, 2005; Cocker, 2014). The aquaculture sector in Egypt has attracted both private and government sector investments, notably in the feed and fish seed production segment of the value chain (Table 2.8). The fish farm estate (FFE) models contribute more than 80 % of aquaculture production in Nigeria and mostly responsible for the development of the Nigerian aquaculture industry value chain (Obwanga *et al.*, 2018). This FFE model is predominantly driven by the private sector and attracting both local and foreign investments in the aquaculture industry (Ozigbo *et al.*, 2014; Atanda & Fagbenro, 2017). Most of the aquaculture development initiatives in Uganda with regards to production and processing is driven primarily by private sector investment (Dickson *et al.*, 2012). The aquaculture sector of South Africa is mainly private sector driven due to aquaculture development policy shift from a production to a value chain driven development strategy (DAFF, 2013; Britz & Venter, 2016).

**Institutional support and skill development**

Institutional support is rendered by the government through the development of policies to create an enabling environment for aquaculture development (Cocker, 2014; Obwanga *et al.*, 2018). All the four countries appeared to have aligned their policies in line with the New Partnership for Africa's Development (NEPAD) 2005 summit priority actions geared towards aquaculture value chain development and commercialization. As a result of this policy shift, the aquaculture sector of these countries began to witness the private sector and foreign investments and growth (Cocker, 2014). The role of capacity building across the aquaculture value chain is undertaken by research institutions, vocational centres and universities. Nigeria and Egypt have many well-established aquaculture research institutions and universities undertaking research, training and technology transfer (Obwanga *et al.*, 2018).

**Table 2.8: SWOT Analysis of Egypt, Nigeria, Uganda and South Africa**

| | **Internal factors** | | **External factors** | |
|---|---|---|---|---|
| **Country** | **Strengths** | **Weaknesses** | **Opportunities** | **Threats** |
| Egypt | I. High production output and value –highest in Africa<br>II. Culture of diverse aquaculture species<br>III. Produces freshwater and marine species<br>IV. Aquafeed manufacturing capacity<br>V. Functional government hatcheries<br>VI. Research and development capacity<br>VII. Vast coastline for mariculture<br>VIII. Major employer of Labour | I. Overstretched and limited water resources<br>II. Dearth of suitable aquaculture sites<br>III. Inefficient production systems<br>IV. Lack of processing capacity<br>V. Production limited by seasonality<br>VI. Dependence on imported fish feed ingredients;<br>VII. Poor infrastructure | I. High per capita consumption of fish<br>II. Burgeoning local demand<br>III. Favourable location for mariculture<br>IV. Strong institutional support from government<br>V. Development of desert aquaculture | I. Lack of significant export due to poor product standard<br>II. Climate change and environmental impact<br>III. Price fluctuation<br>V. Preference for wild captured fish by consumer<br>V. Poor currency performance |
| Nigeria | I. High product value and growing capacity<br>II. Intensive urban and peri-urban production systems<br>III. Feed production capacity<br>IV. Availability of fish seed due to many privately-run hatcheries<br>V. Research and development capacity<br>VI. Well established Catfish value chain<br>VII. Some levels of processing and packaging capacity<br>VIII. Availability of suitable land and inland water<br>IX. Large employer of labour<br>X. Establishment of fish farming estates/clusters in urban/peri-urban areas | I. Highly focused on a single species<br>II. High cost of feed<br>III. Near absence of mariculture<br>IV. Preference for live fish<br>V. Underutilized potential aquaculture land<br>VI. Importation of brood stocks<br>VII. Poor storage and processing facilities<br>VIII. Reliance on imported and expensive feed<br>IX. High cost of inputs<br>X. Poor access to credit facilities<br>XI. Shortage of extension workers and services | I. High per capita consumption of fish<br>II. Huge demand-supply gap<br>III. Growing export market<br>V. Policy shift towards commercial aquaculture<br>V. Government imposed fish importation quotas to protect sector. | I. Illegal fish trade with neighbours<br>II. Poor implementation of legal framework;<br>III. Unstable policies by successive governments<br>V. Growing tilapia production for export |
| Uganda | I. Availability of suitable land and inland water resources<br>II. Lower cost of feed production<br>III. Advent and growth of cage culture<br>V. Availability of fish seed due to many privately-run hatcheries<br>V. Existence of artisanal and commercial scale processing | I. Largely focused on tilapia and catfish species<br>II. Most fish culture is done in earthen ponds<br>III. Limited commercial scale feed production<br>IV. Skill shortage<br>V. Uganda is land locked therefore, absence of mariculture<br>VI. Most fish are sold fresh and unprocessed.<br>VII. Poor storage and processing facilities | I. Huge demand-supply gap<br>II. Growing regional market demand<br>III. Potential for processing and export | I. Poor record of regional export<br>II. weak institutional capacity, poor governance and political instability<br>III. Obsolete policies and framework |

| | Internal factors | | External factors | |
|---|---|---|---|---|
| **Country** | **Strengths** | **Weaknesses** | **Opportunities** | **Threats** |
| South Africa | I. Culture of diverse aquaculture species<br>II. Efficient production technology<br>III. Produces freshwater and marine species<br>IV. Commercial scale aquafeed manufacturing capacity<br>V. Vast coastline for mariculture<br>VI. Research and development capacity<br>VII. Food processing capacity<br>VIII. Established aquaculture producer associations | I. Unprotected open coastal sites exposed to high wave energy<br>II. Focused on high value species with low production output<br>II. Limited research into various segments of aquaculture<br>IV. Lack of extension services<br>V. Limited and overstretched freshwater resources<br>VI. Absence of functional government hatcheries<br>VII. Limited suitable land<br>VIII. Reluctance of financial institutions to fund aquaculture projects | I. Growing demand for affordable protein and shortage in traditional fish products<br>II. Potential for export<br>III. Aquaculture receiving government attention and support<br>IV. Connection with tourism<br>V. Conducive economic climate for aquaculture industry<br>VI. Enabling policies and framework | I. Lack of marketing services, structures and penetration<br>II. Very low par capital consumption of fish<br>III. Complicated Permits and registration procedures.<br>IV. Shortage of expertise and aquaculture professionals<br>V. Dearth of aquaculture veterinary services and disease management<br>VI. Impact of climate change |

*(FAO, 2004-2020; Fagbenro & Adebayo, 2005; El-Sayed, 2007; FAO, 2007-2020b; Nassr-Alla, 2008; FAO, 2010-2020b, 2011; Jamu et al., 2012; El-Sayed, 2013b; Oyakhilomen & Zibah, 2013; Nasr-Allah et al., 2014; Ozigbo et al., 2014; Adewumi, 2015; El-Sayed et al., 2015; Britz & Venter, 2016; Soliman & Yacout, 2016; DAFF, 2017; Rutaisire et al., 2017)*

## 2.6 Conclusion

Aquaculture which was first introduced to Africa by the colonizers as a means of recreational fishing activities later evolved as a means of attaining food security and livelihood from the 1940s (Hecht *et al.*, 2006; Brummett *et al.*, 2008). Aquaculture development activities across the region were initially funded by international partners and donor agencies until 1995 when funding from international donor agencies dwindled (Hecht *et al.*, 2006; Brummett *et al.*, 2008). The interest and growth of aquaculture across the region were revived later from 2005 through the global awareness raised by NEPAD fish for all summit of 2005 and the SPADA interventions coordinated by FAO. The NEPAD 2005 summit promoted the commercialization and value chain development of aquaculture in Africa driven primarily by large scale investment in Egypt, Nigeria, Uganda and Ghana. Aquaculture development in Africa is being sustained by many governments creating an aquaculture development centered conducive business environments through policy reforms and frameworks as a roadmap. Provision of enabling environments resulted in the burgeoning private sector-controlled aquaculture value chain development, notably in Nigeria, Egypt, Uganda and Ghana.

The rapid aquaculture development of Egypt was credited to the paradigm change in the aquaculture operating environment due to the active participation of the government in the downstream sectors of the aquaculture value chain besides the regulatory oversight functions.

The enactment and implementation of market-driven aquaculture development policies and interventions resulted in private sector-controlled aquaculture industry and a well-developed catfish production value chain in Nigeria.

The rapid decline in captured fisheries production from Lake Victoria, Lake Albert and other inland water bodies in Uganda prompted the interest and investments in commercial-scale aquaculture development. Fish farming parks and adoption of cage system were promoted to drive growth in production output.

A combination of factors which include but are not limited to suboptimal environmental conditions and over-regulatory oversight of the South African aquaculture sector unlike Egypt, Nigeria, Uganda and other African countries. The aquaculture sector, however, has potential opportunities due to sector prioritization by the government, access to the international market and a comparatively better economic climate.

Almost all the aquaculture production from the region comes from inland freshwater systems mainly focused on native catfish and tilapia species cultured in tanks, ponds, cages and improved production systems such as RAS and aquaponics.

Key challenges plaguing the pace of aquaculture development in Africa are access to credit facilities, inadequate supply of required quantity and quality of inputs, land ownership and product marketing. The distribution of aquaculture products is further exacerbated by dilapidated and inadequate infrastructure and facilities.

The critical success factors driving aquaculture development and production output of the key players were high per capita consumption of fish, optimal environment, infrastructure, technology, commercialization, provision of enabling environments and skill development.

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# CHAPTER 3: QUANTITATIVE SWOT ANALYSES OF KEY AQUACULTURE PLAYERS IN AFRICA: A CASE STUDY OF EGYPT, NIGERIA AND UGANDA VIS-À-VIS SOUTH AFRICA

## 3.1 Abstract

Africa's current contribution to world aquaculture production in 2018 is still insignificant (2,196,600 tons; ~ 2.7 %) albeit significantly increasing with larger-scale investments in Egypt, Nigeria and Uganda producing substantial quantities of fish. The leading producers are Egypt (1,561,457 tons), Nigeria (291,233 tons) and Uganda (102,737 tons) accounting for 90 % of total aquaculture production in the region. A SWOT (Strength, Weakness, Opportunity and Threats) analyses of these key regional players compared to South Africa (6,181 tons) was performed as South Africa aims to aggressively develop her aquaculture sector to become a significant regional and global player. The quantified SWOT analytical method coupled with the Multi-Attribute Decision-Making method (MADM) within an analytical framework which involves both performance analysis based on predefined evaluation criteria of countries' aquaculture sector were used for a comparative analysis of the production, technology, market, aquaculture policies and framework of Egypt, Nigeria, Uganda and South Africa. Factors such as the adoption of new technologies used in the formulation and production of aqua-feed (i.e. extruded feed); adoption of best farm management practices; commercialization of aquaculture, growing demand-supply gap due to high per capita consumption of fish and government's prioritization of aquaculture sector development through the creation of enabling environment for private sector participation were key strengths and opportunities identified amongst the leading players. The quantified SWOT shows Egypt possess aquaculture development strengths and opportunities; Nigeria has aquaculture development opportunities but weak in competitive strengths; while Uganda and South Africa both possess low, competitive strengths and being faced with threats. Capitalizing on the available opportunities and critical success factors of the leading aquaculture players in Africa, this analysis highlights strategic actions that could boost the development of aquaculture in South Africa. The quantified SWOT analysis was used to determine the competitive position of the aquaculture sectors of the compared countries and can be used as a basis for aquaculture policies and roadmaps.

**Keywords:**

Quantified SWOT; MADM; aquaculture; Egypt; Nigeria; Uganda; South Africa.

## 3.2 Introduction - SWOT Analysis

Africa's contribution to global aquaculture production in 2018 was estimated at 2.196 million tons representing an insignificant 2.67 % and primarily dominated by the production of freshwater finfish (FAO, 2018; Halwart, 2020). This represents a twenty-fold production increase from 110,200 to 2,196 000 tons from 1995 to 2018 with a compound annual growth rate (CAGR) of 15.55 %. The leading producers – Egypt (1,561,457), Nigeria (291,233) and Uganda (103,737), account for about 90 % of total aquaculture production of the region (FAO, 2018; Halwart, 2020). The growth in aquaculture production was due to the advent and intensification of private sector controlled small and medium scale enterprises (SMEs) (Satia, 2010). Also, the development of big commercial enterprises mostly stimulated by the combination of burgeoning public support, expertise, foreign direct investment, interest in aquaculture, global awareness raised through the NEPAD Fish for All Summit of 2005 as well as the implementation of the FAO Special Program for Aquaculture Development in Africa (SPADA) contributed to aquaculture growth (Satia, 2010). The aquaculture sectors of the major producers have been extensively reviewed in the previous chapter (Chapter 2.0).

A Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis is an informative tool frequently used to assess strengths and weaknesses (internal factors) of a company or industry (in this case the aquaculture sector of key African players) and the potential opportunities and threats (external factors) of the operating environment that can have an impact on the sector such as consumers, government policy, markets community pressures etc. (Radheyshyam, 2001; Görener *et al.*, 2012; Rimmer *et al.*, 2013). A SWOT analysis provides a good framework that can help to identify problems, making decisions, planning, implementation of appropriate technology and precautionary measures to be taken to accelerate sustainable aquaculture production (Radheyshyam, 2001). The aim of analyzing external opportunities and threats is to evaluate the opportunities that may be harnessed and to avoid threats from an uncontrollable external environment. The analysis of internal strengths and weaknesses is carried out to appraise the internal activities of a sector (Chang & Huang, 2006). A SWOT analysis is generally used for strategic planning in the business and management fields; however, modern and broad applications of SWOT analyses were identified by Helms and Nixon (2010) as a tool for planning and recommending strategic actions for industries, countries, businesses, non-profit organizations and sectors. SWOT analyses have been disparaged, however, as they do not provide implementation strategies and adequate context for optimization of strategy (Helms & Nixon, 2010), thus the need to link SWOT analysis to other complementary strategic tools. There appears to be a general consensus of the usefulness of SWOT in the primary phases of long-term strategic planning (Helms & Nixon, 2010).

SWOT analysis is the second most widely used analytical tool, ranked after competitors' analysis according to Fehringer *et al.* (2006), and it is the most commonly applied strategic tool by UK organizations (Gunn & Williams, 2007). A recent survey about analytical methods utilized for environmental scanning by South African enterprises also reveals SWOT analysis as the predominant analytical tool (Du Toit, 2016). The simplicity of SWOT analysis is its main advantage over other analytical tools and has resulted in its continuous application in the academic and business communities since the 1960s when it was developed (Phadermrod *et al.*, 2016). The traditional SWOT method despite its advantages has several flaws due to the production of a superficial and imprecise list of factors; depends on subjective opinion; and lack prioritization of the importance of each SWOT factor (Phadermrod *et al.*, 2016). As a result of the weakness of SWOT in prioritizing SWOT factors, some scholars suggested a new approach to SWOT analysis which integrates SWOT with other quantitative methods such as the combination of Analytic Hierarchy Process (AHP) with SWOT (AHP – SWOT) (Kurttila *et al.*, 2000; Pesonen *et al.*, 2001). This results in a new hybrid technique for improving the application of SWOT analysis. The key steps of the AHP-SWOT analysis methods include identification of SWOT factors in each group first; pairwise comparison within and between SWOT groups to determine the relative importance and finally, computation of the degree of importance of SWOT factors based on the comparison matrix. A consistency test is applied to AHP-SWOT to ensure the weights are scored objectively by the evaluation group. However, using SWOT analysis comparison on many entities simultaneously is problematic (Chang & Huang, 2006).

The quantified SWOT analytical approach adopts the concept of Multiple-Attribute Decision Making (MADM), which uses a multi-layer scheme to simplify complicated problems. It is, therefore, able to carry out SWOT analyses on many subjects simultaneously (Chang & Huang, 2006). The Quantified SWOT does not only enhance the AHP-SWOT method but also develops the method using the Grand Strategy Matrix (GSM). The subjects are placed in the four quadrants of the coordinate according to their categories (Fig. 3.1). The ordinate represents the external environment (opportunities and threats), while the abscissa represents the internal environment (strengths and weaknesses).

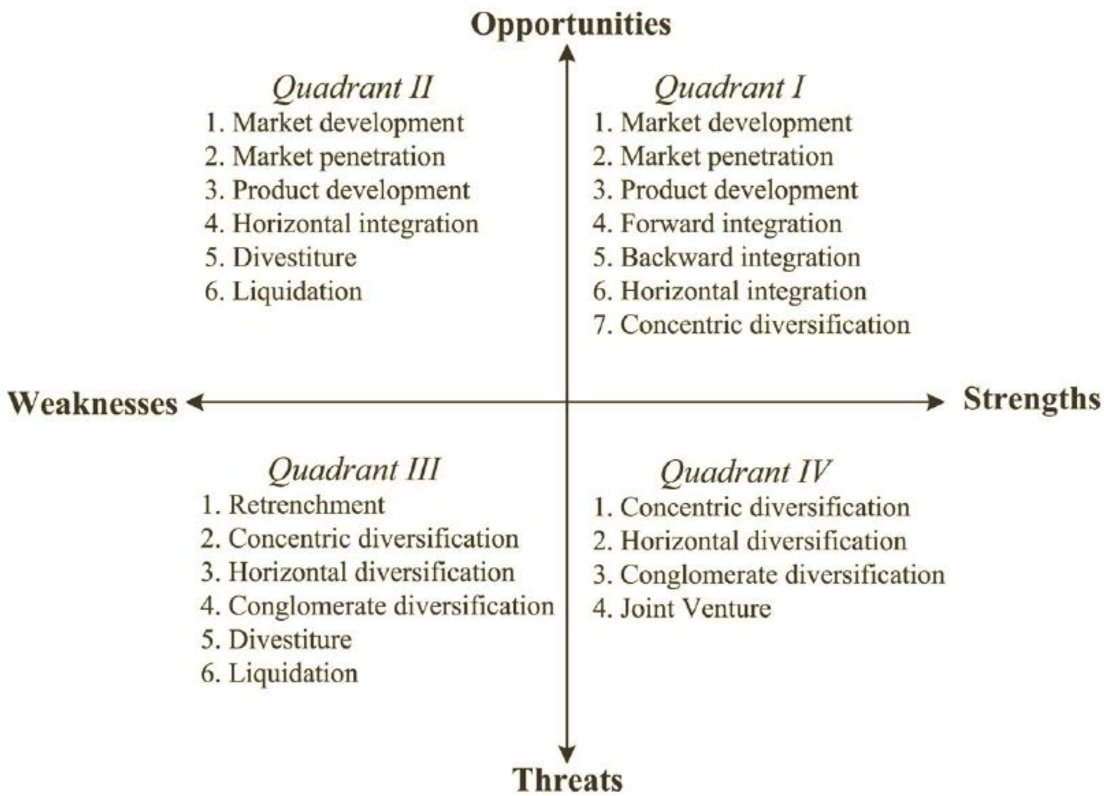


**Figure 3. 1: Quantified SWOT analysis and strategic matrix** source: (Chang & Huang, 2006)

The first quadrant depicts the subject's strengths and market opportunities. Subjects in quadrant I can utilize their strengths to adopt strategies such as product development, market development and market penetration to form competitive strengths. However, if the subjects in quadrant I have more resources, forward, backward and horizontal integration may be efficient strategies (Figure 3.1).

Subjects in quadrant II are those with opportunities for market development; however, weak in competition. Therefore, the most exigent concern is to improve on their weaknesses in order to intensify competitive strengths. Subjects in quadrant III possess low competitive strengths, thus facing threats from other competitors. Defensive strategies, such as concentrating on the most favored markets, can be used to avoid threats. Subjects in quadrant IV are those with competitive strengths but confronted with bigger threats than opportunities. Therefore, diversification or joint venture strategies can be adopted in order to reduce threats (Chang & Huang, 2006). Through Quantified SWOT analysis and showing of the coordinates, subjects will not only ascertain their position in the competition but also have a reference for developing strategies to improve production. Qualitative SWOT Analyses in recent years have been applied to marine and freshwater fisheries studies (Stead, 2005; Çelik *et al.*, 2012; Panigrahi & Mohanty, 2012; Glass *et al.*, 2015) and more prevalent in aquaculture (Ahmed & Luong-Van, 2009; Bolton *et al.*, 2009; Garza-Gil *et al.*, 2009; Cowx *et al.*, 2010; Rimmer *et al.*, 2013). There is, however, no existing application of quantitative SWOT analytical approach to fisheries and aquaculture studies at the time of this study. This, therefore, makes a unique application of this approach, and a more robust version of the SWOT analysis for the following reasons; quantitatively combines several factors to simplify complicated factors and runs a simultaneous analysis of many SWOT factors at the same time. In addition, financial institutions reckon very strongly with SWOT analysis when considering a funding proposal.

The overview of the aquaculture sector and qualitative analyses of the key aquaculture players in Africa - Egypt, Nigeria and Uganda compared to South Africa, have been extensively reviewed (Chapter 2.0). The aim of this study, therefore, is to compare the aquaculture sector of the leading players in Africa (Egypt, Nigeria and Uganda) vis-à-vis South Africa using the Quantified SWOT analytical method. This study thus presents a novel applied quantitative SWOT analysis in aquaculture development and a foundation for future quantitative analysis in fisheries and aquaculture studies.

## 3.3 Methodology

The quantified SWOT analysis used in business management was adapted to analyze the aquaculture sectors of key players in Africa by combining SWOT with multi-attribute decision making (MADM) within a comprehensive analytical framework in order to assess, compare and quantify cross-country aquaculture sectors based on predefined evaluation criteria. This study adopts a 4 – step MADM additive valuation method proposed by Chang and Huang (2006), to quantitatively compare countries' aquaculture sector performances. The four facets of the selected MADM tool comprise "alternatives" with reference to key aquaculture countries being compared, "criteria" referring to the predefined evaluation criteria, "performance" which refers to progress made by countries on key factors and "weights" with regards to the relative importance of each factor (Figure 3.2). In light of the aforementioned, the analytical approach for this study consists of the following steps:

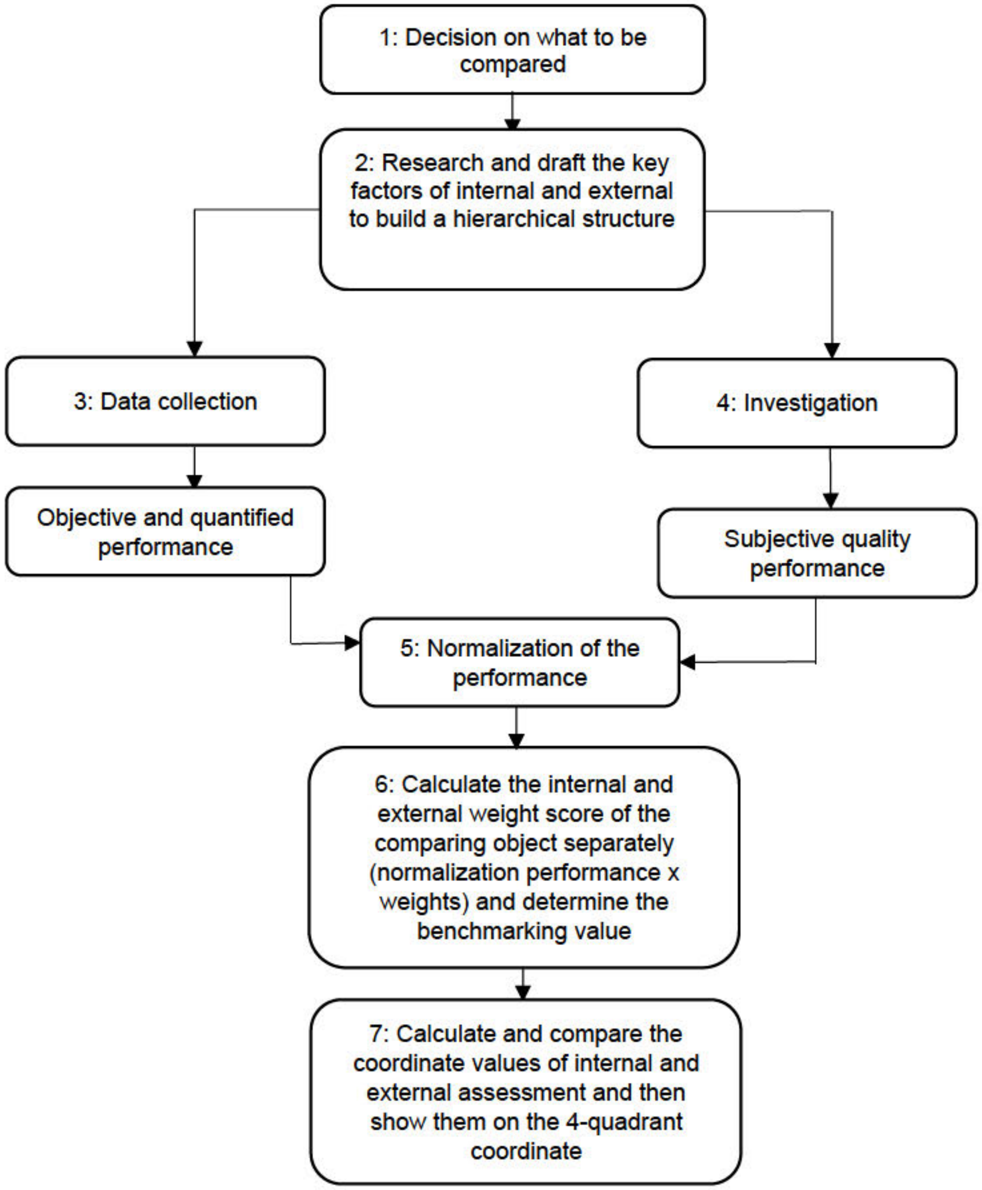


**Figure 3. 2: Flowchart of Quantified SWOT analysis pattern** *(*Adapted from: Chang and Huang (2006)).

### Determination of assessment criteria

Assessment criteria for the internal factors (strengths and weaknesses) and external factors (threats and opportunities) responsible for the development of the aquaculture sector of each country were determined based on the review of the aquaculture industry of the major regional producers and hinged on the SWOT factors, and critical success factors identified that was responsible for their aquaculture development (Chapter 2). The key factors for the internal assessment analysis are listed in Table 3.1. They are:

(I) Production output

(II) Diversity of cultured species

(III) Production technology

(IV) Type of aquaculture - freshwater and/marine

(V) Seed production

(VI) Cost of feed

(VII) Arable land

(VIII) Inland water resources

(IX) Coastal water resources

(X) Labour employed

(XI) Credit and insurance access

(XII) Research and Development

(XIII) Extension Services

(XIV) Best management practices

## Table 3.1: Internal assessment score of key aquaculture players in Africa

| | Internal assessment of key factors | Units | Polarity | Countries | | | |
|---|---|---|---|---|---|---|---|
| | | | | Egypt | Nigeria | Uganda | South Africa |
| 1 | Production output | tons | + | 1,451,841 | 296,071 | 112,343 | 5,185 |
| 2 | Species diversity | No. | + | 16 | 5 | 5 | 20 |
| 3 | Production Technology | 5 Scales | + | 2 | 3 | 2.5 | 4.5 |
| 4 | Type of aquaculture (freshwater and/marine) | 5 Scales | + | 3 | 2 | 1.5 | 4.5 |
| 5 | Seed production | 5 Scales | + | 4.57 | 1.02 | 0.39 | 0.03 |
| 6 | Cost of feed | Cost/tone ($) | - | 870 | 1200 | 840 | 1100 |
| 7 | Land (Arable) | % of Area | + | 2.8 | 37.3 | 34.3 | 9.9 |
| 8 | Inland Water Resources | % of Area | + | 0.632 | 1.4 | 15.39 | 0.38 |
| 9 | Coastal Water Resources | Coastline | + | 2450 | 853 | 0 | 2798 |
| 10 | Labour employed | No. | + | 580000 | 475000 | 24,434 | 3826 |
| 11 | Credit and Insurance access | 5 Scales | + | 0.75 | 1.50 | 1.75 | 2.75 |
| 12 | Research and Development | 5 Scales | + | 4.50 | 4.50 | 2.50 | 4.00 |
| 13 | Extension Services | 5 Scales | + | 1.25 | 2.45 | 3.25 | 1.25 |
| 14 | Best management practices | 5 Scales | + | 2.25 | 3.25 | 3.0 | 4.50 |

Polarity: '+' = benefit criteria; '-' = cost criteria

(FAO, 2003-2020, 2004-2020, 2007-2020, 2010-2020,Jamu et al., 2012,El-Sayed, 2013,Oyakhilomen & Zibah, 2013,Nasr-Allah et al., 2014,Ozigbo et al., 2014,Adewumi, 2015,El-Sayed et al., 2015,Mwanja et al., 2015,Britz & Venter, 2016,Soliman & Yacout, 2016,Cai et al., 2017,DAFF, 2017,Rutaisire et al., 2017)

The factors for the external assessment analysis were grouped into the economic environment; political environment, and geographic location (Table 3.2). Thus, the external criteria details are:

(I) Local fish demand

(II) Export

(III) Per capita fish consumption

(IV) Market size

(V) Aquaculture policies and legislations

(VI) Registrations and permits and

(VII) Strength and weakness of geographic location.

### Table 3.2: External assessment score of key aquaculture players in Africa

| | External assessment of key factors | Units | Polarity | Countries | | | |
|---|---|---|---|---|---|---|---|
| | | | | Egypt | Nigeria | Uganda | South Africa |
| 1 | Local Demand | Tones | + | 1,700,000 | 3,000,000 | 525,000 | 342,000 |
| 2 | Export | Tons | + | 15,810 | 30,000 | 20,000 | 1,400 |
| 3 | Per capital Consumption | Kg/person | + | 16 | 13.3 | 12.5 | 7.5 |
| 4 | Trade value | USD$ | + | 2,180,000,000 | 1,300,000,000 | 250,000,000 | 48,200,000 |
| 5 | Policies, plans, legislation and aquaculture development approaches | 5 Scales | + | 4.17 | 3.5 | 3 | 4.83 |
| 6 | Registrations and Permit | 5 Scales | + | 3 | 4 | 3.5 | 1 |
| 7 | Geographical location | 5 Scales | + | 2 | 4.5 | 3.5 | 3 |

Polarity: '+' = benefit criteria; '-' = cost criteria

(FAO, 2003-2020, 2004-2020, 2007-2020, 2010-2020,Jamu et al., 2012,El-Sayed, 2013,Oyakhilomen & Zibah, 2013,Nasr-Allah et al., 2014,Ozigbo et al., 2014,Adewumi, 2015,El-Sayed et al., 2015,Mwanja et al., 2015,Britz & Venter, 2016,Soliman & Yacout, 2016,Cai et al., 2017,DAFF, 2017,Rutaisire et al., 2017)

### Table 3.3: Performance areas with corresponding criteria, indicators and scores for comparative performance assessment

| Performance area | indicators | Scoring range | | | | |
|---|---|---|---|---|---|---|
| | → | 1 | 2 | 3 | 4 | 5 |
| **Production systems** | Extensive systems Semi-intensive intensive | Majorly Extensive systems | Majorly Semi-Intensive Systems | Intensive and/semi intensive | Intensive system | Highly intensive system |
| **Culture environment** | Freshwater aquaculture Mariculture | Freshwater semi intensive | Freshwater intensive | Mostly freshwater with some mariculture | Freshwater and mariculture | Intensive freshwater and mariculture |
| **Fish Seed** | Hatchery Capacity | Derived from normalisation of production output to the scale of 5 | | | | |
| **Input supply** | Supply chain | 4 middle links | 3 middle links | 2 middle links | 1 middle link | No middle link |
| **Institutional Support** | Policies and framework | Legislation | framework | Legislation and framework | Specific legislation and or specific framework | Specific legislation and specific Framework |
| **Trade and Marketing** | Registrations and permits | Tedious, difficult and lengthy process | Difficult and lengthy process | less difficult and moderate in process | Easy and fast process | Easy, well defined and fast process |
| **Environment** | Suitability for aquaculture | Highly limited | limited | Moderately limited | good | Very good |

## Data Collection

The objective and performance data for the internal and external assessment factors of the key aquaculture players in Africa were collected (Table 3.1 and 3.2) as reviewed from available published information from aquaculture sector experts of each country (FAO, 2003-2020, 2004-2020, 2007-2020, 2010-2020a; Jamu *et al.*, 2012; El-Sayed, 2013; Oyakhilomen & Zibah, 2013; Nasr-Allah *et al.*, 2014; Ozigbo *et al.*, 2014; Adewumi, 2015; El-Sayed *et al.*, 2015; Mwanja *et al.*, 2015; Britz & Venter, 2016; Soliman & Yacout, 2016; Cai *et al.*, 2017; DAFF, 2017; Rutaisire *et al.*, 2017) (Chapter 2). Due to human ethics approval requirements and research budget constraints of assembling industry experts in four countries, we opted for the option of identifying published articles from the industry experts from the selected countries, in addition to published reports from reputable sources such as FAO and respective national aquaculture industry reports.

A stepwise search strategy was conducted to find the most relevant articles in the publications of the identified aquaculture experts in the selected countries thus far. As a first step, the literature research was conducted on ISI web of knowledge website using aquaculture and selected country name as a keyword. Different keyword combinations were then used to as an attempt to identify research focal areas. Because the number of hits was not particularly large, all articles were individually screened. A similar process was followed with the Science Direct database using the same terms. Another search was conducted using the EBSO database. All papers were individually screened and only articles relevant to this chapter were considered. A total of 180 articles were included in the literature review.

## Performance Normalization

This is the definition of weights for the identified internal and external factors (Table 3.1 and 3.2) and performance scoring system (performance normalization) for the aquaculture sector of the key players in Africa. The key factors' performance was separated into two: quantified and qualified performance. The quantified performance were actual statistics, while the qualified performance were subjective scores of the internal and external factors ranging from 1 - 5 points (the higher the score, the better) (Table 3.1, 3.2 and 3.3). The quantified and qualified performance were unified using the method of normalization as proposed by Chang and Huang (2006) (Table 3.4 and 3.5).

- Benefit-criteria normalization (the higher the better)

Equation I

$$r_{ij} = \frac{p_{ij}}{\max\limits_{j} p_{ij}}, \quad \forall_j$$

Where:

**$r_{ij}$:** normalised performance of the $j^{th}$ score

**$P_{ij}$**: performance of the $j^{th}$ score

**Max $P_{ij}$** = Highest performance of the $j^{th}$ score

e.g. (2) diversity of culture species (Table 3.2)

P1= 16, P2 = 5, P3 = 5, P4 = 20 (see Table 3.2, Row 2)

r *i j* (Benefit-criteria normalization) = P *i j* (16) / max P *i j* (20)

r1 = 16/20 = 0.800; r2 = 5/20 = 0.250; r3 = 5/20 = 0.250; and r4 = 20/20 = 1.000

(See Table 3.4, Row 2)

- Cost-criteria normalization (the lower the better)

Equation II

$$r_{ij} = \frac{\min\limits_{j} p_{ij}}{p_{ij}}, \quad \forall_j$$

Where:

**$r_{ij}$**: normalised performance of the $j^{th}$ score

**$P_{ij}$**: performance of the $j^{th}$ score

**Min $P_{ij}$** = Lowest performance of the $j^{th}$ score

e.g. (6) Cost of feed (USD/Ton) (Table 3.1)

P1= 870; P2 = 1200; P3 = 840: P4 = 1100 (see Table 3.2, Row 6)

$r\,i\,j$ (Cost-criteria normalization) = min $P\,i\,j$ (840) / $P\,i\,j$ (870)

r1 = 840/870 = 0.966; r2 = 840/1200 = 0.700; r3 = 840/840 = 1.000 and r4 = 840/1100 = 0.764 (See Table 3.4, Row 6)

### Determination of Benchmarking and SWOT Coordinates Values

The final step was the calculation and comparison of the SWOT coordinate values of the internal and external assessment using total weighted performances. The internal and external weighted score of the compared countries were calculated separately, and the benchmarking values were determined by taking the mean weighted score in line with Chang and Huang (2006) (Table 3.4, 3.5 and 3.6).

The benchmarking values for the internal and external SWOT assessment factors of the compared countries (Egypt, Nigeria, Uganda and South Africa) were subtracted from the mean score of the internal and external factors of each country. The obtained values were used to plot the coordinate values of the compared countries in the SWOT analysis matrix (Table 3.6).

$IC\,j = I\,j - I\,B \qquad j = 1, 2. . . n$

$EC\,j = E\,j - E\,B \qquad j = 1, 2. . . n$

Where:

IC j: the internal assessment coordinate value of the $j^{th}$ country.

I j: internal assessment score of the $j^{th}$ country.

I B: benchmarking value of the internal assessment.

EC j: the external assessment coordinate value of the $j^{th}$ country.

E j: external assessment score of the $j^{th}$ country.

E B: benchmarking value of the external assessment.

$-1 \leq IC\ j \leq +1$

$-1 \leq EC\ j \leq +1.$

**Table 3.4: Internal assessment weighted average score of key aquaculture players in Africa**

| | Internal assessment key factors | Units | Polarity | Countries | | | |
|---|---|---|---|---|---|---|---|
| | | | | Egypt | Nigeria | Uganda | South Africa |
| 1 | Production output | tons | + | 1.000 | 0.204 | 0.077 | 0.004 |
| 2 | Species diversity | No. | + | 0.800 | 0.250 | 0.250 | 1.000 |
| 3 | Production Technology | 5 Scales | + | 0.444 | 0.667 | 0.556 | 1.000 |
| 4 | Type of aquaculture (freshwater and/marine) | 5 Scales | + | 0.667 | 0.444 | 0.333 | 1.000 |
| 5 | Seed production | Units | + | 1.000 | 0.224 | 0.086 | 0.006 |
| 6 | Cost of feed | Cost in Rands | - | 0.966 | 0.700 | 1.000 | 0.764 |
| 7 | Land (Arable) | % of Area | + | 0.075 | 0.091 | 1.000 | 0.025 |
| 8 | Inland Water Resources | % of Area | + | 0.041 | 0.091 | 1.000 | 0.025 |
| 9 | Coastal Water Resources | Coastline | + | 0.876 | 0.305 | 0.000 | 1.000 |
| 10 | Labour employed | No. | + | 1.000 | 0.819 | 0.042 | 0.007 |
| 11 | Credit and Insurance access | 5 Scales | + | 0.273 | 0.545 | 0.636 | 1.000 |
| 12 | Research and Development | 5 Scales | + | 1.000 | 1.000 | 0.556 | 0.889 |
| 13 | Extension Services | 5 Scales | + | 0.385 | 0.754 | 1.000 | 0.385 |
| 14 | Best management practices | 5 Scales | + | 0.500 | 0.722 | 0.667 | 1.000 |
| Weighted average | | | | 0.645 | 0.550 | 0.508 | 0.596 |

**Table 3.5: External assessment weighted average score of key aquaculture players in Africa**

| | External assessment key factors | Units | Polarity | Countries | | | |
|---|---|---|---|---|---|---|---|
| | | | | Egypt | Nigeria | Uganda | South Africa |
| 1 | Local Demand | Tones | + | 0.567 | 1.000 | 0.175 | 0.114 |
| 2 | Export | Tons | + | 0.527 | 1.000 | 0.667 | 0.047 |
| 3 | Per capital Consumption | Kg/person | + | 1.000 | 0.858 | 0.806 | 0.387 |
| 4 | Trade value | USD$ | + | 1.000 | 0.596 | 0.115 | 0.022 |
| 5 | Policies, plans, legislation and aquaculture development approaches | 5 Scales | + | 0.863 | 0.724 | 0.621 | 1.000 |
| 6 | Registrations and Permit | 5 Scales | + | 0.750 | 1.000 | 0.875 | 0.250 |
| 7 | Geographical location | 5 Scales | + | 0.444 | 1.000 | 0.778 | 0.667 |
| Weighted Average Value | | | | 0.736 | 0.871 | 0.537 | 0.342 |

### Randomization and variability of SWOT assessment factors

The benchmarking values (internal and external) were subtracted from the objective and subjective normalized scores of internal and external SWOT assessment factors (Table 3.4 and 3.5). Subsequently, the derived internal and external SWOT values of the subjective performance were randomized 1000 times to minimize bias, while the objective performance was fixed. The mean values obtained were used to determine the effects of the SWOT assessment factors variability on the SWOT quadrant.

### Statistical Analysis

The internal and external SWOT assessment weighted mean values of Egypt, Nigeria, Uganda and South Africa were statistically compared using a one-way analysis of variance (ANOVA) after testing for normality of distribution and equality of variance of tested variables. Fisher's LSD pairwise comparison test was used to determine the significant difference between the weighted mean values of the compared countries at 95 % confidence limits using IBM SPSS 25 statistical software program.

## 3.4 Results

### 3.4.1 SWOT matrix performance of Egypt, Nigeria, Uganda and South Africa

The benchmarking value for the internal assessment of aquaculture sectors of Egypt, Nigeria, Uganda and South Africa was 0.568, while the benchmarking value for the external assessment of these sectors was 0.622 (Table 3.6). The coordinate values of internal assessment of Egypt, Nigeria, Uganda and South Africa were 0.077, -0.017, -0.060 and 0.028, while the coordinates values of their external assessment were 0.114, 0.250, -0.084 and -0.279 respectively (Table 3.6).

The competitive strengths, market and aquaculture development positions of the aquaculture sectors of Egypt, Nigeria, Uganda and South Africa were shown (Figure 3.4). Egypt was located in the first quadrant, which depicts aquaculture development, competitive strengths and market opportunities. Nigeria was situated in the second quadrant, thus possessing aquaculture development opportunities but weak in competition. Nigeria (0.250) had higher aquaculture development opportunities compared to Egypt (0.114). Uganda was located in the third quadrant, therefore, possessing weak competitive strengths and confronted with low aquaculture development and market opportunities. South Africa was situated in the fourth quadrant, thus depicting competitive strengths but weak aquaculture development and market opportunities. Uganda demonstrated lesser aquaculture development and market threats (-0.084) compared to South Africa (-0.279). South Africa (0.028) however, was competitively stronger than Uganda (-0.060) and Nigeria (-0.017) (Table 3.6 and Figure 3.3).

### 3.4.2 Internal and external SWOT assessment weighted mean values of Egypt, Nigeria, Uganda and South Africa

The mean weighted values of internal and external SWOT assessment factors of the assessed countries are reported as follows, Egypt (internal: 0.645 ± 0.36 and external: 0.736 ± 0.23); Nigeria (internal: 0.550 ± 0.30 and external: 0.871 ± 0.17); Uganda (internal: 0.508 ± 0.38 and external: 0.537 ± 0.29) and South Africa (internal: 0.596 ± 0.45 and external: 0.342 ± 0.36) (Table 3.6). The mean weighted internal SWOT value of Egypt was significantly higher (ANOVA LSD: df 3; $p < 0.05$) than that of South Africa (Table 3.6). The mean weighted external SWOT values of Egypt and Nigeria were significantly higher (ANOVA LSD: df 3; $p < 0.05$) than that of South Africa, but there was no significant difference (ANOVA LSD: df 3; $p > 0.05$) in the weighted external SWOT values of Egypt, Nigeria and Uganda as well as Uganda and South Africa (Table 3.6).

**Table 3.6: SWOT assessment weighted mean (± SD) and coordinates values for the compared countries (Egypt, Nigeria, Uganda and South Africa).** *(*) denotes significant difference (p<0.05)*

| | Countries | | | | |
|---|---|---|---|---|---|
| | Egypt | Nigeria | Uganda | South Africa | Benchmarking value [a] |
| The weighted average value of internal assessment [b] | 0.645 * ± 0.36 | 0.550 ± 0.30 | 0.508 ± 0.38 | 0.596 ± 0.45 | 0.568 |
| Coordinates values of internal assessment | 0.077 | -0.017 | -0.060 | 0.028 | |
| The weighted average value of external assessment [b] | 0.736 * ± 0.23 | 0.871 * ± 0.17 | 0.537 ± 0.29 | 0.342 ± 0.36 | 0.622 |
| Coordinates values of external assessment | 0.114 | 0.250 | -0.084 | -0.279 | |

[a] Mean value.
[b] Coordinate value = Weighted average value − Benchmarking value.

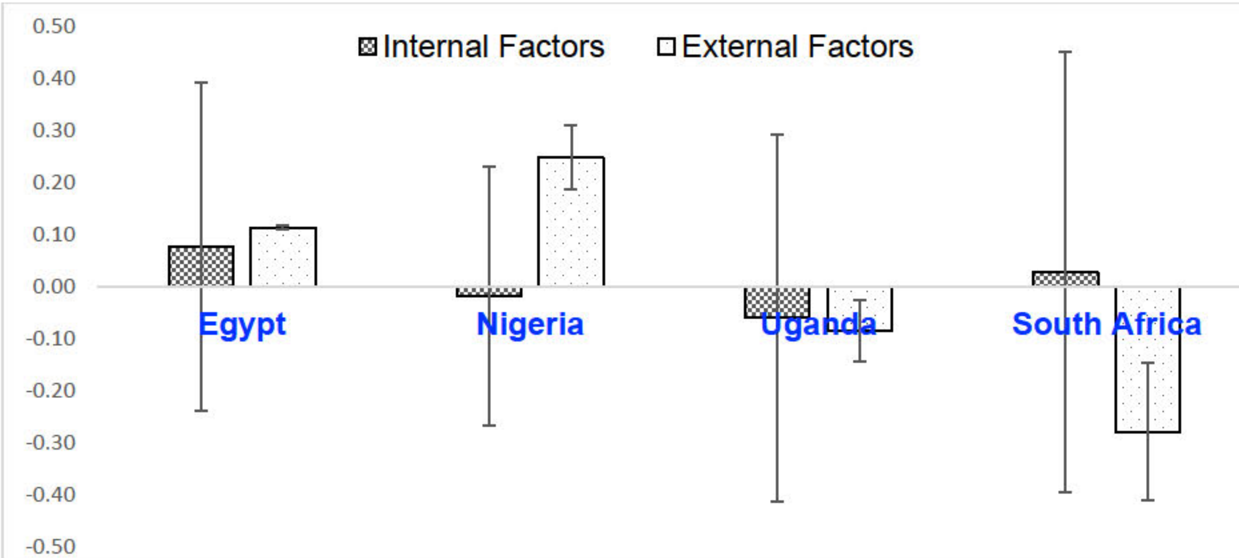


**Figure 3.3: Weighted internal and external SWOT assessment values of key African aquaculture players (Egypt, Nigeria and Uganda) vis-à-vis South Africa**

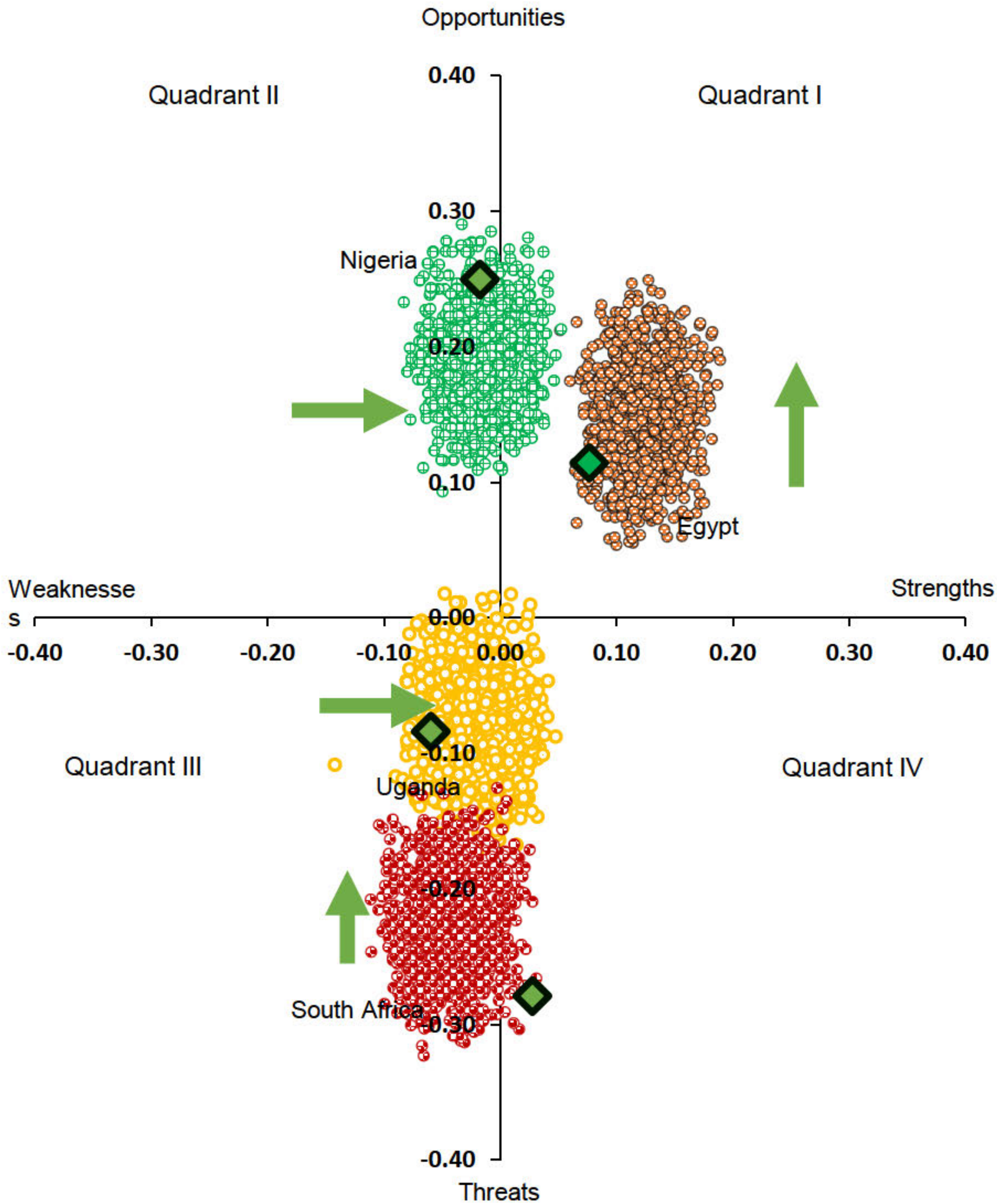


**Figure 3.4: Quantitative SWOT matrix performance of key African aquaculture players (Egypt, Nigeria and Uganda) vis-à-vis South Africa**

## 3.5. Discussion

### 3.5.1 Quantitative SWOT analysis of Egypt, Nigeria, Uganda and South Africa

Egypt in quadrant I, (Figure 3.4), possessed internal competitive strengths and economic opportunities for the development of its aquaculture sector. The distribution of its SWOT variables was more skewed towards the opportunities and strengths axis, thus showing the potential to increase its aquaculture development opportunities and improve on the internal SWOT factors of its competitive aquaculture strengths. Egypt is the highest aquaculture producer (1.56 million tons) (FAO, 2003-2020) in Africa and ranked sixth globally in 2017 (Halwart *et al.*, 2019) due to the rapid development of its aquaculture sector. Egypt was able to leapfrog its aquaculture production output from insignificant output to become one of the leading global aquaculture producers within two decades due to the paradigm shift in the operating environment as a result of the cumulative efforts and direct involvement of the government in the aquaculture sector (FAO, 2003-2020; Cai *et al.*, 2017). Egypt thus had continuously sustained its aquaculture production output from 71 815 tons in 1995 to 1.56 million tons in 2018 (FAO, 2003-2020). The burgeoning private sector participation and investments also aided the rapid expansion of the aquaculture sector (Shaalan *et al.*, 2018), which resulted in the introduction of intensive pond aquaculture systems as a replacement for the extensive and semi-intensive aquaculture systems (FAO, 2003-2020). The high returns on investment mainly drive the growth of intensive farming in Egypt. Egypt recorded the highest mean internal SWOT factor value due to the scale of hatchery and seed production, cost of feed, research and development and economies of scale which translated to its production output (Table 3.4).

Egypt has the highest concentration of hatcheries and seed production capacity in Africa, with 12 government-owned hatcheries, ~ 100 licensed privately-operated hatcheries and over 500 unlicensed operational hatcheries; which account for the continued seed supply and competitive pricing (Macfadyen *et al.*, 2012). Almost all the aquafeed in Egypt are locally produced; with a production capacity of ~ 1 million tons per year (El-Sayed *et al.*, 2015). Aquafeeds are produced by both the government-operated and private operated feed mill with government feed mill accounting for about 20 % of local production, while 80 % were from privately run feed mills (El-Sayed, 2013). The combined local feed production capacity and competitive feed pricing are unmatched by any other African country's aquaculture sector. Key weaknesses limiting the aquaculture sector are limited and overstretched suitable land and inland water resources, which are in competitive use with other agriculture and industrial activities (Soliman & Yacout, 2016). These environmental limitations are also exacerbated by the impacts of climate change factors such as drought, flash floods, salinity changes and sea-level rise (Soliman, 2017). High per capita consumption of fish, the trade value of fish and provision of enabling environment for aquaculture development accounted for the high mean external SWOT assessment factor value of Egypt compared to Uganda and South Africa (Table 3.5). Fish, especially tilapia is the most affordable source of animal protein and represent about 50 % of total animal protein intake in Egypt (Little *et al.*, 2012; Cai *et al.*, 2017). Egypt ranks second in Africa with the per capita fish consumption of ~ 23.5 kg in 2017 after Ghana with a per capita fish consumption of 28 kg (Cai *et al.*, 2017). Aquaculture policies, legislation and development models are implemented as government interventions in both human and institutional capacity as witnessed by the state's participation across the aquaculture value chain (Jamu *et al.*, 2012) Egypt has also implemented strategic market-driven aquaculture development plans and legal framework to guide and protect investments in the sector (Jamu *et al.*, 2012; Cai *et al.*, 2017). Egypt is potentially positioned to strengthen its role in the global aquaculture market, should it adopt a bullish developmental strategy, such as international market penetration, aquaculture product development and standardization which is currently a major threat confronting the sector (Soliman & Yacout, 2016; Shaalan *et al.*, 2018).

Nigeria in the second quadrant, has aquaculture development and economic opportunities to expand its aquaculture sector; however, it is confronted with some levels of weak competitive strengths (Figure 3.4). The distribution of its SWOT variables showed that Nigeria has almost attained the peak of its aquaculture development opportunity potential, based on the external SWOT factors considered in this study. The variables were, however, slightly aligned towards the strength axis, thus showing some levels of being able to strengthen its competitive aquaculture strengths (Figure 3.4). The significant opportunities for the Nigerian aquaculture sector stem from its high per capita fish consumption (18.3 kg) and widening fish demand-supply gap. Fish accounts for about 40 % of animal protein consumed and are cheaper than other sources of animal protein (Cai *et al.*, 2017). Relatively low aquaculture production output (296,071) compared to total fish demand of about 3 million tons per year resulted in the vast fish demand-supply gap (WorldFish, 2018). The widening demand-supply gap, although is partly offset by importation (~800,000 tons) and capture fisheries (~ 710,000 tons); an unbridged gap of about 1.5 million tons of fish still exist in the market (FAO, 2007-2020). Nigeria is the largest importer of fish in Africa due to the massive importation of frozen fish valued at $

1.2 billion in 2013 (FAO, 2007-2020). The enormous amount of money spent on fish importation annually can be substituted to expand the domestic aquaculture production and value chain (Cai *et al.*, 2017). Aquaculture policies, plan and legislation are implemented as market-driven aquaculture development interventions to promote human capacity building, adaptive technologies required for efficient commercial aquaculture development and local economic development in Nigeria (Jamu *et al.*, 2012). The private sector primarily drives the aquaculture industry in Nigeria due to a policy shift towards commercialization of aquaculture (Obwanga *et al.*, 2018). The government is saddled with the responsibility of providing an enabling environment (Ozigbo *et al.*, 2014; Adewumi, 2015). Although the sector has a well-developed value chain; however, it is mainly focused on catfish aquaculture (Cocker, 2014; Obwanga *et al.*, 2018). The internal competitive strengths such as the abundant distribution of arable land (1.7 million ha) and surface inland water area (14 million ha) which are currently under-utilized, can produce about 2.5 million tons of fish annually (FDF, 2012). Over-dependence on single species (catfish) production at the expense of multi-species aquaculture development and the soaring cost of inputs are key weaknesses of the sector amongst others. To harness its vast market opportunities, Nigeria will need to maximize its areas of competitive strengths (developed catfish value chain; land and water availability; fish farming estates/clusters and R&D) and improve on factors responsible for its weaknesses.

Uganda in the third quadrant, indicates that the aquaculture sector possesses lower competitive strengths compared to Egypt, South Africa and Nigeria, and lesser market opportunities compared to Egypt and Nigeria (Figure 3.4). Uganda is poised to strengthen its aquaculture development potential and market opportunities due to the distribution of its SWOT variables which were fairly skewed towards the strengths and along the opportunity axis (Figure 3.4). Fish is an essential source of animal protein source and represents about 30 % of animal protein intake in Uganda (Cai *et al.*, 2017). The key threat confronting the aquaculture sector in Uganda is weak institutional capacity resulting in the poor enabling environment; therefore, limiting the rapid development of aquaculture (FAO, 2004-2020). Uganda is a landlocked country that is richly endowed with suitable land and the abundance of inland water resources (165 lakes), unlike Egypt and South Africa (Mulonde, 2013) (Table 3.1). The total aquaculture production output (~112,343 tons 2017) vis-à-vis available land and water resources, however, portray gross under-utilization of its major competitive strength factors. Uganda's main opportunity lies on the burgeoning local and export markets for its fish products, as significant quantities of the fish consumed in neighbouring countries of Kenya, Democratic Republic of Congo and South Sudan are imported from Uganda (Rutaisire *et al.*, 2017). If the main threats of weak institutional capacity and inability to provide an adequate enabling environment are therefore prioritized and promptly addressed by the government, this is expected to spur investments and commercial aquaculture development. Also, for Uganda to maximize its huge market opportunities, it will need to improve on its weaknesses and strengthen the areas of its competitive strengths.

South Africa in the fourth quadrant, has more considerable competitive strengths, i.e. higher mean internal SWOT factor value (Figure 3.4) compared to Uganda and Nigeria, but faces greater market and aquaculture development threats than all the compared countries. South African SWOT variables showed it had reached the peak of its internal SWOT factors of competitive aquaculture strengths; however, the variables were aligned towards the opportunity axis; therefore, it has some levels of aquaculture development opportunities and market potential (Figure 3.4). South Africa scored relatively higher in the internal SWOT factors due to adoption of efficient aquaculture technology; culture of diverse freshwater and marine aquaculture species; good infrastructure and supporting business institution (Britz & Venter, 2016; DAFF, 2017) (Table 3.1). South African aquaculture sector, however, is still nascent and performs below its potential in terms of production output (5,185 tons) (FAO, 2010-2020b). The major weaknesses of this sector are over-concentration on high-value abalone species with low production output (~ 1 513 tons); limited suitable land and overstretched inland water resources and suboptimal environmental conditions (Britz & Venter, 2016). South Africa has a vast exposed shoreline at the southern part of Africa, with a heavy wave action due to the Southern Ocean frontal systems and Indian Ocean cyclones (FAO, 2010-2020b). The potential for large-scale mariculture such as sea cage systems is, therefore, limited due to few sheltered bays of adequate size, along the coastline (Britz & Venter, 2016).

Although the aquaculture sector has some promising opportunities such as access to international markets; good economic climate; sector prioritization by government and development of enabling policies and frameworks, it is still highly threatened and limited by its external factors. The major combined threats plaguing the development of the aquaculture sector include but are not limited to complicated authorization processes; underdeveloped industry value chain, very low per capita fish consumption (7kg) and scarce skilled resources (IDC, 2015; Mahieu, 2015). The latest food report on South African meat consumption shows that 98 % of the population are meat eaters, with seafood making up 53 % of that consumption as reported by Nielsen (2020), and fish consumption is changing as shown by an increase of more than 26 % from 1994 to 2014 in both the FAOSTAT, FBS and Euromonitor PFBC data sets (Ronquest-Ross et al., 2015), but about 70 % of that is canned fish (Kastern et al 2014). Also, in the light of high mercury content in South African wild caught fish as reported by IOI (https://www.iol.co.za/news/mercury-table-how-safe-is-sa-fish-1958694), aquaculture may be the answer.

South Africa, unlike other African countries, has the most tedious aquaculture permit application process which is difficult for a prospective small/medium scale firm to attain, due to bureaucratic obstruction as regards environmental regulation compliance (IDC, 2015). Therefore, over-regulation of the sector has been a major threat and turnoff preventing the attraction of potential aquaculture investments and expansion. South Africa, on one hand, has well-developed national aquaculture policies and frameworks, unlike Nigeria and Uganda but, on the other hand, lacks a simplified authorization procedure like the other compared countries (FAO, 2010-2020b; IDC, 2015; Mahieu, 2015). Therefore, to fully maximize its internal strength and external opportunities in order to be well-positioned in the global aquaculture sector, South Africa will need to create a simplified one-stop-shop aquaculture authorization process. The culture of fish eating needs to be aggressively promoted to boost local demand for fish as South Africa has one of the lowest per capita consumption of fish (~ 7 kg) compared to global average of ~ 20kg and regional average of 9kg.

## 3.6 Conclusion

This study presents the first attempt at the quantitative comparative assessment of aquaculture sectors of key players in Africa by adopting a quantitative analytical business planning tool for aquaculture development.

The study approach also forms a foundation that can be further developed for other quantified comparative analysis in fisheries management and aquaculture development studies.

SWOT analysis are a highly essential procedure adopted in the formulation of competitive strategy and developmental plan.

Limited accessibility to data of the selected countries and updated records on the aquaculture sector constrained the availability of information required for this study; hence the urgent need to bridge the gap on comprehensive aquaculture data in Africa.

The quantified SWOT analysis was used to determine the competitive position of the aquaculture sectors of the compared countries and can be used as a basis for aquaculture policy and roadmaps.

The position of Egypt in the SWOT analysis placed it in a better position than Nigeria, Uganda and South Africa due to its competitive strengths and opportunities thus responsible for the development and production output of its aquaculture sector. Nigeria exhibited the highest aquaculture development and market opportunities in Africa due to its huge demand-supply gap but needs to address its weaknesses in order to fully maximize its opportunities fully.

Uganda's position indicated low, competitive strengths and market development opportunities; however, the Ugandan aquaculture sector faced fewer threats compared to South Africa.

South Africa's aquaculture sector showed some levels of competitive strengths but minimal market and aquaculture development opportunities due to combinations of internal and external SWOT factors such as sub-optimal environmental conditions, bottlenecked permitting processes, low per capita fish consumption and amongst others. South Africa, therefore, needs to adopt adaptive and environmentally sustainable aquaculture production technologies such as integrated aquaculture systems, i.e., aquaponics to circumvent current challenges hindering the rapid development of its aquaculture sector. Quantitative analysis of suitable aquaculture species that are well adapted and viable with aquaponic systems are, therefore, required to determine the bioeconomic viability of aquaponics as an adaptive and sustainable alternative.

The coordinate values of the quantified SWOT analysis of the compared countries thus revealed the individual country's aquaculture positions in the regional competition and can also be adapted as a guide for developmental strategies, going forward. The analysis provides a useful basis for successful aquaculture strategy formulation and development that is capable of driving the expansion of aquaculture at national and regional levels.

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# CHAPTER 4: QUANTITATIVE SWOT ANALYSIS OF MAJOR AQUACULTURE SPECIES IN SOUTH AFRICA

## 4.1 Abstract

South Africa produces both marine and freshwater aquaculture species, with a combined production output of 6,181 tons of food fish in 2018. Key aquaculture species reportedly cultured include; 4 marine Species - abalone, dusky kob, mussels and oysters and seven freshwater species - tilapia, trout, catfish, marron crayfish, carp, koi-carp and ornamental species. Major aquaculture food fish species – abalone, dusky kob, mussel, oyster, salmon, trout, tilapia, catfish and marron crayfish, were selected and subjected to qualitative and quantitative SWOT analyses by adapting the quantified SWOT analytical method coupled with the Multi-Attribute Decision-Making Method MADM (SWOT-MADM). Internal and external SWOT assessment factors were determined; followed by data collection; performance normalization; determination of benchmarking and SWOT coordinates values. Trout and tilapia were in quadrant I, exhibiting a combination of competitive strengths and market opportunities. Abalone, oyster and marron crayfish were in quadrant II; thus, they possessed market opportunities but weak in competitive strengths as aquaculture species. Salmon and dusky kob were in quadrant III; both species were weak in competitive strengths and faced with more threat factors rather than market opportunities. Mussel and catfish were in quadrant IV; both species thus have competitive strengths but are facing more threats than opportunities. Catfish recorded the highest competitive strengths due to internal assessment factors such as; low FCR, ability to tolerate very high stocking density, rapid growth rate, high survival rate, hardiness and versatility of production systems and locations. Abalone and marron crayfish, on the other hand, both exhibited more market opportunities compared to other key aquaculture species due to external assessment factors like high pricing and good financial indicators. The study is expected to add to the existing body of knowledge and in guiding aquaculture industry stakeholders to make informed decisions with regards to the feasibility of aquaculture species in South Africa.

**Keywords:** SWOT-MADM; aquaculture; aquaculture species; South Africa.

## 4.2 Introduction

This section highlights the qualitative overview of mariculture and freshwater aquaculture species production in South Africa and lays the foundation for the quantitative analysis of these key aquaculture species as well as the rationale for the study.

South Africa practices both marine (mariculture) and freshwater aquaculture (FAO, 2003-2020). A total of 11 species were cultured in 2015 (four marine species; abalone, dusky kob, mussels and oysters and seven freshwater species; tilapia, trout, catfish, marron crayfish, Carp, Koi-carp and ornamental species) (DAFF, 2017b). Both aquaculture sectors adopt extensive (earth ponds, sea cages, long lines and rafts) and intensive (recirculating aquaculture and flow-through pump ashore systems) systems (Britz & Venter, 2016b).

The mariculture sector mostly produces finfish, molluscs, crustaceans and seaweed species in the coastal provinces of Western Cape, Eastern Cape, KwaZulu-Natal and Northern Cape. Finfish culture consists of dusky kob (*Argyrosomus japonicus* – Temminck & Schlegel, 1844), silver kob (*Argyrosomus inodorus* - Griffiths and Heemstra, 1995), Yellowtail (*Seriola lalandi* Valenciennes, 1833). Mollusc production includes mainly indigenous commercial species such as abalone (*Haliotis midae* – L. 1758) and alien species including the pacific oyster (*Crassostrea gigas*- Thunberg, 1793) and Mediterranean Mussel (*Mytilus galloprovincialis* - Lamarck, 1819). Seaweed (*Ulva spp*. and *Gracilaria spp*.) species are cultured and utilized as supplementary feed in abalone farming (DAFF, 2015a).

A few marine species are currently being researched as prospective aquaculture candidates. These species include, but not limited to, yellowtail (*Seriola lalandi*), Spotted

Grunter (*Pomadasys commersonnii* Lacépède, 1801), White Stumpnose (*Rhabdosargus globiceps* Valenciennes, 1830), Yellowbelly Rockcod (*Epinephelus marginatus* - Lowe, 1834), Mangrove Snapper (*Lutjanus argentimaculatus* - Forsskål, 1775), Scallop (*Pecten sulcicostatus* - Sowerby II, 1842), Sea Urchin (*Tripneustes gratilla – L. 1758*), Sea Cucumber (*Holothuria scabra* - Jaeger, 1833) and Octopus (*Octopus vulgaris* - Cuvier, 1797) (DAFF, 2017a). The South African mariculture sector also involves hobbyist and commercial production of marine ornamental fish and plants (DAFF, 2017a).

Freshwater aquaculture species in South Africa include alien species such as rainbow trout (*Oncorhynchus mykiss* - Walbaum, 1792), brown trout (*Salmo trutta – L. 1758*), tilapia (*Oreochromis mossambicus* - W. K. H. Peters, 1852 and *Oreochromis niloticus – L. 1758*) common carp (*Cyprinus carpio – L. 1758*), and marron crayfish (*Cherax tenuimanus* - Smith, 1912). Other native species include the redbreast tilapia (*Coptodon rendalli* - Boulenger, 1897), African Sharptooth catfish (Talamuk, 2016), and ornamental Koi (DAFF, 2017a). These freshwater species represent the bulk of commercial production which are widely farmed in Limpopo, Mpumalanga, KwaZulu-Natal, Western Cape, Gauteng, Free State and North West provinces (DAFF, 2015a, 2017a).

The internal analysis (strengths and weaknesses) and external analysis (opportunities and threats) of key mariculture and freshwater aquaculture species in South Africa have been extensively reviewed and documented by the Department of Agriculture, Forestry and Fisheries (DAFF) using the traditional qualitative SWOT analysis approach (DAFF, 2017a, 2017b, 2017d, 2018b, 2018d, 2018c, 2018e, 2018a). However, like all other traditional SWOT analyses, DAFF's SWOT on key aquaculture species is qualitative in approach and hence limited, due to lack of quantitative methods; as well as its inability to simultaneously perform a SWOT analysis on numerous factors (see section 3.2).

As a result of the limitations associated with qualitative SWOT analysis, this study adopts a new methodology, which integrates SWOT analysis with the quantitative method of Multiple-Attribute Decision Making (MADM), resulting in a hybrid method called SWOT-MADM (Chang & Huang, 2006). Therefore, this study aims to quantitatively assess the internal and external factors of key aquaculture species of South Africa using the Quantified SWOT analytical method SWOT-MADM. The study presents a novel attempt at quantifying SWOT factors of major aquaculture species of South Africa to establish their aquaculture development and market potential. The result of this analysis is expected to contribute to the existing body of knowledge with regards to viable aquaculture species in South Africa.

**Key mariculture species in South Africa**

In 2015, a total of 17 marine species were cultured in South Africa. These species are grouped into five sub-sectors; finfish, abalone, mussels, oysters and seaweed; of which four of these sub-sectors are utilized as food for human consumption, while seaweed is used as abalone feed (DAFF, 2017a). The exhaustive list of these mariculture species and the corresponding scale of operations are highlighted in Section 2.3.4.2 and Table 2.7.

## Abalone

Abalone is edible marine gastropod molluscs (marine snails) which belong to the family Haliotidae (DAFF, 2018a). They are slow-growing and maturing species attached to rocks in intertidal and subtidal shores (DAFF, 2018a). *Haliotis midae* is one of the five abalone species native and cultured in South Africa (DAFF, 2018a). Abalone is predominantly cultured along the shoreline of Northern Cape, Western Cape and Eastern Cape provinces of South Africa due to ocean temperatures offering optimal conditions for production (DAFF, 2018a) (Table 4.1).

The abalone industry in South Africa has rapidly evolved in recent years, due to burgeoning demand; premium prices; favourable environmental conditions; access to infrastructure; and reputation of South African abalone on the global markets (Britz & Venter, 2016b). Abalone is considered an expensive and high-end seafood product (DAFF, 2018a). They are in high demand, particularly in Asia, due to the associated traditional, cultural and medicinal qualities (Troell *et al.*, 2006). South Africa is the third-largest producer of abalone globally, after China and South Korea (DAFF, 2018a).

The South African abalone is highly valuable, economically viable and the most established aquaculture sub-sector, thus portraying good market opportunities; however, entry and operational costs are highly capital intensive (DAFF, 2018a). Abalone is characterized by poor growth performance, as it takes about four years to reach market size (DAFF, 2018a).

### Oyster and Mussel

Marine Mussels are filter-feeding bivalve molluscs belonging to the family Mytilidae. The alien *Mytilus galloprovincialis* (Mediterranean Mussel), is native to the Mediterranean and the eastern Atlantic (Barsotti & Meluzzi, 1968). The Mediterranean mussels were originally introduced into South Africa in the 1970s accidentally, through ballast water and subsequently for aquaculture activities (Grant & Cherry, 1985; CABI, 2016). In South Africa, both the alien Mediterranean mussel (*Mytilus galloprovincialis)* and native Black mussel (*Choromytilus meridionalis* - Krauss, 1848) are cultured (Britz & Venter, 2016a; DAFF, 2017a, 2017c). Production of both mussel species increased from 1,116 tons in 2013 to 1,758 tons in 2015, contributing ~ 49 % of total aquaculture production and represents the highest aquaculture contributor by volume (Britz & Venter, 2016a; DAFF, 2017a, 2017c).

Mussel production systems are entirely situated offshore using relatively simple and traditional production technology (see section 2.3.4.3). Europe is the largest producer of mussels accounting for ~ 34 % of global production (DAFF, 2017c). Production of Mussels in South Africa is economically viable due to key strengths, such as lack of costs associated with feed and seed stocks as a result of the reliance on natural settlement and spat collection (DAFF, 2017c).

The Pacific oyster (*Crassostrea gigas*) is a filter-feeding bivalve species, belonging to the family Ostreidae and are indigenous to Japan (Helm, 2005). Like mussels, the Pacific oyster was both accidentally introduced through ballast water and purposely for aquaculture development (FAO, 2005) *Crassostrea gigas* is the only oyster species farmed in South Africa, with total production of ~ 277 tons and contributed ~ 8 % to total mariculture production in 2015 (DAFF, 2017a). Oyster production shows economic feasibility in South Africa, as a result of key success factors such as reliability and availability of spat as well as zero feed cost-linked production (DAFF, 2017c).

Both mussel and oyster demonstrate strong economic viability for rapid aquaculture development in South Africa. Key operational strengths associated with the culture of both species are zero cost of feeding, reliability and availability of spat as well as a simple production system which is expected to contribute significantly to their positioning and outlook as aquaculture development candidates in South Africa.

**Dusky Kob and Salmon**

The dusky kob (*Argyrosomus japonicus*), is a euryhaline and carnivorous fish belonging to the family Sciaenidae (Froese & Pauly, 2016). They are commonly found in shallow coastal and estuarine waters in the Indo-Pacific, the Caribbean and temperate waters of the Atlantic and Pacific Oceans (Froese & Pauly, 2016). Dusky kob are widely distributed along the Southern Africa coast, from the Cape Point to the east coast of Mozambique (Griffiths, 1996). They are abundantly found within Cape Agulhas and KwaZulu-Natal and shows rapid growth rate in South Africa, attaining a maximum length of ~ 1.8 m, 75 kg body mass and ≥ 40 years age (Griffiths & Hecht, 1995; Griffiths, 1996).

This species was identified as suitable aquaculture candidate; as a result its fast growth rate, late maturity, palatability, food value, declining catches, large size and market demand (Griffiths, 1996; O'Sullivan & Ryan, 2001; Hecht *et al.*, 2006). Dusky kob is produced in earthen ponds and RAS systems at semi-commercial scale in South Africa

(DAFF, 2017b). Currently, the production of dusky kob in South Africa is yet to attain financial feasibility due to the high cost of production; low market prices; and inability to achieve economies of scale due to limited local demand (DAFF, 2017b).

The Atlantic salmon (Salmon *Salmo salar*) is a carnivorous aquaculture species which belongs to the family Salmonidae and are naturally distributed in the North Atlantic Ocean (Froese & Pauly, 2016). This species was introduced to Australia, New Zealand, Argentina, Chile and South Africa as aquaculture candidate (Froese & Pauly, 2016). The production of Atlantic salmon in South Africa is still nascent and is yet to attain a steady and sustainable production scale (Froese & Pauly, 2016). Atlantic salmon smolts production is mainly limited to the inland areas of the Eastern Escarpment and Cape Fold Mountains, endowed with perennial high-quality freshwater sources (DAFF, 2017a). Gansbaai and Saldanha Bay are both potential sites for Atlantic salmon cage culture due to conducive environmental conditions (DAFF, 2017b).

Production of Atlantic in South Africa is economically viable due to burgeoning demand that is currently supplied solely by importations; therefore, local production of this species has the potential to address domestic market demand as well as export opportunities (DAFF, 2017b).

Production of dusky kob in South Africa is currently not economically viable due to the poor outlook of its internal and external qualitative SWOT factors (DAFF, 2017b). As a result, dusky kob's potential as an aquaculture candidate is currently weak. Atlantic salmon, on the other hand, shows good market development opportunities due to growing local demand; however, its internal SWOT factors are weak due to high operational cost and logistics challenges.

The aquaculture species considered in this study were selected based on meeting two significant criteria, which are being food fish and commercially produced in South Africa. This study, therefore, did not consider aquaculture species that are currently still being researched or piloted and did not consider seaweeds.

### Table 4.1: Production guidelines for key mariculture species in South Africa

| Production factors | Abalone | Mussel | Oyster | Dusky Kob | Atlantic Salmon |
|---|---|---|---|---|---|
| **Water conditions** | | | | | |
| **Optimum** | | | | | |
| **Temperature (ºC)** | 16 - 18 | 10 - 20 | 11 - 34 | 18 - 25 | 12 - 16 |
| **Salinity: (ppt)** | 30 - 35 | 15 - 25 | 20 - 35 | 30 - 35 | 33 - 35 |
| **pH:** | 7.8 - 8.2 | 7.8 - 8.2 | 7.8 - 8.2 | 7.8 - 8.2 | 7.5 - 8.5 |
| **Average cost of Seedlings (R)** | 10 | 0.5 | 0.5 | 5 | 6 |
| **Average cost of feed (R)/kg** | 28 | 0 | 0 | 22 | 25 |
| **Feed conversion ratio (FCR)** | 1.5:1 | NA | NA | 2:1 | 1.2:1 |
| **Stocking density ($kg/m^3$)** | 15 | 10 | 10 | 30 | 55 |
| **Survival rate (%)** | 82 | 90 | 90 | 78 | 80 |
| **Market Size (g)** | 100 | 4 | 85 | 1500 | 2000 |
| **Average market price (R)/kg** | 420 | 30 | 12 | 80 | 102 |
| **Production system** | RAS, Flow-through and Cage | Longline, Raft and Rack | Longline, Raft and Rack | RAS, Cage, Flow-through and Pond | Cage, RAS and Flow-through |
| **Location** | Northern, Western and Eastern Cape | Northern, Western and Eastern Cape | Northern, Western and Eastern Cape | Eastern Cape and KZN | Western Cape and Northern Cape |

adapted from (DAFF, 2017c, 2017b, 2018a)

## Key freshwater aquaculture species in South Africa

### Trout

The rainbow trout (*Oncorhynchus mykiss)* is one of the salmonid species of trout belonging to the Salmonidae family and are indigenous to cold-water tributaries and lakes of the Pacific Ocean in North America and Asia (DAFF, 2018e). Trout species (rainbow trout – *Oncorhynchus mykiss* and brown trout – *Salmo trutta)* were introduced into South Africa's major river catchments in the late 1800s; however, only the rainbow trout is farmed commercially (DEA, 2014; DAFF, 2018e). Rainbow trout exhibits very high feed conversion efficiency and grows rapidly, attaining full maturity at ~ 18 months and can tolerate a wide range of environmental conditions unlike other trout species (Salie *et al.*, 2008) (Table 4.2). The Rainbow trout is regarded as a high-value food fish and the most established finfish aquaculture species in South Africa, contributing 82.43 % (1,497.00 tons) of total freshwater aquaculture production in 2015 (WRC & DAFF, 2010; DAFF, 2017a). The trout production sub-sector currently supplies local and regional demand only, due to limited production output as a result of suboptimal environmental conditions (Stander & Brink, 2009; DAFF, 2018e). Trout production outlook appears promising for aquaculture development in South Africa; however, growth in production output is restricted by limited areas suitable for its production and availability of water.

### Tilapia

Nile tilapia (*Oreochromis niloticus*) and Mozambique tilapia (*Oreochromis mossambicus)* are key species of the South African freshwater aquaculture, belonging to the family Cichlidae (FAO, 2010-2020). These species are widely accepted and cultured due to the numerous qualities they possess which include; rapid growth rate (*Oreochromis niloticus*); hardiness and adaptability to diverse environments and culture systems; disease resistance; and salinity tolerance, especially *Oreochromis niloticus* (DAFF, 2018d) (Table 4.2).

The Nile tilapia grows faster and performs better than other tilapia species and is thus considered the most economically feasible tilapia species (IDC, 2015). However, they are classified as an Alien Invasive Species (AIS) in South Africa; therefore, Nile tilapia producers are required to obtain both national and provincial permits in order to commence production (DAFF, 2018d). Mozambique tilapia is native to South Africa and requires provincial permits for aquaculture production (DAFF, 2015b). The significantly faster growth rate of the Nile tilapia makes it the preferred aquaculture species amongst the tilapia species (IDC, 2015). The bureaucracy associated with permits and regulations of Nile tilapia however, can be daunting and challenging for prospective South African producers (DAFF, 2018d).

China, Indonesia and Egypt are the leading producers of tilapia globally, whilst South African production is limited mainly due to unfavourable environmental conditions; high cost of production and underdeveloped value chain (DAFF, 2018d). Domestic production of tilapia contributed ~ 18 % (325 tons) to freshwater production in 2015; as a result, South Africa relies on importation for both local consumption and redistribution into regional markets (Britz & Venter, 2016a; DAFF, 2017a, 2018d).

The internal and external SWOT factors for tilapia production, position this species as a very strong candidate for aquaculture development in South Africa. The higher cost of locally produced tilapia compared to the imported ones from China, however, makes the price of locally produced tilapia less competitive.

### Catfish

The African Sharptooth Catfish, commonly referred to as catfish (*Clarias gariepinus*) is a freshwater aquaculture species which belongs to the family Clariidae and is native and widely distributed in the inland waters of Africa (DAFF, 2018b). Catfish has many qualities that qualify it as a good aquaculture candidate. They are very hardy, can withstand handling stress and be cultured at very high stocking densities, due to their air-breathing capability (DAFF, 2018b). Catfish can tolerate a wide range of physicochemical water parameters and demonstrates a high resistance to diseases in a culture environment (Hecht & Britz, 1990) (Table 4.2). As a result of their broad range of feed acceptability (although performing better on a protein-rich diet), they exhibit very rapid growth rate with low feed conversion ratio (FCR) (WRC & DAFF, 2010; DAFF, 2018b). Catfish are regarded as a high-value food fish in many African countries (especially countries in West, Central and East Africa) due to its palatability (Talamuk, 2016).

Nigeria is the global leader in catfish production with well-established value chain, followed by Uganda (Pouomogne, 2010). South African catfish production is mainly dominated by smallholder farmers, producing about 100 tons of catfish annually (DAFF, 2017a). In recent years, the South African catfish sub-sector has undergone a paradigm shift, with more producers concentrating on catfish fingerling production for the export market, rather than growing catfish to table size (DAFF, 2018b).

### Marron Crayfish

Marron Crayfish (*Cherax tenuimanus*) is a freshwater species of crayfish belonging to the family Parastacidae and are indigenous to South-western Australia and are the third-largest species of freshwater crayfish worldwide (Bryant & Papas, 2007). Marron was first introduced into South Africa in the 1970s, with the first successful marron aquaculture recorded in 1982 in the Western Cape (Nunes *et al.*, 2017). Marron is considered an Alien Invasive Species (AIS) in South Africa (NEMBA Category Two (2) species list); therefore, producers are required to obtain both national and provincial permits prior to production activities (DAFF, 2015b).

The production of this crayfish species is nascent in South Africa, with only two farms recorded in the Eastern Cape (DAFF, 2018c). Production challenges include, but are not limited to, inadequate technical and production information, specifically with regards to alternative production systems, feeding habits and breeding behaviour limit domestic production (DAFF, 2018c). In 2015, a meagre output of four tons was recorded from the only operational farm in South Africa (DAFF, 2017a). As a result of these production challenges, both domestic and international markets experience huge gaps in the supply of marron crayfish.

The internal qualitative SWOT factors of marron crayfish appears weak due to myriads of production challenges but shows strong market development opportunities due to the huge demand-supply gap.

**Table 4.2: Production guidelines for key freshwater aquaculture species in South Africa**

| Production factors | Trout | Tilapia | Catfish | Marron Crayfish |
|---|---|---|---|---|
| **Water conditions** | | | | |
| **Optimum Temperature (ºC)** | 12 - 16 | 28 - 30 | 28 - 30 | 17- 20 |
| **Salinity: (ppt)** | < 10 | < 10 | < 6 | < 10 |
| **pH** | 7.0 - 8.0 | 6.0 – 9.0 | 6.5 – 8.0 | 6.5 – 9.0 |
| **Average cost of Seedlings (R)** | 6 | 4 | 3.5 | 10 |
| **Average cost of feed (R)/kg** | 22 | 15 | 18 | 15 |
| **Feed conversion ratio (FCR)** | 1.2:1 | 1.4:1 | 1.1:1 | 13:1 |
| **Stocking density (kg/m$^3$)** | 50 | 25 | 75 | 4 |
| **Survival rate (%)** | 80 | 90 | 90 | 60 |
| **Market Size (g)** | 1200 | 465 | 1000 | 175 |
| **Average market price (R)/kg** | 60 | 35 | 48 | 250 |
| **Production system** | RAS, Flow-through, Pond and Cage | RAS, Aquaponics, Flow-through, Pond and Cage | RAS, Aquaponics, Flow-through, Pond and Cage | Pond |
| **Location** | KZN, Mpumalanga, Western and Eastern Cape | All Provinces | All Provinces | Eastern Cape |

(DAFF, 2018e, 2018c, 2018d, 2018b)

## 4.3 Methodology

The quantified SWOT analysis was adopted and adapted to analyze defined internal and external factors of key aquaculture species in South Africa by combining SWOT analysis with multi-attribute decision making (SWOT-MADM) (Chang & Huang, 2006) within a comprehensive analytical framework (See section 3.3). The approach for this study consists of the following steps (Figure 3.2):

**Determination of assessment criteria**

Assessment criteria for internal factors (strengths and weaknesses) and external factors (threats and opportunities) of key South African aquaculture species were determined from the review of important factors associated with the culture of these species (abalone, mussel, oyster, dusky kob, atlantic salmon, trout, tilapia, catfish and marron crayfish) (DAFF, 2017a, 2017b, 2017d, 2018b, 2018d, 2018c, 2018e, 2018a).

The factors for the internal assessment analysis were listed as:

(i) Production output (Kg),

(ii) Feed conversion ratio (FCR), Average stocking density (kg/$M^3$),

(iii) Growth rate (g/month),

(iv) Survival rate (%),

(v) Species hardiness,

(vi) Production technology,

(vii) Environmental friendliness,

(viii) Seedling production and

(ix) Suitable location as highlighted in Table 4.3.

## Table 4.3: Internal assessment score of key aquaculture species in South Africa

| | Internal assessment key factors | Units | Polarity | Major Aquaculture species in South Africa | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Abalone** | **Oyster** | **Mussel** | **Dusky Kob** | **Trout** | **Tilapia** | **Catfish** | **Salmon** | **Marron Crayfish** |
| **i** | Production | tones | + | 1479.00 | 277.00 | 1758.00 | 77.00 | 1497.00 | 325.00 | 100.00 | 0 | 4.00 |
| **ii** | FCR | Number | - | 1.50 | 0.80 | 0.80 | 2.00 | 1.20 | 1.40 | 1.10 | 1.20 | 13.00 |
| **iii** | Stocking Density (Average for all Prod Sys) | $Kg/m^3$ | + | 15.00 | 10.00 | 10.00 | 30.00 | 50.00 | 25.00 | 76.00 | 55.00 | 4.00 |
| **iv** | Growth rate | g/month | + | 1.92 | 3.54 | 0.17 | 75.00 | 66.67 | 58.13 | 125.00 | 50.00 | 7.29 |
| **v** | Survival Rate | % | + | 82.00 | 90.00 | 90.00 | 78.00 | 80.00 | 90.00 | 90.00 | 80.00 | 60.00 |
| **vi.** | Species Hardiness | 5 Scales | + | 2.00 | 4.00 | 3.50 | 3.00 | 2.50 | 3.75 | 4.25 | 2.5 | 2.00 |
| **vii.** | Production Technology | 5 Scales | + | 3.00 | 2.50 | 2.50 | 3.00 | 4.25 | 4.50 | 4.75 | 2.5 | 2.00 |
| **viii.** | Environmental Friendliness | 5 Scales | + | 1.00 | 2.25 | 2.25 | 2.75 | 2.00 | 3.50 | 3.00 | 1.5 | 3.00 |
| **ix.** | Seed production (Ease of Hatchery operation) | 5 Scales | + | 3.00 | 3.00 | 2.00 | 2.75 | 3.00 | 4.00 | 3.50 | 2.75 | 3.00 |
| **x.** | Geographical Distribution | No of Prov./Total Prov. | + | 0.33 | 0.44 | 0.44 | 0.22 | 0.44 | 1.00 | 1.00 | 0.22 | 0.11 |

Polarity: '+' = benefit criteria; '-' = cost criteria

(DAFF, 2017a, 2017b, 2017d, 2018b, 2018d, 2018c, 2018e, 2018a)

The factors for the external assessment analysis were determined and listed as follows:

(i) Local consumption,

(ii) Export

(iii) Import

(iv) price (R/kg),

(v) Production cost (R/kg),

(vi) Viable production,

(vii) Profitability index,

(viii) NPV (over 10 years) (R);

(ix) IRR (%),

(x) Total trade value ($),

(xi) Operating expenses (R),

(xii) Capital expenditure (R), (xiii) Labour requirement and (xiv) registrations and permits (Table 4.4).

## Table 4.4: External assessment score of key aquaculture species in South Africa

| External assessment key factors | | Units | Polarity | Major Aquaculture species in South Africa | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Abalone** | **Oyster** | **Mussel** | **Dusky Kob** | **Trout** | **Tilapia** | **Catfish** | **Salmon** | **Marron Crayfish** |
| **i** | Local Consumption | Tons | + | 500 | 207 | 1,881 | 77 | 2254 | 3042 | 120 | 2819.5 | 4.00 |
| **ii** | Export | Tons | + | 751 | 70 | 110 | - | 20 | 325.5 | 3.5 | 78.5 | 0.00 |
| **iii** | Import | Tons | - | 0 | 0 | 233 | 0 | 758 | 3042 | 12 | 2898 | 0.00 |
| **iv** | Price | R/kg | + | 420 | 12 | 30 | 80 | 60 | 35 | 48 | 102 | 250.00 |
| **v** | Production cost | R/kg | - | 358 | 6 | 18.5 | 80 | 48.5 | 30 | 33.75 | 68 | 75.00 |
| **vi.** | Minimum Viable production | Tons | - | 113 | 200 | 500 | 500 | 40 | 73 | 75 | 2000 | 4.00 |
| **vii.** | Profitability Index | | + | 2 | 1.73 | 1.92 | 0.85 | 2.05 | 2.02 | 2.03 | 1.24 | 2.41 |
| **viii.** | NPV (over 10 years) | R | + | 156,884,174.44 | 15,412,000.00 | 28,659,000.00 | -29,027,000.00 | 4,108,733.97 | 9,922,775.00 | 4,073,990.97 | 74,260,000.00 | 7,175,300.04 |
| **ix.** | IRR | % | + | 7.00 | 13.00 | 21.00 | -27.00 | 8.00 | 7.00 | 8.00 | 19.00 | 7.00 |
| **x.** | Trade value (Consumption & Export) | USD$ | + | 34,514,285.71 | 477,746.58 | 4,226,233.10 | 5,720.00 | 9,927,894.58 | 2,506,379.43 | 143,056.33 | 232,308.94 | 71,428.57 |
| **xi.** | OPEX | R/ minimum viable production | - | 105,215,404.04 | 912,000.00 | 9,000,000.00 | 50,000,000.00 | 1,145,498.00 | 1,925,265.82 | 1,389,024.65 | 200,000,000.00 | 2,480,919.32 |
| **xii.** | CAPEX | R/ minimum viable production | - | 51,598,851.72 | 20,330,685.00 | 22,007,000.00 | 140,793,736.00 | 2,785,022.80 | 7,763,805.00 | 2,548,423.78 | 112,588,983.00 | 2,604,934.96 |
| **xiii.** | Labour requirement | | - | 82 | 34 | 40 | 58 | 4 | 8 | 8 | 100 | 4.00 |
| **xiv.** | Registrations and Permit | 5 Scales | - | 4.32 | 3.86 | 3.86 | 4.55 | 4.32 | 3.41 | 3.41 | 4.77 | 3.86 |

Polarity: '+' = benefit criteria; '-' = cost criteria

(DAFF, 2017a, 2017b, 2017d, 2018b, 2018d, 2018c, 2018e, 2018a)

### Data Collection

Objective and performance data for the internal and external indicator analyses of the aquaculture species were collected and tabulated (Table 4.3 and 4.4) by reviewing available published information on the selected species in South Africa (FAO, 2010-2020; DAFF, 2017b, 2017d, 2017a, 2018b, 2018c, 2018e, 2018a, 2018d). Sources of data collection include, but not are limited to, DAFF and FAO country reports (Section 4.2).

### Performance Normalization

Performance normalization involves the definition of weights and performance scoring system of defined internal and external SWOT factors for key South African aquaculture species that were analyzed. The identified SWOT factor performance involves both quantified and qualified performance. The quantified performance were actual indicators, while the qualified performance was subjective scoring of SWOT factors ranging from 1 - 5 points (the higher the score, the better except for the external factor) (Tables 4.3 and 4.4).

Subsequently, the quantified and qualified performance were unified using the method of normalization as proposed by Chang and Huang (2006) (Table 4.5 and 4.6)

- Benefit-criteria normalization (the higher, the better)

  Equation I

$$r_{ij} = \frac{p_{ij}}{\max\limits_{j} p_{ij}}, \quad \forall_j$$

e.g. (V) survival rate (%)

P1 = 82, P2 = 90, P3 = 90, P4 = 78, P5 = 80, P6 = 90, P7 = 90, P8 = 80, P9 = 60 (Table 4.3, Row (v)). r *i j* = Benefit-criteria normalization; P*i j* = 82; P*i j* max = 90

r1 = 82/90 = 0.911, r2 = 1.000, r3 = 1.000, r4 = 0.867, r5 = 0.889, r6 = 1.000, r7 = 1.000, r8 = 0.889 and r9 = 0.667. (Table 4.5, Row (v))

- Cost-criteria normalization (the lower the better)

  Equation II

$$r_{ij} = \frac{\min_j p_{ij}}{p_{ij}}, \quad \forall_j$$

e.g. (v) production cost (R/Kg) (See Table 4.4, Row (v))

P1 = 358, P2 = 6, P3 = 18.5, P4 = 80, P5 = 48.5, P6 = 30, P7 = 33.75, P8 = 68, P9 = 75 (R/Kg) (See Table 4.4, Row (v)). r *i j* = Cost-criteria normalization (the lower the better); P*i j* = 358; P*i j* min = 6r1 = 6/358 = 0.017, r2 = 1.000, r3 = 0.324, r4 = 0.075, r5 = 0.124, r6 = 0.200, r7 = 0.178, r8 = 0.088, and r9 = 0.080. (Table 4.6, Row (v))

**Determination of Benchmarking and SWOT Coordinates Values**

The last step was the calculation and comparison of the SWOT coordinate values of internal and external assessments using total weighted performances. The Internal and external weighted score of the analysed aquaculture species were calculated separately, and the benchmarking values were determined by taking the mean weighted score according to the methods of Chang and Huang (2006) (see Tables 4.5, 4.6 and 4.7). The benchmarking values for the internal and external SWOT factors of the compared aquaculture species (abalone, mussel, oyster, dusky kob, atlantic salmon, trout, tilapia, catfish and marron crayfish) were subtracted from the mean score of the internal and external factors of each aquaculture species. The obtained values were used to plot the coordinate values in the SWOT analysis matrix (Table 4.7).

IC j = I j − I B  j = 1, 2. . . n

EC j = E j − E B  j = 1, 2. . . n

Where:

IC j: the internal assessment coordinate value of the $j^{th}$ aquaculture species.

I j: internal assessment score of the $j^{th}$ aquaculture species.

I B: benchmarking value of the internal assessment.

EC j: the external assessment coordinate value of the $j^{th}$ aquaculture species.

E j: external assessment score of the $j^{th}$ aquaculture species.

E B: benchmarking value of the external assessment.

$-1 \leq IC\ j \leq +1$

$-1 \leq EC\ j \leq +1$.

### Table 4. 5: Internal assessment weighted average score of key aquaculture species in South Africa

| Internal assessment key factors | | Units | Polarity | Major Aquaculture species in South Africa | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Abalone | Oyster | Mussel | Dusky Kob | Trout | Tilapia | Catfish | Salmon | Marron Crayfish |
| **i** | Production | Tons | + | 0.841 | 0.158 | 1.000 | 0.044 | 0.852 | 0.185 | 0.057 | 0.000 | 0.002 |
| **ii** | FCR | Number | - | 0.533 | 1.000 | 1.000 | 0.400 | 0.667 | 0.571 | 0.727 | 0.667 | 0.062 |
| **iii** | Stocking Density | Kg/$M^3$ | + | 0.197 | 0.132 | 0.132 | 0.395 | 0.658 | 0.329 | 1.000 | 0.724 | 0.053 |
| **iv** | Growth rate | g/month | + | 0.015 | 0.028 | 0.001 | 0.600 | 0.533 | 0.465 | 1.000 | 0.400 | 0.058 |
| **v** | Survival Rate | % | + | 0.911 | 1.000 | 1.000 | 0.867 | 0.889 | 1.000 | 1.000 | 0.889 | 0.667 |
| **vi.** | Species Hardiness | 5 Scales | + | 0.471 | 0.941 | 0.824 | 0.706 | 0.588 | 0.882 | 1.000 | 0.588 | 0.471 |
| **vii.** | Production Technology | 5 Scales | + | 0.632 | 0.526 | 0.526 | 0.632 | 0.895 | 0.947 | 1.000 | 0.526 | 0.421 |
| **viii.** | Environmental Friendliness | 5 Scales | + | 0.286 | 0.643 | 0.643 | 0.786 | 0.571 | 1.000 | 0.857 | 0.429 | 0.857 |
| **ix.** | Seed production (Ease of Hatchery operation) | 5 Scales | + | 0.750 | 0.750 | 0.500 | 0.688 | 0.750 | 1.000 | 0.875 | 0.688 | 0.750 |
| **x.** | Geographical Distribution | No of Prov./Total Prov. | + | 0.333 | 0.444 | 0.444 | 0.222 | 0.444 | 1.000 | 1.000 | 0.222 | 0.111 |
| **Polarity: '+' = benefit criteria; '-' = cost criteria** | | **Weighted Average** | | **0.497** | **0.562** | **0.607** | **0.534** | **0.685** | **0.738** | **0.852** | **0.513** | **0.345** |

## Table 4. 6: External assessment weighted average score of key aquaculture species in South Africa

| External assessment key factors | | Units | Polarity | Major Aquaculture species in South Africa | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **Abalone** | **Oyster** | **Mussel** | **Dusky Kob** | **Trout** | **Tilapia** | **Catfish** | **Salmon** | **Marron Crayfish** |
| **i** | Local Consumption | Tons | + | 0.164 | 0.068 | 0.618 | 0.025 | 0.741 | 1.000 | 0.039 | 0.927 | 0.001 |
| **ii** | Export | Tons | + | 1.000 | 0.093 | 0.146 | 0.000 | 0.027 | 0.433 | 0.005 | 0.105 | 0.000 |
| **iii** | Import | Tons | - | 1.000 | 1.000 | 0.000 | 1.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1.000 |
| **iv** | Price | R/Kg | + | 1.000 | 0.029 | 0.071 | 0.190 | 0.143 | 0.083 | 0.114 | 0.243 | 0.595 |
| **v** | Production cost | R/Kg | - | 0.017 | 1.000 | 0.324 | 0.075 | 0.124 | 0.200 | 0.178 | 0.088 | 0.080 |
| **vi.** | Minimum viable production | Tons | - | 0.035 | 0.020 | 0.008 | 0.008 | 0.100 | 0.055 | 0.053 | 0.002 | 1.000 |
| **vii.** | Profitability Index | | + | 0.830 | 0.718 | 0.797 | 0.353 | 0.851 | 0.838 | 0.842 | 0.515 | 1.000 |
| **viii.** | NPV (over 10 years) | R | + | 1.000 | 0.098 | 0.183 | -0.185 | 0.026 | 0.063 | 0.026 | 0.473 | 0.046 |
| **ix.** | IRR | % | + | 0.333 | 0.619 | 1.000 | -1.286 | 0.381 | 0.333 | 0.381 | 0.905 | 0.333 |
| **x.** | Trade value (Consumption & Export) | USD$ | + | 1.000 | 0.014 | 0.122 | 0.000 | 0.288 | 0.073 | 0.004 | 0.007 | 0.002 |
| **xi.** | OPEX | R/ | - | 0.009 | 1.000 | 0.101 | 0.018 | 0.796 | 0.474 | 0.657 | 0.005 | 0.368 |
| **xii.** | CAPEX | R/ | - | 0.049 | 0.125 | 0.116 | 0.018 | 0.915 | 0.328 | 1.000 | 0.023 | 0.978 |
| **xiii.** | Labour requirement | | - | 0.049 | 0.118 | 0.100 | 0.069 | 1.000 | 0.500 | 0.500 | 0.040 | 1.000 |
| **xiv.** | Registrations and Permit | 5 Scales | - | 0.789 | 0.883 | 0.883 | 0.749 | 0.789 | 1.000 | 1.000 | 0.715 | 0.883 |
| **Polarity: '+' = benefit criteria; '-' = cost criteria** | | **Weighted Average** | | **0.520** | **0.413** | **0.319** | **0.074** | **0.441** | **0.384** | **0.343** | **0.289** | **0.521** |

### Randomization and variability of SWOT assessment factors

The benchmarking values (internal and external) were subtracted from the subjective normalization scores of internal SWOT assessment factors and external SWOT assessment factors as well as the objective normalization scores (Table 4.5 and 4.6). Subsequently, the derived internal and external SWOT values of the subjective performance were randomized 1000 times to minimize bias, while the objective performance was fixed. The mean values obtained were used to determine the effects of the SWOT assessment factors variability on the SWOT quadrant.

## Statistical Analysis

The weighted mean values of internal and external SWOT assessment factors of key aquaculture species - abalone, mussel, oyster, dusky kob, atlantic salmon, trout, tilapia, catfish and marron crayfish were statistically compared using a one-way analysis of variance (ANOVA) after testing for normality distribution and equality of variance of variables. Fisher's LSD pairwise comparison test was used to determine if there were significant differences in the weighted mean values of the compared key aquaculture species at 95 % confidence limits using IBM SPSS 25 statistical software program.

## 4.4 Results

### 4.4.1 Quantified SWOT Analysis of Key Aquaculture Species in South Africa

The quantitative SWOT analysis of key South African aquaculture species showed the competitive positions of abalone, oyster, mussel, salmon, dusky kob, trout, tilapia, catfish and marron crayfish (Figure 4.1). Trout and tilapia were both located in quadrant I, depicting a combination of levels of competitive aquaculture strengths and economic opportunities (Figure 4.1). Trout with a mean weighted external assessment value of 0.074, however, has more economic opportunities than tilapia (0.017); while tilapia with a mean weighted internal assessment value of 0.145, has more competitive strengths than trout (0.092) (Table 4.7 and Figure 4.1).

Abalone, oyster and marron crayfish are situated in the second quadrant. They, therefore, possess some levels of economic opportunities but weaker in aquaculture competitive strengths. Marron crayfish shows the highest level of economic opportunity (0.153) compared to abalone (0.145) but weaker in competitive aquaculture strengths (abalone - 0.096; marron crayfish - 0.247). Oyster, though located in the same quadrant with abalone and marron crayfish, however, has lower market opportunities (0.047), but higher aquaculture competitive strengths (- 0.030) than both abalone and marron crayfish (Table 4.7 and Figure 4.1).

Salmon and dusky kob occupy the third quadrant; therefore, both aquaculture species are currently weak in competitive aquaculture strengths and confronted with economic threats. Salmon exhibited lower economic threats (- 0.077) compared to dusky kob (-

0.289), while dusky kob demonstrated a higher competitive strength (- 0.059) than salmon (- 0.079) (Table 4.7 and Figure 4.1).

Finally, mussel and catfish (quadrant IV) both show some levels of competitive aquaculture strengths but facing more threats than market opportunities (Table 4.5 and Figure 4.2). Catfish exhibited the highest competitive strengths (0.259) of all the analyzed aquaculture candidates but is confronted with more economic threats (- 0.020) than opportunities. Mussels showed some levels of competitive strengths as well (0.014) but also faced with economic threats (- 0.048) (Table 4.7 and Figure 4.1).

The SWOT assessment variables of abalone, mussel, salmon and marron crayfish were more positively skewed towards the strength abscissa; oyster, trout and dusky kob were negatively skewed towards the weakness abscissa; while those of tilapia and catfish were more conspicuously skewed towards the weakness abscissa compared to oyster, trout and dusky kob (Figure 4.1).

### 4.4.2 Internal and external SWOT assessment weighted mean values of Key Aquaculture Species in South Africa

The weighted mean values of internal and external SWOT assessment factors of key aquaculture species (abalone, oyster, mussel, dusky kob, trout, tilapia, catfish, salmon and marron crayfish) in South Africa were reported (Table 4.7).

The mean weighted internal SWOT factors value of catfish as an aquaculture candidate was significantly higher (ANOVA LSD: df 8; $p < 0.05$) than those of abalone, oyster, dusky kob, salmon and marron crayfish (Table 4.5). Trout and tilapia internal SWOT factors were significantly (ANOVA LSD: df 8; $p < 0.05$) higher than that of marron crayfish, while there was no significant difference (ANOVA LSD: df 8; $p > 0.05$) in the internal SWOT factors of abalone, oyster, mussel, dusky kob, salmon and marron crayfish (Table 4.7). The mean weighted external SWOT factors values abalone, oyster, trout and marron crayfish were significantly higher (ANOVA LSD: df 8; $p < 0.05$) than that of dusky kob (Table 4.7).

## Table 4. 7: Coordinates values for the compared aquaculture species

| Factors | Abalone | Oyster | Mussel | Dusky Kob | Trout | Tilapia | Catfish | Salmon | Marron Crayfish | Bench marking Value a |
|---|---|---|---|---|---|---|---|---|---|---|
| **Weighted average value of internal assessment b** | 0.497 ±0.29 | 0.562 ±0.37 | 0.607 ±0.36 | 0.534 ±0.26 | 0.685[h] ±0.16 | 0.738[h] ±0.32 | 0.852[abdgh] ±0.29 | 0.513 ±0.26 | 0.345 ±0.33 | **0.593** |
| **Coordinates values of internal assessment** | **-0.096** | **-0.030** | **0.014** | **-0.059** | **0.092** | **0.145** | **0.259** | **-0.079** | **-0.247** | |
| **Weighted average value of external assessment b** | 0.508[d] ±0.47 | 0.410[d] ±0.43 | 0.314 ±0.35 | 0.074 ±0.51 | 0.441[d] ±0.38 | 0.368 ±0.35 | 0.343 ±0.39 | 0.285 ±0.35 | 0.521[d] ±0.44 | **0.363** |
| **Coordinates values of external assessment** | **0.145** | **0.047** | **-0.048** | **-0.289** | **0.078** | **0.005** | **-0.020** | **-0.077** | **0.158** | |

a mean value; b Coordinate value =Weighted average value − Benchmarking value.

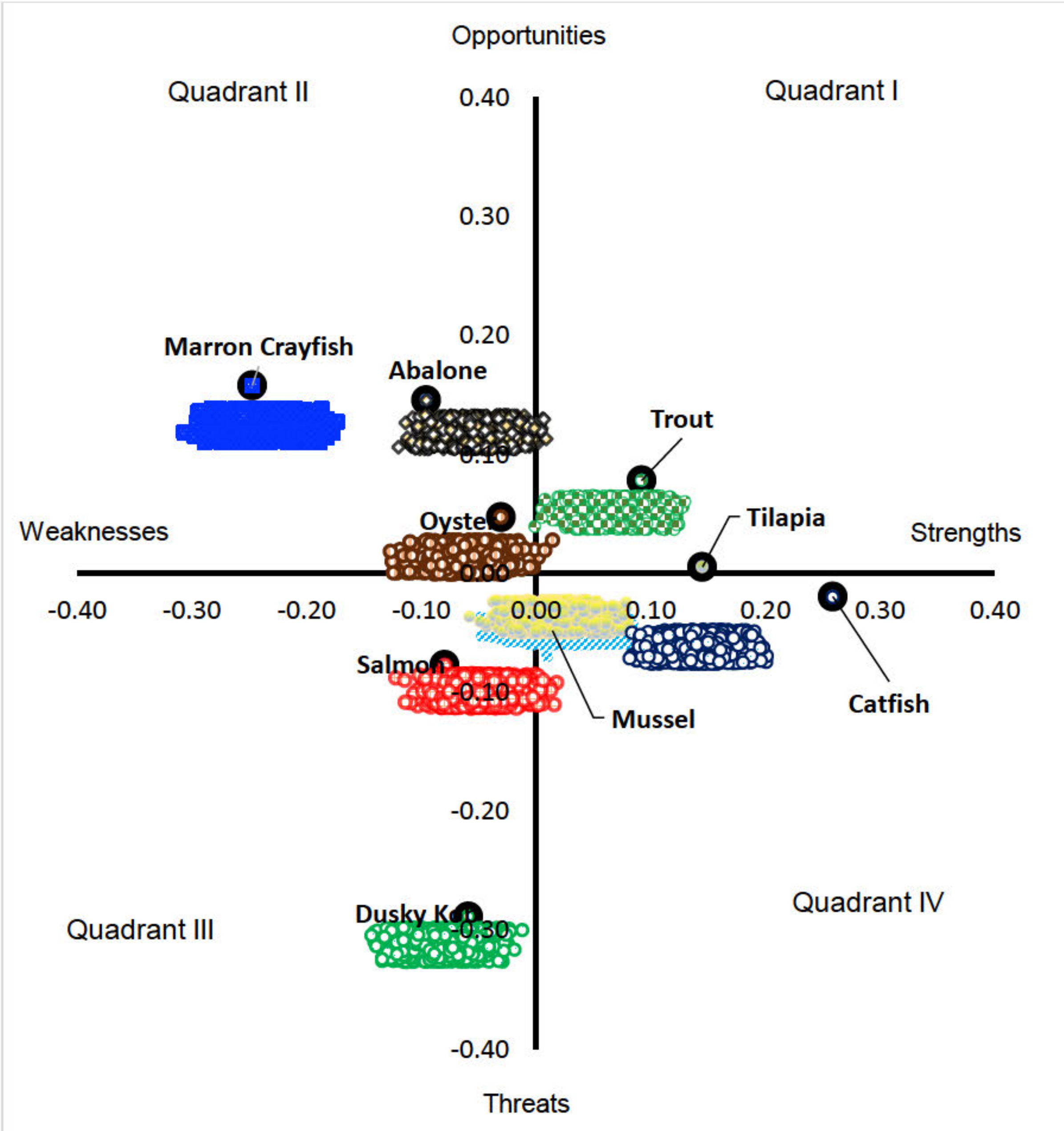


**Figure 4. 1: SWOT matrix performance of key South African aquaculture species**

## 4.5 Discussion

Trout and tilapia were the top-performing species based on their quantified competitive strengths, market opportunities and aquaculture development potentials. At the same time, dusky kob was the least performing aquaculture candidate due to its weak competitive strengths and myriads of threats confronting its aquaculture development and market opportunities in South Africa (Figure 4.1). Although trout and tilapia were both situated in quadrant I, their levels of competitive strengths as well as aquaculture development and market opportunities were different (Figure 4.1 and Table 4.7).

Tilapia as an aquaculture species, showed higher competitive strengths compared to trout, due to internal assessment factors such as hardiness, the versatility of production technology, higher survival rate, environmental friendliness, ease of propagation in captivity and being capable of being cultured in different locations of the country (Table 4.3 and 4.5) (IDC, 2015; DAFF, 2018d).

Tilapia species have been documented to tolerate a wide range of changes in environmental conditions such as dissolved oxygen, salinity, temperature, pH etc. (Popma & Masser, 1999). They are highly resistant to diseases and perform well in various culture systems and environments compared to other species (FAO, 2005-2019). Tilapia species possess some excellent levels of internal SWOT competitive strengths which under normal situations should favour higher production output in South Africa; however, external SWOT factors, particularly over-regulation, cost of production vis-à-vis market pricing, are significant factors hindering production output (IDC, 2015; DAFF, 2018d). In 2015, almost all the tilapia consumed in South Africa were mainly imported from China, with retail selling price per kg lower than the cost per kg of locally produced tilapia (DAFF, 2017a). Tilapia productions in South Africa, largely make use of high capital and intensive production technologies due to sub-optimal environmental conditions, (Britz & Venter, 2016a) unlike Egypt, China, Uganda, Ghana and other tilapia producing countries, thus resulting to cost detriment and inability to achieve economies of scale (IDC, 2015). The use of the widely permitted slow-growing *O. mossambicus* instead of the faster growing *O. niloticus* in a capital-intensive operating system is also responsible for dismal production output and inability to attain economies of scale. *Oreochromis niloticus* is regarded as an alien invasive species (AIS) by National Environmental Management Biodiversity Act (NEMBA), therefore, obtaining the stringent AIS culture permit is often met with bureaucratic bottlenecks (CSIR, 2017), thus discouraging large-scale commercial investments.

The predominant adoption of intensive systems such as RAS and aquaponics although represents long term environmentally friendly technology, however, high operating cost, threats from cheaper imported tilapia and poor growth performance of *O. mossambicus* are responsible for the weak economic opportunities of local tilapia production in South Africa.

The provision of an enabling environment (such as simple and fast permit process for *O. niloticus* in closed systems) which favours and permits the sustainable production of a better performing tilapia species is therefore required in South Africa. A simplified and efficient process of obtaining AIS permit to culture *O. niloticus* is expected to encourage more interests and investments in tilapia production and translate to attaining higher production output and economic efficiency.

The competitive aquaculture strengths of trout were largely dependent on the internal SWOT factors such as better feed conversion ratio; ability to tolerate higher stocking density and faster growth rate compared to tilapia (DAFF, 2018e). The major limiting internal SWOT factors for trout production in South Africa, however, are the limited availability and sub-optimal environmental conditions of suitable culture sites (Stander & Brink, 2009; Britz & Venter, 2016a). Trout production requires an all-year-round average water temperature of ~ 18 $^{o}$C to attain optimal growth performance (DAFF, 2018e) and viable yield, which is unattainable in most of the production sites, particularly due to higher water temperature (> 20 $^{o}$C) during the late summer months from January to March (Stander & Brink, 2009). These limiting SWOT factors (Table 4.3) are largely responsible for the stagnant growth and development (< 2000 tons year $^{-1}$) of trout production in South Africa. Trout, on the other hand, had higher economic viability and market opportunities than tilapia due to external SWOT factors such as trade value, higher pricing, production output and financial indicators (NPV, IRR, profitability index, OPEX and CAPEX) (Table 4.3 and 4.4) (DAFF, 2018e). Trout is widely regarded as a high-value food fish in South Africa, with demand exceeding local supply (DAFF, 2018e). Adoption of environmentally controlled production technologies such as RAS in a climate-controlled environment will be required to negate the effect of environmental suitability; however, this may astronomically soar the cost of production (Stander & Brink, 2009). A 40:60 % (40 % of the production cycle in RAS during summer and 60 % in outdoor systems during winter) combined climate-controlled RAS and outdoor technologies can potentially be a viable and efficient production model to boost South African trout production output. The economic feasibility of the combined production technologies will, however, be required before this model can be recommended as an alternative production model for trout production development in South Africa.

Abalone, oyster and marron crayfish in Quadrant II (Figure 4.1) were not significantly different in weighted mean values of internal and external SWOT factors (Table 4.7). These species possessed varying levels of economic opportunities but were weak in internal SWOT competitive strengths. Abalone and marron crayfish both possessed higher levels of economic opportunities due to external SWOT factors such as high pricing and good financial indicators (DAFF, 2018a,2018c) however, marron crayfish showed the poorest weighted value with regards to competitive strengths compared to other aquaculture species (Figure 4.1). Internal SWOT assessment factors such as low stocking density, poor growth rate, lower survival rates, hardiness and limited geographic locations that are suitable for its culture (Table 4.3 and 4.5) were responsible for the competitive weaknesses compared to the other key aquaculture species (DAFF, 2018c). Oyster occupied the lower level of economic opportunities on the matrix compared with abalone, marron crayfish and trout but shows better competitive strengths than abalone and marron Crayfish (Figure 4.1), due to internal SWOT assessment factors such as good feed conversion ratio, higher survival rate, being environmentally friendly and species hardiness (Table 4.3 and 4.5).

Abalone, though lower in internal SWOT assessment weighted average score compared with other species, besides marron crayfish (Table 4.3 and 4.5), had a higher external SWOT assessment weighted score (Table 4.4 and 4.6). This is due to the premium value, price, and high demand from some Asian countries due to the cultural and medicinal values attached to this species (DAFF, 2018a). South African abalone (*H. midae*) is in high demand globally due to its unique qualities; therefore, commands premium prices at international markets (DAFF, 2018a). Abalone has the lowest growth rate compared to the other key aquaculture species, as it takes up to 4 years to attain market size, however, this major competitive weakness is traded off due to outstanding economic performances as a major aquaculture foreign exchange earner species. The major limitations of its external SWOT factors are high capital and operational costs which are largely compensated with remarkable financial performance (NPV and PI) (Table 4.4 and 4.6). The potential of strengthening the weak competitive position is highly limited due to the biological characteristics of abalone (DAFF, 2018a) (see Table 4.3); however, the aquaculture development potential of abalone is largely hinged on the attractiveness of its market and economic returns (DAFF, 2018a). The abalone sector currently records the highest revenue compared to other key aquaculture sectors in South Africa; therefore continuous injections of capital investments are expected to translate to marginal growth in production output (DAFF, 2017a).

Marron Crayfish has the lowest internal SWOT assessment weighted average value compared to the other species analyzed (Table 4.5) and significantly lower than those trout, tilapia and catfish, but ranks on par with abalone in reference to external SWOT assessment weighted average score (Table 4.4 and 4.6). Marron crayfish currently undergoes a lengthy production cycle of ~ 24 months (DAFF, 2018c), which is a major challenge in achieving stable production quantities annually. In addition to poor growth performance, marron crayfish production is characterized by a low survival rate, inability to withstand high stocking density and restricted production methods (DAFF, 2018c) (Table 4.3). As a result of these production challenges, both domestic and international market demand is grossly under-supplied (DAFF, 2018c). Currently, there is ongoing research on marron crayfish to improve its growth performance and shorten its production cycle; as well as to assess alternative production systems (DAFF, 2017a,2018c). Marron crayfish though occupies a position of economic opportunity on the SWOT matrix (Figure 4.1) due to external SWOT factors such as demand-supply gap, high market pricing, lower capital and operating cost as well as good financial performance (Table 4.4 and 4.6). However, its dismal production performance makes this species a weak aquaculture candidate (Nunes *et al.*, 2017) for rapid aquaculture development compared to other key aquaculture species. The growth of marron crayfish production in South Africa is therefore limited, until further breakthroughs are achieved with regards to the limiting cultivation characteristics, specifically, hardiness, poor FCR and growth performance.

Oyster recorded a higher internal SWOT assessment weighted average score compared to abalone and marron crayfish largely due to zero cost associated with feeding and ease of seedling production (spat) and supply (DAFF, 2017c) (Figure 4.1, Table 4.5 and 4.7) but scored lower in external SWOT assessment weighted average (Table 4.6 and 4.7). Oyster farming in South Africa is mainly dependent on spat importation of the hardier pacific oyster species from Chile, Namibia and Guernsey which are then supplied to grow-out farmers (DAFF, 2017c). The market demands for oyster in South Africa experience fluctuations and the inability to attain international standards of health certification of products are major challenges confronting the development of this sector (Olivier *et al.*, 2013). The oyster sector has great market potentials, especially with the rising demand for seafood on the international market; however, the health and safety concerns need to be addressed to drive the growth and expansion of this sector (Olivier *et al.*, 2013).

Salmon and dusky kob both showed weak competitive strengths and are also confronted with threats due to external SWOT assessment factors (Figure 4.1). These two species have their internal SWOT assessment weighted average scores lower than those of tilapia, trout, mussel and oyster (Table 4.5) and were significantly lower than that of catfish (Table 4.5). Also, both salmon and dusky kob scored lower than other species compared in external SWOT assessment weighted score (Table 4.6 and 4.7). Although salmon and dusky kob were both in the third quadrant, salmon possesses higher market opportunities (higher pricing and better financial indicators) (DAFF, 2017b) than dusky kob (Table 4.4). On the contrary, dusky kob is marginally stronger in competitive strengths than salmon (Table 4.3).

Aquaculture production of salmon in South Africa is yet to achieve steady production due to a combination of internal SWOT factors (production technology and availability of suitable site) and external SWOT factor (economies of scale) unlike countries such as Scotland, Norway, New Zealand, Australia and Chile which have well-established production outputs (DAFF, 2017b). There are ample investment and market opportunities for the local production of salmon, due to the steady growth in consumption, which is wholly supplied by importations (DAFF, 2017b,2017a). Salmon is a high-value food fish with feasible production potential which offers the highest return on investment using scaled cage culture system (DAFF, 2017b). The potential for the viable cage culture system in South Africa is, however, mostly restricted to Gansbaai and Saldanha Bay in Western Cape due to the predominant high energy coastline of South Africa (DAFF, 2017b).

Dusky kob aquaculture in South Africa has the lowest external SWOT assessment weighted average score compared with other aquaculture species (Table 4.6 and 4.7), which impacted its market outlook. Currently, the domestic market size and opportunities for cultured dusky kob is small and limited due to external SWOT assessment factors such as low consumption, high capital and operating costs as well as low pricing (DAFF, 2017b). As a result of these external SWOT factor threats, coupled with the inability to attain economies of scale, commercial dusky kob aquaculture does not currently portend a financially feasible business case in South Africa. Recent comparative trials of specially formulated feed on the growth performance of dusky kob and yellowtail kingfish (*Seriola lalandi*) by Aqua Management Technologies (AMT) could potentially be the breakthrough for the economic performance of finfish production and development in South Africa (IntraFish, 2018). Preliminary results of the pilot studies conducted by AMT on both yellowtail kingfish and dusky kob using their specially formulated feed showed yellow tail attaining an average weight of 2.5 kg from spawned eggs in 12 months, while dusky kob attained an average of 1 kg at 12 months (IntraFish, 2018). Although these studies are yet to be conducted for commercial-scale trials, pilot trials presented production efficiencies comparable to cage culture systems (IntraFish, 2018). Yellowtail production is currently still at a pilot-scale level in South Africa (DAFF, 2017a); however, its outstanding growth performance under intensive land-based culture system could potentially make it a better aquaculture alternative to dusky kob, with potential to drive aquaculture development.

Mussel and catfish both possessed competitive strengths but were weak in economic opportunities due to their external SWOT factors (Figure 4.1). Catfish recorded the highest internal SWOT assessment factor weighted average score, which is significantly higher than those of abalone, oyster, dusky kob, salmon and marron crayfish (Table 4.7). This species demonstrates the strongest competitive strengths due to internal SWOT assessment factors such as lower feed conversion ratio; high stocking density; very rapid growth rate; high survival rate in culture systems; hardy and can be produced across the nation using suitable production technology (DAFF, 2018b) (Table 4.5). Catfish though presents the strongest competitive strengths due to the internal SWOT assessment factors, production output in South Africa is substantially low (~ 180 tons/year) (DAFF, 2015a). It is unclear what the current production data of catfish is in South Africa (DAFF, 2017a). This is due to lack of updated production information and data since 2012, as most South African catfish producers do not report their farming data to the appropriate governmental departments for documentation purposes (DAFF, 2017a). Catfish exhibits a lower external SWOT assessment weighted average score compared to tilapia, trout, abalone, marron crayfish and oyster. This is due to producers scaling down their operations because of production cost exceeding market price (DAFF, 2018b). The market for catfish is relatively small (~ 100 tons/year), albeit growing and primarily driven by migrant communities from other African countries residing in South Africa (DAFF, 2018b). An emerging trend with the production of this species as reported by DAFF (2017a), reveals a change in production strategy by many producers, from table size fish to catfish fingerlings for the export market. Catfish possess some potentials to grow aquaculture production output in South Africa due to its strong competitive advantage over other aquaculture species, especially tilapia. Its market opportunities are, however, dependent on value-addition and consumption by the South African middle class (DAFF, 2018b).

Mussel showed higher competitive strengths than oyster, dusky kob, salmon, abalone and marron crayfish due to internal SWOT assessment factors such as high production output, species hardiness, high survival rate as well as simple and easy-to-operate grow-out technology (DAFF, 2017c) (Table 4.5). The major opportunity leverage for mussel production is lower capital and operational costs due to zero cost associated with grow-out feeding and seed stock, as well as a simple production technology (DAFF, 2017c). As a result of these cost benefits, mussel production in South Africa suggests a financially viable business case (DAFF, 2017c).

Major limitations to this study include unreported production data and information on species like catfish, as well as lack of updated production data for all the considered species from relevant government departments. Therefore, production data gathered for this study were mainly based on the 2015 aquaculture production report published by DAFF in 2018. The quantified SWOT positions of the analyzed species may, therefore, shift within or outside the GSM quadrants with emerging production trends and prevailing macroeconomic climate.

## 4.6 Conclusion

The potential to rapidly grow aquaculture production output in South Africa is largely dependent on a combination of factors such as attaining of economies of scale, cost-effective adaptive culture technologies and provision of tailored enabling environments such as incentives to reduce OPEX, simple authorization procedures and nationwide promotion of fish-eating culture to drive growing local demand.

Trout and tilapia were both freshwater aquaculture species showing appreciable competitive strengths. Trout currently showed the highest economic opportunities among the key finfish cultured in South Africa but limited by suitable sites and optimal environmental conditions. A combined production method may potentially alleviate the challenges experienced with single production technology associated with trout production. The production of tilapia in aquaponic systems compared to RAS will increase the economic viability of tilapia production due to the extra stream of revenue from the integrated plant production (Chapter 5 and 6).

Abalone had the most remarkable market opportunities due to good financial indicators, pricing and absence of importations, however, with marginal growth in production output as a result of weak competitive strengths mainly due to poor FCR and growth performance.

Atlantic salmon and dusky kob were weak in competitive strengths and confronted with more threats than market development opportunities. Salmon, unlike dusky kob, has ample potential for market growth, if challenges such as availability and access to a suitable production site, adaptable production technology and ability to attain economies of scale associated with steady production are adequately addressed. Preliminary findings on the growth performance and yield of yellowtail appear promising and may potentially replace dusky kob as a better performing aquaculture candidate if the commercial trials prove successful. Catfish and mussel showed a higher level of competitive strengths but are yet to achieve economic success.

This study is expected to guide aquaculture industry stakeholders and prospective producers to make informed decisions with regards to the feasibility of aquaculture species in South Africa and may also allow for improvements on the challenges facing the production of the species here analyzed.

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# CHAPTER 5: ECONOMIC VIABILITY OF LOW-COST AQUAPONIC SYSTEM IN SOUTH AFRICA

## 5.1 Abstract

Aquaponics provides a sustainable means of converting aquaculture effluent to nutrients for growing plant. This unconventional, but synergistic system of food production has been documented to be economically feasible and sustainable, particularly in areas with limited land and water resources availability. This study assessed the economic feasibility of a low-cost aquaponics system using production output and economic data. Price trends, cost, revenue, return on investment (ROI), net present value (NPV), internal rate of return (IRR) and profitability analyses were modelled to determine the financial performance of the aquaponic system. The result indicated that this small-scale aquaponic operation are not economically viable (Gross profit margin: 42 %, net profit: - 22 %, ROI: - 8 %, NPV: R81,466, IRR: 13 % and Profitability Index: 0.35) by adopting conventional aquaponics cultural practice (fish : plant revenue model 59 to 41 %) due to higher operating cost of producing a kg of fish (R55) vis-à-vis the market price, compared to plant production. A revenue model of 42 to 58 % fish to plant ratio was marginally feasible (Gross profit: 59 %, net profit: 13 %, ROI: 7 %, NPV: R92,445, IRR: 19 % and Profitability Index: 0.50). A minimum revenue model of 30 to 70 % fish to plant ratio by adopting optimized plant yield cultural techniques to attain economies of scale and viability, is suggested. This study serves as a model for promoting viable and sustainable unconventional food production system to attain food security and local economic development in South Africa.

**Keywords:** economic viability, low-cost aquaponics, fish, vegetables, price trend analysis

## 5.2 Introduction

This section analyses the economic feasibility of a small-scale and low-cost designed aquaponic system described in section 6.3.1. Biomass yield of fish, tomato, pepper, cucumber and basil from these aquaponic systems (section 6.3.2, 6.4 and 5.4) and associated costs of building, as well as running the system were subjected to cost-benefit analysis (Bailey *et al.*, 1997).

Aquaponics offers a sustainable, non-chemical source and cost-effective integrated means of diverting aquaculture effluent as a nutrient for plant production. The synergistic integration in aquaponics eliminates some of the unsustainable factors of managing hydroponic and aquaculture systems independently (Somerville *et al.*, 2014). Aquaponics has been recorded to be more economically viable and productive, especially in areas where water and land resources are limited and in highly competitive demand (Tokunaga *et al.*, 2015). Aquaponics operation is, however complex and involves an investment of substantial start-up capital costs; thus, biomass yield must compensate for the higher investment costs (Somerville *et al.*, 2014). The key economic factors to be considered in setting up an aquaponic system just like any other business include:

i. the total capital outlay required to setup the aquaponics (CAPEX);
ii. the annual operating costs of the system (OPEX); and
iii. realistic market price estimates of the products based on price trend analysis (Engle, 2016).

Due to limited economic data and variability of the economic viability metrics applied in various studies (Engle, 2016), there have been no clear conclusions reached on the economic viability of aquaponics (Engle, 2016). Several studies (Bailey *et al.*, 1997;

Holliman *et al.*, 2008; Baker, 2010; English, 2015; Tokunaga *et al.*, 2015) have documented the production of vegetable to be more profitable than fish production in many commercial aquaponics setups, with up to 90 percent of profitability derived from plant production (Somerville *et al.*, 2014). There are also some exceptions; however, as some aquaponic ventures recorded more profit earnings from specific valuable fish (Somerville *et al.*, 2014). A previous economic feasibility study conducted by Lapere, (2010) on some small-scale aquaponic farms in South Africa showed that most of the aquaponic ventures were not viable due to factors such as design, setup and operational challenges. In the light of the appraisals of the previous studies (Bailey *et al.*, 1997; Holliman *et al.*, 2008; Baker, 2010; Lapere, 2010; English, 2015; Tokunaga *et al.*, 2015) that have been conducted on the economic feasibility of aquaponic ventures and the attendant factors responsible for their economic viability, this study aims to determine the economic feasibility of low-cost aquaponics in South Africa. The biomass yield (Chapter 6), operational and capital cost inputs incurred from the aquaponics setup and management were used to develop a financial model and input requirements for a low-cost, small-scale commercial aquaponic operation.

## 5.3 Methodology

Biomass yield data of fish – tilapia and plants – tomato, sweet pepper, cucumber and basil were obtained from the study in Chapter 6 and subjected to economic analysis modelled in line with the methods of Bailey *et al.* (1997) and Rakocy and Hargreaves (1993) which outline the sequence of procedures to determine the economic feasibility of an aquaponics operation as follows:

I. Determine the system requirements by calculating the growth projections of the fish and plant species,
II. Determine the capital cost of the system,
III. the operational cost,
IV. Revenue projection, and
V. Determination of financial feasibility by modelling the cost factors and revenue analyses into financials.

The cost and revenue analyses from this study in combination with the financial models for the production of tilapia, tomato, peppers, cucumber and basil were used to determine the break-even prices for each standing crop and the entire operation. Cash flow analysis was developed, and payback durations were calculated for the initial capital expenditure of this system.

### 5.3.1 Assumptions

The underlining assumptions factored in the economic analysis of this study are highlighted as follows:

I. The cost of land and greenhouse were not factored in the capital cost as these assets were already in existence.

II. Labour costs were not factored in the capital and operational cost, as the setup of the aquaponic system and operation was undertaken by the researcher during the course of the study. This also correlates with the techno-economic analysis study of small-scale aquaponic farms in South Africa (Lapere, 2010). To lower operating expenses in order to achieve profitability, small scale aquaponic operation is expected to operate on self labour. The opportunity cost of self labour will be the eroded accrued profit that would have been paid to hired personnel. These are not “Commercial” setups, but rather small scale systems provided to drive food security and local economic development via unconventional food production systems.

III. The economic viability of this study did not take into considerations any form of risks that the aquaponic system operations might be exposed to.

IV. The cash flow of this study was largely driven by the plant yield and sales due to the relatively short production cycle of plants compared to fish.

V. Four financial scenarios were proposed based on revenue and funding models.

a. Scenario I: The setup and working capital was raised by equity and not by term loan. The revenue model was derived based on the minimum market price for plant products, i.e. worst-case scenario price.

b. Scenario II: Similar financing structure to scenario I. The revenue model, however, is based on the maximum realistic market price for vegetable products.

c. Scenario III: Similar capital structure to scenario I and II; however, plant production outputs were assumed to be double the actual production based on future expansion of the hydroponic component without significantly increasing operational cost.

d. Scenario IV: The setup and working capital raised by bank term loan, while the revenue model is similar to Scenario II.

### 5.3.2 Price trend analysis

Average monthly prices of tomatoes, peppers and cucumbers from the price trend analysis covering a period of five years were obtained from the fresh produce market statistics 2014 – 2018, compiled by the Directorate of statistics and economic analysis of South Africa (Department of Agriculture, Fishery and Forestry, Directory of Statistics and Economic Analysis, 2014 – 2018) and computed using Microsoft excel software package to determine the price trend analysis of the plants. The data from 2014 to 2018 were selected, being the most recent data accessible from DAFF.

### 5.3.3 Cost analysis

A cost analysis was done to determine the total cost associated with the gravel bed aquaponic setup and operation. The fixed cost and variable costs were calculated and added up to determine the total setup and operating cost of the low-cost aquaponic system.

**Fixed cost / Depreciation cost**

Fixed cost values (CAPEX) were determined by calculating annual depreciation cost for each of the capital expenditures using a straight-line method with no salvage value (English, 2015). These costs were calculated for each aquaponic component using depreciation rates used by Hansen and Hardy (2008) from other aquaponic financial analyses. The annual depreciation cost is a non-cash deduction posted in the income statement and calculated by dividing the value of the asset by its life span. Capital expenditure of components used in the construction of the aquaponic system was derived from the payment invoice of component suppliers (Table 5.1).

**Table 5.1: Capital cost analysis of the aquaponic system**

| Aquaculture Component | Cost ( R ) | Rate |
|---|---|---|
| Greenhouse Tunnel | 40,000 | 10% |
| Fish Tanks | 5,500 | 10% |
| IBC tank (Bio-Mech filter-Sump | 1,300 | 10% |
| Gravel media | 1,000 | 10% |
| Weighing Scale | 200 | 10% |
| Hand Net | 150 | 30% |
| Air Pump | 4,400 | 25% |
| Air Stones and piping | 650 | 10% |
| **Total** | **53,200** | |
| **Hydroponic Components** | | |
| Electrical Pumps 0.5 HP | 1,800 | 25% |
| Plant Trough | 3,600 | 10% |
| PVC pipes and Fittings | 7,500 | 15% |
| Basic plumbing tools | 3,000 | 10% |
| Bell Siphons | 2,400 | 10% |
| Gravel (19mm) 40 Kg/bag | 5,000 | 10% |
| Plant trough Stand | 1,500 | 10% |
| Total | 24,800 | |
| Water test Kits | | |
| Water Kits | 6,000 | 25% |
| **Total** | **6,000** | |
| Others | 2200 | 10% |
| **Total** | **46,200** | |

### Variable cost / Operating cost analysis

The operating expenses (OPEX) of this study include the direct production cost and overhead cost (Hopkin *et al.*, 1973; Barry *et al.*). The direct cost incurred includes feed cost for the fish, additives, plant seedlings, and agricultural lime ($CaCO_3$). Overhead cost is classified as any other costs incurred which were captured neither in the capital cost nor in the direct cost. Such cost includes insurance, electricity, water, telephone and internet bills, transportation, maintenance, travel and accommodation. Staff or labour, insurance and other costs set to zero indicate those costs were not incurred in the study (Table 5.2).

**Table 5.2: Operating cost analysis of the aquaponic system**

| Variables | Unit | Quantity | Cost/unit ( R ) | Total ( R ) |
|---|---|---|---|---|
| **Direct cost** | | | | |
| Tilapia Juveniles | | 800 | 10 | 8,000 |
| Extruded Fish Feed (Cost/20Kg) | 20kg /bag | 20 | 380 | 7,600 |
| Lime | 10 (kg) | 1 | 100 | 100 |
| Plant Seedlings | | 500 | 1.5 | 750 |
| Additives | Litres | 1 | 600 | 600 |
| **Total** | | | | **17,050** |
| **Operating Cost** | | | | |
| Water | Kilolitre | 45 | 30 | 1350 |
| Electricity | (0.90 Kw/hr) | 6030 | 1.97 | 11879.10 |
| Transport (fuel) | Litres | 60 | 15 | 900 |
| Miscellaneous | | | | 283 |
| **Total** | | | | **14,412.10** |
| **Total Variable Cost** | | | | **31,462.10** |

### 5.3.4 Revenue analysis

The revenues analysis was performed by calculating the total sales value of the marketable fish produced from the aquaculture component and total sales value of the marketable plant biomass yield produced from the hydroponic component within the study period. Total biomass production and sales values during the study period were financially documented as annual production output. The total biomass of fish harvested (Table 5.2) multiplied by the prevailing average selling price per kilogram of tilapia fish within the study location was used to determine the total revenue fish (Table 5.4). Total revenue for marketable plant biomass produced (Table 5.3) was determined using the same formula applied for the fish revenue (Table 5.4). Prices of vegetable were computed from the five-year price trend analysis of fresh produce data (Figure 5.1, 5.2, 5.3 and 5.4) (DAFF, 2014-2018).

**Table 5.3: Plant production data using cultural techniques I (Table 6.14)**

| Marketable Yield (kg) using traditional aquaponic cultural technique | | | | | |
|---|---|---|---|---|---|
| **Plant Density/ m2** | **Stem Pruning** | **Tomato** | **Sweet Pepper** | **Cucumber** | **Basil** |
| 5 | 1-tomato/cucumber :2 -Pepper | 22.21 | 5.13 | 21.53 | 1.53 |
| 5 | 1-tomato/cucumber :2 -Pepper | 23.70 | 4.59 | 22.40 | 1.47 |
| 5 | 1-tomato/cucumber :2 -Pepper | 19.86 | 5.11 | 21.44 | 1.37 |
| 5 | 2-tomato/cucumber :3 -Pepper | 29.45 | 6.30 | 29.97 | 1.25 |
| 5 | 2-tomato/cucumber :3 -Pepper | 30.42 | 7.38 | 29.44 | 1.51 |
| 5 | 2-tomato/cucumber :3 -Pepper | 30.41 | 7.30 | 29.36 | 1.31 |
| 8 | 1-tomato/cucumber :2 -Pepper | 29.51 | 8.34 | 32.50 | 1.19 |
| 8 | 1-tomato/cucumber :2 -Pepper | 27.73 | 8.34 | 33.52 | 1.27 |
| 8 | 1-tomato/cucumber :2 -Pepper | 30.92 | 8.69 | 30.83 | 1.21 |
| 8 | 2-tomato/cucumber :3 -Pepper | 45.83 | 11.38 | 45.89 | 0.85 |
| 8 | 2-tomato/cucumber :3 -Pepper | 48.20 | 11.25 | 45.61 | 0.97 |
| 8 | 2-tomato/cucumber :3 -Pepper | 49.81 | 12.23 | 45.59 | 1.10 |
| | | **388.05** | **96.04** | **388.07** | **15.03** |

## Table 5.4: Revenue analysis of the aquaponic system

| Variables (R) | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| **Revenue from fish** | | | |
| Fish Output (kg) | 319 | 319 | 319 |
| Price / kg | 55 | 55 | 55 |
| **Total revenue (Fish)** | **17,545** | **17,545** | **17,545** |
| **Revenue from vegetable** | | | |
| Price of tomato R/kg | 10 | 13 | 10 |
| Output Kg | 263 | 263 | 526 |
| **Total revenue (tomato)** | **2,630** | **3,419** | **5,260** |
| Price of sweet pepper R/kg | 35 | 40 | 35 |
| Output Kg | 59 | 59 | 118 |
| **Total revenue (Sweet pepper)** | **2,065** | **2,360** | **4,130** |
| Price of cucumber R/kg | 12 | 20 | 12 |
| Output Kg | 261 | 261 | 522 |
| **Total revenue (cucumber)** | **3,132** | **5,220** | **6,264** |
| Price of Basil /kg | 250 | 260 | 250 |
| Output Kg | 17 | 17 | 34 |
| **Total revenue (Basil)** | **4,250** | **4,420** | **8,500** |
| **Total revenue** | **29,622** | **32,964** | **41,699** |

### 5.3.5 Financial analysis

The financial analyses of the low-cost aquaponic system were performed using the cost analysis (Section 5.3.6.1) and revenue analysis (Section 5.3.6.2) to determine the overall economic and financial viability of low-cost aquaponic systems in South Africa.

#### Break-even analysis

A break-even analysis was performed on the fish and the plants cultured to determine the minimum price and quantity for the fish and each plant to cover the total production cost. Subsequently, the break-even prices were combined with the prevailing market price to determine the anticipated profit margin from sales of fish and crops.

#### Cash flow analysis

The cash flow statement was projected over five years for the operation of the low-cost aquaponic system. The cash flow was calculated by subtracting annual operating cost, fixed cost, loan and interest repayment from the annual gross revenue. Annual projected operating costs for the subsequent four years were adjusted using the estimated inflation rate. The cash flow values were subsequently used to determine the estimated payback period of capital investment of the system.

## Income statement / Profit and loss statement

The income statement was derived from the following sequence of calculations in a specific format (Hopkin *et al.*, 1973). Firstly, the gross profit is calculated by subtracting the direct cost of sales from the total revenue. Subsequently, the net profit (net profit before tax and net profit after tax) is calculated using the following formulas:

I. *Gross profit = Revenue – Direct cost.*
II. *Net profit before tax = Gross profit – (operating cost + depreciation + Interest)*
III. *Net profit after tax = Net profit before tax – Tax* (Hopkin *et al.*, 1973)

## Financial indicators

Various financial indicators are frequently used in the financial feasibility model; however, the Net Present Value (NPV) and Internal Rate of Return IRR are the two commonly used financial indicators in financial management (Hopkin *et al.*, 1973) which were used in addition to Profitability Index (PI).

## Net present value (NPV)

The NPV is determined by calculating the difference between the present value of cash inflows and the present value of cash outflows over a period of time (Hopkin *et al.*, 1973). This was done by discounting the cash flow to the present time using a discounted rate.

For the NPV of an investment to be accepted, the value should be positive and rejected if the NPV is negative (Ross *et al.*, 2008). The NPV formula is as follows:

NPV = (Cash flows) / (1+r)i

I = Initial Investment

Cash flows = Cash flows in the time period

r = Discount rate

i = time period

**Internal rate of return IRR**

The internal rate of return (IRR) is a financial metric used for estimating the profitability of potential investments (Hopkin *et al.*, 1973). The IRR is a discount rate that makes the NPV of all the cash flows from a particular project to be equal to zero. Due to the nature of the IRR formula, however, it cannot be calculated analytically but either through trial-and-error or using software programmed to calculate IRR. The higher the IRR, the more profitable the venture. The IRR calculations are as follow:

$$0 = NPV = \sum_{n=0}^{N} \frac{CF_n}{(1+IRR)^n}$$

where:

*CFn* = Net cash inflow during the period *n*

*n* = Each period

N = Holding period

NPV = Net Present Value

IRR = Internal Rate of Return

**Profitability Index (PI)**

The profitability index (PI), also referred to as value investment ratio (VIR), or profit investment ratio PIR, is an index that determines the relationship between the costs and benefits of a proposed project, using the following ratio (Hopkin *et al.*, 1973):

Profitability index = Present value of future cash flows / Capital cost.

The Financial analysis was for this study was run on Microsoft Excel software program.

**Profit Margin**

Profit margin measures the profitability of a business activity, essentially calculated by finding the net profit as a percentage of the revenue.

## 5.4 Results

### 5.4.1 Price trend analysis of tomato, sweet pepper and cucumber

The price of tomato peaked in May (R9.09/kg) and July (R8.04/kg) 2014, April (R8.70/kg) and November (R9.22/kg) 2015, April (R8.81/kg) and December (R7.47/kg) 2016, October (R7.26/kg) and December (R7.88/kg) 2017, and in May (R11.34/kg) and October (R8.35/kg) 2018 (Figure 5.1).

Sweet pepper had peak prices in April (R13.85/kg) and July (R12.50/kg) 2014, October (R11.95/kg) and December (R10.59/kg) 2015, April (R12.05/kg) and October (R14.44/kg) 2016, April (R12.81/kg) and October (R13.54/kg) 2017 and October (R15.07/kg) and December (R19.40/kg) 2018 (Figure 5.2).

The price of cucumber peaked in June (R10.36/kg) 2014, August (R8.94/kg) 2015, May (R11.12/kg) 2016, October (R12.84/kg) 2017, and September (R18.22/kg) 2018 (Figure 5.3).

The price of basil peaked in September (R13.59/kg) 2014, June, July and November (R 8.75/kg) 2015, September 2016 (R 21.4/kg), February 2017 (R 26.04/kg) and January 2018 (R 10.3/kg) (Figure 5.4).

The average annual price (R/kg) of the vegetables were as follows: 2014 (6.64 ± 1.20), 2015 (6.59 ± 1.06), 2016 (6.04 ± 1.47), 2017 (6.12 ± 1.41) and 2018 (7.00 ± 1.84) for tomato; 2014 (10.49 ± 1.88), 2015 (8.64 ± 2.11), 2016 (10.66 ± 1.75), 2017 (9.83 ± 2.14) and 2018 (11.12 ± 3.47) for pepper; 2014 (4.38 ± 2.55), 2015 (5.27 ± 2.70), 2016 (4.80 ± 2.70), 2017 (7.93 ± 2.86) and 2018 (11.45 ± 4.40) for cucumber; and 2014 (7.84 ± 4.32), 2015 (6.35 ± 3.85), 2016 (13.25 ± 4.60), 2017 (10.33 ± 5.76) and 2018 (6.65 ± 2.25) for basil (Figure 5.5). The average price (R/kg) of tomato, pepper, cucumber and basil were

6.48 ± 0.40, 10.15 ± 0.96, 6.77 ± 2.96 and 8.89 ± 2.90 respectively from 2014 to 2018 (Figure 5.6).

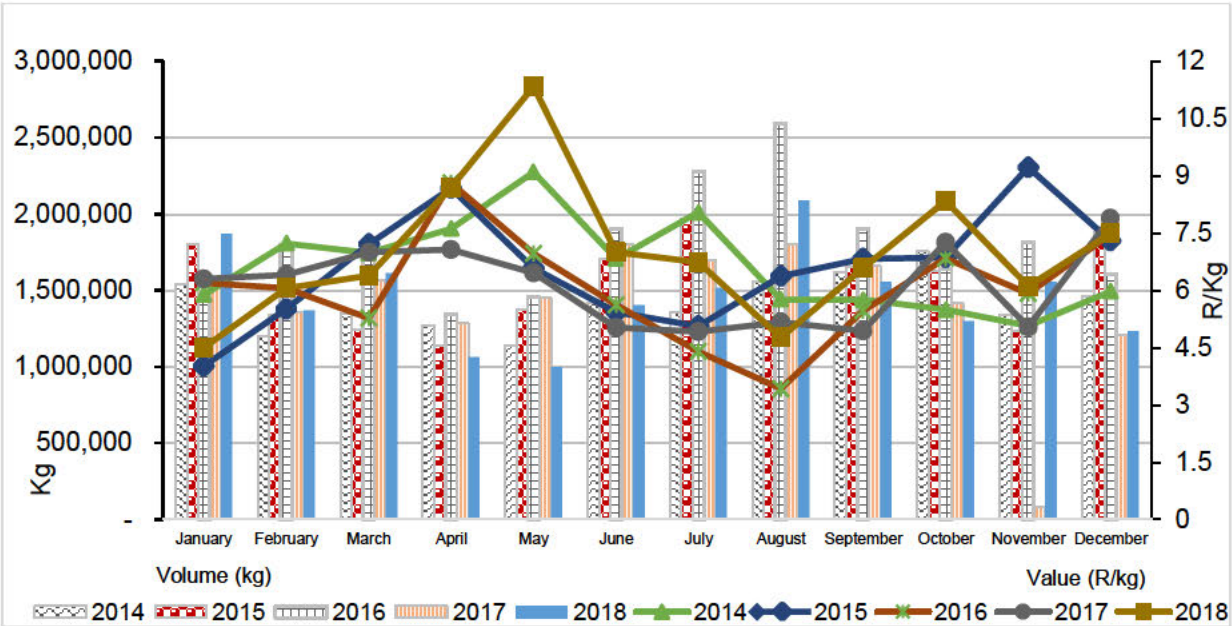



**Figure 5.1: Price and production trend of tomato 2014 – 2018** (DAFF, 2014-2018)

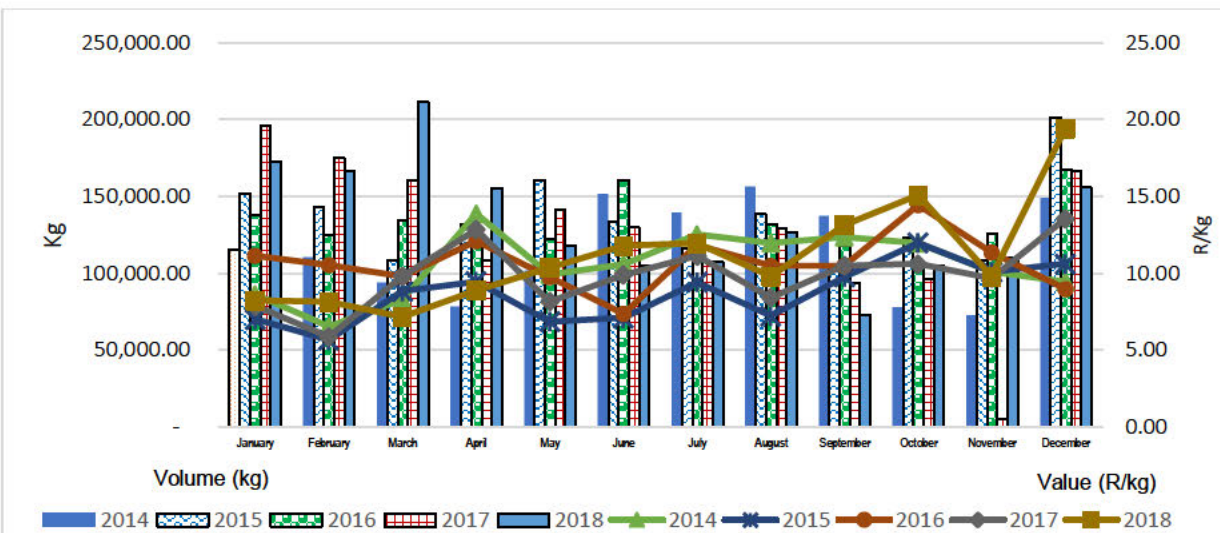



**Figure 5.2: Price and production trend of sweet pepper 2014 – 2018**

(DAFF, 2014-2018)

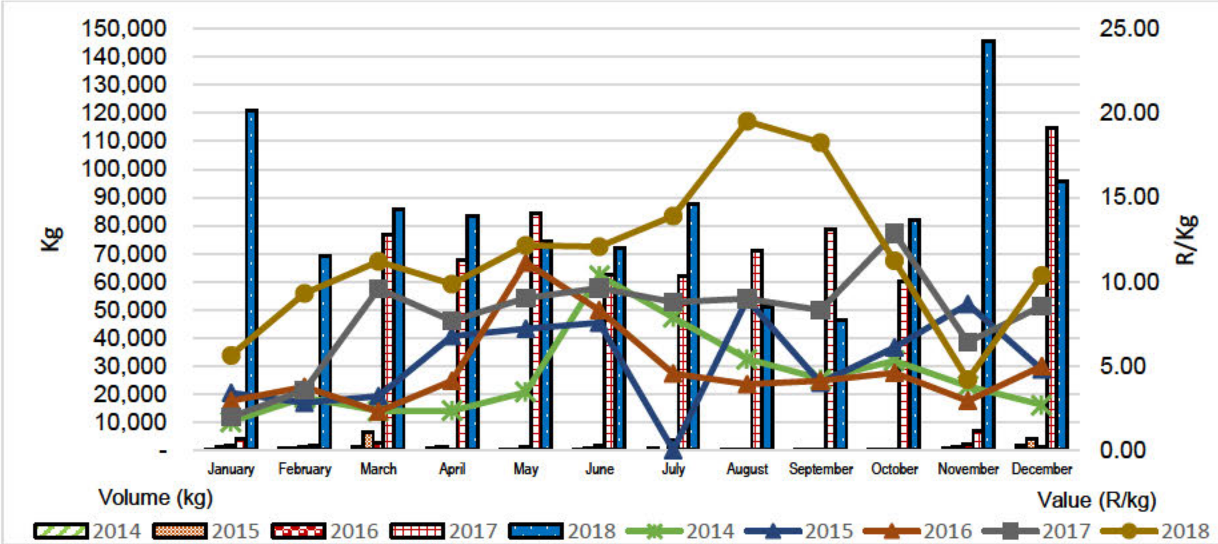



**Figure 5.3: Price and production trend of cucumber 2014 – 2018** (DAFF, 2014-2018)

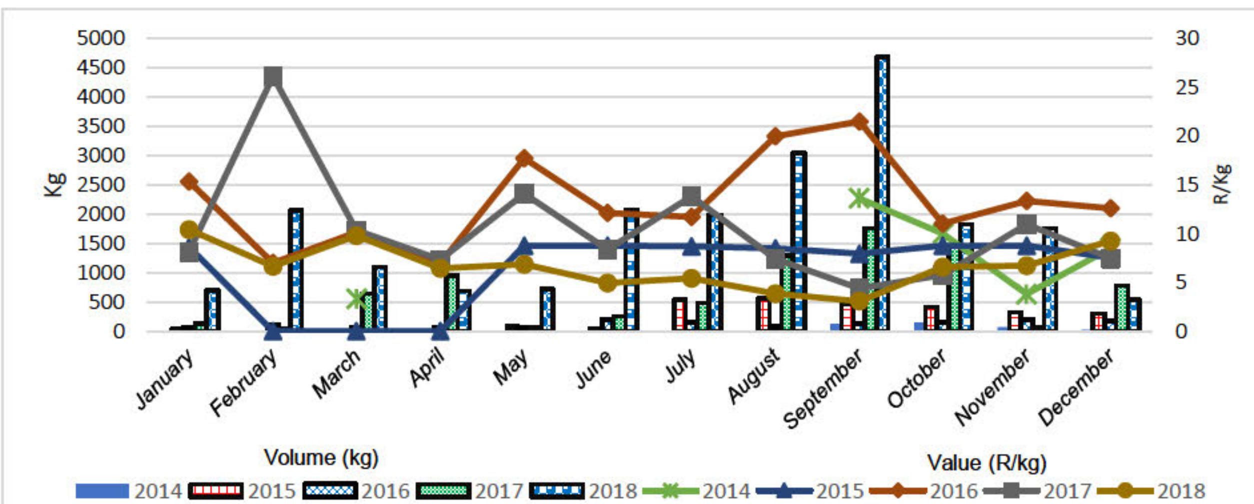
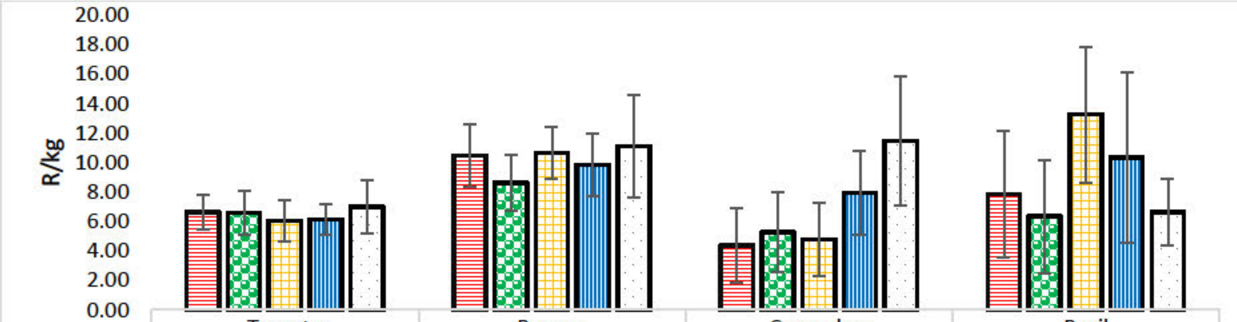
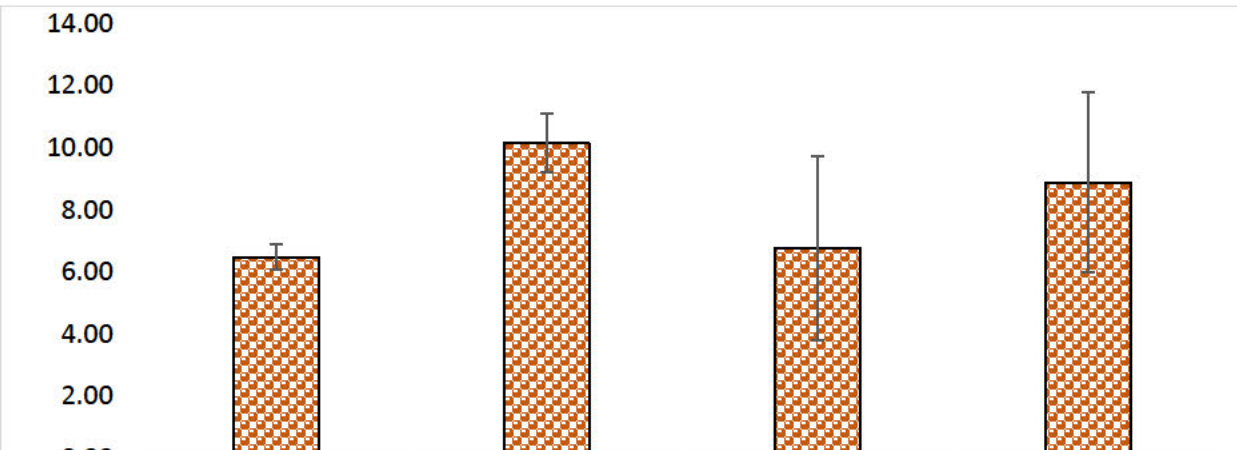



**Figure 5.4: Price and production trend of Basil 2014 – 2018** (DAFF, 2014-2018)




| | Tomato | Pepper | Cucumber | Basil |
|---|---|---|---|---|
| 2014 | 6.64 | 10.49 | 4.38 | 7.84 |
| 2015 | 6.59 | 8.64 | 5.27 | 6.35 |
| 2016 | 6.04 | 10.66 | 4.80 | 13.25 |
| 2017 | 6.12 | 9.83 | 7.93 | 10.33 |
| 2018 | 7.00 | 11.12 | 11.45 | 6.65 |

**Figure 5.5: Average annual price trend of Tomato, Pepper, Cucumber and Basil 2014 – 2018** (DAFF, 2014-2018)




| | Tomato | Pepper | Cucumber | Basil |
|---|---|---|---|---|
| Series1 | 6.48 | 10.15 | 6.77 | 8.89 |

**Figure 5.6: Average price of Tomato, Pepper, Cucumber and Basil from 2014 – 2018** (DAFF, 2014-2018)

### 5.4.2 Economic analysis

#### Cost analysis

The total setup and operational cost of the low-cost gravel bed aquaponic system are made up of the capital/fixed cost, operating cost and direct cost as highlighted in Table 5.5. The total capital cost was R46,200 and total depreciation charge of R4,620 per year (Table 5.6). The total variable cost, which consists of the operating cost and direct cost, was R 30,112 (Table 5.5).

#### Revenue analysis

The revenue analysis was modelled into three scenarios, comprising the total revenue from the yield of fish and plant biomass. The total revenue for scenario I based on minimum realistic market price (worst case scenario) was R29,622, total revenue for scenario II based on realistic best market price was R32,952, and third revenue model (scenario III) based on doubling the plant production capacity of the aquaponics was R41,687 (Table 5.7).

#### Income statement

The income statement is modelled into four scenarios, as detailed in section 5.3.5. Scenario I had a gross profit of R12,560 (42 %) and a net profit of –R6,471 (-22 %), scenario II, had a gross profit of R16,050 (48 %) and a net profit of –R 2,982 (-9 %), scenario III, had a gross profit of R24,637 (59 %) and a net profit of R5,606 (13 %) and scenario IV, had a gross profit of R16,050 (48 %) and a net profit of –R 23,482 (-52%) (Table 5.8).

**Cash flow statement**

The total cash inflows for scenario I, II and III based on capital cost financed by equity contribution were R105,922, R109,411 and R117,999, respectively. The cash inflow for scenario IV based on capital cost financed by term loan was R133,100. The net cash flow due to the difference between the total cash inflows and outflows for scenario I, II, and III were R28,260, R31,750 and R40,337, respectively. The net cash flow for scenario IV was R21,631 (Table 5.10).

**Financial indicators**

The financial performance for the four scenarios is as follows: scenario I (ROE – 8 %, NPV R81,466, IRR 13 % and Profitability Index 0.354); scenario II (ROE – 4 %, NPV R84,639, IRR 15 %, Profitability Index 0.396); scenario III (ROE 15 %, NPV R 96,031, IRR – 22% and Profitability Index 0.55) and scenario IV (ROE, NPV, IRR and Profitability Index were all negatively skewed) (Table 5.11).

## Table 5.5: Total aquaponic setup cost

| Fixed Assets | R | R |
|---|---|---|
| Land & Building (Greenhouse Tunnel) | 40,000 | |
| Gravel Bed Hydroponics Wares | 24,800 | |
| Recirculating Aquaculture System (RAS) Wares | 13,200 | |
| Water Quality Test Kit | 6,000 | |
| Others | 2,200 | |
| **Total Fixed Assets** | **86,200** | **86,200** |
| **Working Capital** | | |
| **Operating Cost** | | |
| Electricity/Diesel | 11,879 | |
| Motor Vehicle Running Costs | 900 | |
| Miscellaneous expenses | 283 | |
| **Direct Cost** | **17,050** | |
| **Total Working Capital** | **30,112** | **30,112** |
| **Total Capital Requirement** | | **116,312** |

## Table 5.6: Fixed/Capital cost and Depreciation

| Aquaculture Component | Cost ( R ) | Rate | Depreciation Charge ( R ) |
|---|---|---|---|
| Greenhouse Tunnel | 40,000 | 10% | 4,000 |
| Fish Tanks | 5,500 | 10% | 550 |
| IBC tank (Bio-Mech filter-Sump | 1,300 | 10% | 130 |
| Gravel media | 1,000 | 10% | 100 |
| Weighing Scale | 200 | 10% | 20 |
| Hand Net | 150 | 30% | 50 |
| Air Pump | 4,400 | 25% | 1,100 |
| Air Stones and piping | 650 | 10% | 65 |
| **Total** | **53,200** | | **6,015** |
| **Hydroponic Components** | | | |
| Electrical Pumps 0.5 HP | 1,800 | 25% | 450 |
| Plant Trough | 3,600 | 10% | 360 |
| PVC pipes and Fittings | 7,500 | 15% | 1,250 |
| Basic plumbing tools | 3,000 | 10% | 300 |
| Bell Siphons | 2,400 | 10% | 240 |
| Gravel (19mm) 40 Kg/bag | 5,000 | 10% | 500 |
| Plant trough Stand | 1,500 | 10% | 150 |
| Total | 24,800 | | |
| Water test Kits | | | |
| Water Kits | 6,000 | 25% | 1,500 |
| **Total** | **6,000** | | |
| Others | 2200 | 10% | 220 |
| **Total** | **46,200** | | **4,970** |

## Table 5.7: Revenue Models

| Variables (R) | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| Revenue (Fish) | 17,545 | 17,545 | 17,545 |
| Revenue (tomato) | 2,630 | 3,419 | 5,260 |
| Revenue (Sweet pepper) | 2,065 | 2,360 | 4,130 |
| Revenue (cucumber) | 3,132 | 5,220 | 6,264 |
| Revenue (Basil) | 4,250 | 4,420 | 8,500 |
| **Total revenue** | **29,622** | **32,964** | **41,699** |

**Table 5.8: Income statement/profit and loss statement**

| Variables | R Scenario 1 | R Scenario 2 | R Scenario 3 | R Scenario 4 |
|---|---|---|---|---|
| Revenue | 29,610 | 33,100 | 41,687 | 33,100 |
| Cost of Sales | 17,050 | 17,050 | 17,050 | 17,050 |
| Gross Profit | 12,560 | 16,050 | 24,637 | 16,050 |
| Profit Margin | 42% | 48% | 59% | 48% |
| | | | | |
| Utility | 1,350 | 1,350 | 1,350 | 1,350 |
| Electricity Cost | 11,879 | 11,879 | 11,879 | 11,879 |
| Miscellaneous Costs | 283 | 283 | 283 | 283 |
| Motor Vehicle Running Cost | 900 | 900 | 900 | 900 |
| Depreciation | 4,620 | 4,620 | 4,620 | 4,620 |
| Term loan interest | - | - | - | 20,500 |
| **Total Admin and Operating expenses** | **19,032** | **19,032** | **19,032** | **39,532** |
| **Profit before Tax** | **-6,471** | **-2,982** | **5,606** | **-23,482** |
| **Margin** | **-22%** | **-9%** | **13%** | **-71%** |
| | **-** | **-** | **-** | **-** |
| **Profit After Tax** | **-6,471** | **-2,982** | **5,606** | **-23,482** |
| **Net profit margin** | **-22%** | **-9%** | **13%** | **-71%** |

**Table 5.9: Break-even analysis**

| Variables | Quantity (Kg) | Total Cost (R) | Break-even Price (R/kg |
|---|---|---|---|
| Tilapia | 319 | 17,545.00 | 55 |
| Tomato | 388 | 4656 | 12 |
| Sweet Pepper | 96 | 3264 | 34 |
| Cucumber | 388 | 6984 | 18 |
| Basil | 15 | 3630 | 242 |

## Table 5.10: Cash flow statement

| Variables | R<br>Scenario 1 | R<br>Scenario 2 | R<br>Scenario 3 | R<br>Scenario 4 |
|---|---|---|---|---|
| **INFLOWS** | | | | |
| Equity/Ordinary Shares | 116,312 | 116,312 | 116,312 | - |
| Term Loan | - | - | - | 100,000 |
| Revenues | 29,610 | 33,100 | 41,687 | 33,100 |
| Total | **145,922** | **149,411** | **157,999** | **133,100** |
| **OUTFLOWS** | | | | |
| Direct Costs | -17,050 | -17,050 | -17,050 | -17,050 |
| Electricity | -1,350 | -1,350 | -1,350 | -1,350 |
| Generator Fuel Cost | -11,879 | -11,879 | -11,879 | -11,879 |
| Miscellaneous costs | -283 | -283 | -283 | -283 |
| Motor Vehicle Running Cost | -900 | -900 | -900 | -900 |
| Term loan principal repayment | - | - | - | -13,307 |
| Interest Payments | - | - | - | -20,500 |
| Capital Expenditure | -46,200 | -46,200 | -46,200 | -46,200 |
| Tax Payment | - | - | - | - |
| **Net Cash flows** | **28,260** | **31,750** | **40,337** | **21,631** |
| Cash C/F | - | - | - | - |
| **Closing cash balance** | **68,260** | **71,750** | **70,337** | **21,631** |

## Table 5.11: Financial Indicators

| Variable | R<br>Scenario 1 | R<br>Scenario 2 | R<br>Scenario 3 | R<br>Scenario 4 |
|---|---|---|---|---|
| **Turnover** | 29,610 | 33,100 | 41,687 | 33,100 |
| **Direct Cost** | 17,050 | 17,050 | 17,050 | 17,050 |
| **GP Margins** | 42% | 48% | 59% | 48% |
| **PBT** | -6,471 | -2,982 | 5,606 | -26,971 |
| **PAT** | -6,471 | -2,982 | 5,606 | -26,971 |
| **Net Profit Margin** | -22% | -9% | 13% | -91% |
| **ROE** | -8% | -4% | 7% | #DIV/0! |
| **NPV** | 81,466 | 84,639 | 92,445 | -25,152 |
| **IRR** | 13% | 15% | 19% | #NUM! |
| **Profitability Index** | 0.354 | 0.396 | 0.503 | |

## 5.5 Discussion

### 5.5.1 Price trend analysis of tomato, sweet pepper and cucumber

The National Fresh Produce Markets (NFPMs) is an enterprise established and structured as a result of combined efforts between the fresh produce industry stakeholders and the government to coordinate standard operating procedures in the NFPMs in South Africa (DAFF, 2016). The NFPMs perform essential functions of price determination, distribution and marketing of fresh produce in South Africa (Rathogwa *et al.*, 2000). This study analyzed monthly traded price and quantity of fresh produce of interest, i.e. tomato, sweet pepper and cucumber, from 2014 to 2018 based on data available on Durban fresh produce market. It was observed from the price trend analysis (Figure 5.1 and 5.2) that the price of tomato and sweet pepper generally peaked around April and June, and between October and December. The price of cucumber mainly peaked in August 2017 and October 2018 (Figure 5.3). Prices of tomato, sweet pepper and cucumber were observed to be generally higher when production outputs were relatively lower, driven by the market forces, i.e. demand and supply. The National Agricultural Marketing Council (NAMC) study also reported prices of fresh produce being generally high in the NFPMs, when traded produce quantities are low and vice versa, thus suggesting that the price determination functions effectively (Rathogwa *et al.*, 2000). The National Fresh Produce Markets are located in major cities in South Africa and vary in the volume and capacity of fresh produce traded. The Johannesburg fresh produce market is the largest in terms of volume and turnover, followed by the Tshwane, Cape Town and Durban in South Africa (JFPM, 2016).

Vegetables are an essential part of the annual crops of the South African agricultural sector and significantly contributes to the creation of employment and the generation of revenues for the municipalities (MARKET, 2017). The vegetable industry performance is generally dependent on climatic conditions, i.e. flood, drought, hail and heatwave and this impact all stages of crop production (JFPM, 2016). These factors are taken into considerations in the analysis of volume and prices of traded commodities. Aquaponic producers can, therefore, plan their vegetable production cycles (Table 6.16) and target the supply of fresh produce to the market during the months when traded volumes from conventional sources are expected to be low due to climatic conditions and other factors in order to benefit from higher market pricing (Section 6.5.5). Aquaponic production of fresh produce will largely benefit from higher market pricing during the peak price period of April – June and October – December is driven by market forces of demand and supply (Figure 5.1, 5.2, 5.3 and 5.4). Aquaponic producers can, therefore, target the production of tomato and pepper to benefit from higher market prices from April to June and October to December while cucumber production and harvesting can be scheduled to leveraged higher market prices between September and November (Table 6.16). The price of basil appears to be reasonably stable all-year-round. Production volume from the conventional farming system, however, fluctuates due to climatic conditions unlike aquaponic production of basil which is not affected by prevailing climatic conditions due to production in a controlled environment.

The restructuring of the FPMs for equitable access to all producers, including small-scale producer farmers through training, provision of market information, receiving and selling their fresh produce as well as linking the small-scale producers with service suppliers

(Chikazunga *et al.*, 2008), will immensely benefit small-scale aquaponic producers in marketing their products.

### 5.5.2 Economic viability analysis

The financial viability of the model low-cost aquaponic system in South Africa was assessed using cost analysis, revenue analysis, income and cash flow statement as well as financial performance indices.

**Cost Analysis**

The capital cost for the construction of the gravel bed aquaponic system includes the cost of the gravel bed hydroponic component, which accounted for 55 percent (R24, 800) of the capital expenditure. The aquaculture component accounted for 28 percent (R13, 200); the water quality test kits and other miscellaneous items accounted for 18 percent (8, 200). The cost of labour was not factored into the construction cost, as the researcher did the construction; thus, the total capital cost summed up to R 46, 200. A straight-line depreciation method in line with related studies (English, 2015; Tokunaga *et al.*, 2015) was used to determine the annual fixed cost of R 4,620 (Table 5.6).

The variable cost is made up of the direct and operational cost variables (R 30,112) as highlighted in Table 5.5. The direct cost consists cost of fingerlings, fish feed, plant seedling and additives. The direct cost accounted for 57 percent (R17, 050) of the total variable cost, mainly made up of feed and fingerlings cost. English (2015) also reported the cost of feed and fingerlings represented a vast majority of the variable cost in the study of the economic feasibility of aquaponics in Arkansas.

The operational cost, which accounted for 43 percent (R13, 062) of the total variable cost, is predominantly made up of electricity cost. The electricity cost during the study was R11,879, approximately 91 percent of the operational cost. The cost of electricity is a significant variable cost incurred that had a huge impact on the net profit margin. Tokunaga *et al.* (2015) reported electricity as the variable with the second-highest cost in their study of the economics of small-scale aquaponics in Hawaii. Energy-efficient pumps and appliances are recommended in aquaponic operations to reduce the cost of operation significantly. In this study, low energy consuming water and aeration pumps were used to minimize the cost of electricity, as they were the only components that required electricity, as they are essential in aquaponic operation (Tokunaga *et al.*, 2015).

The other variables of the operating cost were transportation, water and miscellaneous. The total volume of water used, in addition to water added to the system as replacements for water lost mainly due to evapotranspiration was 45,000 L at the rate of R 30 /kiloliter (R1,350) within the period of 12 months the study lasted.

The cost of labour was not factored in this financial analysis as the researcher was responsible for the maintenance and management of the aquaponic system during the study period. The techno-economic viability study of aquaponics in South Africa also reported small-scale aquaponic operators being responsible for the operations and management of their setup (Lapere, 2010). The sum total of the capital cost of R 46, 200 and variable cost of R30, 112, made up the capital requirement for the setup and operationalization of the aquaponic system.

### Revenue Analysis

The revenue model for this study includes revenue from fish biomass, the marketable yield of tomato, sweet pepper, cucumber and basil. Price per kg of fish was determined using the prevailing market rate for locally produced tilapia; thus, the total fish yield of ~ 319 kg at the rate of R55 /kg resulted in total revenue of R17,533. Revenue from tilapia production accounted for ~ 59, 53, 42, and 59 percent for scenarios I, II, III and IV respectively of the total revenue from the aquaponic systems. The revenue for tomato, sweet pepper and cucumber were modelled, taking into consideration four scenarios (section 5.3.1). Based on scenario I and IV, i.e. the worst-case price scenario or minimum market price, the combined revenue for tomato (R2,630), sweet pepper (R2,065), cucumber (R3,132) and basil (R4,250) was R12,077, accounting for 41 percent of the total revenue (R29, 610). Total plant revenue from scenario II, i.e. the highest realistic market price or best-case scenario, was accounted for ~ 47 percent (R15, 419) of the total revenue. The combined revenue from fish and plant for scenario II was R 32, 952. The plant revenue for scenario III, i.e. doubling plant production output, was R24,154 (~ 58 %) and combined revenue of R41,687. From the cost analysis, the production cost of fish represented at least 90 percent of the total variable cost, thus making the production of tilapia in a small-scale aquaponics unprofitable and not competitive with the imported tilapia from China. The current retail price of whole frozen imported tilapia ranges from R 25 to R 35/kg in many retail outlets, which is lower than the average local production cost of R45/kg. Factors such as economies of scale (minimum production of 50 tons), faster-growing tilapia species, i.e. *O niloticus* and niche product should be considered, to achieve competitive pricing and profitability (DAFF, 2018). Attaining economies of scale in small-scale aquaponic operations appears unrealistic with fish production; however, this can be achieved with plant production in order to attain profitability. Some studies (Bailey *et al*. 1997; Holliman, Adrian, and Chappell 2008; Baker 2010; Tokunaga *et al*. 2015; English, 2015) on the economic viability of both small and large-scale aquaponic operations, found that fish production was unprofitable due to high cost of production, while profitability was predominantly driven by vegetable production. This study shows that scenario III revenue model, where revenue from plants account for 58 percent of total revenue appeared to be more financially viable compared to scenario I and IV where revenue from fish represented 59 percent of total revenue.

**Financial analysis**

The financial analysis of the aquaponic system was performed using income statement analysis, break-even analysis, cash flow statement, NPV, ROI, IRR and Profitability Index.

**Income statement/profit and loss statement**

The income statement aka profit and loss statement document the gross profit, i.e. the difference between the total revenue and direct cost, the operational expenses and the net profit, i.e. the difference between the gross profit and operation expenses. The income statement was modelled into four scenarios, as detailed in the study assumptions in section 5.3.1. The difference in the scenario I, II, and III were based on the different production outputs and revenue models, as discussed in the revenue analysis. Scenario

IV modelled a case study of funding the required capital outlay for the setup of the aquaponic system from a term loan as enumerated in Appendix AI. The net profit from scenario IV (–R 23, 482; –71 %) demonstrated the poorest performance due to term loan repayment and interest charges, compared to scenario I (–R 6,471; - 22 %), scenario II (–R2, 982; –9 %) and scenario III (R5,606; 13 %). Lapere (2010) also reported poor financial performance with aquaponic farms financed by debt due to loan repayments and interest charges. The annual depreciation cost of fixed assets was captured under the operating expenses according to international financial reporting standards; however, these are non-cash deductions.

**Break-even analysis**

The break-even analysis shows the minimum price the fish and plant yield can be sold without incurring a financial loss. The analysis shows that the selling price of tilapia must be higher than R 55/kg. The minimum price for tomato was R 12/kg, sweet pepper R 34/kg, cucumber R 18/kg and basil R 242 /kg (Table 5.9). Using the scenario II revenue model, the selling price of fish was R 55 /kg, tomato R13/kg, sweet pepper R 40/kg, cucumber R 20 /kg and basil R 260/kg. English (2015) reported tilapia being sold at 98 percent below the break-even point due to the prevailing market price but reported profitability with the selling price of lettuce and basil.

### Cash flow analysis

The cash flows models were used to determine the liquidity and payback periods of the invested capital in the aquaponic system under the four financial scenarios as described in section 5.3.1. Scenario IV showed the lowest net cash flow after the first financial year, with projected cash flow showing a negative net cash flow at the second year of operation, due to high cost of debt servicing (Appendix AI). Scenarios I, II and III demonstrated good cash flows due to lack of interest charges and loan repayments. Due to lower turnover in scenario I and II, they had a payback period of 2.5 and 1.5 years respectively, compared to Scenario III with a payback period of 1 year; thus, scenario III had the shortest payback period and the highest net cash flow.

### Financial Indices

The overall economic viability and financial performance of the aquaponic setup were assessed using the turnover, direct cost, return on investment (ROI), NPV, IRR and profitability index (PI) as financial indicators (Table 5.11). The financial indicators were modelled using the four scenarios described in section 5.3.1. Scenario I and IV both had a negative ROI and IRR. Scenarios II and III both showed positive ROI, NPV however, scenario I had a negative IRR while scenario III was the only model that showed positive IRR. All the four models had a PI that was less than one. The ROI measures the profitability of the invested capital in setting up and operating the aquaponic system in relation to its cost. Scenario III was the only positive ROI (7 %). The NPV determines the net cash flow of the aquaponic operations over a ten year period; therefore, a positive

NPV recorded in scenario I. (R81,466), scenario II (R84,639) and scenario III (R92,445) showed the projected revenues generated by the aquaponic operation over a period of ten years surpasses the expected costs, using the present value of the rand. Scenarios I, II and II all showed a positive NPV therefore, they were profitable, while scenario IV with a negative NPV (–R 48,571) will result in a net loss. Scenario III, with an IRR of 22 %, showed the best financial performance based on higher turnover and profitability. Profitability index is benchmarked against the value of 1.0; therefore, PI greater than 1.0 indicates positive projected future net cash flows. The PI (scenario: I = 0.35, II = 0.39, III = 0.50 and IV = negative) determined from the four financial scenarios from this study were all less than the benchmark value of 1.0, therefore, indicates negative future net cash flows. The aquaponic operation needs to attain economies of scale in production output, to attain a profitability index that is greater than 1.0 and overall desirable financial performance. To achieve a profitability index greater than 1.0 in an aquaponic operation, the minimum production output of fish must be 50 tons per year in South Africa (DAFF, 2018).

Some studies (Bailey *et al.,* 1997; Holliman *et al*., 2008) found that the fish production unit of aquaponics operation is unprofitable as recorded in this study. The intensive hydroponic production of vegetable was, therefore, suggested to drive the profitability of aquaponics production. A survey conducted on some international aquaponics operators by Love *et al*., (2015) indicated a significant relationship between the revenue from non-food aquaponics plant products and operational profitability. Small-scale aquaponic growers in South Africa can also explore the production of high value non-food plants such as authorized cannabis (*Cannabis sativa*) production for medicinal uses.

The location of aquaponics operations vis-à-vis its target markets also plays a vital role in profitability; therefore, aquaponics farms must leverage premium price markets (Tokunaga *et al.*, 2015). Aquaponics farmers in South Africa can leverage geographical locations such as highbrow neighborhoods and niche markets to drive higher prices and profitability of the operation.

The financial indicators of this study clearly showed that the adoption of conventional aquaponic cultural practices (Technique I) which largely focus on maximizing revenue output on tilapia production while adopting lower plant density and stem pruning planting method (see the following chapter for the discussion on this topic) was not economically viable in South Africa (Table 5.11). Based on the viable financial performance recorded by previous studies (Bailey *et al.* 1997; Holliman *et al*., 2008; Baker 2010; Tokunaga *et al*. 2015; English, 2015), and a higher cost benefits ratio recorded with the adoption of best cultural practices and planting schedule (Section 6.5.5), small-scale aquaponic operators can optimize production output and attain economic viability. The following chapter (Chapter 6) therefore, assessed the effects of varying stem pruning and plant density on the yield of plants and the financial indicators. The findings (Chapter 6) will thus inform the required fish to plant revenue model due to cultural technique adopted to attain economies of scale (Section 6.5.5).

## 5.6 Conclusion

The prices of fresh produce in South Africa are driven mainly by the forces of demand and supply, due to the effects of climatic conditions on the conventional production of fresh produce. The impacts of market forces on the price determination of fresh produce provide market opportunities for aquaponic producers to leverage, in order to achieve higher turnover and profitability, particularly during the peak price periods. The aquaponic operation here investigated showed poor financial performance with the adoption of conventional aquaponic cultural practice (Technique I and Scenario I) due to higher operating cost associated with fish production compared to plant production. A financial scenario which modelled a fish to plant revenue model of 42 to 58 % ratio showed positive financial indices with ROI, NPV and IRR, except for the profitability index that was lower than the benchmark of 1.0. The aquaponic operation must attain economies of scale with either fish or plant production, or with both fish and plant production, to achieve profitability index higher than the benchmark of 1.0. Due to a very high operational cost associated with fish production compared to vegetable production, it will be more cost-effective for smallholder aquaponic operators to attain economies of scale and higher profitability with a higher ratio of plant to the fish revenue model. This latter model should be recommended to small-scale aquaponic operators and prospective operators to drive sustainable and efficient food production systems to attain food security at household levels and local economic development in South Africa. Future studies to assess the financial performance of a small-scale aquaponic operation, adopting the fish to plant targeted revenue model of 30 to 70 % and 20 to 80 % will be needed to validate the economic viability of these models.

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# CHAPTER 6: BIOMASS YIELD OF FISH, TOMATO, SWEET PEPPER AND CUCUMBER IN A LOW-COST DESIGNED AQUAPONIC SYSTEM

## 6.1 Abstract

The combined yield of *Oreochromis mossambicus* and fruit crops – tomato, sweet pepper and cucumber were investigated in a low-cost designed gravel bed aquaponic system with the aim of maximizing total yield. The study was conducted from March 2018 to February 2019. Growth performance of fish was measured using growth rate parameters, length-weight relationship and condition factor. The effect of plant density and plant stem pruning was used to determine plant yield. Tomato, sweet pepper and cucumber were subjected to two plant density (5 and 8 plants.$m^2$). Tomato and cucumber plants were pruned to one stem and two stems, and sweet pepper plant to two stems and three stems. A complete randomized design in triplicate was used. An FCR of 1.25; 97.5 % survival rate; specific growth rate of 1.64 %, LWR $r^2$ of 0.945, regression coefficient b of 3.1 and condition factor K of 1.93 was recorded. Total yield, marketable yield, unmarketable yield, fruit mass and number fruits.$m^2$ was recorded. Tomato and cucumber plants pruned to two stems produced significantly (T-Test: df 10; $p < 0.05$) higher total and marketable yields than plants pruned to one stem. Sweet pepper plants pruned to three stems produced significantly (T-Test: df 10; $p < 0.05$) higher total and marketable yield than those pruned to two stems. A plant density of 8 plants.$m^2$, produced higher (T-Test: df 10; $p < 0.05$) total and marketable yield of tomatoes, sweet peppers and cucumbers compared to 5 plants.$m^2$. Biomass yield of aquaponics can be optimized for higher economic viability by manipulating environmental conditions, adopting strategic culture management practices and targeting higher market price through scheduled production.

**Keywords:** biomass yield, *Oreochromis mossambicus*, tomato, pepper, cucumber, aquaponics

## 6.2 Introduction

The suboptimal environmental conditions of South Africa which make the most part of the country unsuitable for conventional aquaculture production (Section 2.4.4.6), leaves the country with the option of adopting highly intensive and long term environmentally friendly technology such as aquaponics, (Section 4.5) to drive sustainable aquaculture development. This study assessed the yield of fish, tomato, pepper and cucumber grown in a low-cost designed gravel bed aquaponics based on the review of high yield culture technique success recorded by previous studies (Davis & Estes, 1993; Jovicich *et al.*, 1999; Jovicich *et al.*, 2004; Ghebremariam, 2007; Maboko & Du Plooy, 2008; Maboko & Du Plooy, 2009; Maboko *et al.*, 2012; Maboko, 2013) to attain economic viability.

Aquaponics is the integration of a recirculating aquaculture system with hydroponics, a soilless plant cultivation system (Section 1.4). This unconventional system of food (fish and plant) production utilizes the effluent waste from the aquaculture unit as a nutrients source for the plant production unit (hydroponics), aided by nitrifying bacteria which converts ammonia to nitrate, which is taken up by the plant, thus filtering the water for the fish. Aquaponics is suitable for highly intensive concurrent production of fish and plant, resulting in about 90 % water footprint save and significantly higher plant yield compared to conventional farming methods (English, 2015).

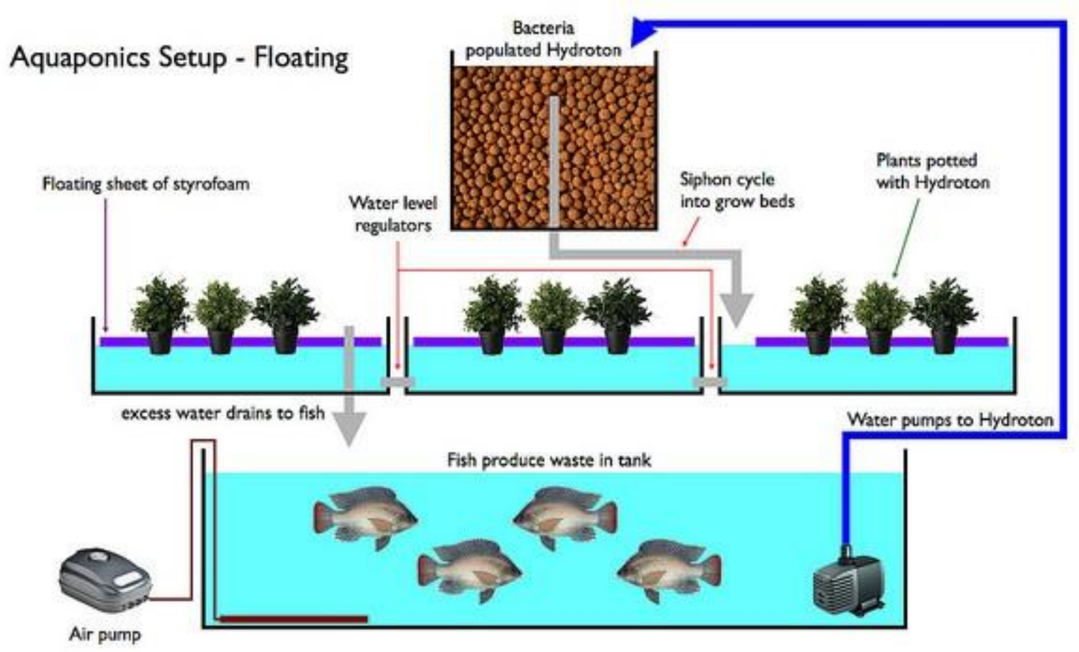


**Figure 6. 1: Simple aquaponic system setup. (source: https://www.primalsurvivor.net/aquaponic-gardening/)**

### 6.2.1 Operational dynamics of aquaponic system

In an aquaponic system, effluent water from the fish tank runs through filters, plant grow media and back to the fish tank in a continuous cycle (Figure 6.1) (Somerville et al., 2014). The filtration compartment consists of a mechanical filter, which captures solid wastes from the water and subsequently a biofilter which processes dissolved wastes (Somerville *et al.*, 2014). The biofilter provides adequate surface area for bacteria to oxidize toxic ammonia into nitrate, an accessible nutrient form for plant uptake, a process called nitrification (Somerville *et al.*, 2014). The nutrient water then runs through the plant grow beds, where the plants' take-up these nutrients via the roots and the water finally returns to the fish tank filtered (Somerville *et al.*, 2014). This process involves the management of an ecosystem where fish, plants, and bacteria symbiotically exist and function together to provide a healthy and balanced environment for growth (Figure 6.2).

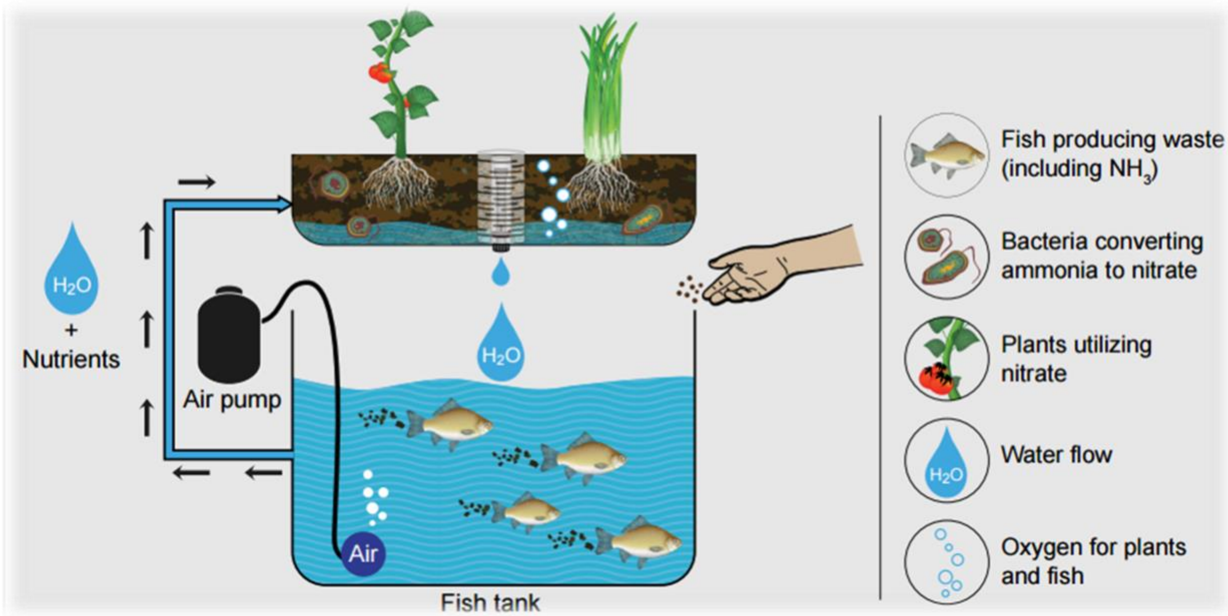


***Figure 6. 2: Biological components in aquaponics*** **(Somerville *et al*., 2014)**

### 6.2.1.1 Important components of aquaponics

Aquaponic systems typically consist of essential components which include fish tank, mechanical filter, biofilter, and plant grow units (hydroponics). All aquaponic systems require energy for circulation and aeration of water through the components irrespective of the type of design adopted (Jena *et al.*, 2016).

**Fish Tank**

Selection of fish tank type is essential when setting up an aquaponic unit, as fish tanks could account for about 20 % of the total setup cost (Somerville *et al.*, 2014). Important factors to be considered in selecting a fish tank are material, shape and colour. Round tanks with flat base are often recommended as they allow water to circulate consistently and aggregate solid waste close to the tank centre using centripetal force (Jena *et al.*, 2016). Square tanks with flat bottoms are also good; however, not as efficient as circular tanks in solid waste removal (Jena *et al.*, 2016).

Round tanks were used for this study for efficient water circulation and solid waste management due to high stocking density used in this work.

**Mechanical Filtration**

This is the process of solid and suspended feacal and uneaten feed removal from fish tanks (Rakocy, 2012). Waste management is an essential aquaculture practice in aquaponics as accumulated solid wastes potentially pose deleterious effects to both the fish and the system due to clogging thus disrupting the flow of water (Yavuzcan Yildiz *et al.*, 2017). Mechanical filters are designed in various forms which include sand/bead filter, sedimentation tanks, and radial-flow clarifiers (Bao *et al.*, 2019). The choice of mechanical filter to be used in an aquaponic setup is dependent on the stocking density and the quantity of solid waste to be removed (Lekang, 2008). A gravel column filtration system was adopted for this study, designed to perform a dual purpose of both mechanical and biological filtration, thus reducing footprint and setup cost.

### Biofiltration

Biofiltration is the process by which aerobic bacteria breaks down ammonia to nitrite, and subsequently nitrite into nitrate (Badiola *et al*., 2012). Ammonia and nitrite are toxic to fish even at very low concentrations while plants require nitrates for growth; therefore, biofiltration is a vital component of aquaponics (Somerville *et al.*, 2014). The biofiltration unit is made to provide a large surface area that is supplied with aerated water to create a conducive growth medium for nitrifying bacteria (Badiola *et al.*, 2012). The nitrifying bacteria break down ammonia in the following sequence: the ammonia-oxidizing bacteria (genus *Nitrosomonas)* convert ammonia ($NH_3$) to nitrite ($NO_2$-) subsequently, the nitrite-oxidizing bacteria (genus *Nitrobacter*) convert nitrite ($NO_2$-) to nitrate ($NO_3$-) (Somerville *et al.*, 2014). The volume of the biofiltration unit should at least be 17 % of the fish tank, for efficient operation (Somerville *et al.*, 2014). Most biofilter media are designed from plastic materials and are shaped to have a very large surface area to volume ratio (Somerville *et al.*, 2014). Commonly used biofilter media are bio balls, volcanic gravel, PVC shavings, plastic bottle caps, nettings, pouffes, nylon shower and nylon scrub pads (Somerville *et al.*, 2014).

To attain lower capital cost as well as to reduce the footprint of the aquaponic system design and setup, this study adopted a 2-in-1 design for the biofilter and mechanical filter tagged bio-mechanical filter. The bio-mechanical filter unit is filled with gravel which performs a dual purpose of biofiltration, by providing surface areas for nitrifying bacteria activities as well as solid waste capture and mineralization.

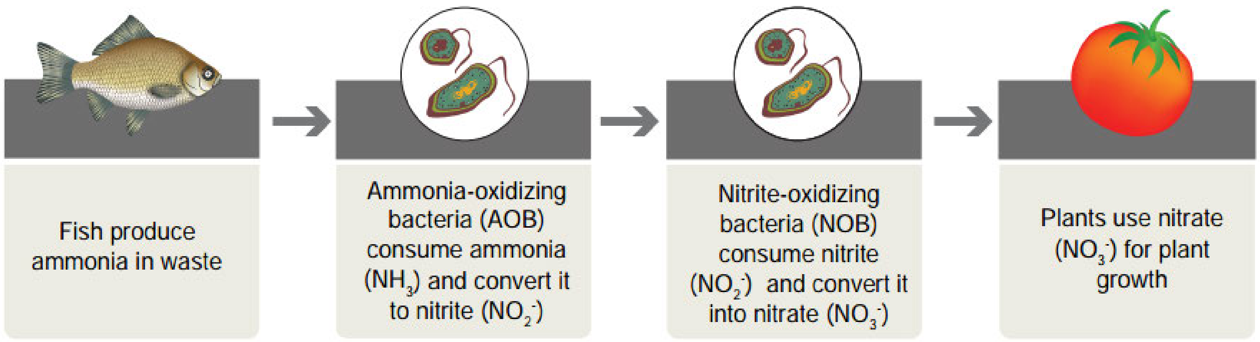


**Figure 6. 3: The nitrification process in an aquaponic system**

(Somerville *et al.*, 2014)

## Hydroponic Unit

The hydroponic unit refers to the plant-growing sections in an aquaponic system (Somerville *et al.*, 2014). There are three major designs of the hydroponic component, and they are media bed, where plants are grown on a substrate; nutrient film technique (NFT), where plants are grown with their roots inserted in wide pipes flowing with a trickle of culture water; and deep water culture (DWC) or floating raft aquaponics, where plants are suspended on a water tank with the aid of a floating raft (Somerville *et al.*, 2014).

### *Media bed system*

Media bed systems are a popular design for a small-scale aquaponic system where inert media such as gravel or expanded clay are used as a substrate to support plant roots in the grow bed (Lapere, 2010; Rakocy, 2012). The media bed system can be designed in various ways, either as a constant flow or flood-and-drain system (Rakocy *et al.*, 2006). This study adopted the flood-and-drain system where nutrient-rich water floods the media bed to a set level and drains through an auto-siphon unit. The flood-and-drain media bed system ensures access to both fresh nutrients and adequate aeration by plant roots (Rakocy *et al.*, 2006).

### *Deepwater culture system (DWC)*

The deep water culture (DWC) technique requires the suspension of plants in polystyrene sheets, while the roots are submerged in the water (Somerville *et al.*, 2014). The DWC is widely adopted in large-scale commercial aquaponic systems for monoculture of specific crop, usually leafy vegetables (Somerville *et al.*, 2014). It is highly suitable for mechanization and more complicated than media bed techniques (Somerville *et al.*, 2014).

### *Nutrient Film Technique (NFT)*

The nutrient film technique (NFT) involves the shallow flow of nutrient-rich aquaponic water through horizontal pipes (Somerville *et al.*, 2014). Plants are placed in the boreholes on the pipes where the roots are able to access the thin film of nutrient-rich water (Somerville *et al.*, 2014). The NFT and DWC are both standard systems utilized for commercial operations as both are more financially viable compared to the media bed units for large-scale operations (Rakocy, 2012; Somerville *et al.*, 2014).

The table below highlights the strengths and weaknesses of the three main aquaponic culture systems:

**Table 6. 1: Key strengths and weaknesses of the aquaponic culture techniques** adapted from *(Somerville et al., 2014)*

| Culture systems | Strengths | Weaknesses |
|---|---|---|
| **Media Bed** | ▪ Easy to design and operate.<br>▪ Suitable for growing any type of plant and supports tall fruiting vegetables.<br>▪ Various media type can be used.<br>▪ High aeration for plants.<br>▪ Captures and mineralizes solids. | ▪ Can be very heavy depending on the choice of media used.<br>▪ Media can be expensive and not readily available.<br>▪ Higher rate of evaporation compared to DWC and NFT.<br>▪ More labour-intensive to build. |
| **Deep Water Culture (DWC)** | ▪ Cost-effective compared to media bed.<br>▪ Minimal water loss due to evaporation.<br>▪ Can withstand short interruption of power supply.<br>▪ Minimal labour required to plant and harvest.<br>▪ Polystyrene raft acts as a thermal insulator. | ▪ Complex filtration technique required.<br>▪ Large volume water required and thus very heavy.<br>▪ Difficult to support tall plants.<br>▪ Polystyrene rafts are easily damaged.<br>▪ High dissolved oxygen and air pump required for plant root aeration. |
| **Nutrient Film Technique (NFT)** | ▪ Cost-effective compared to media bed.<br>▪ Suitable for herbs and leafy vegetables.<br>▪ Minimal water loss due to evaporation.<br>▪ Lightweight system.<br>▪ Has the lowest water volume requirement compared to media bed and DWC.<br>▪ Easy to plant and harvest with minimal labour required. | ▪ Complex filtration technique required.<br>▪ Water and air pump are required.<br>▪ Cannot withstand power outages.<br>▪ Easy clogging of water-inlet pipe. |

In the light of the strengths and weaknesses portrayed by the three major aquaponic culture systems, this study adopted the media bed aquaponic system due to its suitability to grow and support tall fruiting vegetables (Table 6.1). As a result of the media bed being able to support the production of high-value fruiting vegetables, it, therefore, exhibits a higher bioeconomic viability than DWC and NFT.

### 6.2.2 Fish production in aquaponics

Many fish species have been successfully cultured and recorded excellent growth performance in aquaponic systems such as tilapia, catfish, carp species, trout, barramundi, salmon, jade perch, largemouth bass and Murray cod (Diver, 2000). Tilapia, however, is the most widely cultured and adapted species in aquaponic systems, mainly due to their adaptive and tolerance capability to fluctuating water conditions (Diver, 2000) (See Section 4.5). Careful consideration should be taken with the selection of fish to be stocked in an aquaponic system. Factors such as the supply of healthy fish from reputable suppliers and local regulations governing the production of selected species should be considered during planning stages (Somerville *et al.*, 2014). Extruded fish feed pellets manufactured under standard conditions are suitable for feeding fish in aquaponics as they contain balanced nutritional requirements for fish health and growth performance (Somerville *et al.*, 2014). Omnivorous fish like tilapia requires about 32 % crude protein in their diet for excellent growth performance (DAFF, 2018). Fish can either be fed using a specific percentage of body weight per day or till satisfaction (*ad libitum*) (IDC, 2015).

Water quality in fish tanks needs to be maintained at optimum levels and adequately monitored to ensure optimum growth environment for fish (see section 4.0). *Oreochromis mossambicus,* a native species of tilapia was selected for this study due to its hardiness, less stringent regulations and permit requirements, as well as its suitability for aquaponic systems.

### 6.2.3 Plants production in aquaponics

Numerous types of plant such as vegetables, flowers, herbs, and small trees have been successfully cultivated in aquaponics designed for domestic, commercial and research purposes (Somerville *et al.*, 2014). This study, however, mainly focused on the growth of fruiting vegetables (tomatoes, peppers and cucumbers) to maximize economic returns and a leafy green vegetable (basil). Generally, leafy green herbs and vegetables perform very well and are adapted to aquaponic systems due to their low to medium nutrient requirements (Diver, 2000; Somerville *et al.*, 2014). Common fruiting vegetables such as tomatoes, peppers and cucumbers have higher nutrient demands, therefore, are well suited and adapted to aquaponics with a high stocking density of fish (Diver, 2000; Rakocy, 2012; Somerville *et al.*, 2014). Most root crops and some sensitive plants do not perform well in DWC and NFT aquaponics as they require special attention, however, they can be successfully cultured in deep media bed aquaponics (Somerville *et al.*, 2014). Hence, this study largely focusses on media bed aquaponics to achieve optimal plant yield and economic viability.

The choice of plants to be grown in an aquaponic system is mainly determined by the level of nutrient demands, i.e. low-nutrient-demand plants (leafy greens, herbs and legumes); medium-nutrient-demand plants (cabbages, carrots and bulbing plants); and high-nutrient-demand plants (botanical fruits – tomatoes, peppers, cucumbers, and strawberries) as well as the type of hydroponic system (Diver, 2000; Rakocy, 2012; Somerville *et al.*, 2014). The polyculture of herbs, leafy greens and fruiting vegetables can be successfully achieved with the media bed aquaponics, while monoculture practices are mainly prevalent in the commercial DWC and NFT systems for vegetable production (Somerville *et al.*, 2014).

Generally, aquaponic plants like other conventionally grown plants require sunlight, water, air and nutrients, i.e. macronutrients and micronutrients. The essential water quality parameter required for the plant is the pH due to its effects on the essential nutrients' availability, while temperature range within 18 – 26 °C is suitable for most plants (Somerville *et al.*, 2014). Crop cultural practices, especially planting density, and the number of stems per plant has been documented to significantly increase the fruit yield per plants (Franco *et al.*, 2009). Stem pruning and plant spacing are essential practices in maximizing plant production area and improving yield and quality of tomato (Ara *et al.*, 2007). Previous studies have also established linear increase in fruit yield in pepper and cucumber with increasing plant density and stem pruning (Nasto *et al.*, 2009; Maboko *et al.*, 2011; Amundson, 2012; Maboko *et al.*, 2012; Ayala-Tafoya *et al.*, 2019). Plant yield and economic returns, especially with fruiting vegetables can, therefore, be potentially improved in aquaponic operations with the adoption of best cultural practices.

In the light of the suboptimal environmental condition for aquaculture development that is prevalent in most parts of South Africa (Britz & Venter, 2016) (Section 2.4.4.6), adaptive and environmentally friendly intensive aquaculture technology such as aquaponics offers a sustainable cultural technique alternative (Section 1.3 and 4.5). The capital and operational expenses associated with highly intensive aquaponic operations are usually higher compared to conventional production systems (Section 4.5) therefore biomass yield must be maximized to balance investment cost (Somerville *et al.*, 2014) (Section 5.2). This study thus aims to maximize the biomass yield of fish, tomato, pepper and cucumber with specific emphasis on the effects of plant density and stem pruning on plant biomass yield in a low-cost gravel bed aquaponic system. The overarching strategic goal of the study is to establish the most viable aquaponic techniques for achieving sustainable and accelerated aquaculture development with the potential to aid food security in South Africa. The biomass production outputs from this chapter will form the production data required in the preceding economic viability study (Chapter 5.0).

## 6.3 Methodology

This section is structured in line with the principles of bioeconomics as defined by Allen et al. (1984), which evaluates the production of a biological species in three functional areas:

i. the culture system design and management;
ii. the biological characteristics of the cultured species of interest; and
iii. the economic performance of the culture system and marketing of the cultured species. The economic viability of the system is here assessed the previous chapter (Chapter 5.0).

This study was conducted from March 02, 2018, to February 28, 2019, in the Glass House research facility of the University of KwaZulu-Natal, Westville, Durban, South Africa. Ethical approval to handle fish were approved (protocol reference number: AREC/069/017D) by the animal research ethics committee of the University of KwaZulu-Natal.

### 6.3.1 Aquaponic system design, setup and operation

Two identical experimental gravel medial bed aquaponics was constructed from affordable and locally available materials and setup in a glasshouse, covering a total area of 72 m$^2$. Each aquaponic system (Figure 6.4) consist a circular fish holding tank (2500 L) – made from 5000 L JoJo water tank, a 3-in-1 compartmentalized tank (1000 L) made from a pre-used intermediate bulk container (IBC), with half of the compartment filled with gravel stones and serving a dual purpose of solid removal and bed biofilter (~ 500 L), while the other half serves a sump tank (~ 500 L) for the collection of filtered water. The other components include an oxygen pump (100 L/M), water pump (1.5 HP), piping and the hydroponic unit (960 L). Each of the hydroponic units consists of six subunits of gravel bed (1 m x 0.8m x 0.2 m; 160 L) fitted with a bell siphon made from IBC. Each aquaponic system had a total volume of 3.25 $m^3$ (3 250 L) and a surface area of 22 $m^2$.

### 6.3.2 Fish and plant experimental setup

The fish tanks were stocked with 350 juveniles of sex-reversed all male *Oreochromis mossambicus* (10.55 ± 0.11 cm; 20.9 ± 0.85g) per tank (150 /$m^3$ stocking density) 15 days prior to the introduction of plants, to allow nitrate buildup in the system for plant nutrient uptake. Agricultural lime ($CaMg(CO3)_2$) was applied to adjust the water pH during the experiment. The fish was sourced from East Coast Aquaculture Pty, South Africa. Fish were fed at the rate of 1.25 % body weight twice daily (8:00 and 18:00) with a commercially formulated brand of extruded tilapia feed. Water physicochemical parameters were measured and recorded twice daily prior to the feeding of fish. Fish were sampled every four weeks, total length cm and weight (g) recorded to adjust feed ration with a total biomass of fish. Water was replenished in the aquaponic systems to compensate for water loss due to evapotranspiration. Water loss due to evapotranspiration was about 4.5 % of the system volume weekly. Water flows continuously from the fish tank by gravity to the Bio-mechanical filtration unit, then flow to the sump tank where the water is pumped (3.3 $m^3$ /h) to the hydroponic units and back to the fish tank. Fish tanks were aerated continuously throughout the experiment by means of air diffuser connected to a central air pump.

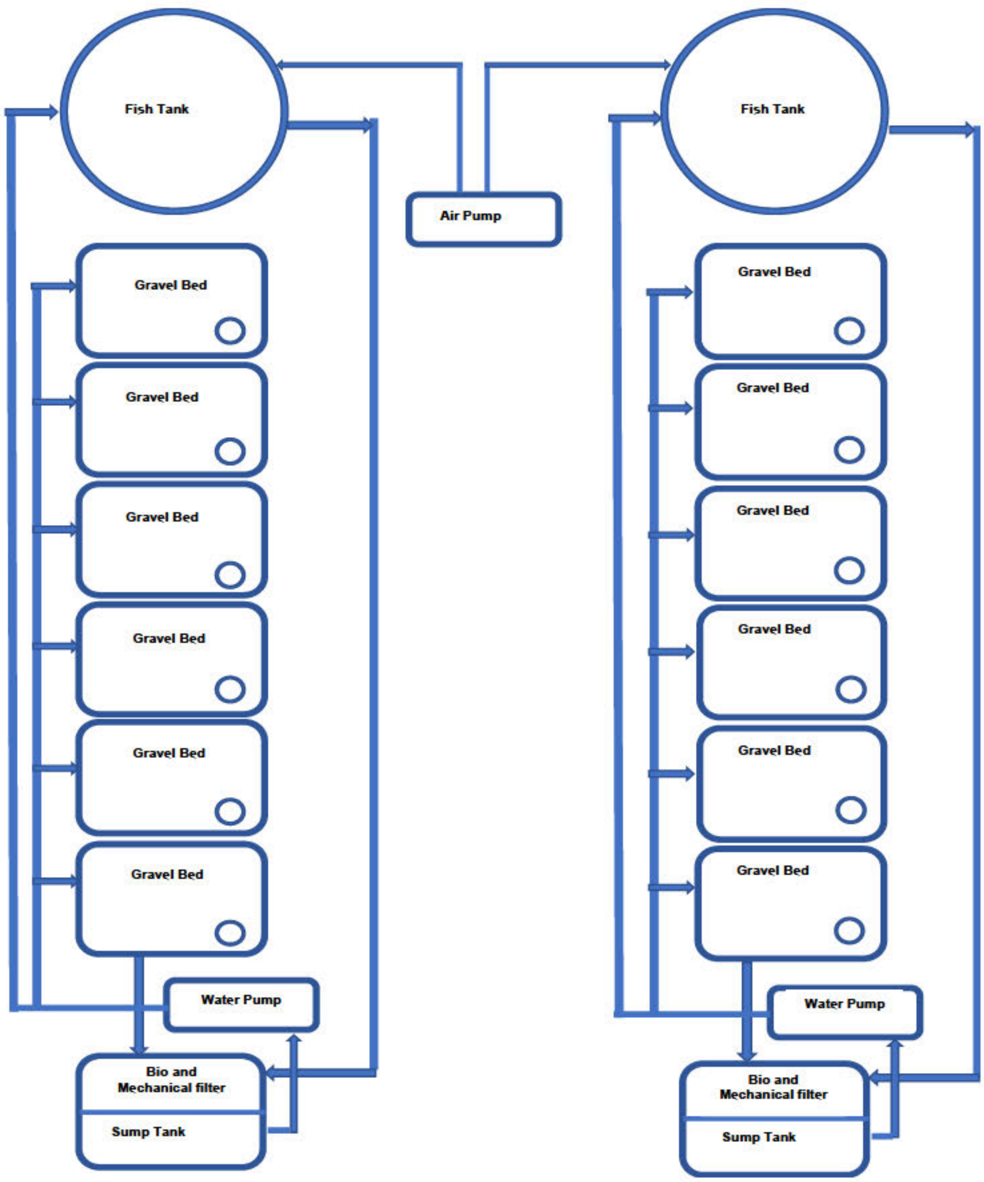


**Figure 6. 4: Gravel bed aquaponic system design**

Seedlings of tomato plants (*Solanum lycopersicum* L. cv. FA593), sweet pepper (*Capsicum annuum*), Cucumber (*Cucumis sativus*) and Basil (*Ocimum basilicum*) were obtained from Sunshine Seedlings, South Africa. Seedlings were transplanted into the gravel bed hydroponic units in production cycles starting with tomato after acceptable nitrate levels (80 – 100 mg/L) (Somerville *et al.*, 2014) were attained within the aquaponic systems. The plants (tomato, pepper and cucumber) were subjected to a complete randomized two by two block design in triplicates. The factors (Section 6.2.3) were plant density (5 and 8 plants $m^{-2}$) and stem pruning levels (pruning to one, two stems per plant and three stems). Tomato and cucumber were hosted in the gravel bed units into different treatments of:

- T1 (5 plants/$m^2$; with one stem pruning); is the control, i.e. conventional cultural method (used for economic analysis in Chapter 5)
- T2 (5 plants/$m^2$; with two stem pruning);
- T3 (8 plants/$m^2$; with one stem pruning), and
- T4 (8 plants/$m^2$; with two stem pruning)

While pepper was hosted in the gravel bed units into different treatments of:

- T1 (5 plants/$m^2$; with two stem pruning); is the control, i.e. conventional cultural method (used for economic analysis in Chapter 5)
- T2 (5 plants/$m^2$; with three stem pruning);
- T3 (8 plants/$m^2$; with two stem pruning), and
- T4 (8 plants/$m^2$; with three stem pruning)

to determine the yield per meter squared based on plant density and stem pruning (Maboko *et al.*, 2011, 2012). Five Basil plants were hosted in each of the gravel bed in a mixed planting with the other plants to serve a dual purpose of a leafy vegetable and biological pest control in the greenhouse (Parolin *et al.*, 2015). The tomato, cucumber and pepper plants were cultivated using a high wire system as a support system (Van de Vooren *et al.*, 1986) and spanned a growth period of 16 weeks after transplanting. The plants were pruned regularly (either one or two stems with no fruit removal) to remove auxiliary suckers. Each plant was supported by twine to keep it upright (Somerville *et al.*, 2014; Schmautz *et al.*, 2016). The growing points of the tomato plants were removed once the plant attained a height of about 1 m, to enhance nutrient diversion for fruiting (Maboko & Du Plooy, 2013).

### 6.3.3 Data collection and analysis

The physicochemical parameters (temperature $^{o}$C, dissolved oxygen (DO) mg/l, salinity psu and pH) were measured twice daily (08: 00 am and 18:00 pm) before the fish were fed and recorded in the aquaponic systems with a multiprobe system water quality meter. Water samples were collected weekly from the aquaponics to analyze the nutrient contents nitrite-nitrogen ($NO_2^-$–N) and nitrate-nitrogen ($NO_3^-$–N) using master freshwater test kits. The health of fish was observed daily during feeding and fortnight sampling for the weight (g) and length (cm.) measurement. The total body length (L) and body weight (W) data were documented according to the methods described by Silva *et al.* (2015). The factors a and b for the length-weight relationship (LWR) were calculated using a natural logarithmic transformation of the equation $W = a L^b$, ($\ln W = \ln a + b \ln L$), where W is the body weight (g); L is the total body length (cm.); a is exponent describing the rate of change of weight with length (the regression line intercept on the Y-axis), and b is the allometric coefficient, i.e. the regression line slope. The LWR Length-weight were used to determine the condition of fish growth and performance. Fish growth is isometric ($b = 3$) or allometric: (negative allometric $b < 3$, or positive allometric: $b > 3$). When the value of "b" is less than 3.0, fish exhibit negative allometric growth, i.e. the fish is lighter in weight in relation to its length, when "b" is equal to 3.0, the fish growth is isometric, i.e. proportional length-weight growth and ideal body form and when "b greater than 3.0, this indicates positive allometric growth which means fish weighs more in relation to its length (Silva *et al.*, 2015; Dede & Deshmukh, 2019).

The Fulton's Condition Factor / Ponderal index (K) was determined using the formula; Conditional Factor (k) = Weight / $(\text{Length})^3$ x 100 (Silva *et al.*, 2015).

The mean final body weight (FBW) was determined by dividing total fish biomass (g) in each fish tank by the total number of fish (standing crop). The absolute growth rate, specific growth rate (SGR), survival rate (SR) and feed conversion ratio (FCR), were determined using the following calculations (Abdel-Tawwab, 2003):

Absolute Growth Rate (g/day) = (FBW - IBW) / t

Specific Growth Rate (SGR %/day) = (ln FBW - ln IBW) / t X 100;

where: FBW is the final body weight (g); IBW is the initial body weight (g); ln= natural logarithmic; t = time in days.

Feed Conversion Ratio (FCR) = Feed intake (g) / weight gain (g)

Feed Conversion Efficiency (FCE) = Weight gain (g) / Feed intake (g) X 100

Survival Rate (SR %) = standing crop at the end of the study/ total fish stocked at the beginning X 100.

Harvested plant biomass (ripe tomato, bell pepper, cucumber and basil) were freshly weighed (g) and counted for each experimental treatment. Total marketable (> 30 mm, not overripe, fairly uniform in size and colour and well-shaped) and unmarketable yield (exhibited cracking, rotting, zippering, rotting, rain check, blossom end rot (BER), catface or extra small size category < 30 mm fruit diameter), as well as physiological and pathological disorders (Schmautz *et al.*, 2016), were recorded.

### 6.3.4 Statistical analysis

Linear regression was used to determine the relationship between total fish length and body mass. Main effects analysis of variance (ANOVA) after testing for normality of data distribution and equality of variance were used to compare significant means. Treatment was separated using Independent t-test to test for a statistical difference in means of plant yield due to the effects of plant density and stem pruning at a 95 % level of confidence using SPSS version 26 software.

## 6.4 Results

### 6.4.1 Growth performance of *Oreochromis mossambicus*

The mean initial length and weight of stocked *Oreochromis mossambicus* juveniles were 10.55 ± 0.11 cm and 20.9 ± 0.85 (g) respectively, and the mean final length and weight were 26.82 ± 0.11 cm and 408.7 ± 1.98 (g) respectively. The overall growth parameters were as follows; the mean percentage weight gain was 1855.50 %, absolute growth rate 1.07 g, specific growth rate (SGR) 1.64 %, feed conversion ratio (FCR) 1.25, feed conversion efficiency (FCE) was 79.96 % and survival rate of 97.5 (Table 6.3). The length-weight relationship of the fish growth shows a significant linear regression ($p < 0.05$) with a coefficient of determination value ($r^2$) of 0.9453 (Figure 6.4) and Fulton's conditional factor of 1.93. The exponent value (a) that describes the rate of change of weight with length is 0.687, and the allometric coefficient (b) was 3.10 (Figure 6.6). Total fish biomass yield was 318,786 g.

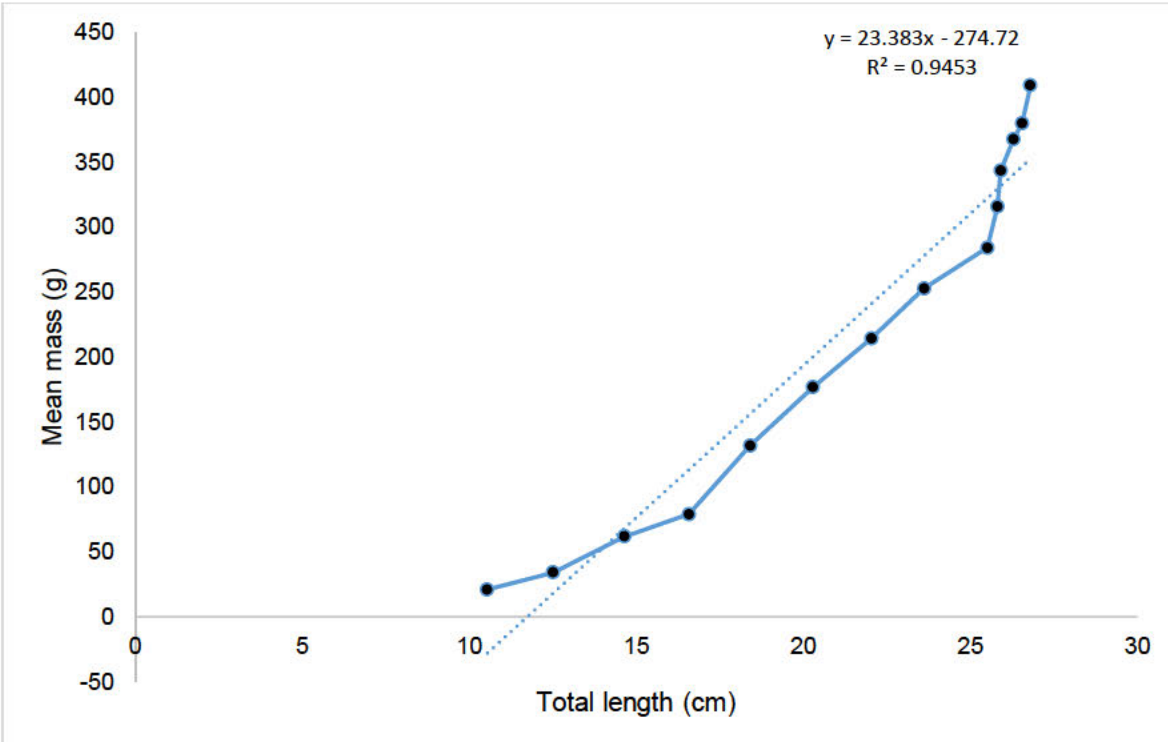


**Figure 6.5: Length-weight relationship of aquaponic cultured *O. mossambicus***

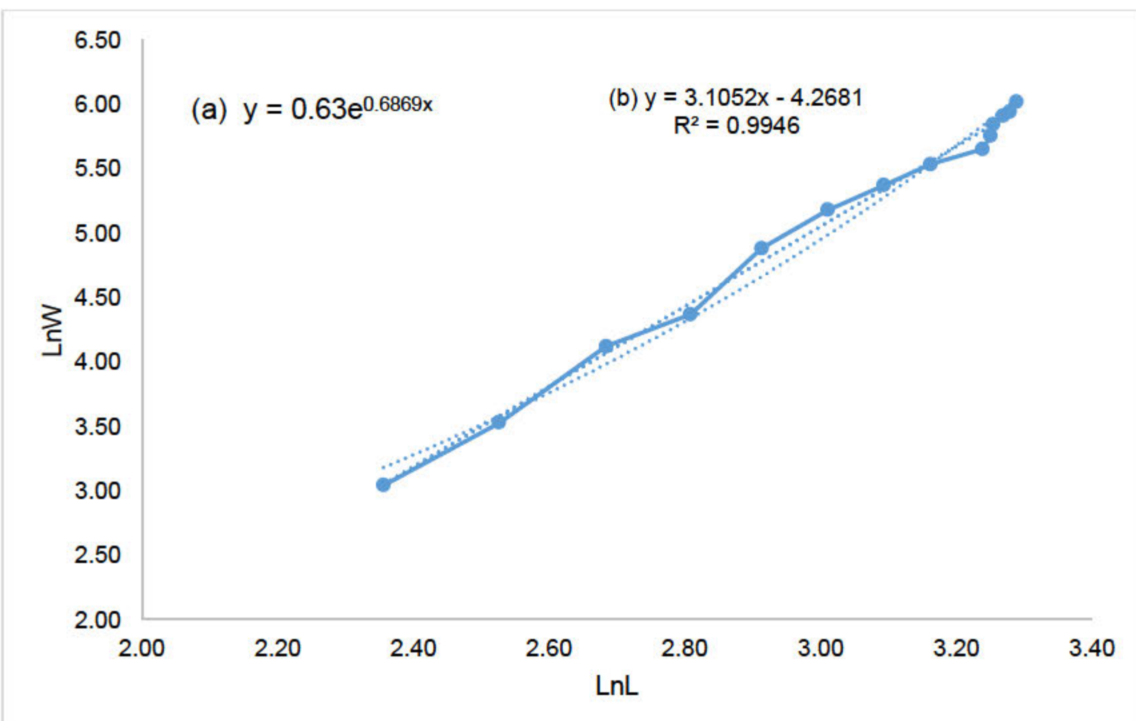


**Figure 6.6: Logarithmic LWR of aquaponic cultured *O. mossambicus***

## Table 6.2: Overall growth parameters of O. mossambicus juveniles

| Parameters | Values |
|---|---|
| Total number of fish stocked | 800 |
| Total Mortality | 20 |
| Final No. of fish | 780 |
| Survival rate (%) | 97.5 |
| Average feed consumed by individual (g) | 485 |
| Mean Initial individual weight (g) | 20.9 |
| Mean final individual weight (g) | 408.7 |
| Mean individual weight gain (g) | 387.8 |
| Weight gain (%) | 1855.50 |
| Absolute/Daily weight (g) | 1.07 |
| Specific growth rate (%) | 1.64 |
| FCR | 1.25 |
| FCE (%) | 79.96 |
| Total initial biomass (g) | 17,120 |
| Total feed consumed (g) | 398,483 |
| Total biomass yield (g) | 318,786 |
| Total weight gained (g) | 301,666 |

## Table 6.3: Growth analysis of *O. mossambicus* juveniles in a low-cost aquaponic system

| Date | Mean Length cm | Initial Mean Weight (g) | Final Mean Weight (g) | Mean Weight Gain (g) | % Weight Gain | Daily Growth Rate (g/day) | Specific Growth rate (%) | Mortality | Survival (%) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 10.55 ± 0.11 | 20.9 ± 0.85 | 0.00 | | | | | | |
| 4 | 12.51 ± 0.17 | 34 ± 0.99 | 34 ± 0.99 | 13.10 | 62.68 | 0.47 | 9.19 | 15.00 | 98.85 |
| 8 | 14.65 ± 0.11 | 61.5 ± 0.28 | 61.5 ± 0.28 | 27.50 | 80.88 | 0.98 | 11.84 | 5.00 | 99.61 |
| 12 | 16.59 ± 0.14 | 78.8 ± 0.42 | 78.8 ± 0.42 | 17.30 | 28.13 | 0.62 | 10.18 | 0.00 | 100.00 |
| 16 | 18.42 ± 0.13 | 131.5 ± 0.28 | 131.5 ± 0.28 | 52.70 | 66.88 | 1.88 | 14.16 | 0.00 | 100.00 |
| 20 | 20.31 ± 0.25 | 176.7 ± 4.24 | 176.7 ± 4.24 | 45.20 | 34.37 | 1.61 | 13.61 | 0.00 | 100.00 |
| 24 | 22.06 ± 0.04 | 214.15 ± 0.21 | 214.15 ± 0.21 | 37.45 | 21.19 | 1.34 | 12.94 | 0.00 | 100.00 |
| 28 | 23.63 ± 0.14 | 252.4 ± 1.84 | 252.4 ± 1.84 | 38.25 | 17.86 | 1.37 | 13.01 | 0.00 | 100.00 |
| 32 | 25.52 ± 0.21 | 283.8 ± 1.27 | 283.8 ± 1.27 | 31.40 | 12.44 | 1.12 | 12.31 | 0.00 | 100.00 |
| 36 | 25.83 ± 0.06 | 315.2 ± 0.42 | 315.2 ± 0.42 | 31.40 | 11.06 | 1.12 | 12.31 | 0.00 | 100.00 |
| 40 | 25.93 ± 0.02 | 343.3 ± 0.28 | 343.3 ± 0.28 | 28.10 | 8.91 | 1.00 | 11.91 | 0.00 | 100.00 |
| 44 | 26.31 ± 0.08 | 367.15 ± 0.21 | 367.15 ± 0.21 | 23.85 | 6.95 | 0.85 | 11.33 | 0.00 | 100.00 |
| 48 | 26.57 ± 0.06 | 379.6 ± 0.42 | 379.6 ± 0.42 | 12.45 | 3.39 | 0.44 | 9.01 | 0.00 | 100.00 |
| 52 | 26.82 ± 0.11 | 408.7 ± 1.98 | 408.7 ± 1.98 | 29.10 | 7.67 | 1.04 | 12.04 | 0.00 | 100.00 |

**Table 6.4: Mean monthly environmental and water physicochemical parameters**

| Month | Min T (°C) | Max T (°C) | Average room T (°C) | Humidity (%) | pH | Dissolved Oxygen (mg/l) | Nitrite (mg/l) | Nitrate (mg/l) |
|---|---|---|---|---|---|---|---|---|
| March | 22.53 ± 1.68 | 26.80 ± 1.78 | 25.40 ± 1.55 | 81.10 ± 4.68 | 6.92 ± 0.19 | 7.62 ± 0.43 | 0.43 ± 0.57 | 59.53 ± 22.96 |
| April | 19.33 ± 1.40 | 24.33 ± 1.50 | 21.67 ± 1.45 | 83.10 ± 6.52 | 7.05 ± 0.18 | 7.70 ± 0.23 | 0.23 ± 0.12 | 74.47 ± 9.55 |
| May | 18.47 ± 1.60 | 22.80 ± 2.57 | 20.07 ± 2.67 | 84.57 ± 7.91 | 7.04 ± 0.21 | 7.54 ± 0.42 | 0.42 ± 0.11 | 58.53 ± 2.97 |
| June | 17.53 ± 1.64 | 22.53 ± 1.55 | 18.53 ± 2.47 | 78.67 ± 7.53 | 6.92 ± 0.19 | 7.73 ± 0.23 | 0.23 ± 0.11 | 54.47 ± 2.90 |
| July | 17.40 ± 1.80 | 23.53 ± 2.45 | 18.73 ± 3.81 | 71.53 ± 13.90 | 7.12 ± 0.11 | 7.57 ± 0.38 | 0.38 ± 0.11 | 49.20 ± 2.14 |
| August | 18.67 ± 1.54 | 22.53 ± 2.72 | 19.40 ± 2.20 | 77.23 ± 6.95 | 7.13 ± 0.10 | 7.42 ± 0.35 | 0.35 ± 0.11 | 43.27 ± 2.49 |
| September | 18.13 ± 1.41 | 21.93 ± 1.94 | 19.13 ± 1.73 | 78.23 ± 11.09 | 6.85 ± 0.15 | 7.59 ± 0.40 | 0.40 ± 0.11 | 43.27 ± 2.49 |
| October | 19.40 ± 1.80 | 22.73 ± 2.05 | 21.27 ± 2.02 | 76.37 ± 5.86 | 7.08 ± 0.13 | 7.60 ± 0.36 | 0.36 ± 0.11 | 42.33 ± 2.23 |
| November | 20.73 ± 1.62 | 24.00 ± 2.00 | 22.43 ± 1.87 | 80.70 ± 7.11 | 7.10 ± 0.12 | 7.73 ± 0.23 | 0.23 ± 0.11 | 42.27 ± 2.22 |
| December | 20.80 ± 1.97 | 24.07 ± 2.22 | 22.57 ± 2.09 | 79.07 ± 7.21 | 7.01 ± 0.13 | 7.57 ± 0.38 | 0.38 ± 0.11 | 41.40 ± 1.84 |
| January | 22.80 ± 1.70 | 26.33 ± 1.68 | 24.87 ± 1.64 | 79.07 ± 5.85 | 7.04 ± 0.18 | 7.52 ± 0.34 | 0.34 ± 0.10 | 38.33 ± 1.91 |
| February | 22.93 ± 1.71 | 26.33 ± 2.09 | 24.93 ± 1.82 | 79.80 ± 5.85 | 6.97 ± 0.23 | 7.65 ± 0.32 | 0.32 ± 0.11 | 37.94 ± 1.79 |

### 6.4.2 Plant (tomato, pepper and cucumber) yield analyses in a low-cost designed gravel bed aquaponic system

#### 6.4.2.1 Yield of tomato due to plant density and stem pruning

The total yield (31.67 ± 8.87 kg/ $m^2$) and marketable yield (25.40 ± 8.40 kg/ $m^2$) of tomato with a plant density of 8 /$m^2$ (T3 and T4) were significantly (T-Test: df 10; $p < 0.05$) higher than those with a plant density of 5 /$m^2$ (T1 and T2). The number of marketable fruits per square meter (224 ± 76.73) from tomato cultivated with a plant density of 8 /$m^2$ (T3 and T4) was significantly (T-Test: df 10; $p < 0.05$) higher compared to those with a plant density of 5 /$m^2$ (T1 and T2). The average fruit mass and percentage of marketable fruit were not significantly different (T-Test: df 10; $p > 0.05$) between 5 /$m^2$ (T1 and T2) and 8 /$m^2$ (T3 and T4) plant densities.

The total yield (32.35 ± 8.08 kg/m$^2$) and marketable yield (26.74a ± 6.95 kg/m$^2$) of tomato plants pruned to two stems (T2 and T4) were significantly (T-Test: df 10; $p < 0.05$) higher than tomato plants pruned to one stem (T1 and T3). The number of marketable fruits per square meter (235 ± 64.70) and percentage of marketable fruits from two-stem (T2 and T4) pruned tomato plants were significantly (T-Test: df 10; $p < 0.05$) higher than the one-stem pruned plants (T1 and T3). The average fruit mass and unmarketable yield were not significantly different (T-Test: df 10; $p > 0.05$) between the one-stem (T1 and T3) and two-stem pruned (T2 and T4) tomato plants (Table 6.6).

The interactive effect between plant density and stem pruning on the number of marketable fruits per square meter were significantly different (T-Test: df 10; $p < 0.05$) with increasing stem pruning but not significantly different (T-Test: df 10; $p > 0.05$) for unmarketable yield (Table 6.7).

**Table 6.5: The effect of plant density on tomato yield**

| Plant density (/m$^2$) | Marketable yield (kg/ m$^2$) | Number of marketable fruits/ m$^2$ | Unmarketable yield (kg/ m$^2$) | Total yield (kg/ m$^2$) | % Marketable fruit | Average fruit mass (g) |
|---|---|---|---|---|---|---|
| 5 | 15.85$^b$ ± 5.36 | 136.67$^b$ ± 45.68 | 4.48 $^b$ ± 0.46 | 20.33 $^b$ ±5.54 | 76.67 ± 6.19 | 115.76 ± 3.37 |
| 8 | 25.40$^a$ ± 8.40 | 224$^a$ ± 76.73 | 6.27 $^a$ ± 1.32 | 31.67$^a$ ± 8.87 | 79.29 ± 5.54 | 113.85 ± 2.25 |

values in a column with the same superscript letter are not significantly different (*p>0.05*), using Independent t-test

**Table 6.6: The effect of stem pruning on tomato yield**

| Stem pruning | Marketable yield (kg/ m$^2$) | Number of marketable fruits/ m$^2$ | Unmarketable yield (kg/ m$^2$) | Total yield (kg/ m$^2$) | % Marketable fruit | Average fruit mass (g) |
|---|---|---|---|---|---|---|
| One stem | 14.52$^b$ ± 4.01 | 125.67 $^b$ ± 34.53 | 5.12 ± 1.18 | 19.64$^b$ ± 4.92 | 73.47$^b$ ± 4.12 | 115.39 ± 3.29 |
| Two stems | 26.74$^a$ ± 6.95 | 235$^a$ ± 64.70 | 5.62 ± 1.53 | 32.35$^a$ ± 8.08 | 82.49$^a$ ± 2.69 | 114.22 ± 2.65 |

values in a column with the same superscript letter are not significantly different (*p>0.05*), using Independent t-test

**Table 6.7: Interactive effect between plant density and stem pruning on the marketable and unmarketable yield of tomato**

| Interaction (Density and Stem) | Number of marketable fruits/m$^2$ | Unmarketable yield (kg/m$^2$) |
|---|---|---|
| D5S1 | 96.67$^d$ ± 17.56 | 4.35 ± 0.37 |
| D5S2 | 176.67$^b$ ± 10.41 | 4.60 ± 0.59 |
| D8S1 | 154.67$^c$ ± 12.22 | 5.89 ± 1.26 |
| D8S2 | 293.33$^a$ ± 12.22 | 6.64 ± 1.53 |

values in a column with the same superscript letter are not significantly different ($p>0.05$), using Independent t-test

### 6.4.2.2 Yield of sweet pepper due to plant density and stem pruning

The total yield (10.39 ± 1.53 kg/m$^2$), marketable yield (7.48 ± 1.11 kg/m$^2$), number of marketable fruits per square meter (57.47 ± 8.76), percentage of marketable fruit (71.97 ± .94) and fruit mass of sweet pepper (130.19 ± 1.60 g) with a plant density of 8 /m$^2$ (T3 and T4) were significantly higher (T-Test: df 10; $p < 0.05$) than sweet pepper with a plant density of 5 /m$^2$ (T1 and T2) (Table 6.8).

The total yield (9.54 ± 2.46 kg/m$^2$) and the number of marketable fruits per square meter (52.25 ± 14.56) due to the effect of three-stem pruning (T2 and T4) of sweet pepper plants were significantly higher (T-Test: df 10; $p < 0.05$) compared with the two-stem pruned plants (T1 and T3). Marketable yield, percentage of marketable fruits and average fruit mass of sweet pepper plants due to stem pruning were not significantly different (T-Test: df 10; $p > 0.05$) (Table 6.9).

The interactive effect of plant density and stem pruning on the number of marketable fruits per square meter and unmarketable yield (kg/m$^2$) were significantly different (T-Test: df 10; $p < 0.05$) with increasing stem pruning and plant density (Table 6.10).

**Table 6.8: The effect of plant density on sweet pepper yield**

| Plant density (/m²) | Marketable yield (kg/ m²) | Number of marketable fruits/ m² | Unmarketable yield (kg/ m²) | Total yield (kg/ m²) | % Marketable fruit | Average fruit mass (g) |
|---|---|---|---|---|---|---|
| 5 | $3.92^{b} \pm 1.18$ | $31.25^{b} \pm 9.19$ | $2.23^{b} \pm 0.22$ | $6.15^{b} \pm 1.34$ | $62.87^{b} \pm 5.59$ | $125.50^{b} \pm 2.61$ |
| 8 | $7.48^{a} \pm 1.11$ | $57.47^{a} \pm 8.76$ | $2.91^{a}$ ±_0.43 | $10.39^{a} \pm 1.53$ | $71.97^{a} \pm .94$ | $130.19^{a} \pm 1.60$ |

values in a column with the same superscript letter are not significantly different (*p>0.05*), using Independent t-test

**Table 6.9: The effect of stem pruning on sweet pepper yield**

| Stem pruning | Marketable yield (kg/ m²) | Number of marketable fruits/ m² | Unmarketable yield (kg/ m²) | Total yield (kg/ m²) | % Marketable fruit | Average fruit mass (g) |
|---|---|---|---|---|---|---|
| two stems | 4.71± 1.97 | $36.47^{b} \pm 14.56$ | $2.29^{b} \pm 0.27$ | $7.00^{b} \pm 2.24$ | 65.28 ± 7.48 | 128.12 ± 3.26 |
| Three stems | 6.70 ± 1.99 | $52.25^{a} \pm 14.56$ | $2.85^{a} \pm 0.51$ | $9.54^{a} \pm 2.46$ | 69.56 ± 3.86 | 127.56 ± 3.43 |

values in a column with the same superscript letter are not significantly different (*p>0.05*), using Independent t-test

**Table 6.10: Interactive effect between plant density and stem pruning on the marketable and unmarketable yield of sweet pepper**

| Interaction (Density and Stem) | Number of marketable fruits/m² | Unmarketable yield (kg/m²) |
|---|---|---|
| D5S2 | $23.33^{d} \pm 2.89$ | $2.05^{b} \pm 0.50$ |
| D5S3 | $39.17^{c} \pm 3.82$ | $2.40^{b} \pm 0.15$ |
| D8S2 | $49.69^{b} \pm 2.12$ | $2.54^{b} \pm 0.74$ |
| D8S3 | $65.33^{a} \pm 1.22$ | $3.29^{a} \pm 0.19$ |

values in a column with the same superscript letter are not significantly different (*p>0.05*), using Independent t-test

### 6.4.2.3 Yield of cucumber due to plant density and stem pruning

The total yield (34.51 ± 6.55 kg/m²), marketable yield (27.01 ± 5.81 kg/m²), number of marketable fruits per square meter (104 ± 23.73), and fruit mass of cucumber (260.36a ± 3.88 g) with a plant density of 8 /m² (T3 and T4) were significantly higher (T-Test: df 10; $p < 0.05$) than cucumbers with a plant density of 5 /m² (T1 and T2) (Table 6.11).

The total yield (32.46 ± 8.78 kg/m²), marketable yield (25.72 ± 7.17 kg/m²), percentage of marketable fruit (79.13 ± 3.24 %) and the number of marketable fruits per square meter (101.42 ± 26.41) due to the pruning effect of cucumber plants to two stems (T2 and T4) were significantly higher (T-Test: df 10; $p < 0.05$) than those pruned to one stem (T1 and

T3) (Table 6.12). The interactive effect of plant density and stem pruning on the number of marketable fruits per square meter and unmarketable yield (kg/m$^2$) of cucumber were significantly different (T-Test: df 10; $p < 0.05$) with increasing stem pruning and plant density (Table 6.13).

**Table 6.11: The effect of plant density on cucumber yield**

| Plant density (/m$^2$) | Marketable yield (kg/ m$^2$) | Number of marketable fruits/ m$^2$ | Unmarketable yield (kg/ m$^2$) | Total yield (kg/ m$^2$) | % Marketable fruit | Average fruit mass (g) |
|---|---|---|---|---|---|---|
| 5 | $16.13^b \pm 3.46$ | $64.58^b \pm 14.35$ | $4.72^b \pm 0.95$ | $20.85^b \pm 4.01$ | $77.11 \pm 3.53$ | $250.04^b \pm 3.16$ |
| 8 | $27.01^a \pm 5.81$ | $104^a \pm 23.73$ | $7.50^a \pm 1.22$ | $34.51^a \pm 6.55$ | $77.97 \pm 3.20$ | $260.36^a \pm 3.88$ |

values in a column with the same superscript letter are not significantly different (*p>0.05*), using Independent t-test

**Table 6.12: The effect of stem pruning on cucumber yield**

| Stem pruning | Marketable yield (kg/ m$^2$) | Number of marketable fruits/ m$^2$ | Unmarketable yield (kg/ m$^2$) | Total yield (kg/ m$^2$) | % Marketable fruit | Average fruit mass (g) |
|---|---|---|---|---|---|---|
| One stem | $17.41^b \pm 4.89$ | $67.17^b \pm 17.33$ | $5.48 \pm 1.52$ | $22.90^b \pm 6.24$ | $75.95^b \pm 2.57$ | $257.86 \pm 6.63$ |
| Two stems | $25.72^a \pm 7.17$ | $101.42^a \pm 26.41$ | $6.74 \pm 1.94$ | $32.46^a \pm 8.78$ | $79.13^a \pm 3.24$ | $252.55 \pm 5.30$ |

values in a column with the same superscript letter are not significantly different (*p>0.05*), using Independent t-test

**Table 6.13: Interactive effect between plant density and stem pruning on the marketable and unmarketable yield of cucumber**

| Interaction (Density and Stem) | Number of marketable fruits/m$^2$ | Unmarketable yield (kg/m$^2$) |
|---|---|---|
| D5S1 | $51.67^d \pm 2.89$ | $4.20^c \pm 0.52$ |
| D5S2 | $77.50^c \pm 2.50$ | $5.24^b \pm 1.09$ |
| D8S1 | $82.67^b \pm 4.62$ | $6.76^b \pm 0.76$ |
| D8S2 | $125.33^a \pm 4.62$ | $8.23^a \pm 1.23$ |

values in a column with the same superscript letter are not significantly different (*p>0.05*), using Independent t-test

### 6.4.3 Bioeconomic analysis of aquaponic cultural techniques adopted

The marketable yield and value of tomato, based on cultural technique 1, 2, 3 and 4 were 263.07 kg; R 2630.71, 361.14 kg; R 3611.41, 352.62 kg; R 3526.22 and 575.37 kg; R 5753.67 respectively. The value of tomato increased by ~ 119 % with technique 4 compared with technique 1 (Table 6.14).

The marketable yield and value of sweet pepper based on cultural technique 1, 2, 3 and 4 were 59.32 kg; R 2076.25, 83.92 kg; R 2937.04, 101.48 kg; R 3551.77 and 139.46 kg; R 4880.98 respectively. The value of sweet pepper increased by ~ 135 % with technique 4 compared with technique 1 (Table 6.14).

The marketable yield and value of cucumber based on cultural technique 1, 2, 3 and 4 were 261.44 kg; R 3137.31, 355.11 kg; R 4261.34, 387.39 kg; R 4648.70 and 548.34 kg; R 6580.09 respectively. The value of sweet pepper increased by ~ 135 % with technique 4 compared with technique 1 (Table 6.14). Total basil leaves produced within the 12-month production period was ~ 15 kg worth about R 3700.

The gross revenue from technique 1, 2, 3 and 4 were R 29,610, R 32,713, R 33,330 and R 38,418 respectively. Gross profit margin increased from 42 % with the technique 1 to 56 % with technique 4 (Table 6.15).

Based on the five-year price trend analysis of FPMs in Durban, South Africa (Section 5.4.1), a planting schedule and harvesting cycle was designed with the aim of harvesting and selling aquaponics produce (tomato, pepper, cucumber and basil) when the market prices are usually higher for each plant produce (Table 6.16).

## Table 6.14: Fruit vegetable cultural techniques and corresponding yield

| Techniques | Plant Density/ m² | Stem Pruning | Tomato (kg) | Tomato (R value) | % increase |
|---|---|---|---|---|---|
| 1 | 5 | 1-tomato/cucumber:2 -Pepper | 263.07 | 2630.71 | 0 |
| 2 | 5 | 2-tomato/cucumber :3 -Pepper | 361.14 | 3611.41 | 37.28 |
| 3 | 8 | 1-tomato/cucumber:2 -Pepper | 352.62 | 3526.22 | 34.04 |
| 4 | 8 | 2-tomato/cucumber :3 -Pepper | 575.37 | 5753.67 | 118.71 |
| Scenario | Plant Density/ m² | Stem Pruning | Pepper (kg) | Pepper (R value) | % increase |
| 1 | 5 | 1-tomato/cucumber:2 -Pepper | 59.32 | 2076.25 | 0 |
| 2 | 5 | 2-tomato/cucumber :3 -Pepper | 83.92 | 2937.04 | 41.46 |
| 3 | 8 | 1-tomato/cucumber:2 -Pepper | 101.48 | 3551.77 | 71.07 |
| 4 | 8 | 2-tomato/cucumber :3 -Pepper | 139.46 | 4880.98 | 135.09 |
| Scenario | Plant Density/ m² | Stem Pruning | Cucumber (kg) | Cucumber (R value) | % increase |
| 1 | 5 | 1-tomato/cucumber:2 -Pepper | 261.44 | 3137.31 | 0 |
| 2 | 5 | 2-tomato/cucumber :3 -Pepper | 355.11 | 4261.34 | 35.83 |
| 3 | 8 | 1-tomato/cucumber:2 -Pepper | 387.39 | 4648.70 | 48.17 |
| 4 | 8 | 2-tomato/cucumber :3 -Pepper | 548.34 | 6580.09 | 109.74 |

## Table 6.15: Financial performance based on plant cultural techniques

| Variable | R<br>Technique 1 | R<br>Technique 2 | R<br>Technique 3 | R<br>Technique 4 |
|---|---|---|---|---|
| **Turnover** | 29,610 | 32,713 | 33,330 | 38,418 |
| **Direct Cost** | 17,050 | 17,050 | 17,050 | 17,050 |
| **GP Margins** | 42% | 48% | 49% | 56% |
| **PBT** | -6,471 | -3,369 | -2,752 | 2,336 |
| **PAT** | -6,471 | -3,369 | -2,752 | 2,336 |
| **Net Profit Margin** | -22% | -10% | -8% | 6% |
| **ROI** | -8% | -4% | -4% | 3% |
| **NPV** | 81,466 | 84,287 | 84,848 | 89,473 |
| **IRR** | 13% | 14% | 15% | 18% |
| **Profitability Index** | 0.354 | 0.391 | 0.399 | 0.462 |

## Table 6. 16: Planting schedule and cycle for tomato, pepper, cucumber and basil

| Plant | January | February | March | April | May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tomato | Transplanting | | | | Harvesting | Termination | | Transplanting | | Harvesting | | Termination |
| Pepper | Transplanting | | | Harvesting | Termination | | | Transplanting | | Harvesting | Termination | |
| Cucumber | | | | | | | Transplanting | | | Harvesting | Termination | |
| Basil | Transplanting | | | | | | | Harvesting | | | | Termination |

## 6.5 Discussion

The biomass yield of aquaponic systems as a result of the growth performance of fish and the yield of plants determines the economic feasibility of aquaponic operations (Lennard & Leonard, 2006). This study presents the biomass yield of both fish and plant with the overarching aim of attaining economic viability and efficient operation at a lower cost.

### 6.5.1 Water quality, growth performance and length-weight relationship of *Oreochromis mossambicus*

The survival rate of *Oreochromis mossambicus* juveniles with a mean initial weight of 20.9 g, length of 10.55 cm and a stocking density of 150 /$m^3$ was 97.5 % during 364 days of the study (Table 6.2 and 6.3). To achieve maximum production output, physicochemical parameters of water (Table 6.4) were monitored and managed within a suitable range for the production of tilapia (DAFF, 2018). Average monthly range of water temperature, pH, dissolved oxygen, nitrite and nitrate were within tolerable limits, for the synergistic performance of fish, plants and nitrifying bacteria in aquaponic systems (Table 6.4) (Salam *et al.*, 2014; Rayhan *et al.*, 2018). The average water temperature recorded during this study ranged between 20 – 24 $^{o}$C due to prevailing environmental temperature. The optimum water temperature range for *O. mossambicus* is between 28 – 30 $^{o}$C (DAFF, 2018), however, tilapia are typically cultured in a water temperature range of 22 to 23 °C in aquaponics, to balance the temperature requirement of the nitrifying bacteria and plants; as plants perform better at marginally lower temperatures compared to fish (Nelson & Pade, 2008). Attaining optimal temperature requirement for tilapia throughout culture period in South Africa will require heating of water during cold winter period. This will invariably soar the capital and operating cost of a small-scale or low-cost aquaponic operation, thus impacting on profitability. The adequate concentration of dissolved oxygen is essential to drive the optimal functioning of the aquaponic ecosystem as fish, plants and bacteria depend on dissolved oxygen for their survival and optimum performance (Salam *et al.*, 2014; Rayhan *et al.*, 2018). In the course of the study, dissolved oxygen was kept at an optimum range of 7.42 ± 0.35 to 7.73 ± 0.23 mg/l which is above the suitable level of 5 mg/l recommended by Riche and Garling (2003) for the optimal growth performance of tilapia in RAS systems. The balance of pH within an acceptable range for the optimal performance of the fish, plants and nitrifying bacteria is an essential procedure that requires daily and closes monitoring in aquaponics. A pH range of 6.5 to 9.0 was reported by Bolorunduro and Abdullah (1996), as optimum for tilapia growth, while the optimum pH range for nitrifying bacteria and plants are 6 – 8.5 and 5.5 – 7.5 respectively (Somerville *et al.*, 2014). A compromised pH level maintained around 7 is recommended to achieve a balanced, functional aquaponic ecosystem (Somerville *et al.*, 2014; Rayhan *et al.*, 2018). The water pH levels were maintained between 6.85 ± 0.15 and 7.12 ± 0.11 during the study and were within the recommended limits for aquaponic operations (Somerville *et al.*, 2014). Nitrite and nitrate levels were maintained at 0.23 ± 0.11 – 0.43 ± 0.57 mg/l and 37.94 ± 1.79 – 74.47 ± 9.55 mg/l respectively, which were within acceptable levels (nitrite < 1 mg/l and nitrate 5 – 150 mg/l) recommended for a healthy aquaponic ecosystem (Somerville *et al.*, 2014). Nitrite levels above 1 mg/l and nitrate concentrations above 400 mg/l are considered extremely deleterious to fish growth and performance (Boyd, 1998).

The growth performance parameters of *Oreochromis mossambicus* were similar to the findings of Dampin *et al.* (2012) and day *et al.* (2016). The survival rate of 97.5 % recorded during this study were similar to the survival rates of > 90 % achieved in aquaponic studies of Rahmatullah *et al.* (2010), Effendi *et al.* (2015), Saufie *et al.* (2015) and Lima *et al.* (2018). The specific growth rate (SGR) of 1.64 % and daily growth rate 1.07 g/day were observed and corresponded with the findings of Kanial (2006) and Lima *et al.* (2018) whom both recorded similar values for SGR and daily growth rate for tilapia cultured in aquaponic systems. The obtained FCR (1.25) were lower than the expected FCR of 1.4 to 2.0 for tilapia (Salam *et al.*, 2014) and FCRs recorded by the studies of Kanial (2006), Effendi *et al.* (2015) and Saufie *et al.* (2015). The presence of natural food such as mosquito larva, insects, red worms and plant leaves used as a supplementary feed, but not accounted for in the feeding regime could have significantly lowered the FCR as compared to other studies. Final length (26.82 ± 0.11 cm) and weight (408.7 ± 1.98 g) obtained at 52 weeks of culture was similar to the findings of Dampin *et al.* (2012) at 48 weeks of culture. Total weight gained of 301,666 g and total fish yield 398,483 g were recorded at 52 weeks at termination.

The length-weight relationship (LWR) is an essential aspect of fish biology (Faradonbeh *et al.*, 2015). The LWR coefficients of determination ($r^2$) for this study was 0.9453 (Figure 6.5) with a significant linear regression ($p < 0.05$). The significant $r^2$ values were closely related to the coefficients of determination values obtained for tilapia in the studies of Ighwela *et al.* (2011), Silva *et al.* (2015) and Dede and Deshmukh (2019). The exponent "a" which describes the rate of change of length with weight and the coefficient of regression "b" are key parameters in an LWR study (Dede & Deshmukh, 2019). Several factors could be responsible for the variations in the regression coefficient values; however, the physicochemical properties of water and the availability of food are the key causative factors (Mommsen, 1998). The value of "b" obtained in this study was 3.1 (Figure 6.6); thus b is approximately equal to 3.0; therefore, the growth performance of the *Oreochromis mossambicus* shows that the fish body forms were proportional in relation to their weights indicating isometric growth of the fish (Froese, 2006). Similar findings were recorded for the regression coefficient (b) for *Oreochromis niloticus* (Ighwela *et al.*, 2011) and *Oreochromis mossambicus* (Dede & Deshmukh, 2019) in their LWR studies. The regression coefficient value gives an indication of the growth form of the cultured fish, as fishes tend to change their body outline and the specific gravity of tissues during their growth stages (Dede & Deshmukh, 2019).

The condition factor (K), is generally used to assess the health condition of fish and provides information on the interactive effects of environmental factors on the wellbeing of the fish (Ayoade, 2011). Fish with conditional factor (K) value greater than 1 ($K > 1$) shows better health condition than fish with K value lesser than 1 ($K < 1$) (Wootton, 1998). The mean condition factor K recorded for *Oreochromis mossambicus* was 1.93, which was similar to the K values reported for *Oreochromis niloticus* K = 1.86 (Ighwela *et al.*, 2011) and *Oreochromis mossambicus* K = 1.84 (Dede & Deshmukh, 2019). The determined K value of 1.93 in this study was greater than 1.0, which indicates that the health status of the cultured fish was in good condition. The condition factor is a vital aquaculture management tool that aquaculture managers can use to assess the health status of their fish stock as well as the biotic and abiotic environmental conditions of their aquaculture systems (Anene, 2005; Araneda *et al.*, 2008).

### 6.5.2 Yield of tomato due to plant density and stem pruning

The yield of tomato plants due to the effects plant density and stem pruning were studied in a low-cost designed gravel bed aquaponic system with the aim of maximizing production output per square meter and economic viability of aquaponic production of tomato. Total yield, marketable yield and number of marketable fruits per square meter significantly increased with increase in plant density (Table 6.5). The results of this study agreed with the findings of related studies conducted by Charlo *et al.* (2006), Ara *et al.* (2007), Fanasca *et al.* (2007), Maboko *et al.* (2011) and Amundson (2012). The unmarketable yield was significantly higher with a plant density of 8 plants /$m^2$, compared to a plant density of 5 plants /$m^2$. Percentage of marketable yield was higher, but not significant, with a plant density of 8 plants /$m^2$ than 5 plants /$m^2$.

Total yield, marketable yield, percentage of marketable fruit, number of marketable fruits per square meter were significantly higher with plants pruned to two stems compared to plants pruned to one stem (Table 6.6). These findings were in agreement with the result of studies carried out by Ara et al. (2007), Maboko and Du Plooy (2008), Maboko and Du Plooy (2009), Maboko *et al.* (2011) and Amundson (2012). Significant increase in marketable fruits with plants subjected to two-stem pruning was attributed to the incidence of reduction in fruit cracking, as plants pruned to one stem tend to produce larger fruit size (Maboko & Du Plooy, 2008; Maboko & Du Plooy, 2009; Maboko *et al.*, 2011).

The interactive effect between plant density and stem pruning showed significant levels of interactions with unmarketable yield and number of marketable fruits (Table 6.7). Plant density of 8 plants /$m^2$ pruned to two stems significantly produced higher number of marketable fruits per square meter, followed by a plant density of 5 plants /$m^2$ pruned to two stems. Stem pruning showed the significantly higher effect on the production of marketable fruits compared to plant density, as plant density of 5 plants /m$^2$ pruned to one stem produced the lowest number of fruits per square meter. Jovicich *et al.* (1999) reported similar findings with sweet pepper with a plant density of 4 plants /m$^2$ pruned to four stems and Maboko *et al.* (2011) with a tomato plant density of 3 plants /m$^2$ pruned to two stems. The optimum plant density per square meter is largely dependent on many factors such as the genotype, plant management practices and environmental conditions Ayala-Tafoya *et al.* (2019). Higher productivity of plants with increasing density is due to greater capture sunlight and increasing photosynthetic activities resulting in plant growth and fruit production Peil and de Albuquerque Neto (2014).

### 6.5.3 Yield of sweet pepper due to plant density and stem pruning

The yield of sweet pepper due to the effect of plant density per square meter showed that total yield, Marketable yield, Average fruit mass, number of marketable fruits per square meter and percentage marketable fruit were significantly higher at a plant density of 8 plants /m$^2$ compared to a plant density of 5 plants /m$^2$ (Table 6.8). The results obtained were related with the studies of Nasto *et al.* (2009), Aminifard *et al.* (2010) and Maboko *et al.* (2012) that reported significantly higher yield of pepper at a higher plant density.

The total yield and number of marketable fruits per square meter of sweet pepper plants pruned to three stems were significantly higher compared to plants pruned to two stems. The marketable yield and percentage of marketable fruits were not significantly different between the plants pruned to three stems and those pruned to two stems. Marketable yield and percentage marketable fruit were higher with plants pruned to three stems, but not significantly different from those plants pruned to two stems (Table 6.9). Both Nasto *et al.* (2009) and Maboko *et al.* (2012) reported that higher pepper plants yield with an increasing number of stems.

The interactive effects between the density of sweet pepper plants and stem pruning indicated some significant levels of interactions with the number of marketable fruits and unmarketable yield (Table 6.10). Plants pruned to three stems with a density of 8 plants /m$^2$ significantly yielded a higher number of marketable fruits per square meter, followed by the plant pruned to two stems with a density of 8 plants /m$^2$ and plant pruned to three stems with a density of 5 plants /m$^2$. Plants pruned to two stems with a plant density of 5 plants /m$^2$ recorded the lowest number of marketable fruits per square meter due to the interactive effects of plant density and stem pruning. There was no significant difference in the unmarketable yield of plants pruned to two stems with a density of 8 plants /m$^2$, plants pruned to three stems with a density of 5 plants /m$^2$ and plants pruned to two stems with a density of 5 plants /m$^2$. Maboko *et al.* (2012) also reported a higher number of marketable yield due to the interactive effect of the increase in plant density and number of stems. The combined effects of increasing plant density and stem pruning resulted in significantly higher ($p < 0.05$) plant yield and fruit quality of sweet pepper plants in aquaponic operation.

### 6.5.4 Yield of cucumber due to plant density and stem pruning

The yield of cucumber plants in the gravel-bed aquaponic system was studied to determine the effect of plant density per square meter and stem pruning on the yield and quality cucumber plants. Total yield, marketable yield, average fruit mass and the number of marketable fruits per square meter due to plant density were significantly higher with a plant density of 8 plants /$m^2$ compared to a plant density of 5 plants /$m^2$ (Table 6.11). The results obtained were similar to the findings reported on tomato yield (section 6.5.2) and sweet pepper yield (section 6.5.3). A study conducted by Ayala-Tafoya *et al.* (2019) on the effect of plant density on cucumber yield in a greenhouse, also reported higher yield with increasing plant density.

Total yield, marketable yield, percentage of marketable fruits and number of marketable fruits per square meter of cucumber plants pruned to two stems were significantly higher than plants pruned to one stem. Unmarketable yield and average fruit mass were not significantly different between plants pruned to one stem and two stems (Table 6.12). This result correlated with the findings of Ayala-Tafoya *et al.* (2019) on the yield of cucumber plants due to the effect of stem pruning, Maboko *et al.* (2012) and Maboko *et al.* (2011), also reported similar findings with sweet pepper and tomato respectively. The interactive effects between the plant density and stem pruning of cucumber plants significantly affected the number of marketable yields per square meter and unmarketable yield (Table 6.13). Plants pruned to two stems with a plant density of 8 /$m^2$ significantly produced higher number of marketable fruits per square meter, followed by the plant pruned to one stem with a plant density of 8 /$m^2$ and plant pruned to two stems with a plant density of 5 plants /$m^2$. Cucumber plants pruned to one stem with a plant density of

5 /m$^2$ produced the lowest number of marketable fruits per square meter due to the interactive effects of plant density and stem pruning. Plants with a density of 8 plants /m$^2$ pruned to two stems recorded the highest unmarketable yield. There was no significant difference in the unmarketable yield of plants pruned to one stem with a plant density of 8 /m$^2$ and plants pruned to two stems with a plant density of 5 /m$^2$. Plants pruned to one stem with a density of 5 plants /m$^2$ had the lowest unmarketable yield due to the interactive effects of plant density and stem pruning. This result corroborates the findings of Ayala-Tafoya *et al.* (2019) where the interaction of higher plant density and two stems pruning of cucumber plants, resulted in a significantly higher yield of cucumbers compared to those pruned to one stem and with a lower plant density per square meter.

### 6.5.5 Bioeconomic analysis of aquaponic cultural techniques adopted

There was a linear relationship between the plant yield and economic returns, as the plant with the lowest yield presented the lowest revenue (Table 6.14). Adoption of best cultural practices have been demonstrated to increase marketable yield significantly, (Nasto *et al.*, 2009; Maboko *et al.*, 2011; Amundson, 2012; Maboko *et al.*, 2012; Ayala-Tafoya *et al.*, 2019) and revenue (Mazed *et al.*, 2015) from several studies. The combined effects of plant cultural practice of plant density and stem pruning of tomato, sweet pepper and cucumber showed that planting method with the highest plant population per meter square (8 plants / m$^2$ ) in combination with the highest stem pruning (2 stems: tomato and cucumber and 3 stems: pepper) recorded the highest marketable yield and revenues (Table 6.14). The study of Mazed *et al.*, (2015) on the combined effects of fertilizer application and stem pruning on the yield and economic returns of tomato production also showed that yield and revenue increased with increasing levels of fertilizer application and stem pruning. Application of fertilizer would have soared the operating cost of plant production; however, this study did not require the addition of conventional fertilizers as plant nutrients were derived from the aquaculture effluent.

Economic analysis performed using the conventional aquaponic plant cultural practice (technique I; Table 6.14) recorded the lowest revenue (Table 6.14) and was not financially viable (Table 6.15; Chapter 5.0). Financial performance of the aquaponic system increased with the optimization of plant cultural practice as the level of planting method moved from technique I to IV (Table 6.15). The cost-benefit ratio of tomato per hectare also increased with increasing fertilizer application and stem pruning (Mazed *et al.*, 2015). Tomato, sweet pepper and cucumber recorded 119 %, 135 % and 110 % revenue increase respectively by adopting cultural technique IV compared to I. (Table 6.14).

Based on the viable financial performance recorded by previous studies (Bailey *et al.* 1997; Holliman, Adrian, and Chappell, 2008; Baker 2010; Tokunaga *et al*. 2015; English, 2015), and a higher cost benefits ratio recorded with the adoption of best cultural practices and planting schedule small-scale aquaponic operators can optimize production output and attain economic viability. Aquaponic operations in South Africa, therefore, needed to be restructured to achieve economies of scale by adopting a minimum of fish: plant revenue model of 30: 70 %. The combined effects of optimized management practices; planned production scheduled, and higher plant output-driven revenue model will significantly reduce annual operating cost (variable cost) and drive a higher profitability index.

Strategic planting schedule can also help aquaponic operators to maximize revenue and economic returns. The analysis of fresh produce market price trends, over a period of five years (2014 – 2018) showed when the prices of tomato, pepper and cucumber are likely to peak (Section 5.4.1, 5.5.1). In addition to the adoption of optimized cultural practices to increase yield and economic viability, a crop production cycle was designed which showed when to cultivate and harvest tomato, pepper and cucumber to leverage the periods of higher market prices (Table 6.16 and Section 5.5.1). The forces of demand and supply coupled with environmental impacts on yields and production output of conventional agricultural systems determine the market volume and prices of fresh produce in South Africa (Section 5.5.1)(JFPM, 2016).

## 6.6 Conclusion

The biomass yield of *Oreochromis mossambicus* and the culture of tomato, sweet pepper and cucumber in low-cost designed aquaponic systems were optimized in this study using different plant cultural practices. Growth performance of fish based on high survival rate, FCR, length-weight regression coefficient and the condition factor indicated a good health condition of both the fish and the culture environment. The yield and fruit quality of tomato, sweet pepper and cucumber were significantly higher with increasing plant density and stem pruning. The combined effects of plant density and stem pruning resulted in significantly increased yields and fruit qualities of tomatoes, sweet peppers and cucumbers. Tomato, sweet pepper and cucumber plants pruned to 2 stems and 3 stems significantly produced higher total yield and marketable yield in the aquaponic system.

This study showed that biomass yield of plants in this aquaponic system and the resultant economic viability was largely driven by the adoption of optimized cultural techniques (Table 6.14 and 6.15) as well as planned planting and harvesting cycles (Table 6.16 and Section 5.5.1). Aquaponic operations could, therefore, be planned to attain economic viability by maximizing biomass yield through the adoption of the best cultural techniques and strategic planting schedules.

This study did not investigate and determine the optimal plant density per square meter and stem pruning for the cultured plants (tomato, sweet pepper and cucumber) due to resource and time constraints. Further studies are therefore, needed to ascertain the optimum plant density and stem pruning, to maximize yield and economic viability of aquaponic production for these plants. The study initially set out to compare the feasibility of both *O. niloticus* and *O. mossambicus* in a small-scale aquaponics, however, all efforts to secure a permit to culture *O. niloticus* for research purposes were futile, as the relevant authorities in KwaZulu-Natal did not approve the use of *O. niloticus*. This is also a reflection of the slow growth of aquaculture industry in South Africa due to administrative bureaucracies involved in permitting a better performing species for aquaculture purposes.

I would add this to your thesis as well

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# CHAPTER 7: GENERAL CONCLUSIONS AND RECOMMENDATIONS

The quantitative SWOT analyses of key aquaculture players in Africa (Egypt, Nigeria and Uganda) vis-à-vis South Africa presents a novel comparative technique in comparative aquaculture studies and can also be applied in fisheries management studies. Egypt was the leading aquaculture producer in Africa due to its competitive strengths and aquaculture development opportunities. Nigeria exhibited huge aquaculture development opportunities due to its huge underserved market size. Uganda showed higher marginal aquaculture opportunities than South Africa due to a higher per capita fish consumption. A major constraint to the study was limited access to updated aquaculture data of evaluated countries. Comprehensive investment in timely fisheries and aquaculture data compilation and repository will facilitate access to data for research and industry aquaculture development initiatives.

A quantitative analysis was also performed to determine the competitive development potential of key aquaculture species in South Africa as a guide for aquaculture business development. Trout and tilapia both showed some levels of competitive strengths; however, trout demonstrated higher economic opportunities than tilapia, while tilapia showed a higher level of competitive aquaculture strengths. Tilapia and trout production were both limited by suitable environmental conditions; thus, the adoption of highly intensive RAS and aquaponics methods for tilapia production. To achieve rapid development of tilapia culture in South Africa, controlled and simple permitting application process of *O. niloticus* with documented better growth performance compared to *O. mossambicus* is highly recommended for aquaponics and RAS operators to promote and drive large-scale investment in tilapia production. Abalone, oyster and marron crayfish also present good market opportunities as a result of good financial performance, pricing and absence of importations, but are limited in production outputs as a result of their weak competitive strengths, mainly due to poor FCR and growth performance. Catfish and mussel both presented a higher level of competitive strengths compared to other species; however, currently showed poor market opportunities. Provision of the required enabling environments such as incentives to reduce operating expenses, quick and straightforward authorization procedures and nationwide promotion of fish-eating culture to drive local demand is highly recommended to accelerate aquaculture development in South Africa.

Aquaponics, as an unconventional food production system, potentially offers a sustainable and more economically feasible means of food production. This technology could potentially address challenges such as climate change impacts on conventional food production, land and water resources limitation and food security. South Africa, an arid country, is currently experiencing food insecurity at household levels due to socioeconomic and climate change factors. Adaptive capabilities to mitigate the threats to food security and economic development are required in South Africa.

Aquaponics setups are complicated and require substantial capital investment; therefore, production output must offset the high cost of investment to achieve socioeconomic feasibility. This study assessed the biotech-economic viability of a low-cost, small-scale commercial aquaponics as a model to drive aquaculture development, food security and local economic development in South Africa. To achieve this aim, a macroeconomic qualitative and quantitative SWOT and critical success factors analyses of leading aquaculture players in Africa were performed to benchmark the aquaculture production in South Africa. A low-cost but efficient small-scale commercial aquaponic model was designed, constructed and operationalized to assess the biomass yield (fish and plants) and economic feasibility of a low-cost commercial aquaponics in South Africa. The economic feasibility of the modelled low-cost commercial aquaponic system was assessed using fresh produce price trend analysis, cost analysis, revenue analysis, ROI, NPV, IRR and profitability index. Conventional aquaponics cultural practice, which largely focuses on fish as the primary source of revenue was not economically viable due to the higher cost of operation associated with the production of fish as compared to vegetables in aquaponics. A modelled revenue of 42 to 58 % fish – plant ratio resulted in the marginal economic viability of the aquaponic system; therefore, small-scale aquaponic operators need to attain economies of scale especially with plant production output to be economically viable. This study recommends a minimum revenue model of 30 – 70 % fish to plant ratio, to significantly reduce the operating cost of small-scale aquaponic operators and attain economic viability. Future studies will be required to determine the economic performance of small-scale commercial aquaponics using the 30 – 70 % and 20 – 80 % fish to plant revenue models. Aquaponic producers can also leverage the period of peak prices in FPMs by adopting planned planting and harvesting schedule to maximize revenue and profitability due to their higher operating cost.

The study of fish (*Oreochromis mossambicus*) and plant (tomato, sweet pepper, cucumber and basil) yield were assessed to determine the production output of the low-cost and small-scale commercial aquaponic system. The growth and performance of fish were comparable to the documented growth parameters, fish health and environmental standard for *O. mossambicus*. Tomato, sweet pepper and cucumber yield and fruit quality performed significantly better at a higher plant density and stem pruning. The interactive effects of a higher plant density and with an increasing stem pruning for tomato, sweet pepper and cucumber resulted in significantly higher yields and fruit quality. Plant biomass yield from aquaponics can, therefore, be economically sustained with the adoption of the combined cultural practice of higher plant density and by increasing stem pruning of fruit vegetables (Table 7.1). A future study would be required to determine the maximum plant density and stem pruning to optimize yield, fruit quality and economic feasibility of these vegetables in the aquaponic system as this study used limited plant density and stem pruning in this system.

**Table 7.1: Comparative biomass yield and revenue based of varying plant cultural techniques**

| Plant cultural practice | | | | |
|---|---|---|---|---|
| **Technique** | **Total marketable yield (kg/ m²)** | **Total fish yield (kg)** | **Total Revenue (R)** | **% Revenue increase to Technique 1** |
| 1 | 601.31 | 319 | 29,747.27 | 0 |
| 2 | 816.45 | 319 | 32,412.79 | 8.96 |
| 3 | 857.77 | 319 | 32,929.69 | 10.70 |
| 4 | 1,277.84 | 319 | 37,667.74 | 26.63 |

This study has established that the bioeconomic feasibility of aquaponic operations in South Africa is attainable and will be primarily driven by improving plant biomass yield via the adoption of optimized cultural techniques to achieve a minimum of 70 % revenue model from plant production. The knowledge and practicality of attaining economies of scale in aquaponic operations in South Africa is expected to spur burgeoning interests and investments in aquaponic setup and operations which should boost both fish and plant production output. The critical success factor for the development of aquaculture in South Africa lies in the ability to attain economies of scale and viability; and to achieve these factors, unconventional management practices must be adopted to increase production output and minimize operating cost. Aquaponics is, therefore, a sustainable and viable technology potentially positioned to drive accelerated aquaculture development and food production.

This low-cost aquaponic model design and operational techniques are currently being piloted in suburban communities of KwaZulu-Natal, South Africa, as part of the provincial government and University of KwaZulu-Natal joint initiative to drive food security and local economic development via unconventional food production systems.

# APPENDIX

## Appendix AI: Loan repayment schedule

| | | | | |
|---|---|---|---|---|
| **Amount (R):** | **100,000** | | **Tenure (Yr)** | **5** |
| **Period Interest rate** | **20.50%** | | **No. of payments** | **5** |
| **Period** | **Outstanding Principal** | **Period Payment** | **Principal** | **Interest** |
| 0 | 100,000 | | 100,000 | 0 |
| 1 | 86,693 | (33,806.56) | (13,307) | (20,500.00) |
| 2 | 70,659 | (33,806.56) | (16,034) | (17,772.16) |
| 3 | 51,338 | (33,806.56) | (19,321) | (14,485.10) |
| 4 | 28,055 | (33,806.56) | (23,282) | (10,524.21) |
| 5 | - | (33,806.56) | (28,055) | (5,751.32) |

## Appendix AII: Balance sheet statement

| Variables | R<br>Scenario 1 | R<br>Scenario 2 | R<br>Scenario 3 | R<br>Scenario 4 |
|---|---|---|---|---|
| **Fixed Assets** | | | | |
| Fixed Assets (Cost) | 46,200 | 46,200 | 46,200 | 46,200 |
| Accum. Depreciation | 4,620 | 4,620 | 4,620 | 4,620 |
| Fixed Assets (NBV) | 41,580 | 41,580 | 41,580 | 41,580 |
| **Current Assets** | | | | |
| Cash and Bank | 30,232 | 35,769 | 45,875 | 25,651 |
| | 30,232 | 35,769 | 45,875 | 25,651 |
| Current Liabilities (accrued tax) | - | 311 | - | - |
| Net Assets | **71,812** | **77,038** | **87,455** | **67,231** |
| | | | | |
| Ordinary Share Capital | 76,312 | 76,312 | 76,312 | - |
| Portion of term loan outstanding | - | - | | 86,693 |
| Retained Earnings | (4,499) | 726 | 11,143 | (19,463) |
| Shareholders' Funds | **71,812** | **77,038** | **87,455** | **67,231** |
| | - | - | - | - |

## Appendix AIII: Scenario I: Plant density 5/ $m^2$: Stem pruning 1(tomato/cucumber):2 (Pepper)

| Plant Density/ m2 | Stem Pruning | Tomato | Sweet Pepper | Cucumber | Basil |
|---|---|---|---|---|---|
| 5 | 1-tomato/cucumber :2 -Pepper | 22.21 | 5.13 | 21.53 | 1.53 |
| 5 | 1-tomato/cucumber :2 -Pepper | 23.70 | 4.59 | 22.40 | 1.47 |
| 5 | 1-tomato/cucumber :2 -Pepper | 19.86 | 5.11 | 21.44 | 1.37 |
| 5 | 1-tomato/cucumber :2 -Pepper | 22.21 | 5.13 | 21.53 | 1.53 |
| 5 | 1-tomato/cucumber :2 -Pepper | 23.70 | 4.59 | 22.40 | 1.47 |
| 5 | 1-tomato/cucumber :2 -Pepper | 19.86 | 5.11 | 21.44 | 1.37 |
| 5 | 1-tomato/cucumber :2 -Pepper | 22.21 | 5.13 | 21.53 | 1.53 |
| 5 | 1-tomato/cucumber :2 -Pepper | 23.70 | 4.59 | 22.40 | 1.47 |
| 5 | 1-tomato/cucumber :2 -Pepper | 19.86 | 5.11 | 21.44 | 1.37 |
| 5 | 1-tomato/cucumber :2 -Pepper | 22.21 | 5.13 | 21.53 | 1.53 |
| 5 | 1-tomato/cucumber :2 -Pepper | 23.70 | 4.59 | 22.40 | 1.47 |
| 5 | 1-tomato/cucumber :2 -Pepper | 19.86 | 5.11 | 21.44 | 1.37 |
| | | **263.07** | **59.32** | **261.44** | **17.48** |

## Appendix AIV: Scenario I: Plant density 5/ $m^2$: Stem pruning 2 (tomato/cucumber):3 (Pepper)

| Plant Density/ m2 | Stem Pruning | Tomato | Sweet Pepper | Cucumber | Basil |
|---|---|---|---|---|---|
| 5 | 2-tomato/cucumber :3 -Pepper | 29.45 | 6.30 | 29.97 | 1.25 |
| 5 | 2-tomato/cucumber :3 -Pepper | 30.42 | 7.38 | 29.44 | 1.51 |
| 5 | 2-tomato/cucumber :3 -Pepper | 30.41 | 7.30 | 29.36 | 1.31 |
| 5 | 2-tomato/cucumber :3 -Pepper | 29.45 | 6.30 | 29.97 | 1.25 |
| 5 | 2-tomato/cucumber :3 -Pepper | 30.42 | 7.38 | 29.44 | 1.51 |
| 5 | 2-tomato/cucumber :3 -Pepper | 30.41 | 7.30 | 29.36 | 1.31 |
| 5 | 2-tomato/cucumber :3 -Pepper | 29.45 | 6.30 | 29.97 | 1.25 |
| 5 | 2-tomato/cucumber :3 -Pepper | 30.42 | 7.38 | 29.44 | 1.51 |
| 5 | 2-tomato/cucumber :3 -Pepper | 30.41 | 7.30 | 29.36 | 1.31 |
| 5 | 2-tomato/cucumber :3 -Pepper | 29.45 | 6.30 | 29.97 | 1.25 |
| 5 | 2-tomato/cucumber :3 -Pepper | 30.42 | 7.38 | 29.44 | 1.51 |
| 5 | 2-tomato/cucumber :3 -Pepper | 30.41 | 7.30 | 29.36 | 1.31 |
| | | **361.14** | **83.92** | **355.11** | **16.28** |

## Appendix AV: Scenario I: Plant density 8 /m$^2$: Stem pruning 1(tomato/cucumber):2 (Pepper)

| Plant Density/ m2 | Stem Pruning | Tomato | Sweet Pepper | Cucumber | Basil |
|---|---|---|---|---|---|
| 8 | 1-tomato/cucumber :2 -Pepper | 29.51 | 8.34 | 32.50 | 1.19 |
| 8 | 1-tomato/cucumber :2 -Pepper | 27.73 | 8.34 | 33.52 | 1.27 |
| 8 | 1-tomato/cucumber :2 -Pepper | 30.92 | 8.69 | 30.83 | 1.21 |
| 8 | 1-tomato/cucumber :2 -Pepper | 29.51 | 8.34 | 32.50 | 1.19 |
| 8 | 1-tomato/cucumber :2 -Pepper | 27.73 | 8.34 | 33.52 | 1.27 |
| 8 | 1-tomato/cucumber :2 -Pepper | 30.92 | 8.69 | 30.83 | 1.21 |
| 8 | 1-tomato/cucumber :2 -Pepper | 29.51 | 8.34 | 32.50 | 1.19 |
| 8 | 1-tomato/cucumber :2 -Pepper | 27.73 | 8.34 | 33.52 | 1.27 |
| 8 | 1-tomato/cucumber :2 -Pepper | 30.92 | 8.69 | 30.83 | 1.21 |
| 8 | 1-tomato/cucumber :2 -Pepper | 29.51 | 8.34 | 32.50 | 1.19 |
| 8 | 1-tomato/cucumber :2 -Pepper | 27.73 | 8.34 | 33.52 | 1.27 |
| 8 | 1-tomato/cucumber :2 -Pepper | 30.92 | 8.69 | 30.83 | 1.21 |
| | | **352.62** | **101.48** | **387.39** | **14.68** |

## Appendix AVI: Scenario I: Plant density 8/ m$^2$: Stem pruning 2 (tomato/cucumber):3 (Pepper)

| Plant Density/ m2 | Stem Pruning | Tomato | Sweet Pepper | Cucumber | Basil |
|---|---|---|---|---|---|
| 8 | 2-tomato/cucumber :3 -Pepper | 45.83 | 11.38 | 45.89 | 0.85 |
| 8 | 2-tomato/cucumber :3 -Pepper | 48.20 | 11.25 | 45.61 | 0.97 |
| 8 | 2-tomato/cucumber :3 -Pepper | 49.81 | 12.23 | 45.59 | 1.10 |
| 8 | 2-tomato/cucumber :3 -Pepper | 45.83 | 11.38 | 45.89 | 0.85 |
| 8 | 2-tomato/cucumber :3 -Pepper | 48.20 | 11.25 | 45.61 | 0.97 |
| 8 | 2-tomato/cucumber :3 -Pepper | 49.81 | 12.23 | 45.59 | 1.10 |
| 8 | 2-tomato/cucumber :3 -Pepper | 45.83 | 11.38 | 45.89 | 0.85 |
| 8 | 2-tomato/cucumber :3 -Pepper | 48.20 | 11.25 | 45.61 | 0.97 |
| 8 | 2-tomato/cucumber :3 -Pepper | 49.81 | 12.23 | 45.59 | 1.10 |
| 8 | 2-tomato/cucumber :3 -Pepper | 45.83 | 11.38 | 45.89 | 0.85 |
| 8 | 2-tomato/cucumber :3 -Pepper | 48.20 | 11.25 | 45.61 | 0.97 |
| 8 | 2-tomato/cucumber :3 -Pepper | 49.81 | 12.23 | 45.59 | 1.10 |
| | | **575.37** | **139.46** | **548.34** | **11.68** |

## Appendix B: Ethics Approval, Permits and Euthanizing Protocols
## Appendix BI: Animal Research Ethics Approval

UNIVERSITY OF ™
WAZULU-NATAL
INYUVESI
YAKWAZULU-NATALI

06 October 2018

**Mr Babatunde Ayoade Adeleke (215077928)**
**School of Life Sciences**
**Westville Campus**

Dear Mr Adeleke,

**Protocol reference number: AREC/069/017D**
**Project title:** Bioeconomic feasibility of Aquaponics for the sustainable development of Freshwater Fin Fish Aquaculture in South Africa

**Full Approval – Research Application**

With regards to your revised application received on 06 March and 10 September 2018. The documents submitted have been accepted by the Animal Research Ethics Committee and **FULL APPROVAL** for the protocol has been granted.

**Any alteration/s to the approved research protocol, i.e Title of Project, Location of the Study, Research Approach and Methods must be reviewed and approved through the amendment/modification prior to its implementation. In case you have further queries, please quote the above reference number.**

Please note: Research data should be securely stored in the discipline/department for a period of 5 years.

**The ethical clearance certificate is only valid for a period of one year from the date of issue. Renewal for the study must be applied for before 06 October 2019.**

**Attached to the Approval letter is a template of the Progress Report that is required at the end of the study, or when applying for Renewal (whichever comes first). An Adverse Event Reporting form has also been attached in the event of any unanticipated event involving the animals' health / wellbeing.**

I take this opportunity of wishing you everything of the best with your study.

Yours faithfully

..............................

**Professor S Islam, PhD**
**Chair: Animal Research Ethics Committee**

**/ms**
Cc Supervisor: Dr Deborah Robertson-Andersson and Mr Gan Moodley
Cc Registrar: Mr Simon Mokoena
Cc Academic Leader Research: Professor M Singh
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## Appendix B II: Approved Ethical Protocols for Fish

### 1.1 Overview

Fishes used in research and testing must be treated with the respect accorded to other vertebrate species.

Projects involving the use of fishes for testing should be described within a protocol.

Protocols should be approved by a research ethics committee prior to the commencement of the work.

Fish should be maintained in a manner that provides for their optimal health and well-being, consistent with the demands imposed by the experimental protocol.

Fish should not be subjected to stress that is avoidable and that is not required by the nature of the relevant protocol.

If pain or distress is a justified component of the study, the intensity and duration of the pain /distress must be minimized and if a fish is observed to be experiencing severe intractable pain and or distress it should be immediately killed using an appropriate method of euthanasia.

### 1.2 Capture (Code: C)

Anyone acquiring or transporting fishes, or conducting research on fishes, must be familiar with, and comply with all relevant international, national and provincial legislation and policies governing the capture of fishes.

Prior to capture of wild fish, the local fisheries/conservation officers must be notified.

Investigators should be aware of the list of native species that are endangered threatened or vulnerable and their use should be limited unless the study is potentially beneficial to the wild population.

Wild fishes should be captured, transported and handled in a manner that ensures minimal morbidity and mortality.

As capture induces stress, which can lead to disease, recently captured fish should be more intensely monitored for signs of disease.

The number of captured fish should be the minimum number required to accomplish the study.

### 1.3 Holding (Code: Ho)

Facilities should be kept clean and in an orderly manner.

Tanks should be disinfected before and after every experiment.

Water quality parameters should be monitored at an appropriate frequency for the facility and should allow predictive rather than reactive management of water quality.

Water quality parameters refer to all factors – physical, chemical and biological that influence the well-being of the fish.

The term quality implies that no factor should exceed concentrations likely to be toxic in the context of the facility or study and should remain in the species-specific range for life-sustaining factors.

The most common water quality factors are temperature, dissolved oxygen, pH, suspended solids/ sediments, Carbon dioxide, nitrogen super-saturation, ammonia, nitrate and nitrite. Temperature, dissolved oxygen, pH should be measured daily with other parameters taken as necessary.

Good water quality measuring equipment should be available, regularly calibrated and well maintained. Records of water quality should be maintained and should be retrievable for retrospective analysis in the event of problems.

Water quality must be monitored at a time reflecting the greatest demand on the system (usually after feeding) and maintained within acceptable parameters for the species being held.

Fish should not be subjected to rapid changes in temperature, particularly increases. The definition of rapid is more than 2° C in 12 hours (unless due to a natural upwelling event).

Fishes should be kept in water with adequate oxygen, which for most species is above 90 % saturation.

Water pH should be maintained at a stable and optimal level as changes in pH may influence other water quality parameters.

As low pH results in the production of more toxic ammonia, if pH drops ammonia testing should be done immediately.

Free ammonia and nitrite are toxic to fishes and their accumulation must be avoided.

Salinity changes are stressful for fishes and should be conducted slowly with attention to fish endpoints.

### 1.4 Handling (Code: Ha)

Handling and transport are inherently stressful events with removal from water eliciting a maximal emergency physiological response and should therefore only be carried out when absolutely necessary with air exposure being less than for 1 min.

Fish can be transferred by appropriate net and hands, keeping the fish moist during handling.

Care must be taken at all stages to avoid abrasions and removal of scales and the fish's protective mucous coat, which serves as a physical and chemical barrier to infection as well as being important in osmoregulation and locomotion.

Excessive weight loading on fish at the bottom of nets should also be avoided.

Excessive crowding of fish prior to handling and transport can be stressful, with potential decreases in oxygen levels and water quality, increased chances of abrasion, and should thus be avoided if possible.

Fish should not be subject to rapid changes in temperature, particularly rapid increases in temperature.

Fish should be monitored more regularly monitored following a handling event.

Handling procedures should only be carried out by competent individuals using techniques that minimize the potential for injury.

Fish should only be handled when necessary and the number of handling episodes should be minimized.

Restraint and handling of fishes should be carried out in a manner to minimize visual stimulation. Where feasible, fishes should be protected from direct sunlight and rapid changes in lighting while being restrained.

### 1.5 Transport (Code: T)

Anyone acquiring or transporting fishes, or conducting research on fishes, must be familiar with, and comply with all relevant international, national and provincial legislation and policies governing the capture of fishes and their transfer from one water body or jurisdiction to another.

The transportation container should be well insulated to minimize temperature changes during transport, and possibly cooled to decrease metabolism.

All containers need lids to prevent the loss of fish and or water.

Whenever possible prior to transport fish should be fasted for 12 to 48 hours depending on species, age and water temperature, to ensure an empty gut and minimize nitrogenous waste and water pollution and conserve metabolic energy.

Once loaded and at regular intervals (if possible) water quality and behavioural variables should be monitored, to check that there are no problems.

On arrival particular care must be taken to check water temperature, to ensure that fishes are not exposed to thermal shock during transfer.

Small quantities of fishes can be transported in plastic or polyethylene bags in a cooler to maintain water temperature as close to that of the fishes initial starting temperature.

**1.6 Acclimatization (Code: Acc)**

After transport and before use in experiments fishes should be acclimated to laboratory conditions during a period of quarantine and acclimation.

Acclimatization is temperature dependant but fish will be considered acclimatized after 24 hours.

On arrival at a new facility fish should be handled as little as possible.

Care should be taken to prevent thermal shock. Thermal shock is defined as an abrupt change in temperature of 2 – 3 °C.

If fishes have been transported in plastic bags, the bags should be floated in the receiving tank until the temperature has equilibrated.

If in tanks receiving water should be added to the tank slowly until equilibrium is reached.

If however the fish arrive in water that is of poor quality they should be transferred immediately.

Fish should be gradually reintroduced to feeding during acclimatization.

### 1.7 Record keeping and documentation (Code: RKD)

Detailed Standard Operating Procedures (SOPS) should be developed for the maintenance and care of all fishes and for sanitation of tanks, rooms and equipment.

Checklists should be used for each group of fish so that records are maintained of all cleaning, maintenance and experimental procedures.

At a minimum the following records should be maintained on all captive fish holding area:
Source of fish and date of arrival

Species and sex (if identifiable)

Estimate of age and weight

Name of principal investigation and list emergency contacts

Animal use protocol number including expiration date

Transfer history of fish

Number of fish in tank

Daily records of: husbandry (including feeding regime)

Maintenance

experimental procedures

water quality parameters

morbidity/ mortality.

Readily accessible in the facility records:

History of the fish, including disease and on-going health status

Documentation of regulatory compliance

Copy of animal use protocol

Basic physical and behavioural parameters indicative of well-being in fishes should be monitored daily and written records should be maintained.

Any perturbation of these parameters should be investigated and the causes identified and corrected.

### 1.8 Food, feeding and nutrition (Code: FN)

Fish feed should be purchased form sources that manufacture feed according to standards employed in the feed industry for fish and according to published nutrient requirements for the species, if available.

Feed bags should be labelled with the date of manufacture and analysis information.

Feed should be stored in demarcated areas that are dark, constant humidity and pest free.

Fishes must be fed at appropriate intervals and with a nutritionally adequate, properly sized feed, unless otherwise stated in research protocols.

Fish should be fed to satiation and fish should be monitored during feeding to ensure that fish are not overfed, which is detrimental to their health.

Under no circumstances should mouldy feed be used as it is highly toxic.

### 1.9 Anaesthesia (Code: A)

Anaesthetics should be used in experiments where there is expected to be intensive handling or manipulation with a reasonable expectation of trauma and physiological insult to the fish. Anaesthetics including tranquillisation and post-operative analgesia, should be chosen on the basis of their documented ability to provide predictable results, including immobilization, analgesia and rapid induction and recovery, be appropriate for each individual procedure, while allowing a wide margin of safety for the animal and operators.

Recovery can be enhanced by placing the fish in clean (not anaesthetic) water at the same temperature as the original water.

Regardless of the application, anaesthetics should be tested in a small sample of fish, as the effect of aesthetic can vary with local water conditions as well as with the species, life stage, and size of the fish.

Personal working with aesthetic agents in fish should be properly trained and protected with personal protective equipment.

#### 1.9.1 Immersion Anaesthesia (Code: AIM)

Fish can be immersed in a solution of 0.2 ml phenoxyethanol/L for approximately 1 minute.

The depth of anaesthesia is dependent upon time immersed and temperature of the water.

The fish will be removed worked on then returned to a clean environment and respiration observed.

**1.10 Sampling of Body Fluids (Code: SBF)**

Sedation or anaesthesia should be used to restrain fish for collection of body fluids. It is important to recognise that both restrain and anaesthesia may alter physiological parameters.

The skin and other sites should be properly cleaned and prepared to insure maximum cleanliness.

**1.11 Faeces removal (Code: FR)**

The fish should be removed from the anaesthetic solution, blotted dry on the underside and stripped of faeces by applying gentle pressure to the abdomen between the anal fin and the anus.

As soon as the faeces have been expelled fish should be returned to clean water and observed for normal behaviour.

**1.12 Physiological Measurements (Code: PM)**

The animal is placed in a metabolic chamber and various measurements are done using specialist analysers connected to the chamber.

**1.12.1 Respirometry (Code: PRT)**

Measurement of energetics and the response of an animal to ambient temperature is done by quantification of oxygen consumption or carbon dioxide production using a respirometer and analyser.

Oxygen consumption rate has become the conventional metabolic measure for fishes because dissolved oxygen can be determined with relative ease and reliability. The iodometric or Winkler method of measuring 02 concentrations (mg or mL O2/L water is highly accurate when fresh reagents are available to fix and titrate water samples. Clark-type polarographic electrodes (see below) measure 02 tension or partial pressure (P02) and are easier and faster to use than the Winkler method. These measurements are carried out in a metabolism chamber, using a closed system.

### 1.12.2 Measurement of food consumption (Code: PF)

Animals are usually placed in metabolic cages and fed the experimental diet for several days before the commencement of the experiment. Staggered periods are then necessary. . Daily weighing of animals, food supplied and eaten, are done.

Body composition of small animals, particularly water and fat content is determined following euthanasia of animals (see Section 1.12).

### 1.13Euthanasia (Code: EU)

Humane methods for animal slaughter are based on the principle that the animal is killed quickly with minimum fear and pain or suffering. The most humane euthanasia techniques should be used bearing in mind the health and safety of the personal. A defined endpoint should be established for studies which involve potential pain and /or discomfort.

In any study where there is expected morbidity and mortality, the criteria for early euthanasia should be clearly defined. Depending on the study and the time of morbidity, monitoring should be done daily. Frequency of monitoring should allow for the timely removal of fish before severe morbidity occurs. Frequency of monitoring should be increased where mortality is expected to be high.

From a welfare point of view, the most important factors in slaughter technique are the methods of handling fish during transfer to the killing facility up to the point of stun and the immediacy of loss of consciousness caused by the stunning method.

Studies involving the exposure of fishes to environmental extremes should select the earliest end point possible. Where feasible, the euthanasia of fishes should consist of a two-step process, with initial anaesthesia to the point of loss of equilibrium, followed by a physical method to cause brain death.

A standard operating procedure should be established for any standard treatments and include the definition of endpoints should fish be adversely affected. When large numbers of fish need to be euthanized, the use of immersion anaesthetic at lethal dose in the holding tank is acceptable.

### 1.13.1. Submersion overdose of anaesthetic (AES)

The use of immersion anaesthetic at lethal dose is acceptable as a means of euthanasia. Additionally, exsanguination under anaesthesia is also an acceptable method of euthanasia.

### 1.13.2 Euthanasia in Which Drugs Cannot be Used (Code: AECO)

Euthanasia with carbon dioxide may be accomplished by recharging a container with carbon dioxide from a gas cylinder introduced via a plastic tube into a covered box, bucket, or plastic bag. Place frog in the container and close. After frog no longer moves, check for loss of heartbeat. Other non-chemical means of euthanasia are described in the 1986 Report of the AVMA Panel on Euthanasia (see Appendix II). Explain you special need for these alternative methods under item 8.3 of the Application Form

When applied correctly, percussive slaughtering methods appear to achieve humane slaughter in many fish species. Percussive slaughtering techniques should entail the physical destruction of the brain tissue by pithing of crushing the brain, followed by pithing or cervical dislocation.

### 1.13 Release of fish to the wild (Code: RF)

In general, research fishes that have been kept in captive environments must not be released in to the wild.  Release into the wild is only permissible under appropriate licence from DWAFF.

### 1.14 Disposal of dead fish (Code: DF)

Fish must be disposed of according to acceptable national and municipal regulations for the disposal of biological materials

## Appendix C: Abstracts

### Appendix CI:

### QUANTIFIED SWOT ANALYSIS OF MAJOR AQUACULTURE SPECIES IN SOUTH AFRICA

**Adeleke, B.A*, Moodley, G.K, Taylor, S.M and Robertson-Andersson, D.V,**

**Marine Biology, School of Life Sciences, University of KwaZulu-Natal, Westville, Durban, KZN.**

**RLEDI-GSBL, University of KwaZulu-Natal, Westville, Durban, KZN. South Africa**

**tundeadeleke@gmail.com**

South Africa produces both marine and freshwater aquaculture species, with a combined production output of 5 418 tons of food fish in 2015. Key aquaculture species reportedly cultured include; 4 marine Species - abalone, dusky kob, mussels and oysters and 7 freshwater species - tilapia, trout, catfish, marron crayfish, carp, koi-carp and ornamental species. Key aquaculture food fish species – abalone, dusky kob, mussel, oyster, salmon, trout, tilapia, catfish and marron crayfish were identified, and subjected to quantitative and qualitative analyses of SWOT factors by adapting the quantified SWOT analytical method coupled with the Multi-Attribute Decision Making Method MADM (SWOT-MADM). Internal and external assessment factors were determined; followed by data collection; performance normalization; determination of benchmarking and SWOT coordinates values. Trout and tilapia are positioned in quadrant I, showing a combination of competitive strengths and market opportunities for aquaculture development in South Africa. Abalone, oyster and marron crayfish are situated in quadrant II; thus, they possess market opportunities but weak in competitive position as aquaculture species. Salmon and dusky kob are positioned in quadrant III; therefore, both species are weak in competitive strengths and faced with more threat's factors rather than market opportunities. Finally, mussel and catfish are in quadrant IV; therefore, both species have competitive strengths but are facing more threats than opportunities. Catfish recorded the highest competitive strengths due to internal assessment factors such as; high FCR,

ability to withstand very high stocking density, rapid growth rate, high survival rate, hardiness and versatility of production systems and locations. Abalone and marron Crayfish on the other hand, both exhibited more market opportunities as compared to other key aquaculture species due to external assessment factors like high pricing and good financial indicators. The study is expected to add to existing body of knowledge and guide aquaculture industry stakeholders to make informed decisions with regards to feasibility of aquaculture species in South Africa.

**Appendix CII:**

## QUANTIFIED SWOT ANALYSIS OF MAJOR AQUACULTURE SPECIES IN SOUTH AFRICA

**Adeleke, B.A*, Moodley, G.K, Taylor, S.M and Robertson-Andersson, D.V,**
**Marine Biology, School of Life Sciences, University of KwaZulu-Natal, Westville, Durban, KZN.**
**RLEDI-GSBL, University of KwaZulu-Natal, Westville, Durban, KZN. South Africa**
**tundeadeleke@gmail.com**

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## Appendix D

# PhD Dissertation

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