KICK-STARTING AQUAPONICS PRODUCTION IN SOUTH AFRICA

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Submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy in Bioresources Systems

Bioresources Engineering

School of Engineering

Collage of Agriculture, Engineering and Science

University of KwaZulu-Natal

Pietermaritzburg

November 2018

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DACLARATION 2: CONFERENCE AND PUBLICATIONS

Conference 1: Based on Chapter; 1, 2&3

N. Mchunu, G. Lagerwall and A. Senzanje. 2017. Optimizing aquaponics production in South Africa through the development of a model using local species and environmental conditions. *Ukulinga Howard Davis Memorial Symposium*. University of KwaZulu-Natal, Pietermaritzburg, South Africa. (**Conference**- Oral presentation).

Manuscript 1: Chapter 1

Mchunu, N., Lagerwall, G., Senzanje, A., 2017. Food Sovereignty for Food Security, Aquaponics System as a Potential Method: A Review. J. Aquac. Res. Dev. 08, 1–9. https://doi.org/10.4172/2155-9546.1000497.

Manuscript 2: Chapter 2

Mchunu, N., Lagerwall, G., Senzanje, A., 2018. Aquaponics in South Africa: Results of a national survey. Aquac. Reports 12, 12–19. https://doi.org/10.1016/j.aqrep.2018.08.001.

Manuscript 3: Chapter 3

Mchunu, N., Lagerwall, G., Senzanje, A., 2019. Aquaponics model specific to South African conditions. South African J. of. Agric. Extenstion 47, 73–91. www.scielo.org.za/scielo.php?script=sci_arttext&pid=S0301-603X2019000100007.

Manuscript 4: Chapter 4

Mchunu, N., Lagerwall, G., Senzanje, A., 2020. Aquaponics production simulation using decision-making tool. *Accepted in African Journal of Food Agriculture Nutrition and Development.*

Manuscript 5: Summary of PhD thesis

Mchunu, N., Lagerwall, G., Senzanje, A., 2020 Kick-starting aquaponics production in South Africa. *Under review in Agriculture and Food Security Journal.*

[***Note***] There were unavoidable repetitions along the thesis as a result of the paper format style. Each chapter is constructed for publication in journals. This thesis adopted the formatting style of the Aquaculture Reports Journal because major chapters of this thesis were submitted to this journal.

ACKNOWLEDGEMENTS

My supervisor Dr Gareth Lagerwall for accepting me to the School of Engineering programme which has now given me everything, and for his guidance and support during the development of this study. Most of all thank you for believing in me to execute and complete this task. Thank you.

My Co-Supervisor Dr Aidan Senzanje for taking interest in my study, critical and meaningful comments. Thank you for your senior advice and leadership during difficult times. Thank you.

Mr David Clark for advising and helping me with excel functions during model development.

Mr Henks Stander of the University of Stellenbosch for assisting with sending out my online survey link to your aquaponics contact list and for providing us with your aquaponics production records, many thanks!

NRF, University of KwaZulu Natal and JW Nelson Scholarship for providing funding for this study

My families (Mchunu and Zondi) and my friend's, particularly, Khanyisani Blessing Sibiya and Dr Zamalotshwa Goodness Thungo, for reviwing my thesis for grammar and typo errors, Sipho Michael Mantshongo, Mlekeleli Michael Bhengu, Lindokuhle Good Enough Zondi/Ntshingila, Nkosiyazi Elias Mkhize, Bongumusa Arrange Mchunu, Nonjabulo Zamanguni Yvonne Mchunu and my wife for all the care and social support. Many thanks.

To all my 2009 first year UKZN generation whom have also completed their PhD. Yes, guys we did it, now let go out there and be productive to move our communities, science and Africa forward.

DEDICATION

This work is dedicated to my children, "My children, I thank my God Jesus Christ almighty everyday for each and every one of you. I love you with all my heart, you are my gold, my motivation, my reason for living, thank you for giving me all motivation I needed to achieve this, loving you fulfils me completely. I ask you to do me one favour, just one favour only; "believe that Jesus Christ of Nazareth is God", he gave me everything and he will give you everything as well.

To all my late family members whom never stayed long enough to witness this. Particularly, my mother KaMaZibuko and my sister Nokuthula Mchunu whom in 2009 financially sacrificed everything for me to enter University. Tshengisile Mchunu for encouraging me during my high school phase to focus and study hard to help our family. My aunt, Staff Mchunu, for guiding and leading me toward accepting God Jesus Christ as my life and saviour when I was 9 years old. Lastly to my brother, friend and father, Msinga "Bheki, loool" Mchunu for teaching and showing me how to pray, especially the early morning "3am" mountain prayers, it really worked for me, ngyabonga kakhulu ndoda, your departure really hurt me a lot.

"Ulale uphumule MaWadeyi".

Most of all, this work is dedicated to my God, Jesus Christ almighty. Thank you so much father God for all the strength, love and care you provided, thank you for always making "a miracle" plan for me. Many many thanks!!

Mangife ngikuwe Nkosi-uJesu Chrestu wase Nazareth, ungibonisile amandla nobukhulu bakho emhlabeni. Okwenzele mina ukwenze nakwabanye. Impela "kuyenzeka", akukhathalekile ukuthi ungubani, unjani, futhi usuka emndenini, ekhaya noma endaweni enjani, kodwa uma ukholwa futhi uthembela kuJesu Chrestu kuphela konke kuyenzeka.

"Ungalilahli Ithemba, the helper will come, God Jesus Christ will provide"

GENERAL ABSTRACT

Aquaponics have related food and nutrition security benefit that are important for this country (South Africa). Aquaponics has been shown as an emerging practice in the world but particularly in South Africa. The summary of literature shows that, there is insufficient aquaponics information, data, resources and tools to assist local practisers to operate aquaponics. The primary aim of this study was to develop an aquaponics decision-making tool to assist local aquaponics practisers, enthusiasts and new entrants to have a better opportunity to get started, and to obtain optimum production results in their systems. To achieve this aim, specific objectives were: (a) To determine the aquaponics uses and spatial distribution of current aquaponics in South Africa, (b) To develop an aquaponics decision making tool specific to South African conditions, and (c) to apply the decision making tool to determine the potential aquaponics production yield.

To achieve the objectives, a mixed research method approach was adopted, which combined the methods and procedures of quantitative and qualitative data in a single study, using different sources of data. Data was collected from a number of different individuals, some of whom already have an aquaponic system in place, using a self-administered web based questionnaire, observations, key informants by face-to-face interviews. Secondary data such as literature relevant to the topic was also used. The Unified Modeling Language (UML) was used to design the aquaponics decision making tool/model, Arc GIS was used to determine aquaponics spatial distribution, Microsoft Excel was used to implement the tool/model, SPSS and GenStat statistical software were used to determine dominant variables and interactions among variables.

To collect survey data, ethical clearance was applied for at UKZN Human Social Sciences Research Ethical Committee (HSSREC) in the research office. After the ethical clearance was obtained (Ref No: HSS/0106/016D), the online survey was implemented with pre-coded question categories to be completed by the participants. The survey questionnaire categories, included question categories for growers and non-growers. The grower's category was answerable to those whom had an operational aquaponic system in place, while non-growers was answerable to everyone whom were keen in the study. The grower's category questionnaire contained questions about; aquaponics general information, fish production and

plant production. The non-growers contained one question category which was designed to trace and track interest toward aquaponics in this country. A survey link was publicized through an email list of farmers provided by the Aquaponics Association of South Africa (AASS). Weekly email reminders, and sometimes phone calls were used to remind participants to complete the survey. In addition, social media platforms (Facebook, Twitter and WhatsApp) were used for sharing the survey link and posting weekly reminders. Local aquaponics companies were also contacted through browsing Google search engine and making contact by phone call, email and sometimes by field visit. The questions were both closed and open-ended.

To develop the decision making tool/model, this study acknowledged that, while modeling and model development has great potential to provide for better decision-making to obtain optimum results. Its use and success is greatly dependent on the acceptability and benefits to the end user/beneficiaries. The Microsoft Excel platform was used as it proved to be user friendly and easily accessible to most South Africans. The primary data from the online aquaponics survey and a summary of well empirically tested aquaponics production ratios were used to parametrized model. The aquaponics production ratios can be adopted and are applicable anywhere else in the world. This was useful to the study because it was economically and practically unfeasible for the scope and time of this project to conduct experiments in every province of this country to inform the model. Moreover, the University (University of KwaZulu-Natal) process to conduct studies on animals particularly fish requires a certificate of two year course of fish handling, which was impossible for the funding, scope and time of this study.

To conduct aquaponics production studies using the aquaponics decision-making tool/model, a summary of the data from the literature, field visits and observations were used. The data showed that different scales of aquaponics production can be ranged and distinguished. Hobby systems have a fish stocking density of 10-20 kg/m^3 and 500-1 000 m^3 fish tanks. Subsistence systems have a fish stocking density of 20-40 kg/m^3 and 1 000-2 000 m^3, while economic scale systems have a fish stocking density of 100-300 kg/m^3 and 4 000-50 000 m^3 fish tanks. Based on this data, simulation experiments were designed. This study was designed as 2×3×3 factorial study giving 18 interactions. Because aquaponics are the production of fish and crops concurrently, therefore yield production had two levels- fish and crop, fish stocking density had three levels- low, optimum and higher and aquaponics scale of production had 3 levels- hobby, subsistence and commercial scale. The summary of data of aquaponics variables from the literature was used as optimum level, lower and higher levels were based on experimental design. Daily fish feed and planting area variables were analysed as interactions. The interaction was, yield × daily fish feed × fish stocking density × scale of production and planting area × fish stocking density.

In the national aquaponics survey, a total of 187 responses were captured within three months, 44 respondents had a fully operational aquaponics. Most respondents in non-grower's category were female (53%) most respondents did not know what an aquaponic system is (60%), however, were interested in aquaponics concept and principles (84%). In grower's category, the most commonly cultivated fish was tilapia (82%). The most commonly raised plants were leafy vegetables (75%).

The developed tool/model was able to predict the main aquaponics inputs variables, namely; fish stocking density, daily fish feed and required planting area. The fit for fish stocking density, daily fish feed and planting area was R^2=0.7477, 0.6957 and 0.4313 respectively. The RMSE was 14 for fish stocking density which deviated by 29 % from observed and simulated, RMSE was 218 for daily fish feed which deviated by 14 % to the observed and simulated data and RMSE was 4 for planting area which deviated by 25 % to the observed.

Yield production (kg) of both fish and plants increased significantly ($p<0.05$) as fish stocking density was increased. In hobby scale, plants yield was higher than fish yield in all levels of fish stocking density, the plant-fish yield (kg) was 40-33, 80-67 and 150-133 respectively. In subsistence scale, fish-plant yield (kg) was 240-200, 300-267 and 400-333 respectively. In commercial scale, fish-plant yield (kg) was 600-533, 1 100-1 000, 1 500-1 333 respectively. Daily fish feed increased significantly with increase in fish stocking density across all scale of aquaponics production (hobby<subsistence<commercial). In hobby scale, at low fish stocking, 0.65 kg feed produced 1 kg fish, at optimum, 0.65 kg feed produced 1 kg fish and at higher fish stocking, 0.37 kg feed produced 1 kg fish. In subsistence scale at low fish stocking density, 0.38 kg feed produced 1 kg fish, at optimum level, 0.63 kg feed produced 1 kg fish and at higher level, 0.65 kg feed produced 1 kg fish. In commercial scale, in low fish stocking, 0.64 kg feed produced 1 kg fish, at optimum, 0.63 kg feed produced 1 kg fish and at higher fish stocking, 0.64 kg feed produced 1 kg fish. Plant culture have more yield output than fish culture in all aquaponics scale of production.

Because aquaponics are still not practised by many and are mostly characterised by smaller systems, aquaponics in South Africa can be considered an emerging practice. Most of the current aquaponics practitioners have limited aquaponics production knowledge and a significant number of people, particularly youth are interested in aquaponics. We therefore conclude that attention should be paid to raising the awareness about the potential of aquaponics, and raising the technological knowledge of aquaponics operators to increase the number of aquaponics operations and to increase the total amount of food produced in and with aquaponics.

The developed model can be adopted by new aquaponics entrant's, enthusiasts, extension officers and by agricultural facilitators as an aquaponics start-up platform to obtain maximum yield from these systems. Hobby scale aquaponics system could not produce sufficient yield to support human subsistence. Commercial aquaponics practisers can adopt higher fish stocking density than low and optimum levels as the yield of plant has significantly higher biomass than fish. Because fish feed could be expensive, fish feed could become a constraint in aquaponics production sustainability particularly in a developing country like South Africa.

The main hypothesis of this study was that, aquaponics is an emerging practise worldwide, aquaponics in this country are also emerging and that local practisers have low aquaponics skills and knowledge. This study has clearly established the emerging nature of aquaponics in this country as shown by both, low level of knowledge among current practisers and small number of systems across the country. This study has prompted for an easy use tool/model to help current aquaponics practisers and new entrants to have a better opportunity to obtain maximum result output. This study has also provided a potential aquaponics production data and information, which could be obtained if these systems are properly implemented. However, further experiments will need to be conducted to verify, calibrate and validate these results.

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1. INTRODUCTION AND LITERATURE REVIEW

The increase in population and urbanization has resulted in increased need for food and water particularly in South Africa (Mchunu *et al.*, 2018b). South Africa is a water and nutrient scarce country and there is a need to conserve this resource pool (Molobela and Sinha, 2011; Sinefu, 2011). South Africa is among other 30 driest countries in the world, having an annual average rainfall of 500 mm (Sinefu, 2011). This is a lower rainfall amount than worldwide annual averages of 860 mm (Mabhaudhi, 2012). Water resources in this country are scarce and limited in nature (Mabhaudhi *et al.,* 2013). The International Water Management Institute (IWMI) has listed South Africa as a water constrained country (Mabhaudhi, 2012). The resultant effects is crop failure and reduced crop yield, particularly for poor and needy people in this country.

A summary of data from the literature shows that the continuous use of synthetic fertilisers over time depletes natural soil diversity resources which are needed for field production (Murugan and Swarnam, 2013). Challenges such as soil-borne diseases, weeds, and soil infertility, associated with soil plant production has made the field soil culture risky and at times undesirable (Andersson, 2015). Moreover, adverse climate change effects such as hails, drought and floods which are associated with global warming have risen the instability of field crop production (Maliszewski *et al.,* 2011). Because of the need to produce more and good quality food without further damage to the natural environment, and to mitigate adverse climate change effect, even though it comes with extra cost, controlled environment soilless agricultural systems can be explored.

Nitrogen (N) and phosphorous (P) are the main essential macro nutrients that are utilized in high quantities by plants to produce food (Rafiee and Saad, 2005a). These nutrients can be sufficiently sourced from fish excretion waste through an aquaponic system if it is properly designed and implemented (Turcios and Papenbrock, 2014). However, these nutrients continue to be more limiting in agriculture as it is expected that in the near future phosphate rock could run out (Bonvin, 2013). Similarly, the production of nitrogen fertilizers from atmospheric N is also expensive. While biological N fixation has great potential, its use also requires other nutrients to grow the legumes, alternative sources of these nutrients need to be sought if sustainability through agriculture is to be achieved particularly in this country (Mchunu *et al.*, 2018b).

Soilless systems can be a solution toward adverse climate change effects and unfavourable field production conditions (Love *et al.*, 2014). Among the list of soilless systems, there are three mostly adopted soilless production systems in agriculture, namely; aquaculture and hydroponics (Food and Agriculture Organisation (FAO), 2015), and recently aquaponics (aquaponics systems) (Love *et al.*, 2015; Love *et al.*, 2014). Each system has a related benefit of saving water and sustainable food production (Goddek *et al.*, 2015). Aquaculture and hydroponic production are common and well documented systems across the world, including Africa.

Hydroponic culture is a method of growing plants using mineral nutrient solutions, in water, without soil (Sikawa and Yakupitiyage, 2010). In hydroponics, terrestrial plants are grown with their roots in the mineral solution only (in Nutrient Film Technique and in Floating raft system), or in an inert medium, such as perlite or gravel (Monnet *et al.*, 2002). Aquaculture is the farming and husbandry of aquatic organisms under controlled or semi-controlled conditions (Allison, 2011; United State Agency for International Development (USAID, 2013) (USAID, 2013). Aquaculture plays a critical role in food and nutrition security and in providing livelihoods for millions of people across the world including Africa (USAID, 2013; FAO, 2015). However, for years aquaculture has been plagued with challenges to achieve sustainable fish solid waste management for all time good water quality (Khater *et al.*, 2015).

The net nitrogen (N) and phosphorous (P) concentration in the aquacultural effluent equals to the average nutrient requirement of most vegetables, flowers and herbs (Khater *et al.*, 2015). The same effluent pose a pollution problem if disposed of in the environment (Mnkeni and Austin, 2009). The resultant effect of aquacultural waste and effluent runoff can contribute to negative environmental impacts associated with eutrophication thereby affecting fish well-being (Turcios and Papenbrock, 2014). Eutrophication is the significant richness of nutrients in lakes and in other water bodies, predominantly due to water run-offs from crop lands, which trigger a growth of plant life (Worsfold *et al.*, 2016).

Aquaponics is the production of fish and vegetables concurrently by combining aquaculture and hydroponic production systems into one system (Rakocy, 2007). Aquaponics has been described as superior since it combines these two systems (FAO, 2014). Aquaponics are common and well known in the developed countries being most popular in Australia (Goddek *et al.,* 2015). Aquaponics could still be a new term and emerging technology in this country (Love *et al., 2015;* Love *et al.,* 2014*)*. This create opportunities for new niche for sustainable food production, which is necessary and important to ensure food availability at all times. To make good use of aquacultural fish waste, aquaponics were developed (Rakocy, 2007). In aquaponics, fish waste generated from aquaculture is used with a dual mitigation effect, (a) to maintain good water quality in the fish component, and (b) to produce healthy food suitable for an active healthy life (Khater *et al.,* 2015; Lam *et al.,* 2015). Moreover, aquaponics related benefits include the use of less water than conventional agriculture and in addition, establishes a platform for nutrient recovery and reuse (Munguia-Fragozo *et al.,* 2015). This is important for this country to address water scarcity and food insecurity problems.

South Africa is one of the food and nutrition insecure nations in the world (Statistics South Africa, 2014). Fish meat contains nutrient package that allows for an active healthy life with related economic production (Lam *et al.,* 2015b). Aquaponics has the potential to sustainably produce sufficient fish for everyone (FAO, 2014). As such, aquaponics may be useful in this country which has limited agricultural production resources such as water, fertile croplands, high urbanisation rate and increasing urban poverty (Statistics South Africa, 2014).

In addition to food production, aquaponics plays a critical role in safeguarding our environment. Aquaponics being a closed system, avoids nutrients runoff, which contaminates the environment, making aquaponics a potential organic food production system (Khater *et al.,* 2015). Aquaponics uses zero chemicals than conventional agriculture, as such, aquaponics has gained new attention worldwide attributed to its use of natural nutrient source material from fish to support plant production (Love *et al.,* 2014). Aquaponics could gain similar attention in this country. Aquaponics studies need to be conducted for this country to provide aquaponics enthusiasts with information and resources to get started.

1.1. **Problem statement**

The aquaponics related food and economic benefits are important for this country. The study conducted by Love *et al.* (2014; 2015), recorded a total of 257 respondents from an international aquaponics survey study which included 20 countries around the world, South

Africa was part of this study. In this study only one response was captured and recorded for South Africa. This study established the emerging nature of aquaponics in the world, particularly in South Africa. Since aquaponics are an emerging practice in South Africa, it suggest that, there is limited data, information, resources and tools available, if any, to assist local people in this country to have an opportunity to establish and operate aquaponics.

A summary of data and information from the literature shows aquaponics as an challenging system to operate. To establish a conducive microbial conditions and calculating fish stocking density and daily fish feed. For aquaculture fish tank, for optimum hydroponic plant production in a given planting area has been shown to be the most challenging task (Thorarinsdottir, 2015). Moreover, the average climatic conditions in this country may not be suitable to support an independent fish cultivation for a sustainable livelihood and viable economic production (Diver and Rinehart, 2010; FAO, 2014; Sikawa and Yakupitiyage, 2010). The optimum fish production, particularly all tilapias species which is mostly cultivated and suitable to aquaponics, requires a yearly average of 22 (minimum) and 28 (optimum) degree Celsius water temperature (Liang and Chien, 2013).

Decision tools or models have been shown to be helpful in sensitive and complex agricultural systems such aquaponics (Lennard, 2012; Rakocy, 2007). In this country, Thamaga-Chitja (2008) findings where she developed a decision-making tool for smallholder farmers of Swayimane in Pietermaritzburg could be used to show and explain the importance of decision-making tools. The tool she developed helped smallholder farmers optimise organic food production. In 2004, Wilson Lennard PhD studies developed an optimisation aquaponics model for Murray cod fish combined with leafy vegetables particularly lettuce (Lennard, 2004). Similarly his model boosted aquaponics production and to this day it is still helping people around the world

Developing an aquaponics decision-making tool could be useful to help new aquaponics practitioners in this country. Because models (decision-making tool) can save time and production costs (Mabhaudhi *at al.*, 2013), models can act as a support tools for planning, decision-making, and yield forecasting (Fallis, 2013). However, it is also important to note that aquaponics models and models in general are not and cannot be a substitute for real production on the field (Mabhaudhi, 2012). However, when calibrated and validated with data from field experiments, they can help lower the overall costs of field experiments with regards to time and space.

1.2. Justification

A significant quantity of research work has been focused on hydroponics and aquaculture production systems. Fish waste is rich in nitrogen, and nitrogen is one of the most limiting macronutrients in agriculture (Wortman, 2015), fish waste can nitrify and fertilize hydroponic culture in aquaponics. Simultaneously, fish waste also produces significant quantities of phosphorus and trace elements which are important for plant production (Graber and Junge, 2009). Studies by Rakocy (1989) over a period of 30 years, have shown that aquaponics can be a competitive alternative to the field and hydroponic production with the advantage of fish and greens being produced concurrently while input costs are reduced.

Most aquaponic foods are considered healthy because they are produced by natural nutrients (Sace and Fitzsimmons, 2013). There is also a growing trend of urban poverty in this country (Statistics South Africa, 2014), and aquaponics are suitable for urban areas. This is ideal and needed in this country to sustain an active healthy life (USAID, 2013 and FAO, 2014). However, there is limited data, if any, which relates to aquaponics in South African to provide options for sustainable food production. As such, if aquaponics were to be adopted in this country to address problems associated with human population growth, limited croplands, water scarcity and food insecurity, there is a need to conduct more studies to develop resources and tools such as one which were developed by Lennard (2004) and Thamaga-chitja (2008) to provide aquaponics production information.

The primary aim of this study was to develop an aquaponics decision-making tool to help local aquaponics practitioners and new entrants to optimise and get started with aquaponics in this country.

1.3. Research questions

(a) What are the current aquaponics uses, management practices and distribution in South Africa?
(b) Can aquaponics decision-making tool really make aquaponics easy for a layperson?

(c) Can aquaponics decision-making tool if developed and implemented determine the potential yield production?

1.4. Objectives

(a) To determine the status and spatial distribution of aquaponics in South Africa.
(b) To develop aquaponics decision-making tool for South Africa.
(c) To apply aquaponics decision-making tool to determine the potential yield production.

1.5. Hypothesis

(a) Local people do not know what an aquaponic system is and current aquaponics practisers do not have adequate knowledge and skills to operate and manage an aquaponic system.
(b) Aquaponics decision-making tool will simplify aquaponics production for easy use.
(c) Aquaponics decision-making tool, if developed and implemented, can predict aquaponics yield production.

1.6. Originality statement

This study will contribute to the worldwide quest to determine the, status, locality and number of aquaponics systems in the world, because aquaponics have been shown to be emerging practice and few by population. There is no study which has determined the status of aquaponics for South Africa. The study will further develop a computer based user aquaponics decision-making tool which incorporate unique inputs function, such as locality by province and region, aquaponics environment and desired yield selector making the tool more specific and suitable to South Africans. The study will also provide potential yield production output for various aquaponics scale of production, which can be used for investment purposes. The information produced from this study could be used to formulate and inform aquaponics policy development for this country which currently do not exist.

1.7. General Overview of Soilless Systems

In soilless production, plants are raised without using soil as a growth medium, in most cases it is because of related soil infertility (low potential areas), erosion, adverse weather conditions and soil borne diseases problems associated with risk of field production (Andersson, 2015). The method of not using soil as a crop stand saves significant water because in soil systems water can leach to ground water (Diver and Rinehart, 2010). There are various common and available soilless productions systems which, include hydroponic, geoponics, aquaponics, vertical gardens and tunnel or greenhouse aquaculture (FAO, 2014). Soilless production plays a critical and unique role in providing out of season food (meat and crop plants), herbs and flowers (Roosta, 2014). Soilless systems have been a viable option to food and nutrition security in many developing countries including Nigeria and South Africa (Ibironke, 2013). However, there is little known or documented information about these systems in Africa, particularly in this country. It is now well documented that the systems that make up aquaponics are hydroponic and tank aquaculture, and these systems are well documented from most literature. Aquaponics lags behind, because it is still an emerging practise worldwide (Love et al., 2015).

1.8. Aquaponics history and evolution

In South Africa, aquaponics emerged from the aquaculture industry as fish farmers were exploring methods of raising fish while trying to decrease their dependence on the land, water and other resources (Mchunu et al., 2018a). However, the production method of combining fish and crop production into one integrated system is not new (Turcios and Papenbrock, 2014). The earliest evidence of integrated aquaculture can be traced to Chinampa in Mexico and Asia (South China, Thailand, and Indonesia) where fish were used to support rice growth in the field production (Jones, 2002), also see Figure 1 and 2. Chinampa is an artificial floating garden made from reeds and covered by mud coming from the bottom of the lake (Turcios and Papenbrock, 2014). The success of the Chinampa method and rice production in Asia subsequently prompted for the quest to produce variety of crops through an integrated system, and around the 1970s, the term aquaponics was born (Jones, 2002).

The term aquaponics can be attributed to the works of the New Alchemy Institute and the works of Dr. Mark McMurtry at the North Carolina State University (Acquacoltura Italia, 2015). In the mid 1980's, Mark McMurtry and Professor Doug Sanders created the first known closed loop aquaponic system (Acquacoltura Italia, 2015). At the same time, in the 1970s, research on using plants as a natural bio-filter in aquaculture started and was lead by Dr. James Rakocy from the University of the Virgin Islands (Acquacoltura Italia, 2015). In 1997, Rakocy and his team developed the use of deep-water culture hydroponic grow beds in a large-scale aquaponic system (Acquacoltura Italia, 2015; Jones, 2002).

Aquaponics is mostly dominant in Australia (Lennard, 2012), the interest toward aquaponics gained attention because it demonstrated to farmers and growers an effective and innovative way to escape water scarcity and risk of field crop production (Jones, 2002). Followed was Wilson Lennard PhD studies where he sought to optimize aquaponics production (maximum plant growth and nutrient removal from fish tanks) using Murray Cod fish species and the Green Oak lettuce variety in Australia (Lennard, 2004). Lennard showed that an optimal balance of fish to plants can be achieved while water is reused (circulated) within the system. Aquaponics continues to be evolving with time and generation, recent studies are more focused on commercial productivity, decoupled systems has been explored in a quest for economic productivity of aquaponics.

Figure 1 Mexico Chinampa plant production system, the artificial beds float in a nutrient rich lake (Jones, 2002).

Figure 2 Integration of rice field production with fish production, fish survives on rice and excrete nutrients to support rice production eliminating the used fertilisers (Acquacoltura Italia, 2015).

1.9. **Aquaponics**

1.9.1. Recirculating aquaponics systems (RAS)

A review of literature shows that recirculating aquaponics, are the production of fish and vegetable concurrently by water circulation methods (Sace and Fitzsimmons, 2013). The literature includes Love et al. (2015), who defined aquaponics as a bio-integrated system that links recirculating aquaculture with hydroponic vegetable, flower, herb production (Figure 3). The water circulation methods save significant quantities of water (Turcios and Papenbrock, 2014), which is important to countries like South Africa which have a water scarcity problem (Mabhaudhi et al., 2013). The recirculating aquaponics systems are designed to raise large quantities of fish in relatively small volumes of water (20 kg of fish per 1 000 m^3 volume of water), making aquaponics an innovative and ideal food production method suitable for everyone (Wilson, 2005).

In addition to food production, aquaponics plays a critical role in agricultural evolution and advancement. In circulating aquaponics, effluent that is generated from the fish tanks is pumped and used to fertigate plants in hydroponic culture (Rakocy, 2007). In return, this process is useful to the fish, because plants roots system together with rhizobacteria helps to extract nutrients from the water solution cleaning up water. The nutrients materials produced from fish metabolic waste, manure, and decomposing uneaten fish feed, are pollutants that could build up to lethal levels in fish tanks, in circulating aquaponics. This waste is directly supplied to hydroponic culture as liquid nutrient source material (Monnet et al., 2002). In recirculating aquaponics hydroponic culture functions as a biofilter (Graber and Junge, 2009) by removing ammonia, nitrates, nitrites, and phosphorus and other trace elements. This enables the freshly cleansed water to be recirculated back into the fish tanks (Liang and Chien, 2013).

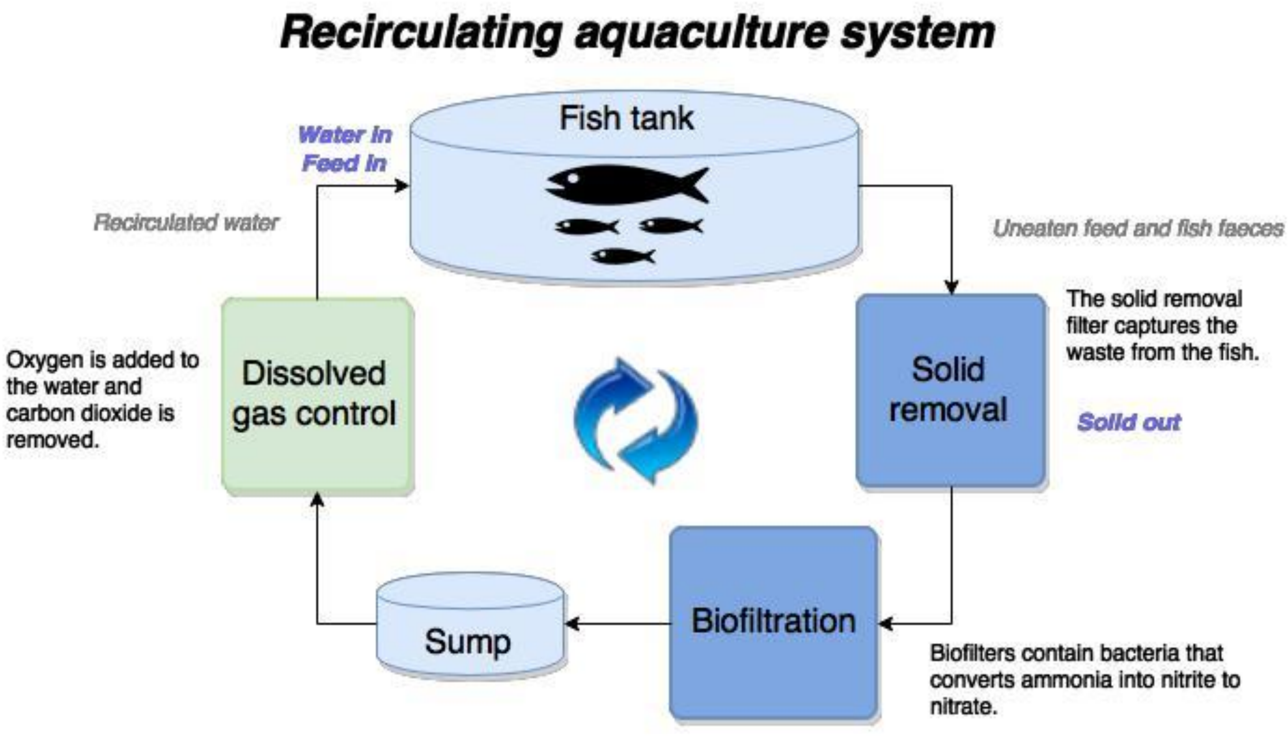

Figure 3 A schematic overview of a recirculating aquaponic system (Thorarinsdottir, 2015).

1.9.2. Decoupled aquaponics

In decoupled aquaponics water flow is split into two independent components (Goddek et al., 2016), where fish and plant systems are occasionally linked to each other, only in situations where plants need nutrient boosts or when water in the fish tank requires purification to remove waste accumulation in the fish unit (Monsees et al., 2016). In decoupled aquaponics, optimal environmental conditions for both the plant and fish production units can be manipulated without interfering with the whole system (Figure 2). Decoupled aquaponics has gained attention with the development of commercial aquaponics where investment and risks are high (Morshuizen, 2013). Decoupled aquaponics avoids system collapse, when problems develop in the fish or in the plant components, each component can be isolated and be run as a stand-alone system, aquaculture or hydroponic culture, while the solution is being investigated (Goddek et al., 2016). The method to separate water and nutrient loops in decoupled systems provides for a better control of water chemistry in both systems (Kratky, 2009). The interesting discussion is, are the decoupled aquaponics systems more economically viable and advantageous than traditional aquaponics systems, considering that decoupled systems require more infrastructure investment?

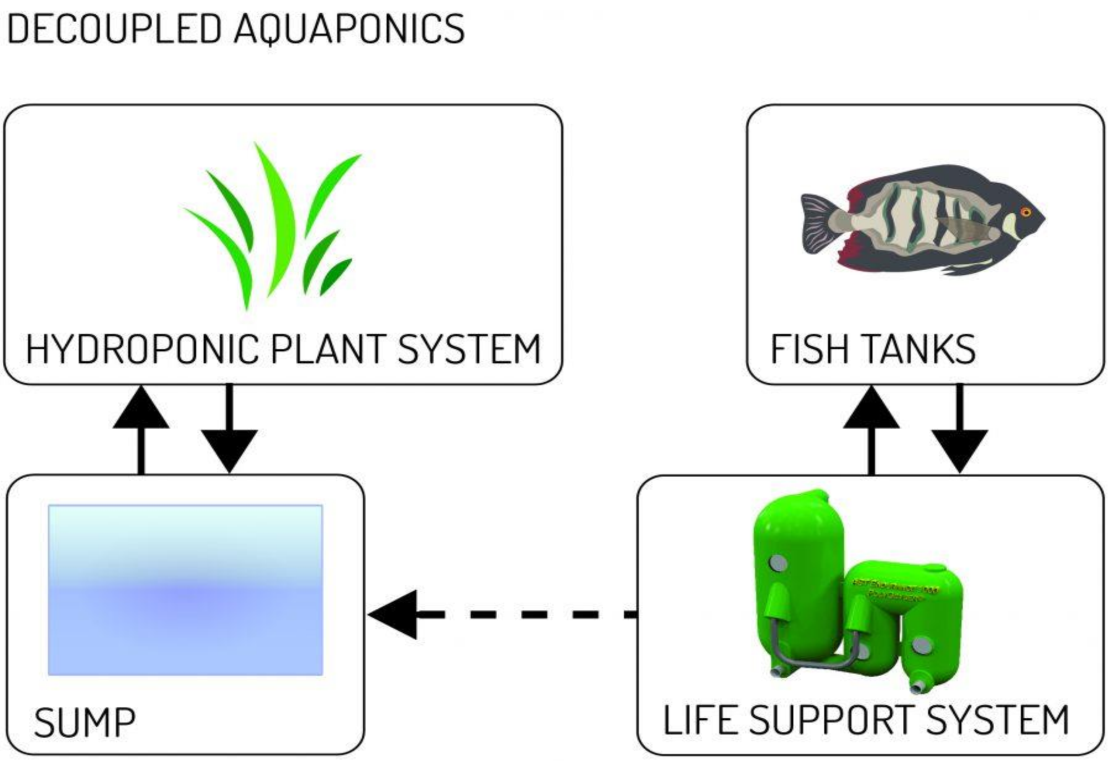

Figure 4 A schematic overview of a traditional decoupled system (Thorarinsdottir, 2015).

1.9.3. Mechanical filtration

Fish feed and solid removal is a critical step in RAS in order to maintain a good water quality and to prevent a system collapse (Graber and Junge, 2009b). Fish waste makes fish vulnerable to diseases and gills damage in particular, concurrently increases ammonia in water, reduces oxygen spaces or concentration as a result of higher biochemical oxygen demand, reduces biofilter efficiency and promotes clogging that leads to the formation of anaerobic (Sace and Fitzsimmons, 2013a). The principle of solid removal in aquaponics is to reduce the retention time of solids in the system as much as possible so that solids do not break down into smaller particles which makes them costly and difficult to treat, because they replace oxygen space in the fish tank. (Goddek et al., 2016). Mechanical filters are generally located after fish tanks and before the biofilter to remove solids produced from uneaten fish feed and fish faeces (Thorarinsdottir, 2015). There are different biofilter products in the market, Table 1 summarizes the pros and cons of different mechanical filter options available.

Table 1 Advantages and disadvantages of different mechanical filter options (Thorarinsdottir, 2015).

Filters	**Advantages**	**Disadvantages**
Clarifier	• Maintenance-free. • No electricity needed, requires only purging the system from sludge.	• Low water volume compared to alternatives. • Water retention depends on the particle size to be removed.
Bead filter	• Simple operations. • Limited space for water treatment. • Suitable for small or medium farms.	• Requires electricity. • Maintenance is needed. • Beads needs to be replaced. • Water needed for backflush with • relative disposal. • Number of flushes depend on the solid load.
Sand filter	• Simple • Suitable for small or medium farms.	• Requires electricity for pumping, • Not practical with organic wastes because particles make clogs. • More frequent backflush.

Drum filter	• Effective for big farms. • Water movement is by gravity.	• Requires electricity. • Some maintenance needed requires periodically replacements of screens. • Water needed for backflush with relative disposal. • Number of flushes depends on the solid load and the mesh of the screen.

1.9.4. Bio-filtration

In aquaponics, the biofilter is located after the mechanical filter. The biofilter is a component which facilitates the mineralization process of nutrients, particularly nitrogen (Lund, 2014). In aquaponics, fish waste produces significant quantities of ammonia-N and solids which have been shown to contain average plant nutrients sources that equal to the most vegetables nutrient requirements, hence, important for plant production (Buzby and Lin, 2014). However, for fish waste to be made available to most plants, it has to go through a mineralization process (Nyamangara et al., 2009). Mineralization is the process by which organic matter (solids) breaks down in the environment (aquaponics) (Hu et al., 2015).

There are five main mechanisms that are responsible for mineralization, which in turn determines nutrient release pattern in aquaponics, these mechanisms are, ammonification, nitrification, denitrification, immobilisation and volatilisation (Rafiee and Saad, 2005). Mineralization occurs quickly, less than a week (3-7 days) when conditions are perfect for bacteria to reproduce (Johnson et al., 2005). The conditions that favour optimum mineralization are high aeration, adequate moisture, appropriate pH, and balanced mineral nutrients (Roosta, 2014). The environmental and growth media mineralogy factors affect the microflora players and their actions, which in turn determine the rate of mineralization in the system and the amount mineralized over time (Nyamangara et al., 2009). Microbial activity is limited at a temperature near freezing and at low pH less than 5.5 and increases with rising temperature and pH. Maximum nitrogen mineralization occurs when the temperatures in the system reach 30–36 ^{o}C. However, the decline in N mineralization indicates low microbial activity and a degradation of the biological properties of the grow medium (Lund, 2014). When temperature, moisture and pH is favourable for microorganisms to metabolize, it results in mineralization whereas, the opposite of the process leads to immobilisation.

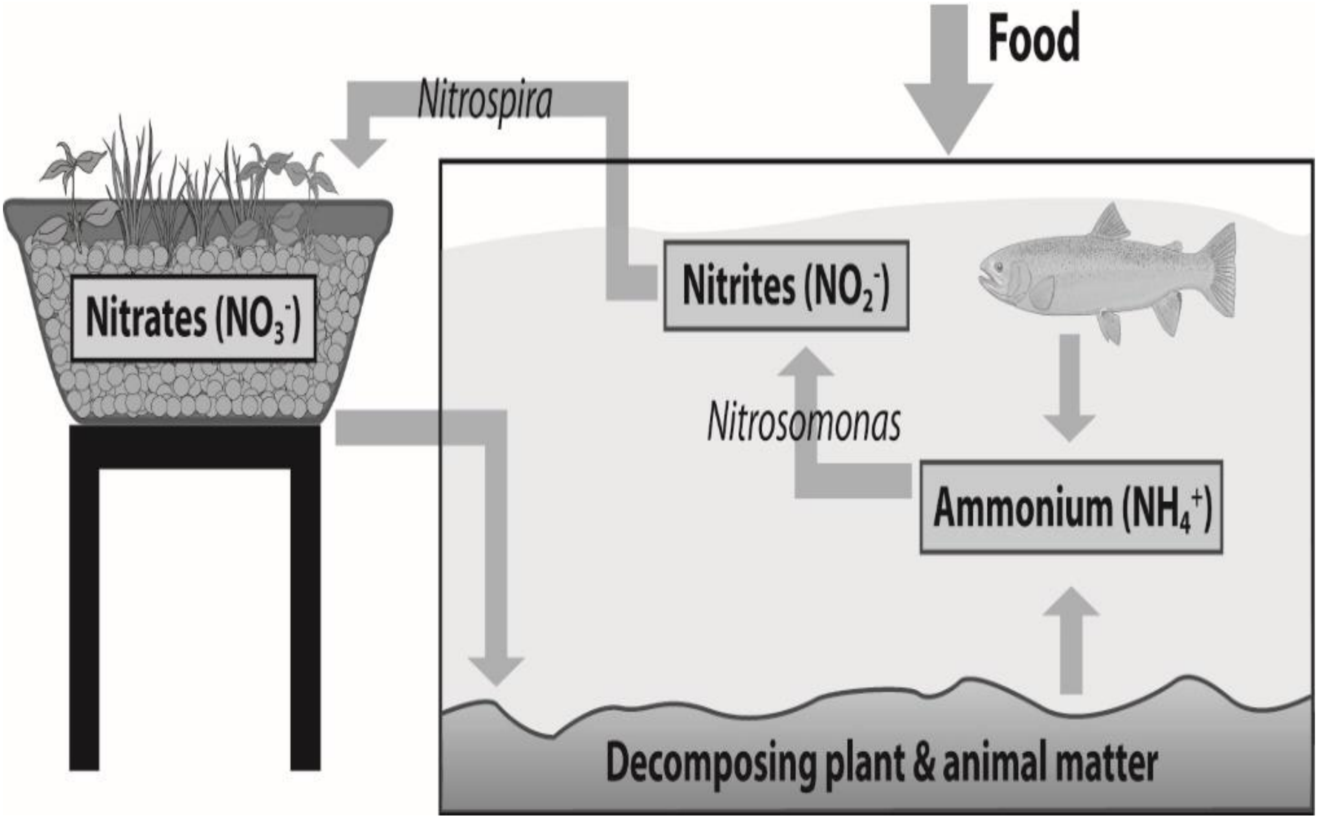

Figure 5 Aquaponics nutrient flow as it shows mineralization and nitrification process where decomposing plant and animal matter are incorporated in water and transformed into nitrate by *Nitrosomonas* and *Nitrospira* bacteria species before supplied to hydroponic culture (FAO, 2014).

1.9.5. Feed Conversion Ratios (FCR) and Species Combination for Aquaponics

Feed Conversion Ratio (FCR) is defined as the amount of dry feed required to produce one kg of wet fish (Nunes et al., 2014). Rafiee and Saad (2005) viewed FCR as the ratio between daily fish feed and fish biomass. The main factors determining FCR efficiency are: type of feed, fish used, water temperature, and fish stocking density (Palm et al., 2014). Pelleted fish feed, optimum fish stocking density and water temperature results into high FRC range, 1.0 to 1.2 (Ahmad et al., 2004). Different fish have different FCR value (Table 2), fundamentally because they differ in biology (morphology and physiology) (Figure 6). There are herbivores, carnivores and omnivorous fish species, and there are cold and warm-blooded fish species, resulting in different management requirements. For instance, fresh water catfish is very sensitive to water temperature (Endut et al., 2010).

Table 2 Feed conversion ratio of different fish species

Fish species	FRC average
Tilapia *(Oreochromis mossambicus)*	1.4 -1.8
Cat fish *(Clarias gariepinus)*	2 - 2.5
Perch *(Perca flavescens)*	1.2 -1.5
Bass *(Micropterus salmoides)*	1.6 – 2.0
Trout *(Oncorhynchus mykiss)*	1.2 - 1.5

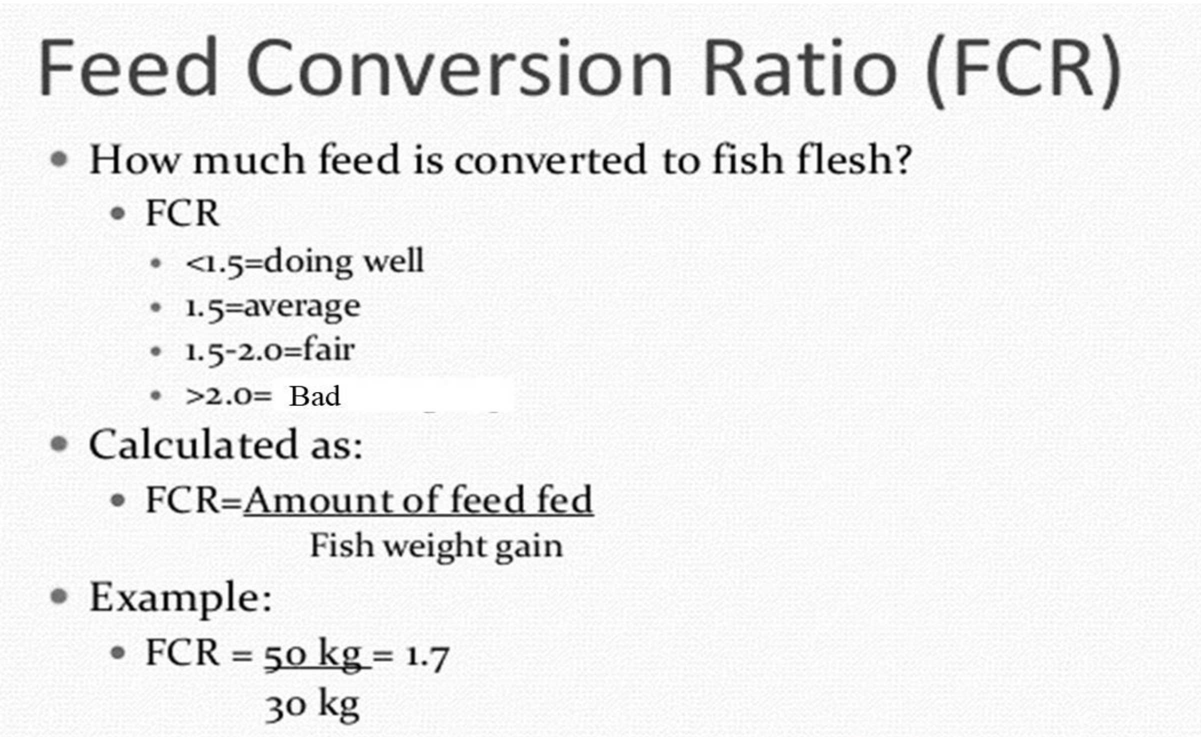

Figure 6 Formula for calculating feed conversion ration different fish have different FCR value, the bigger the FRC value, the inefficient that fish species toward fish feed (Maucieri et al., 2019).

Generally, in aquaponics fish are stocked at 1 kg per 100 m^3 water, even though this is a low stocking density, it convert to support approximately 20 lettuce plants in the hydroponic culture (Sace and Fitzsimmons, 2013). Diverse types of fish species could be cultivated in a controlled or regulated aquaponics environment conditions (Lennard, 2004). The cold and warm water fish species are both promptly and easily adapted to recirculating aquaculture systems (Allison, 2011). These fish species include tilapia, trout, catfish, perch and bass (FAO, 2015). However, the management and practices vary with the type of species raised, because different fish have different morphological and physiological environmental requirements (Wortman, 2015). Fish characteristics that determine the suitability of fish to aquaponics, include the ability of a fish to breed fast, fast growth rate, flexibility to fish feed, resistance to extreme water quality conditions (low pH, high ammonia-N and low dissolved oxygen) and withstanding harsh water temperatures. Leafy vegetables such lettuce, spinach, herbs etc., have low to medium nutritional requirements, and are well adapted to aquaponics (Goddek et al., 2015). The fruit vegetables such as bell peppers, tomatoes and cucumbers have a higher nutritional demand and perform better in a heavily stocked and well established aquaponics (Buzby and Lin, 2014) as shown in Table 3.

Most commercial aquaponics are based on tilapia production (Rafiee and Saad, 2005). Tilapia are an ideal species because they mostly grow in temperatures that are similar to those required by the plants. They also grow fast and are tolerant to a wide range of environmental climatic conditions. This is what makes tilapia one of the most cultured fish across the world (Popma and Masser, 1999). It is also documented that Barramundi and Murray cod fish species have been raised in recirculating aquaponics in Australia (Lennard, 2004). It is vindicated in various literature, including over 30 years of research by James Rakocy at the University of Virgin Island (UVI). Tilapia have been combined with most vegetables including lettuce, cucumber, tomatoes, herbs and most of the other leafy and fruity vegetables, and have been shown to be highly viable and productive in most cases or areas of the world (FAO, 2015).

Table 3 Feed rate ratio and planting density (FAO, 2015)

Vegetable type	**Feed Rate Ratio (g/m^2/day)**	**Planting density (m^2)**
Leafy	40-50	20-25
Fruiting	50-100	4-8

1.9.6. Approaches to Optimise Aquaponics Nutrient Flow

There are currently two scientifically proven approaches to address feed conversion ratios in aquaponics. The first model was developed by Rakocy from the University of Virgin Island (UVI), and the model was named after him and his team - UVI/Rakocy (Rakocy et al., 2006). The nutrient flow approach was developed from more than 20 years of research in aquaponics by Rakocy (Rakocy, 1989). He proved that fish produces significant quantities of nutrients particularly nitrogen and phosphorous which are important for plant production. However, fish have different nutrient requirements to plants, as such, the fish waste produced will not fully support the complete life cycle of growing plants. In turn, there will be a need to supplement other nutrients particularly trace elements for optimum plant production. The significant nutrients for crop production that are missing from fish feed are: Ca, K and Fe to which these nutrients are significantly important for crop plant production.

The UVI approach was recently challenged and adapted by Lennard when he was conducting a Ph.D. study that sought to optimise aquaponics production in Australia (Lennard, 2004). Out of a series of scientific experiments, one of Lennard's Ph.D research outputs was the aquaponics model that predicted nutrient conversion of Murray cod for hydroponic production of vegetables (Lennard, 2004). Both the UVI and Lennard approaches agreed with each other, in that fish nutrient requirements are different from those of plants, and as such, when you try to balance one element others become short or in excess. Both approaches support the view that, to achieve sustainable nutrient flow, other elements will need to be supplemented.

There is a clear scientific evidence that aquaponics is a complicated system, as it requires balancing nutrients and a sound simultaneous knowledge of two significantly different agricultural enterprises (fish and greens). As such, if aquaponics were to contribute in food and nutrition security in this country, there will be a need for innovative tools to make aquaponics work.

1.9.7. Aquaponics management

According to aquaponics production mass balance calculations, if the the system is optimal conversion ratio (FCR) of 1 should be achieved and the plant biomass production should be 7-10 times more than the fish biomass production (Thorarinsdottir, 2015). In practice, this is equivalent to, 4 kg of plants per 1 kg of fish (Thorarinsdottir, 2015). This is achievable with a sound aquaponics management system practice. The main aquaponics production parameters are pH, water temperature, concentration of macro- and micronutrients, air temperature, dissolved oxygen and light. Light is usually ignored by aquaponics operators (Palm et al., 2014). These parameters need to be maintained at optimal levels for a highly viable system. In temperate areas spring crops would suit cold-water fish species and on warm seasons warm water fish species and macrothermal plants such as tomato, cucumber and basil would fit well (Roosta, 2014). In greenhouses environment climatic variables such as, relative humidity, air temperature and water temperature can be fully controlled. This both allows for an extended growing season and farmers to produce throughout the year. However, costs need to be carefully calibrated to target market prices in order to have a chance to make profits, because as greenhouse construction is very expensive (Boulard et al., 2011). Additional factors to manage are to prevent disease, insects, and other sources of pollution from entering into the system (Thorarinsdottir, 2015).

Fish management requires the maintenance of optimal growth conditions particularly water for the species cultured (Allison, 2011). Because water is the natural backbone to all agricultural systems, in aquaponics it is the most crucial input (Rafiee and Saad, 2005). Even though fish is a water creature, but fish health and quality could also be affected if water quality is poor and degenerated (FAO, 2014). In particular, a fish raised in recirculating tank culture, requires good water quality conditions as fresh water fish are very sensitive to environmental conditions (Liang and Chien, 2013).

Critical water quality parameters include dissolved oxygen (to be kept between the range of 4-8 mg/L), carbon dioxide, ammonia, nitrate, nitrite (to be kept between the range of 3-100 mg/L), pH, chlorine, and other characteristics (Endut et al., 2010; FAO, 2015a) also see Table 4. The choice of fish production should take into account the local market demand and the profitability, but at the same time the capacity of the system to maintain optimal environmental conditions in order to keep costs under control (Russell, 2002). Because, fish stocking density, fish growth rate, feeding rate/volume and environmental fluctuations can prompt rapid changes in water quality. As such, a constant and uniform water quality monitoring is required to keep the system running (Thorarinsdottir, 2015).

Table 4 Management activities and intervals to maintain an optimal and viable aquaponic system (Bugbee, 2004).

Management intervals	**Parameters**
Daily	DO, Temperature and pH
Twice weekly	TAN, Nitrate and Alkalinity
Twice monthly	P, Fe (Fe = 2 ml/m^2 and precipitate at alkaline pH), Ca and K.

P refers to Phosphorous, Fe refers to Iron, Ca refers to Calcium, K refers to Potassium, DO stands for dissolved oxygen and TAN refers to total ammonia nitrogen.

1.9.8. Aquaponics trends and challenges

Government in South Africa wants to improve and create food and nutrition security but at the same time frustrate the process of legalizing Nile Tilapia production in this country, Nile tilapia is the most suited aquaponics species (Palm et al., 2014). Traditional pond fish production is much cheaper than that of aquaponics fish production (Sikawa and Yakupitiyage, 2010), however, South Africa is just too cool for independent fish production particularly pond production (MacKellar et al., 2014). Aquaponics requires a sound skills and knowledge of both fish and plants ecosystems, such as skills and knowledge in pH maintenance, nutrition supply and expense and revenue (Goddek et al., 2015), all of this is challenged by the fact that most South African population is under literate (Statistics South Africa, 2014).

Recent aquaponics trends show that in a typical aquaponic system denitrification usually occurs during mineralization and ammonium-N transformation processes (Johnson et al., 2005). The environmental concerns about denitrification are the emission of nitrous oxides which is mainly related to the effect on global warming and the role of nitrous oxides in ozone destruction (White et al., 2004). The destruction of O_3 is catalyzed by NO, halogens, hydroxyl, and hydrogen, a possible source of NO is from N_2O, the product of denitrification, which can diffuse into the upper atmosphere and lead to atmospheric holes, hence causing problems for plants and animal life from excessive exposure to ultraviolet radiation (Allison, 2011). However, there is limited data or information to suggest a potential policy to address this issue, more studies will need to be conducted to fully understand the relationship between aquaponics gas emissions and environmental air pollution.

1.9.9. Aquaponics and Food Security

Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (Ministry of Agriculture Food Security and Cooperatives, 2006). There are four food security pillars which define, defend and measure food security status locally, nationally and internationally. These are food availability, food accessibility, food utilization and food stability (Drangert, 1998). Food availability is achieved when nutritious food is available at all times for people to access. Food accessibility is achieved when people at all time, have economic ability to obtain nutritious food available according to their dietary preferences. Food utilization is achieved when all food consumed is absorbed and utilized by the body to ensure a healthy active life. Food stability is achieved when all the other pillars are achieved (Faber et al., 2011).

Aquaponics provide an excellent opportunity for food and nutrition security because it produces fish and vegetables at the same time (USAID, 2013). In addition, aquaponics could address food sovereignty for food security if aquaponics are implemented as a programme for local people to own these systems. This could be a milestone in agriculture since people would control the means of production of the food they directly eat (Faber et al., 2011). In turn, it would boost food and nutrition status of society, because fish is a significant source of protein, essential amino acids, and vitamins, which are an import for food security (FAO, 2015). Even in small quantities, fish can improve dietary quality by contributing essential amino acids often missing or underrepresented in vegetable-based diets (FAO, 2014). In addition to proteins, fish and fish oils are a source of omega three fatty acids that are most crucial for normal brain development in unborn babies and infants (USAID, 2013). However, the USAID concern is that less nutritious fish are available to the poor as a result of lack of economic access related to lack of affordability and buying power (USAID, 2013). In this regard, if aquaponics could be implemented as a programme it presents a perfect opportunity for sustainable meat (fish) and greens (vegetables) production, which in particular is convenient to enhance food nutrition and water security, particularly in RSA (Faber et al., 2011).

However, the technology associated with soilless systems, aquaponics in particular, is complex (FAO, 2014). It requires the ability to simultaneously manage the production and marketing of two different agricultural products. Hence, a successful aquaponics enterprise requires special training and skills, or an easy to use computer control system (Lennard, 2004; Rakocy, 2007a). This suggests the need for capacity development training or skilled development programmes before implementing aquaponics projects. Hence, it is possible to argue that if food security is to be achieved via aquaponics production, skills development must be implemented first. Nevertheless, aquaponics presents a perfect opportunity for sustainable food production for food security.

1.10. **Tilapia production in RSA**

The South Africa’s Council for Scientific and Industrial Research (CSIR) has recently launched a survey on Nile tilapia. The main aim is to understand spatial distribution of the exotic species in country's watercourses. According to CSIR the survey forms part of a national Strategic Environmental Assessment (SEA) to promote sustainable aquaculture development in South Africa. Aquaculture is considered to be one of the fastest growing food production systems in the world and *Oreochromis niloticus* and its hybrids account for approximately 80 percent of worldwide tilapia production (Van der Waal, 2000).

There is hybridisation concerns in this country, the introduction of the potentially invasive *O. niloticus* into South African river systems, via escapees from aquaculture facilities, is a cause of concern for the conservation of indigenous tilapia, such as *Oreochromis mossambicus* (Mozambique tilapia), which are at risk through hybridisation and competition. Moreover, in South Africa, aquaculture has contributed up to 17 percent of the invasive fish species. As such, the South Africa's Department of Environmental Affairs and Tourism has placed a halt on *O. niloticus* farming in the provinces inhabited by *O. mossambicus*, namely Limpopo, Mpumalanga and KwaZulu-Natal provinces, these provinces are mostly suitable for Nile Tilapia production, this affect the total production of fish in this country (D'Amato et al., 2007).

Nile tilapia farming is only permitted in six of the nine national provinces. Fish farmers these three provinces, which have the ideal climatic conditions to farm tilapia, are appealing to government to allow them to cultivate *O. niloticus*. The farmers' appeals are supported by the argument that Nile tilapia are already in the waterways of the restricted provinces. There are major rivers that cross into South Africa from neighbouring countries, such as Mozambique and Zimbabwe, that have been farming Nile tilapia for decades. A commercial strain of genetically modified tilapia is that; it achieves about 500 g in eight months, while an indigenous *O. mossambicus* takes 11 to 14 months to achieve the same weight. In addition, it has a number of disadvantages including early maturation, precocious reproduction and poor body shape. On the other hand *O. niloticus*, has the benefit of 30 years of selection, improvement on body shape, high fillet yield and disease resistance, with related viable economic production (D'Amato et al., 2007; Van der Waal, 2000).

Characteristics which make *O. niloticus* a successful invasive species include aggressive spawning behavior, high levels of parental care including mouth brooding, the ability to spawn multiple broods during a single season, and a wide-ranging diet which includes phytoplankton, zooplankton, detritus, epiphyton, insects and other fish. The potential impacts associated with the introduction of *O. niloticus* to the new environment, include changes in ecosystem structure. This includes decreased abundance, and the extinction of native species due to habitat and trophic overlaps and competition. Particularly, for spawning sites, introduction of new pathogens and parasites, habitat destruction, changes in water quality, hybridization which result in loss of genetic integrity and loss of biodiversity needed for sustainability (D'Amato et al., 2007; Van der Waal, 2000).

According to D'Amato et al. (2007), *O. mossambicus* is the most tolerant of a range of salinities of all tilapia species; it tolerates brackish or even hyper-saline water in estuaries, where it can survive lower temperatures than in freshwater. The Nile tilapia does not thrive at high salinities (above 20 ppt) and low temperatures (below 12°C). While Mozambique tilapia may survive temperatures as low as 9°C, research shows that the improved strains of Nile tilapia cannot tolerate temperatures below 12°C (Figure 7). In the restricted provinces, the high-lying areas are too cold for Mozambique tilapia, but O. niloticus could be farmed in greenhouse tunnels. Fish grown in recirculating aquaculture systems (RASs) are of little risk to the environment if correct control measures are implemented.

At the end it all comes down to a farmers needs, resources available and some level of knowledge and skill, into choosing fish species for an aquaponic system. Most of all, it is the location that matters, as it was shown that Nile Tilapia is restricted in KZN, Mpumalanga and Limpopo. The rising argument is that, same results in total yield production could be achieved with Mozambique Tilapia as with Nile Tilapia, provided sufficient budget and time in order to optimize their parameters.

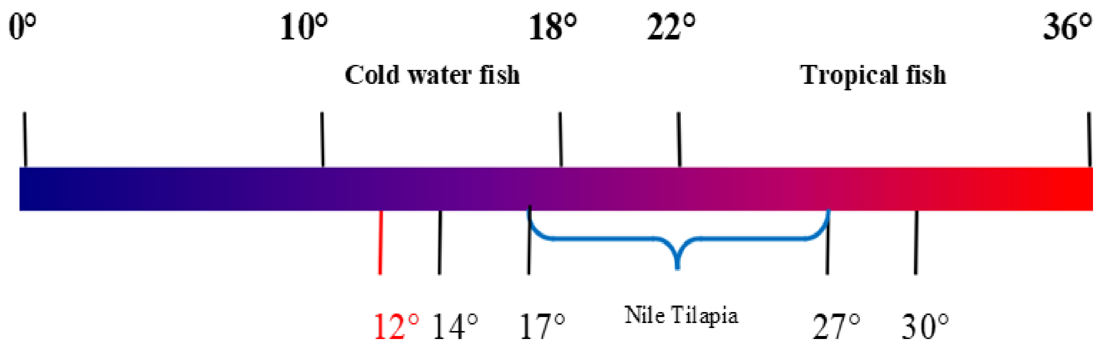

Figure 7 Temperature scale range from 0 to 36 ^{0}C showing tilapia, cold water and tropical fish optimum temperatures tolerances (Thorarinsdottir, 2015).

1.11. **Principles of Modeling and Model Development**

Modeling is the simplified representation of a real system, in this case, aquaponics, and it requires a complete understanding of systems processes (Janse, 1997). In aquaponics, this include processes such as nitrogen mineralization, nutrient flow in the system (fish to plant), plant and fish ecosystem (Mazzotti and Vinci, 2007). Aquaponics can be very complex and sometimes near to impossible where there is lack of expertise. This is because aquaponics requires a sound simultaneous understanding of two agricultural enterprise (fish and crop plants) ecosystems.

Models help to outline, organize and represent thoughts and understanding into a form of computer model or software (Daggupati et al., 2015). Models can act as a support tool for planning, decision making, output forecasting, and identifying research gaps (Mabhaudhi et al., 2013). As such, a model has the capacity to help solve or simplify aquaponics complexity for any ordinary person to use and foster related food security and economic production, However, it must also be noted that model application varies with systems dynamics and resources available (Schieritz and Milling, 2003).

The use of models involves standard protocols, including defining the purpose (why adopting the study? and for whom to benefit?), selecting the model (selection of model is based on the initial purpose, who are the end users?), collecting data, sensitivity analysis, calibration, and corroboration (testing), uncertainty analysis, scenario analysis, results in interpretation and communication of uncertainty and post audit (Mazzotti and Vinci, 2007). Following the modeling protocol serves a number of important benefits which otherwise could result into model failure if ignored.

Advantages of Model protocols (Birkett and de Lange, 2001).

- Reduces potential modeler bias,
- Provide a roadmap to be followed,
- Allow others to assess decisions made in modeling,
- Allow others to repeat the study, and
- Improves the acceptance of model results

During model development, there are three major procedural processes that are critical, namely, parameterization, calibration and validation. Parameterization is a process of identifying all parameters and variables that will be involved in a model. Calibration is the process of modifying the model parameters to obtain a model representation of the processes of interest (Mazzotti and Vinci, 2007; Trucano et al., 2006). Validation is the process of confirming that the predictions of a code adequately represent measured physical phenomena (Daggupati et al., 2015). Similarly, Arnold et al. (2012) also described model validation as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

The main purpose of models is to assist people and organizations to address their; social, economic and environmental issues (Janse, 1997). The purpose of the model design depends on the targeted end users or beneficiaries of the model. In regions where significant population beneficiaries lack expertise such as South Africa (Statistics South Africa, 2014), a modeler need to adopt user friendly and easily accessible software's (Thamaga-chitja, 2008).

Among others platforms, Microsoft has provenl to be user friendly and popular worldwide including in South Africa. Moreover, Microsoft in cooperate easy use and well tested functions like VBA, Solver, dropdown list, cell locks, and other relevant lookup functions which are important for new modeler entrance. Other platforms such as Java, Matlab, Python, C++ and many others are very effective and easy to use when principles are mastered, however, these platforms require licenses and may not be available to developing country, most of all are very difficult and nearly impossible for new modeler entrance.

When it is decided what model to develop, the next step now is to plan and present the models in a form of a flow chart or diagram, this practice has seen successful model development and implementation process (Booch et al., 1998). Because of a need to guarantee successful models, Unified Modeling Language (UML) was developed. Ever since then UML gained attention and popularity because scientist were now able to communicate their ideas with each other regardless of their location in the world. The main UML principle lies in diagrams different shapes as a form of a instructing and communicating (8, 9, 10, 11 and 12).

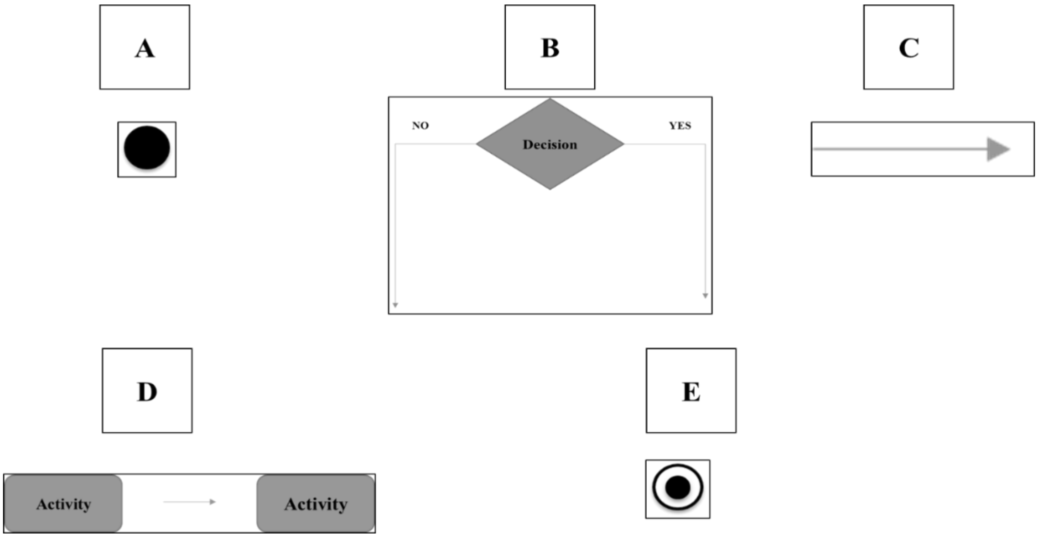

Figure 8 UML shapes; A) represents the beginning of a process or workflow in an activity diagram. B) Represents a decision process and always has at least two paths branching. C) Shows the directional flow, or control flow, of the activity. D) Indicates the activities that make up a model process and E) Marks the end state all flows of a process.

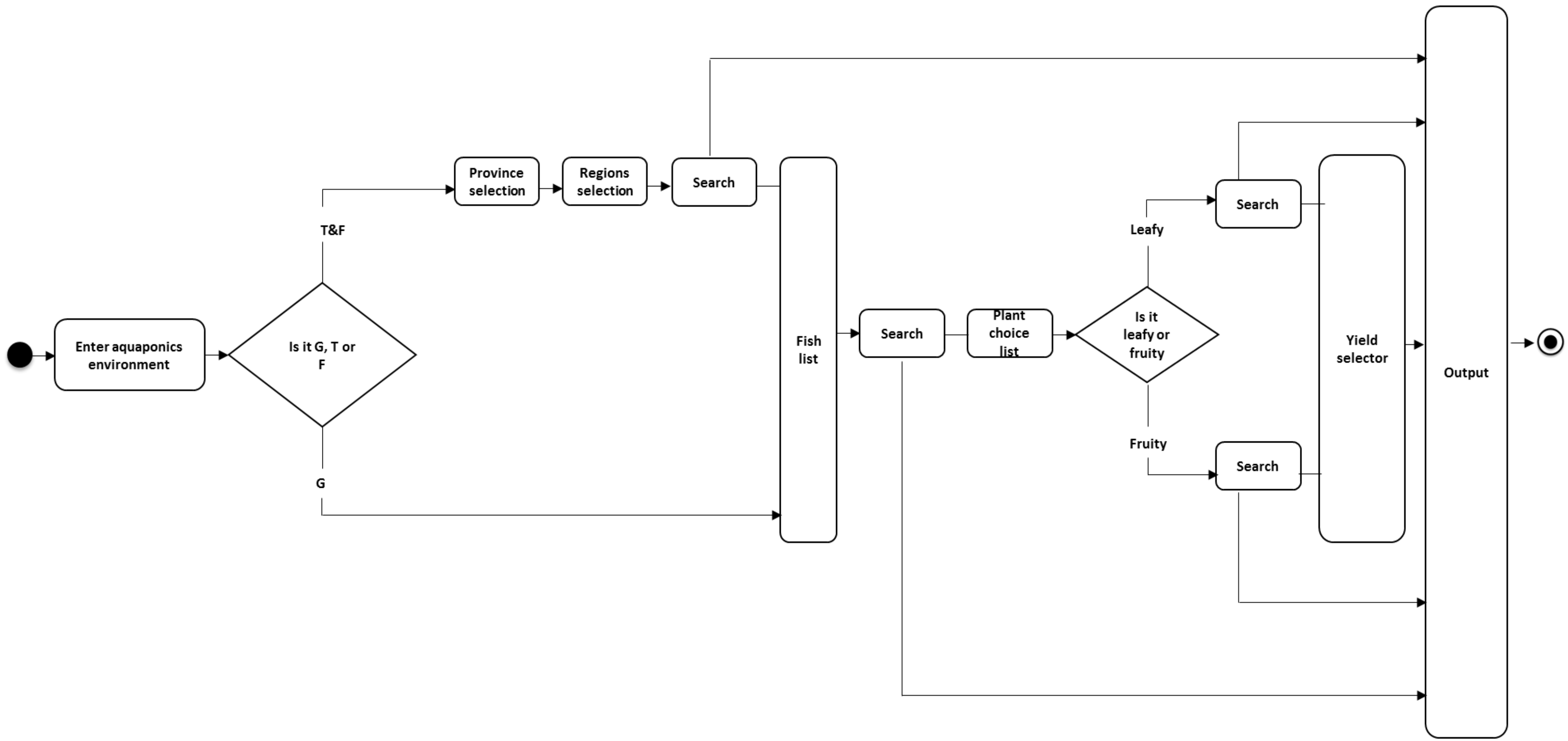

Figure 9 UML as it relates to aquaponics model flow chart, G stand for greenhouse, T stand for tunnel and F stand for field.

1.12. General Discussion and Conclusions

The need to increase food production is in response to the increase in population, which has resulted in greater use of water and synthetic fertilizer in agriculture. This has resulted in instability within agricultural biodiversity, which is needed for sustainable agricultural production. The quest to address the challenge has resulted in the exploration of soilless production systems, particularly aquaponics. Aquaponics are a mutual benefiting system, where fish and vegetables are produced at the same time through linking aquacultural fish waste as a natural nutrient source to grow plants in hydroponic culture in a circulating system. In return, plants clean water by taking up most total nitrogen to maintain water quality for fish well-being.

However, aquaponics are still an emerging practice in Africa including South Africa. This then suggest that, there is limited information, if any, to help aquaponics farmers to make the best decision for their system. Nevertheless, aquaponics are shown to have a high potential to address water scarcity, food and nutrition insecurity. This is because aquaponics saves water more than conventional agriculture, in addition provide a platform for nutrient cycle and opportunity for organic food production. However, to manage two agricultural enterprises (fish and vegetables) poses a major challenge. As a result, developing a model could help farmers to get started with aquaponics. However, this suggests that if the majority people in this country were to benefit from aquaponics, greater stakeholder intervention is needed.

Nile tilapia is shown to be the most suited and cultivated fish species in most aquaponics around the world, because of its ability to withstand harsh and various pH and temperature ranges. Tilapia is also easy to breed and manage. Aquaponics foods are easily marketable because food produced from aquaponics are healthier than most production systems including field production.

The research gaps were noticed in the field of genetic engineering. New research could be developed to manipulate fish growth period to fit well with hotter seasons of RSA. In order to avoid or escape winter colds which has been shown as significant factor in collapsing fresh water pond aquaculture. More studies also need to be done to integrate indigenous knowledge with scientific knowledge in order to effect a successful aquaponics implementation. More research need to be done to measure and quantify nitrogen losses in aquaponics and it related effect in the sustainability components.

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2. AQUAPONICS IN SOUTH AFRICA: RESULTS OF A NATIONAL SURVEY

Published in Journal of Aquaculture Reports

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ABSTRACT

Aquaponic system is a productive, innovative and sustainable fish and vegetable production system that could contribute to the needed innovation in agriculture in the face of drought, soil pollution and climate change. Aquaponics are still an emerging practice worldwide, but particularly in South Africa. This study was conducted in 2016 using an online survey questionnaire to collect aquaponics information about the types of systems used, the management and spatial distribution in South Africa. The survey questionnaire was designed with question categories, which included questions category for aquaponics practisers/operators and none aquaponics practisers/operators. The practiser's category was answerable to those who had an operational aquaponics in place, while non-practisers was answerable to everyone whom were keen in aquaponics. The practiser's question category included questions about aquaponics information, fish production and plant production. The non-practisers included one question category which included all questions tracking interest toward aquaponics. A total of 187 responses were captured within three months, a total 44 respondents had a fully operational aquaponics. Most respondents in none aquaponics operator's category were female (53%) in the same category, most respondents did not know what an aquaponic systems is (60%), however, were interested in aquaponics term and principles (84%). In aquaponics operator's category, the most commonly raised fish was tilapia (82%). The most commonly raised plants were leafy vegetables (75%). Since aquaponics is still not practised by many and aquaponics systems are small in size, aquaponics in South

Africa can be considered an emerging practice. Most of the current aquaponics practitioners have limited aquaponics production knowledge. We therefore conclude that attention should be paid to raising the awareness about the potential of aquaponics, and raising the technological knowledge of aquaponics operators to increase the number of aquaponics operations and to increase the total amount of food produced in and with aquaponics.

Keywords: Aquaponics, Leafy vegetables, Tilapia, Small systems

Introduction

Aquaponics is the concurrent production of fish and vegetable crops through linking fish waste from aquaculture to the hydroponic culture of crops (Love et al., 2014). These wastes and effluents act as a natural nutrient source to support crop production in the hydroponic culture, all implemented in a sustainable circulating method (Olukunle, 2014; FAO, 2015). In this process, plants clean the water by taking up most nutrients (ammonium-N, nitrate-N, phosphate-P and trace elements), thus promoting fish well-being and growth (Rakocy, 2007). Aquaponics has gained new and rapid attention as a vector toward achieving sustainable food production and combating malnutrition and poverty, both in cities and in rural settings (FAO, 2015). As sources of nitrogen and phosphorous for sustainable field crop production continue to be limited (Mchunu et al., 2018), aquaponics could be a welcome food production solution (Lennard, 2010).

The idea of aquaponics may be useful to a country like South Africa that has limited agricultural production resources (water and fertile croplands), high urbanisation rate and exponentially increasing urban poverty (Mchunu et al., 2018). Aquaponics can provide good quality food diversity (protein and greens) for rural and urban areas (Liang and Chien, 2013b). In addition to food production, aquaponics can play a critical role in environment well-being. Being a closed system, it avoids fertiliser runoff which contaminates the environment (Rakocy, 2004; Munguia-Fragozo et al., 2015) and has the potential to contribute significantly to sustainable organic food production. Most aquaponics foods are considered healthy since they are naturally produced organic material (Sace & Fitzsimmons, 2013).

Different scales of aquaponics production can be distinguished (Fallis, 2013; FAO, 2014; Love et al., 2015). Hobby systems have a fish stock of 10-20 kg/m^3 and 500-1 000 l fish tanks.

Subsistence systems have 20-40 kg/m^3 and 1 000-2 000 l while economic scale systems have a stock of 100-300 kg/m^3 and 4 000-50 000 l fish tanks (FAO, 2014). However, yields usually differ across systems, particularly in commercial systems, because not one model works for all (environment, market demand and quality) (Stander and Kempen, 2014). In hobby-scale systems, farming is practised with no interest to consume the harvest. In subsistence systems, farming is practised as a livelihood instrument whereas in commercial systems everything is produced with market sale incentive (Love et al., 2014).

There is suffient information to show that aquaponics is gaining attention worldwide (Love et al., 2014; 2015), and soon could gain similar attention in South Africa. At the same time not enough is known about aquaponics in this country to provide options for sustainable food production. Hence, the main objective of this study was to determine the current status of aquaponics uses and spatial distribution in order to determine a suitable approach to develop and promote aquaponics production in this country.

Materials and Methods

Study area

The study was carried out in South Africa which is bordered by the Atlantic Ocean on the west and the warm Indian Ocean on the east and therefore has a spectacularly comfortable yearly average temperature (Figure 1), along with a wide range of fish and plant biodiversity (Swap et al., 2002).

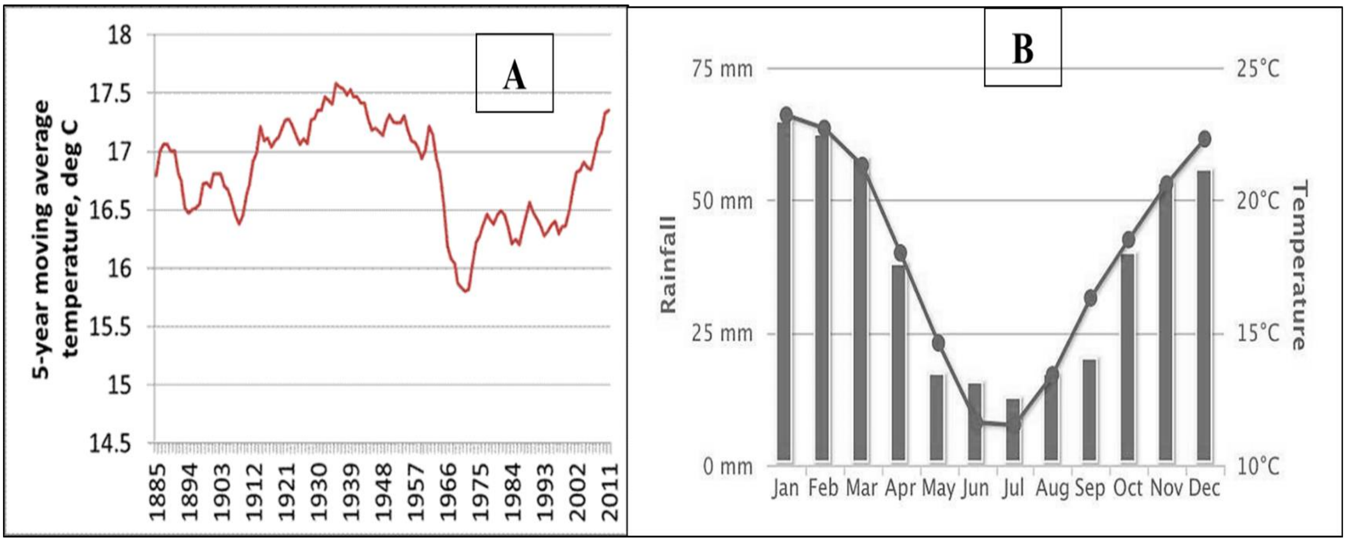

Figure 1 A) The long term average South African climate which could determine the potential for aquaponics in this country (South African Weather Service, 2011) and B) A closer look into a usual yearly South African climate variables ranges (rainfall and temperature) (South African Weather Service, 2011).

Survey

A national (all provinces of South Africa) internet survey was conducted with pre-coded questionnaire categories to be voluntary administered to interested participants. The LimeSurvey platform (University of KwaZulu-Natal (UKZN) Online Surveys) was used to design a questionnaire. Data were collected for a period of three months, from September to November 2016. A minimum of 45 aquaponics farmers and 200 interested participants was targeted throughout the country. Based on an international survey on aquaponics which recorded 257 responses worldwide and only one response from South Africa (Love et al., 2015), aquaponics was hypothesized to be not commonly known, small and emerging practice and therefore the all-inclusive sampling method was employed in this study. Hence, the sampling method included all people who were interested in the study and all aquaponics farmers and owners in South Africa who were willing to participate in the study without any specific requirement to be involved in the study.

All systems were welcomed, from hobby, subsistence and commercial scales. The sampling technique also included the chain sampling method. Chain sampling method it when data collection is facilitated by participating respondents, by transferring or sharing research information among each other, instead of a researcher (Love et al., 2014).

Data collection and analysis

The study followed a mixed method approach, which combined the methods and procedures of quantitative and qualitative data in a single study, using different sources of data. In this context, the study collected data from people who already have an aquaponics in place using a self-administered web based questionnaire, observations by transect walks, key informant face-to-face interviews and secondary literature relevant to the topic in discussion. The online survey platform was the main data collection method and therefore accounts for most of the data. When the final draft of survey questionnaire was complete, ethical clearance was applied for at UKZN Human Social Sciences Research Ethical Committee (HSSREC) in the research office. After the ethical clearance was obtained (Ref No: HSS/0106/016D), the online survey was implemented with pre-coded question categories to be completed by the participants. The survey questionnaire categories, included questions category for growers and Non-growers.

The grower's category was answerable to those who had an operational aquaponics in place, while Non-growers was answerable to everyone who were keen in aquaponics. The grower's category question included questions about aquaponics information, fish production and plant production. Non-growers included one question category which included all questions tracking interest toward aquaponics. The questions were both closed and open-ended. The question categories included demographic information (age, gender and education level), aquaponics information (location of aquaponics by province and city, scale of operation, aquaponics environment, level of system automation, enterprise focus, aquaponics trouble shoot options and aquaponics management), fish production data (fish raised, fish tank size, fish stocking density, fish feed information, fish management and fish yield) and plant production data (plants raised, method of plant production, plant production management information and plant yield).

A survey link was publicized through an email list of farmers provided by the Aquaponics Association of South Africa. Weekly email reminders, and sometimes phone calls were used to remind participants to complete the survey. In addition, social media platforms (Facebook, Twitter and WhatsApp) were used for sharing the survey link and posting weekly reminders. Local aquaponics companies were also contacted through browsing Google search engine and making contact by phone call, email and sometimes by field visit. These methods increased the number of responses captured per week, and were used for three months after which no more responses were received and the survey was terminated.

The analysis tools included IBM SPSS 24 edition (SPSS inc., 2016) and ArcGIS 10.2 edition (ArcGIS inc., 2016). In SPSS, the frequencies function was used to determine the dominant system characteristics. ArcGIS was used to determine the spatial distribution of various aquaponics setups within South Africa. The localities of the aquaponics operations as provided by the survey participants were transformed into coordinates, and incorporated with province shapefiles for South Africa using the ArcMap function to generate an aquaponics distribution map. Furthermore, content data recorded from workshops and aquaponics meetings was used to determine dominant fish and plant species cultured, fish and crop combinations, factors driving adoption of aquaponics, dominant scale of production, factors that determine scale of production, factors that determine yield and factors driving sound aquaponics management.

Results

The survey

A total of 187 responses were captured, only 44 respondents who had a fully operational aquaponics. Hence, the target to capture 45 aquaponics operators was not achieved. All respondents produced some quantity of fish and crops, which was important to understand different scales of production. All provinces had a chance to see and complete the survey, except for one province, Limpopo province, in which the survey never captured any response.

Demographics

For the category of aquaponics operators respondents were mostly male by percentage (98%) (Figure 2 A), with age ranging from 18 to 69 years, the dominant age range was 30 - 49 years (73%), followed by 50 - 69 years (18%) and lastly 18 - 29 years (9%) (Figure 2 B). Most survey respondents (98%) had completed tertiary education (Figure 2 C). Most respondents in none aquaponics operators category were female (53%).

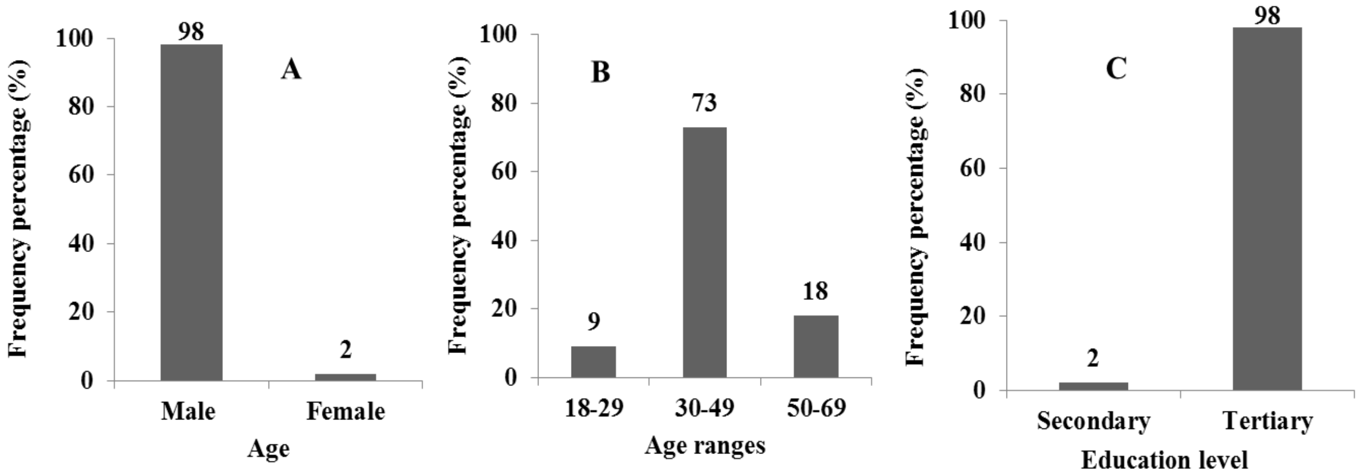

Figure 2 Gender (A), Age distribution (B), and Educational level (C) of aquaponics operators in South Africa. (n= 44).

Aquaponics system locality, distribution, design and scale of production

The dominant aquaponics locations by province were KwaZulu-Natal (KZN, 32%), Gauteng Province (GP, - 20%), Eastern Cape (EC) and Western Cape (WC, 16% each). Other provinces had fewer operations: Free State (FS, 7%), North West (NW, 5%), Mpumalanga (MP) and Northern Cape (NC, 2% each). Most hobby scale systems were located in KZN while commercial systems were mostly located in GP and WC, whereas subsistence scale was evenly distributed among all provinces (Figure 3). All respondents had some experience practising aquaponics. The duration of practise ranged from less than 12 months to 10 years. Most respondents had started operating aquaponics for a period of less than 12 months at (45%), followed by 1-4 years (32%) and 5-10 years (23%) (Figure 4 A). Most respondents (71%) constructed their own aquaponics system, followed by those whose system was constructed by a service provider (27%). For 2 % of the respondents their aquaponics system was set up by the Department of Agriculture (DoA) (Figure 4 B). Most respondents (39%) perceive themselves to be practising at a hobby scale, followed by subsistence (36%) and commercial (25%) (Figure 4 C). Most respondents (80%) used a tunnel environment for aquaponics production, followed by open field (11%), greenhouse (5%) and closed field (4%), respectively (Figure 4D).

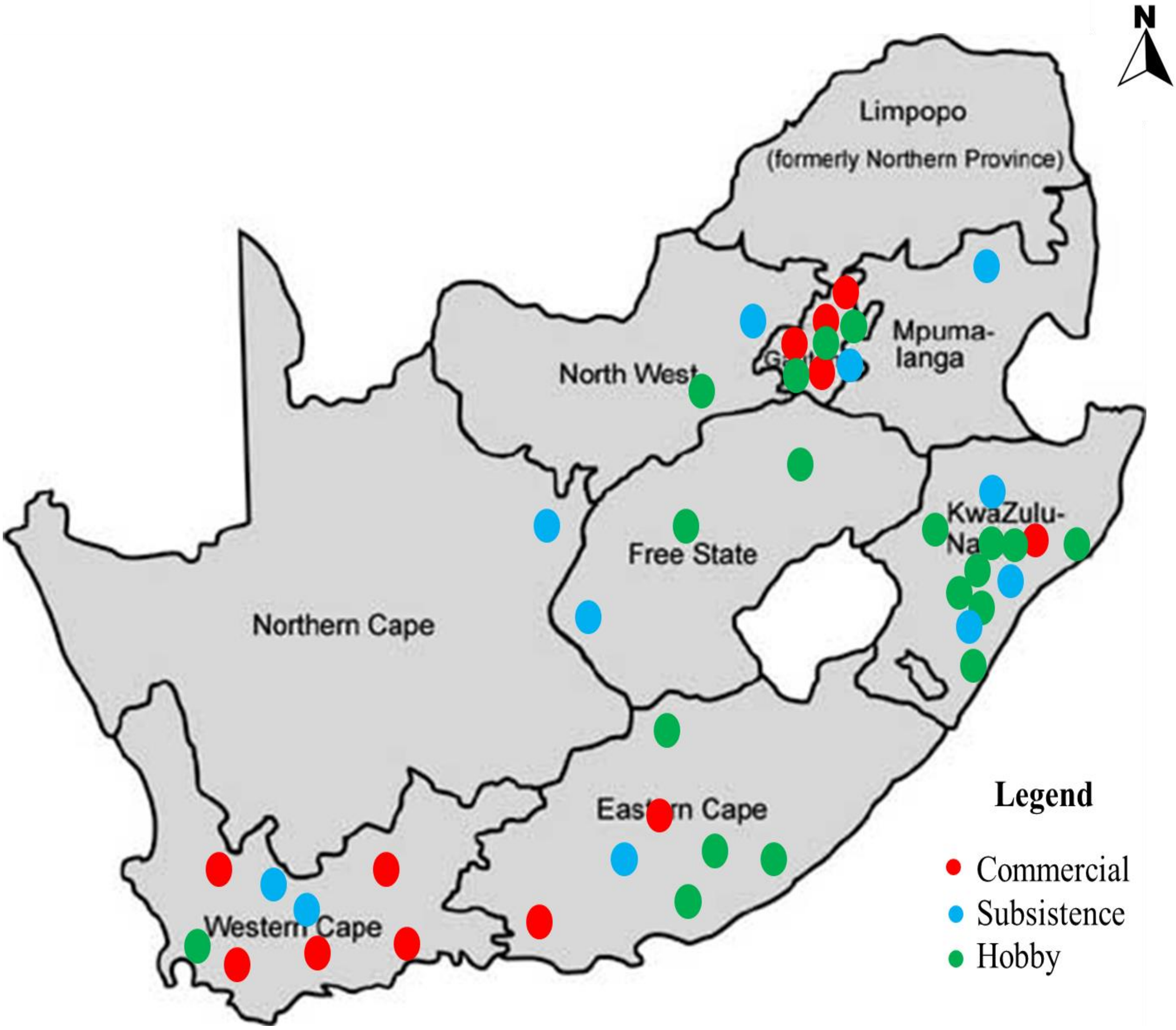

Figure 3 Aquaponics distribution in South Africa using the online survey data that was collected for the period of three months in 2016, the dots with respective colors represent aquaponics operators (respondents) with their respective aquaponics scale of practice see legend in the map. (n= 44).

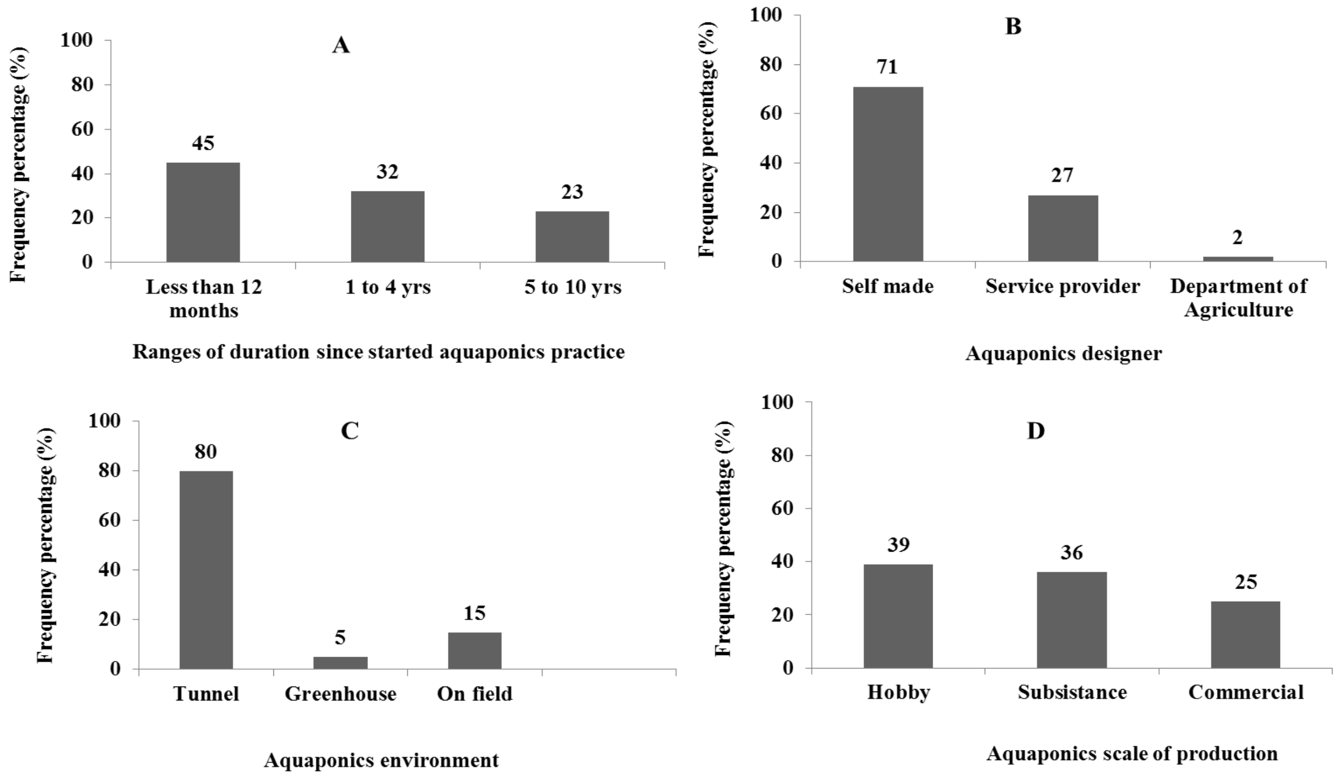

Figure 4 Respondent's years of aquaponics practice (A), aquaponics design (B), aquaponics environment (C), and perception of scale of aquaponics production (D). (n= 44). For aquaponics environment (C), tunnel refers to the aquaponics that are housed in environments covered by polyethylene sheet, designed to allow minimum and maximum effect of wind spend, solar radiation, relative humidity and air temperature, by automatic evaporative cooling method which is facilitated by wet walls and cooling fans; greenhouse is the aquaponics environment where all environmental conditions (solar radiation, wind spend, air temperature and relative humidity) are fully controlled to suit any species in any given time of the year; and field production refers to aquaponics that are completely exposed to the outside environmental conditions (solar radiation, wind spend, air temperature and relative humidity) with zero control. For scale of production categories (D), see definition in introduction.

Aquaponics system management and enterprise focus

Most respondents (68%) had semi-automated aquaponics, followed by manual operating (25%) and fully automatic systems (7%) (Figure 5 A). Most respondents had moderate knowledge to manage water quality (dissolved oxygen, suspended solids and nutrient, particularly mineral nitrogen) in their systems (45%), followed by low knowledge (32%) and skilled (22%) (Figure 5 B). Most respondents' had moderate knowledge to manage pH in their system (48%), followed by skilled (27%) and lastly those who had low knowledge (25%) (Figure 5 C). Most respondents' enterprise focus was on producing both fish and plants (41%), followed by fish only (39%) and plants only (23%) (Figure 5 D).

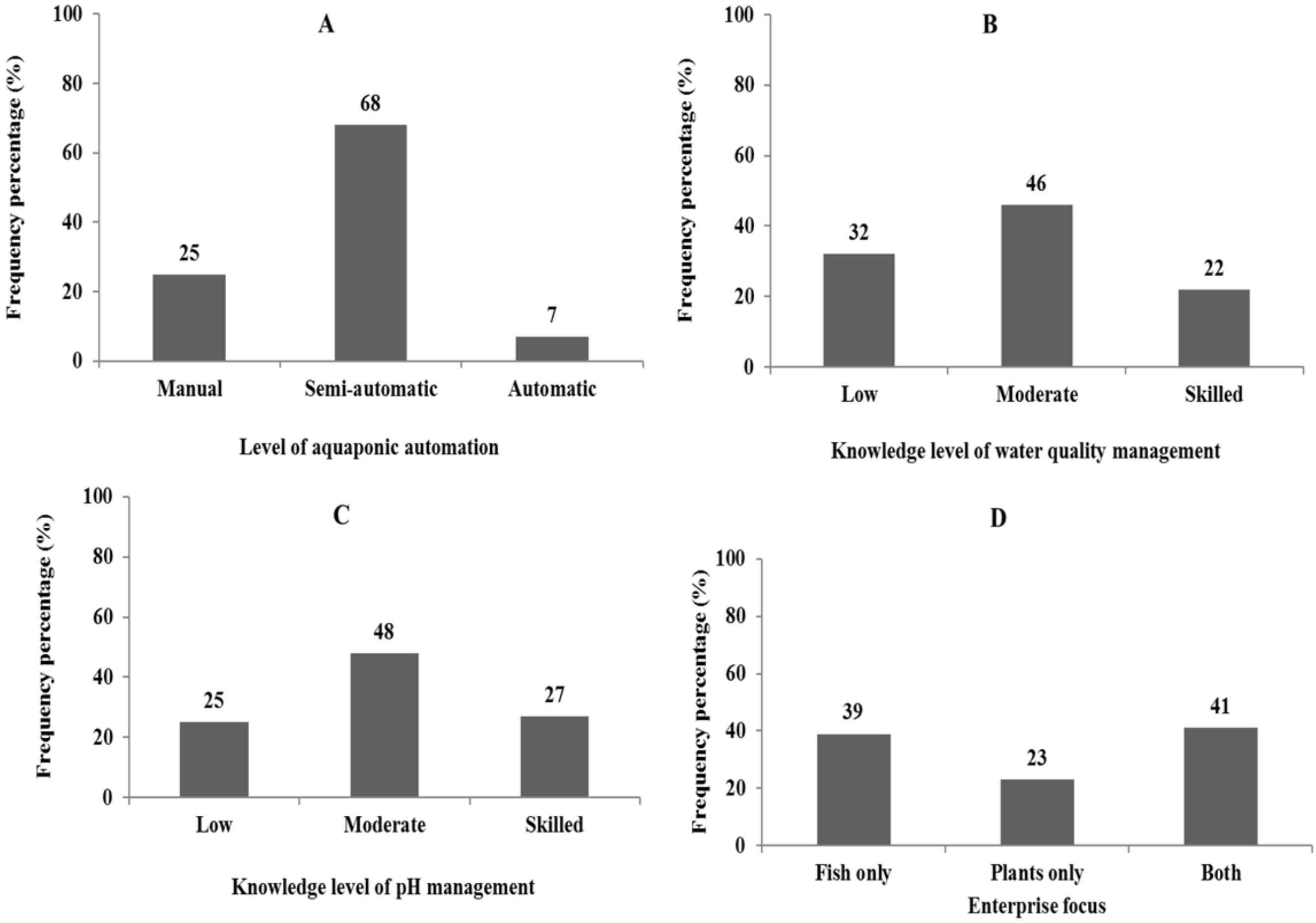

Figure 5 Respondent's level of aquaponics automation (A), water quality knowledge level (B), pH management knowledge level (C) and enterprise focus (D). (n= 44). For more explanation, see text.

Fish Information: fish choice, feed, characterisation, cost and management

The question about fish species raised was a multiple tick question, which is why sums of percentages can add up to more than 100%. The most commonly raised species were tilapia (82%) and trout (30%), with lower occurrence of barbel/catfish (18%), ornamental fish (16%), and bass and bluegill (both 2%) (Figure 6 A). The most dominant stocking density ranges (in kg m^3) were 15-19 (52%), 20-30 (18%), and more than 50 (16%). Less common were 10-14 (9%), 1-4 and 5-9 kg m^3 (2% each). The most commonly used fish feed protein contents were

30% (52%), 40% (46%) and 10% protein (2%) (Figure 6 B). In terms of feed type, the most commonly used were pellet (98%), live feed (27%), and aquatic plants (14%) (Figure 6 C). In terms of feed cost per month, most farmers used between zero and 1 000 rand (R) toward fish feed (47%-43%), followed by R 1 000-2 000 (5%) and R 3 000-5 000 (5%). In terms of fish disease systems, most farmers (82%) did not have any system for detecting and treating fish disease and only 18% declared to have such a system in place (Figure 6 D). In terms of fish development (fish disease and tracking growth), most aquaponics farmers (52%) had low knowledge to detect fish diseases, followed by moderate knowledge (25%) and skilled (23%) (Figure 6 E). Similarly, most farmers had moderate knowledge in tracking fish growth by percentage (57%), followed by skilled (23%) and low knowledge (20%) (Figure 6 F).

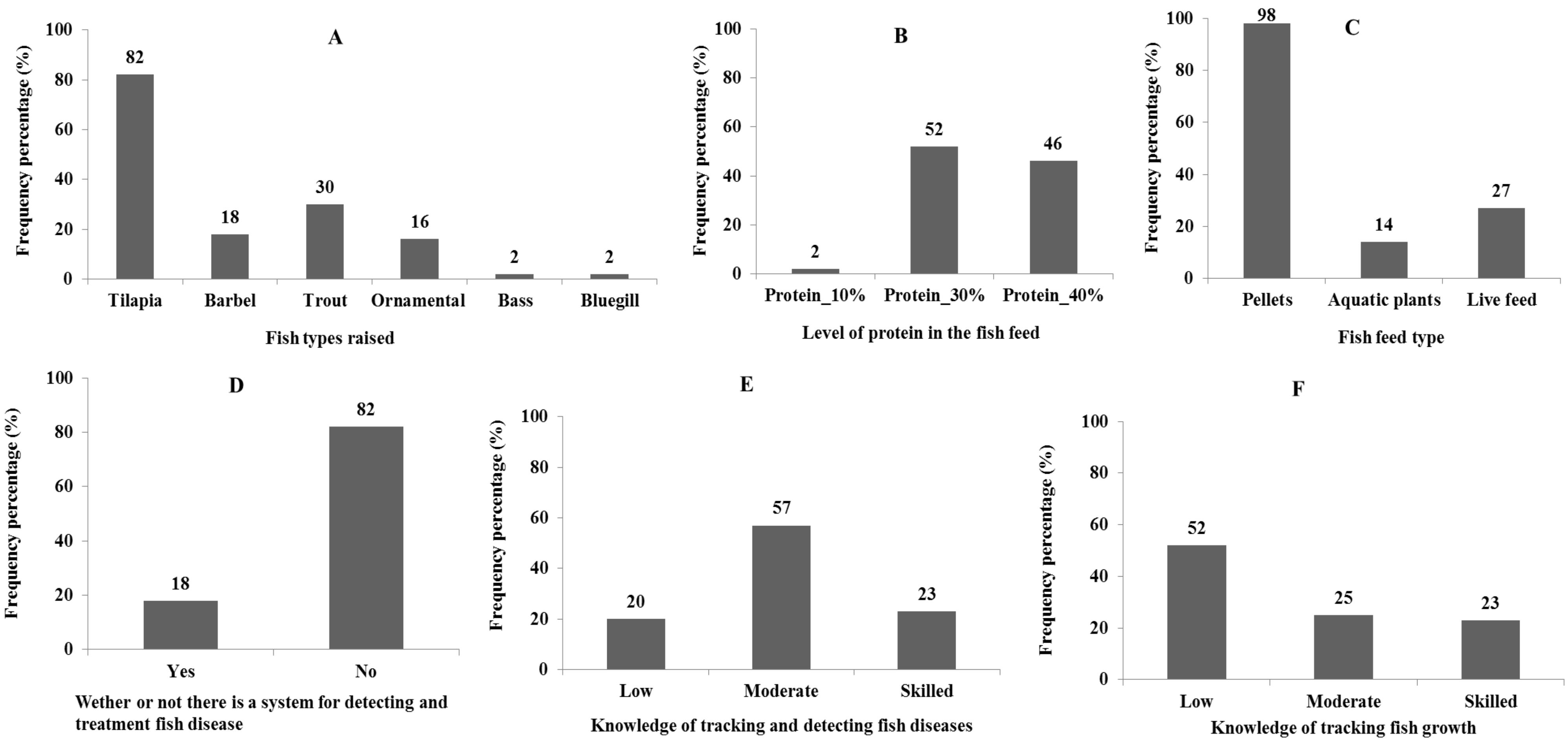

Figure 6 Respondents aquaponics fish of choice A), feed level of protein (B), type of fish feed (C), whether yes or not farmers have system for detecting and treating fish disease (D), knowledge of tracking and detecting fish diseases (E), knowledge of tracking fish growth (F). (n= 44). For respondent’s fish of choice, tilapia (*Oreochromis niloticus*) was the most selected. For more explanation on other figures, see text.

Harvest and yield

In terms of harvest, most farmers (47%) harvested fish in 6 months, with 39% of farmers harvesting after one year- and 7% harvesting every week to every month (Figure 7 A). In terms of yield, most farmers (62%) harvested a yearly yield of 1-10 kg, followed by 10-20 kg (18%), 500-999 kg (12%) and 20-49 kg and 55-99 kg (both 2%) and (4%) produced nothing (Figure 7 B).

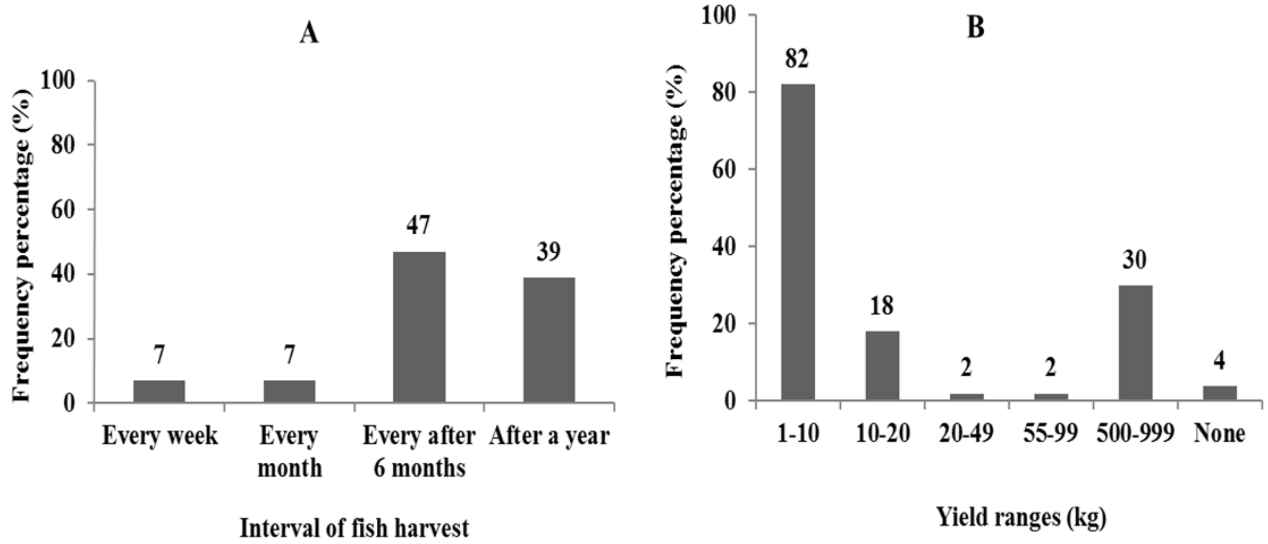

Figure 7 Aquaponics users fish harvest interval (A), average yearly fish harvest (kg) (B). (n= 44). For more explanation, see text.

Plant production information

In terms of plants, the most commonly raised plant were salad greens (75%), lettuce (55%), basil (50%), herbs (46%), peppers (32%), cucumbers (25%), ornamental plants (18%), beans and peas (16%), tomatoes (16%), carrots (9%) and cut flowers (7%) (Figure 8 A). The most adopted crop production methods were growth medium bed (GMB) (96%), nutrient film technique (NFT) (16%) and deep water culture (DWC) (14%) (Figure 8 B). The most adopted irrigation methods in GMB were flood and drain (80%), constant flow (Figure 8 C). The most commonly used growth media were gravel (68%), growstones (18%), and peat (2%) (Figure 8 D).

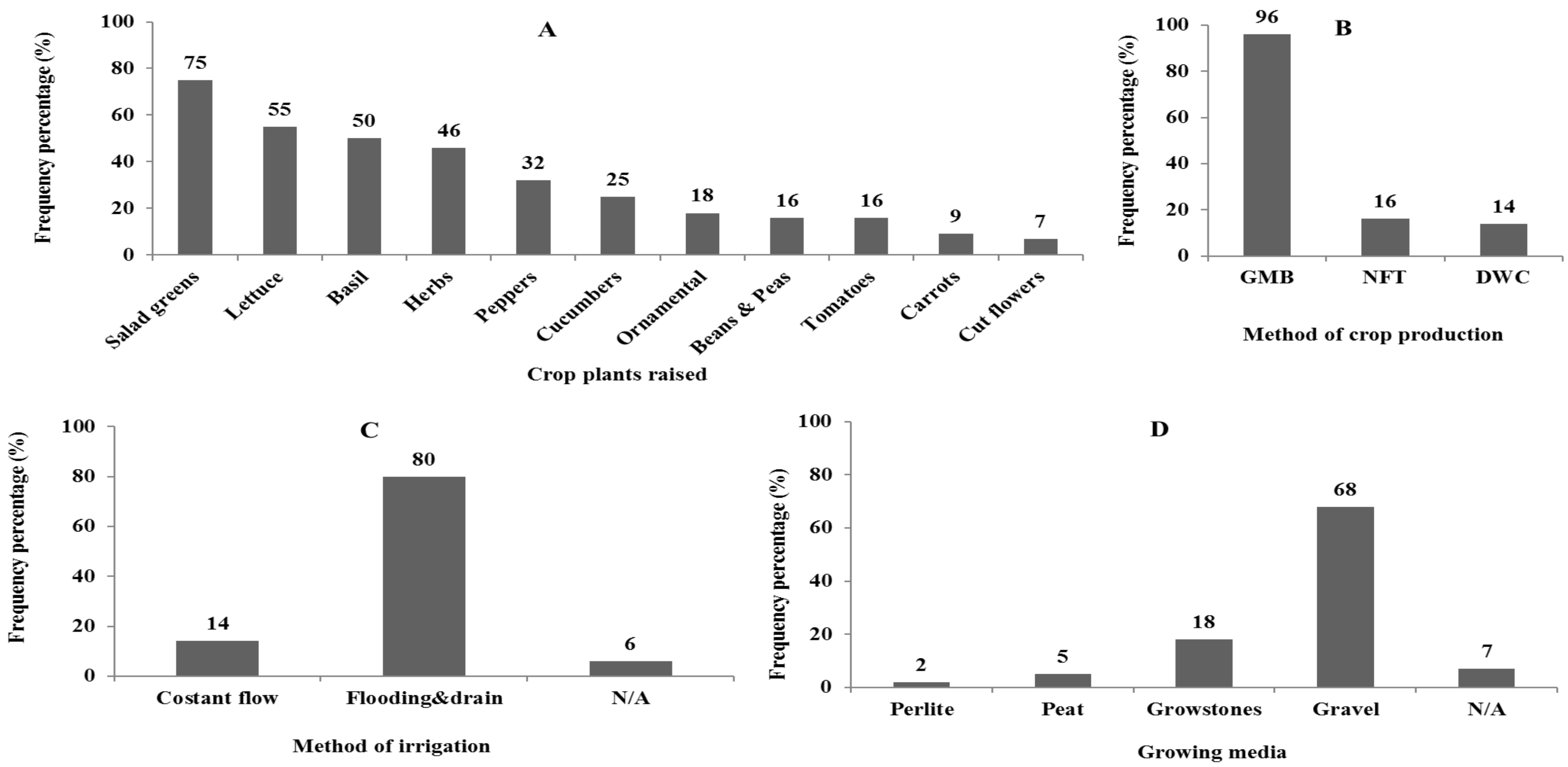

Figure 8 Respondent's aquaponics plants of choice (A), method of crop production (B), method of irrigation (C), plant growing medium (D). (n= 44). For plant growing media, gravel refers to very course and hard inert stones used in soilless systems to facilitate aeration; growstones is the media that is made from recycled glass and is used to anchor plant roots in hydroponic systems; peat is the soilless growing medium that contains peat moss and perlite refers to a volcanic mineral which is used in soilless systems to provide good aeration. For more explanation on planting medium, see text.

Crop production management, harvest and yield

In terms of plant management, most farmers had moderate knowledge of diagnosing plant nutrient deficiencies (77%), followed by skilled (18%) and low knowledge (5%) (Figure 9 A). Farmers sought to address plant nutrient deficiencies by increasing fish feed (68%), supplement nutrients (30%) or using both methods (2%) (Figure 9 B). Most hobby and subsistence farmers addressed plant nutrient differences by increasing fish feed, while most commercial farmers only supplemented needed nutrients. In terms of harvest, most farmers harvested their plant yield every month (64%), while others harvested every week (32%) or every day (4%) (Figure 9 C). In terms of yield, most farmers harvested a yield between 1-5 kg (54%), followed by 5-10 kg (14%), 20-29 kg (11%), 30-49 kg and 100-499 kg both at (7%), 50-99 (5%) and lastly 0.1-0.5 kg at (2%) (Figure 9 D).

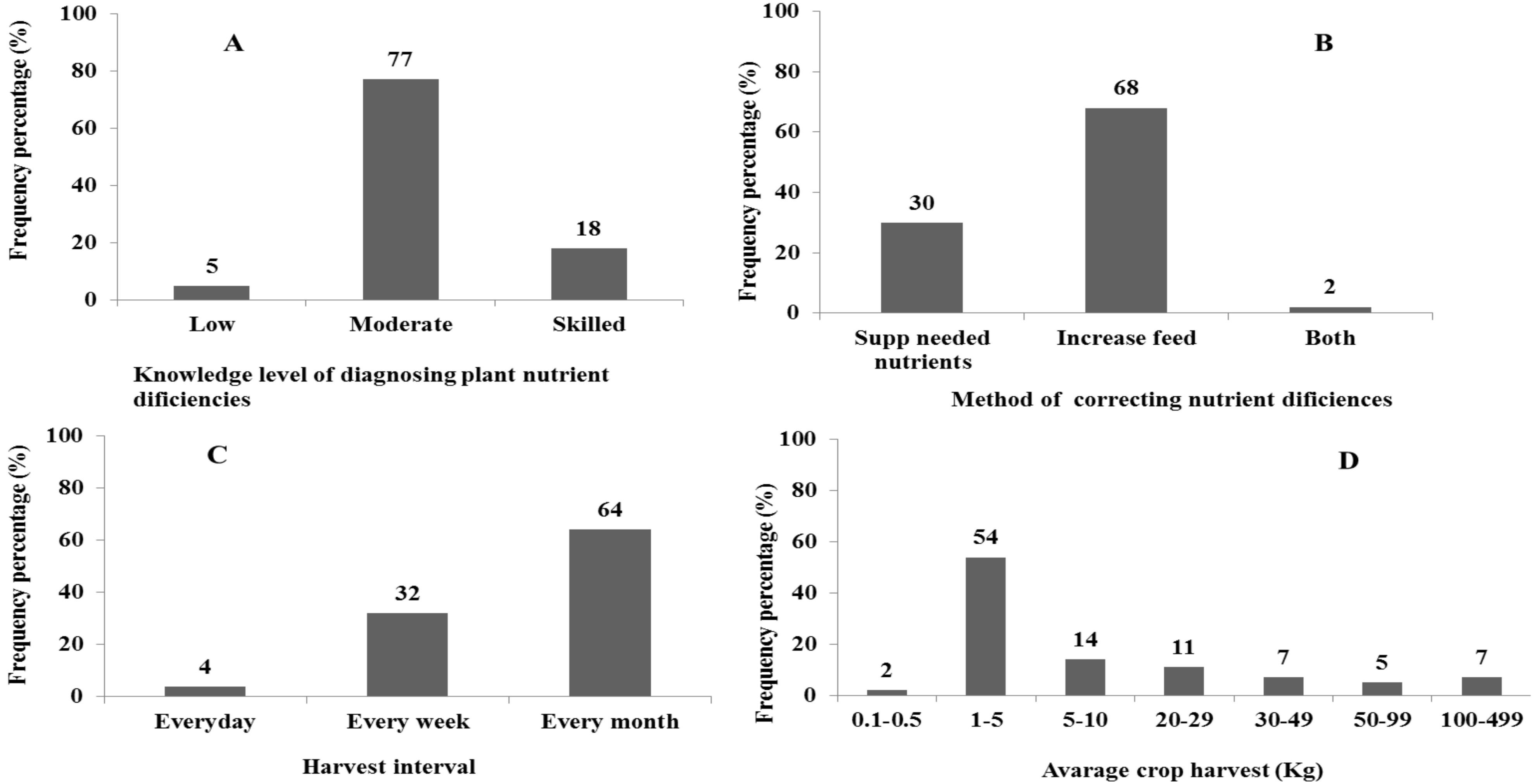

Figure 9 Respondents aquaponics level of knowledge about nutrient management A), method of supplementing nutrients B), harvest interval C) yearly average plant harvest D). (n= 44). For more explanation, see text.

Non-aquaponics operators

Most respondents did not know aquaponics, no (60%) and yes (40%) (Figure 10A). Nevertheless, most respondents were interested in practising and owning an aquaponic system, yes (84%) and no (16%) (Figure 10B). Most respondents who were interested in aquaponics were women youth, between the age ranges of 18-29. Most respondents were interested to aquaponics to grow their own food (61%), followed by those who were concerned about environmental sustainability (40%), commercial production (34%) and education and training (15%) (Figure 11). Most respondents were interested in commercial scale of production (31%), followed by subsistence (29%) and hobby (26%), 16 (%) abstained- those who did not answer (figure 12).

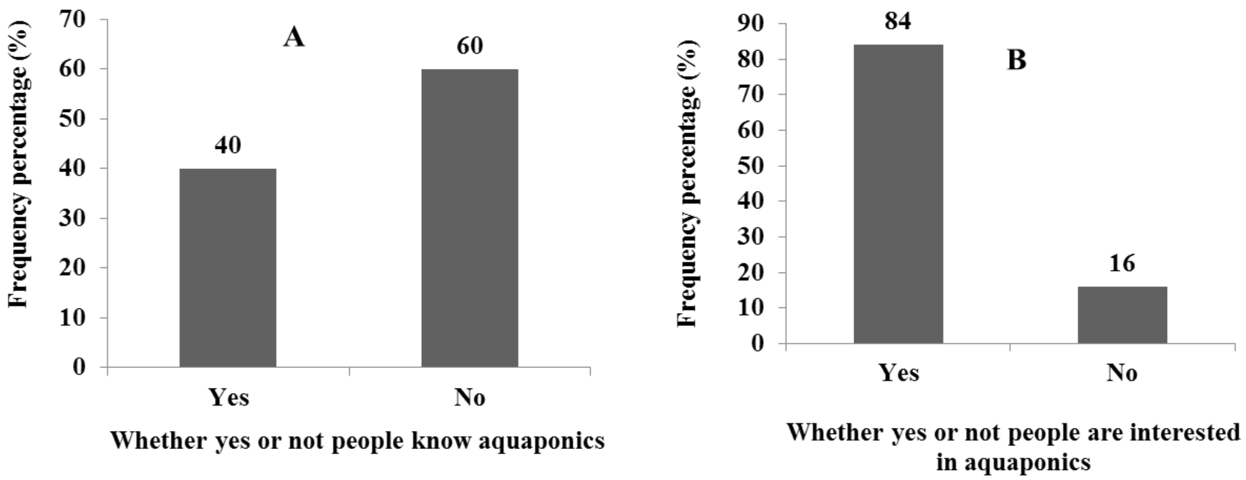

Figure 10 None growers' response to whether they know aquaponics or not (A), whether respondents are interested in aquaponics (B). (n= 187).

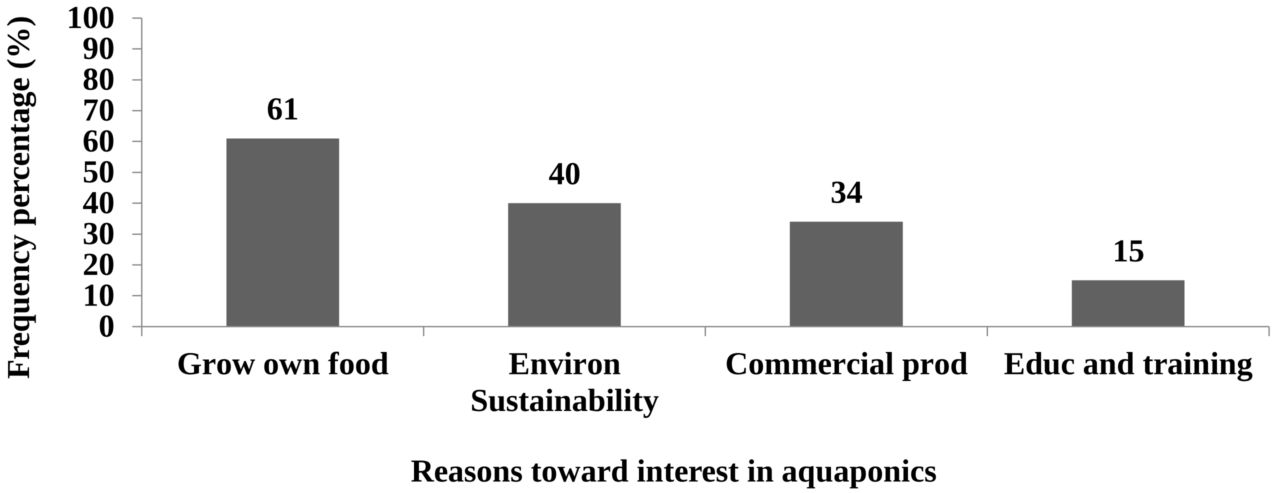

Figure 11 Respondents reasons why there are interested in aquaponics. (n= 187).

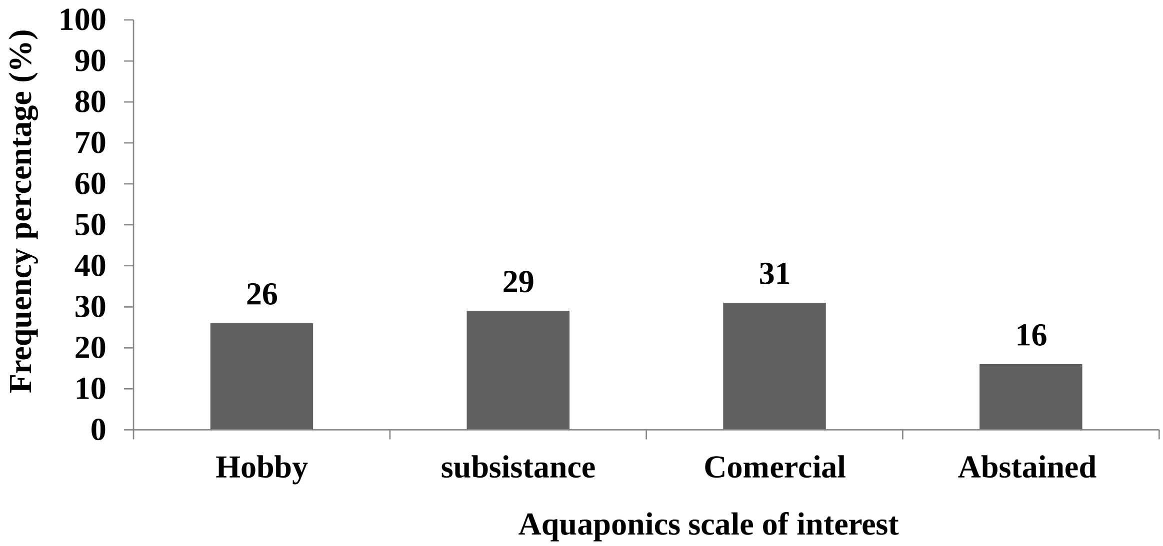

Figure 12 Respondents preferred aquaponics scale of interest. For scale of production see definition in introduction. (n= 187).

Discussion

Aquaponics as a new activity in South Africa

The number of responses captured from the study showed that the aquaponics sector in South Africa is indeed still very small and emerging. This is supported by the higher number of responses from farmers with less than 12 months since the start of their aquaponics operation, which confirms that aquaponics is still an emerging practice in South Africa. This is in agreement with Love et al. (2014; 2015) who reported a limited aquaponics population in an international survey study which included 20 countries around the world.

The emerging nature of aquaponics in South Africa is also shown in respondent's fish stocking density. The fish stocking density of 15-19 kg/m^3 is low and suggests small-scale hobby and subsistence systems (Sace and Fitzsimmons, 2013). Most commercial farmers adopt a higher fish stocking density of 60-200 kg/m^3 in 5 000 m^3 tanks (FAO, 2014). The high percentage of respondents with 15-19 kg/m^3 stocking density suggests that these respondents have smaller systems at hobby and subsistence scale. Moreover, the higher percentage of farmers with smaller systems is attributed to the high start-up cost of aquaponics (Love et al. 2014; 2015). Farmers fear risking resources while productivity is uncertain, and therefore start small (hobby scale) and only expand to more commercial scale as they gain experience. It is also reflected in respondents expenditure toward feed cost: the high number of farmers who used zero (ZAR) (natural manures) and those who used less than R1 000 toward fish feed is consistent with the finding that most farmers have small systems which require low feed inputs (Nunes et al., 2014).

The observed increase in starting aquaponics practitioners can be explained by the recent drought, food safety concerns, land reform, urban poverty, limited resources and increasing population size in South Africa, because these have been the main challenges facing South Africa in recent years (Faber et al., 2011; Mabhaudhi et al., 2013; Mchunu et al., 2018; Van der Waal, 2000). The male domination of the aquaponics sector in South Africa is not consistent with the United Nations Sustainable Development goals that seek to empower women and children for sustainable development (United Nations, 2017).

Characteristics of the aquaponics systems in South Africa

Tilapia *(Oreochromis niloticus)* is the most dominant species cultured in South African aquaponics which is in agreement with reports in FAO (2014) and Love et al. (2014 and 2015). Tilapia grows well in a recirculating tank culture with tolerance to fluctuating water conditions such as pH, temperature, oxygen, and dissolved solids; tilapia can tolerate a wide range of water temperatures (9-42.5°C), dissolved oxygen as low as 0.1 mg/l, and unionized ammonia concentration of 2.4 mg/l (Jana 1998, Bugbee, 2004; D'Amato et al., 2007). This explains why tilapia is the mostly adopted aquatic animal in aquaponics. The lower percentages for other fish species can be attributed to limiting environmental conditions in South Africa. While fruity vegetables have a higher economic value and return, most respondents raised leafy vegetables (salad greens, lettuce, basal and herbs). Because of their low agronomic requirements, leafy vegetables use less nutrients than fruity vegetables (Rakocy, 2004) and grow fast when all nutrients are supplied (FAO, 2014). Moreover, leafy vegetables can be raised in higher density (up to 30 plants m^{-2}) than fruity vegetables (maximum 8 plants m^{-2}) (USAID, 2013; FAO, 2014).

The high percentage of fish-only enterprises is attributed to the fact that most aquaponics operations started as aquaculture farms and then evolved to aquaponics, as noted in the Annual General Meeting (AGM) meeting of the Aquaponics Association of South Africa (AASA) of 20th October 2017 at Hailodar Fish Farm in Pretoria, South Africa. As a result, farmers have better access to the market for fish than to crop markets. These findings are not consistent with some of the literature and with recent findings by Love et al. (2014; 2015), who found that most aquaponics farmers focus on plants because they can be harvested after 1-3 months while fish take much longer to harvest. The higher recorded interest in fish production can be explained by the increased concern over nutrition insecurity and health risks such as infertility, immune problems, accelerated aging, faulty insulin regulation, and changes in major organs and the gastrointestinal system, associated with eating imported food in South Africa (Faber et al., 2011; Mchunu et al., 2017).

The higher responses for 30% protein feed characterization could be associated with cost, as it is expensive to use higher protein fish feed (Nunes et al., 2014). It could also be simply attributed to a lack of knowledge. Growth Medium Bed (GMB) was the dominant method of crop production. GMB does not need a biofilter to remove excess nutrients from the water as GMB itself acts as a biofilter (Hu et al., 2015). NFT and DWC require a biofilter to facilitate nitrification (Wilson, 2005) and therefore carry extra biofilter costs, thus explaining the high percentage for GMB. Gravel medium is the dominant method of crop production, as it is easily accessible and readily available compared to other media (Sikawa and Yakupitiyage, 2010). The flood and drain system is a cheap, simple and easy to use method to return dissolved nutrients to the rearing tank, while giving plants enough time to take up the nutrients (FAO, 2014). The medium should be kept regularly flushed with nutrients and air, allowing maximum microbial activity (nitrification) to occur (Roosta, 2014b). This explains the high number of respondents who use the flood and drain irrigation method. Most farmers had moderate to skilled knowledge of detecting plant nutrient deficiencies. This is positive in terms of management because moderate skills could be adequate to manage the plant component. The everyday crop harvest is attributed to commercial practice (scale) whereas the monthly crop harvest month is attributed to hobby and human subsistence practice (scale).

Main aquaponics constraints in South Africa

The high percentage of farmers who use a tunnel environment compared to greenhouses and fields suggests that aquaponics requires further climatic adjustment or control in order to operate in South Africa. This is in agreement with Van der Waal (2000) who reported that economically viable pond aquaculture in South Africa is near impossible due to the average environmental climatic conditions which do not meet the minimum temperature requirements of many species. This was further validated with aquaponics operators in South Africa through field visits, workshops and meetings. Even tilapia which is known and popular for withstanding harsh environmental conditions (FAO, 2014) cannot be produced profitably in ponds in South Africa and requires adjustment of fish tank water temperature. While greenhouse aquaponics could be the solution, the establishment of a fully operational controlled facility to grow fish is very expensive (White et al., 2004). As the majority of South African population still live below 20 ZAR which equals to 1.49 USD per day (Statistics South Africa, 2014), there is a need for financial resources to support new entrants to get started with aquaponics.

The high percentage of farmers with moderate to low level of knowledge about water quality and the high number of respondents who use manures as fish feed is worrisome, as this practice has been shown to be not effective in biomass production and has aggravated water quality problems (Wilson, 2005). This suggests that most of the current aquaponics users in this emerging sector do not fully understand aquaponics and supports the hypothesis of the study that there is insufficient information and data to help farmers maximize the productivity of their systems. As a result, while the aquaponics concept still need to be disseminated to stimulate adoption by new entrants, existing aquaponics farmers need support to improve their production systems and practices.

The high number of respondents who do not have a fish health system in place and the lack of knowledge of detecting fish diseases and tracking fish growth suggests an incomplete and poor aquaponics orientation (Munguia-Fragozo et al., 2015) and again show that farmers need support to improve fish production and management. Freshwater aquaculture systems require sound aquaculture management skills because the metabolic processes of fish are sensitive to temperature (Allison, 2011). Fish well-being is the main determinant of inputs into aquaponics systems, since all nutrients required by plants enter the system through the fish culture component (Lennard, 2004). In addition, this raises concern over food safety, as the fish produced could be of poor quality and unsafe for eating.

The high number of respondents who increase fish feed to address plant nutrient deficiencies suggest a poor aquaponics practice and management. The nutrient requirements of fish are different from those of plants, and the waste produced cannot fully support the complete life cycle of growing plants. For optimal plant growth, there is a need to supplement other nutrients, particularly trace elements (Rakocy et al., 2004). Among the deficient nutrients in fish feed/waste are iron (Fe), potassium (K) and calcium (Ca), nutrients that account for most crop failures in agriculture, and in aquaponics in particular (Graber and Junge, 2009b). This is also shown in the aquaponics model developed by the University of Virgin Island (UVI) which was later adapted by Lennard in 2004. The model proved that no matter how much one increased fish feed, plant requirements could not be achieved, but instead this practice would result in increased water quality management cost (Rakocy, 1989).

None aquaponics operators

The higher percent (%) of respondent who did not know what an aquaponics is, suggest that aquaponics in this country is not popular or is not a common food producing practice. This is in agreement with the hypothesis of this study that, since aquaponics are the emerging practise worldwide (Love et al., 2014), here in South Africa it might be new a practise. The significant number of youth particularly women who are interested in aquaponics suggest that South Africa has the niche and opportunity to contribute toward Sustainable Development Goals (SDGs) if aquaponics could be implemented in this country. Aquaponics could promote youth involvement in agriculture particularly women, thus provide a better opportunity for sustainable aquaponics development in South Africa.

This also validates the hypothesis purported by (Mchunu et al., 2017) that, “if agriculture could be made innovative, sophisticated, adventurous and simple, youth involvement in agriculture could increase significantly”. The higher percentage response for “grow my own food" option suggest that, there is a significant concern by local people about health associated with food safety for food security. Because genetically modified foods have infested local market as a response to deal with food demand associated with population growth and urbanisation (Allison, 2011). The extent has resulted into low healthy status and performance of most people in the world (FAO, 2015a). This suggest that if aquaponics could be implemented, most local people could live healthy active life.

The higher response for "environmental sustainability could be explained by climate change effect in South Africa. The higher response for "commercial production and education and training options" could be explained by unemployment, poverty and economics breaks down. This suggest that if aquaponics could be implemented in South Africa, sustainable food production and development could be achieved as well. One of economic sustainability principle suggest that, ranks of income and employment must be increased and maintained as required, with outstanding consideration given to socially and geographically satisfactory distribution (Palm et al., 2014). As such, the higher interest of respondent toward commercial scale of production suggests that if aquaponics could be advertised and implemented, economic sustainability could be achieved promoting sustainable society.

Recommendations for more supportive policy

The agricultural policies of South Africa do not include aquaponics. From this study it is clear that there is a lack of empirical aquaponics studies to influence government policy making process that could assist with funding, credit and extension support, to support starting aquaponics entrepreneurs in this country. If there was enough aquaponics information, knowledge and data available, the policy to be developed could be based on concepts such as, one home one aquaponic system and one school one aquaponic system, aquaponics as the curriculum in secondary education and as an ecological model in government tertiary education. However, this suggest that more aquaponics studies need to be conducted to explore all components of an aquaponic system, particularly in relation to South African fish and plant species, and environmental conditions. Furthermore, gender representation in aquaponics sector need to be addressed.

Conclusion

The main objective for this study was to determine the status of current aquaponics uses and spatial distribution in South Africa. The main research question was, what are the current aquaponics uses, production and management practises and distribution in South Africa? The main hypotheses was that, most local people do not know what an aquaponic system is and current aquaponics practisers do not have adequate knowledge and skills to operate and manage an aquaponic system. Most current aquaponics in South Africa are being used for small-scale production, housed in tunnel environment, small in terms of the number of practitioners. Most commercial aquaponics are located in Gauteng, Western Cape and Eastern Cape. Indeed most local people did not know what an aquaponic system is and current aquaponics practisers do not have adequate knowledge and skills to operate and manage an aquaponic system. However, significant number of youth are interested in aquaponics concept and practise. Policies such as "one home one aquaponic system" and "one school one aquaponic system" could be implemented to further disseminate the concept of aquaponics and increase the knowledge level among starting practitioners. However, better support to starting aquaponics entrepreneurs will be important for South Africa in order to attract investors and practitioners.

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3. AQUAPONICS DECISION MAKING TOOL

Published in South African Journal of Agricultural extension

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ABSTRACT

Aquaponics requires a sound simultaneous understanding of two agricultural ecosystems (fish and plants) in order to have a productive system. This is the major challenge to current local aquaponics practisers in this country. The aim of this study was to develop a decision-making to help South Africans have a better opportunity to establish and operate aquaponics systems. This study was designed as a mixed approach combining different methods and sources of data to develop the model. The Unified Modeling Language (UML), Microsoft Excel, national online survey, observations, structured and unstructured interviews were used to develop the model. The developed model was able to predict the main aquaponics input variables, namely: fish stocking density, daily fish feed and required planting area. The developed model allows location selection by region and province making it more specific to South African conditions. The fit for fish stocking density, fish feed rate and planting area was R^2=0.7477, 0.6957 and 0.4313 respectively. The RMSE was 14 for fish stocking density which deviated by 29 % from observed and simulated, RMSE was 218 for daily fish feed which deviated by 14 % to the observed and simulated data and RMSE was 4 for planting area which deviated by 25 % to the observed. The model can be used by current aquaponics practisers and be adopted by new aquaponics entrants, extension officers and agricultural facilitators as an aquaponics start-up platform.

Key words: Fish stocking density, daily fish feed, plant-growing area, aquaponics model

Introduction

Agricultural extension is the application of scientific research and knowledge to agricultural practices through farmer education (Ministry of Agriculture Food Security and Cooperatives, 2006). In practice, agricultural extension could be described as the delivery of information to farmers, particularly small-scale farmers (Faber et al., 2011). Aquaponics (aquaponics systems) are the production of fish and vegetable concurrently through by linking aquacultural fish waste to hydroponically growing plants as a natural nutrient source material (Goddek et al., 2015). In return, the plants clean and purify water to keep fish healthy in the aquaculture component (Turcios & Papenbrock, 2014).

Aquaponics has a related benefit of food security and economic productivity (Ibironke, 2013). Aquaponics are small and limited by size and population respectively worldwide (Love et al., 2014 and 2015). Aquaponics has been shown to be a complex system because fish has different nutrient requirement to those of plants (Turcios and Papenbrock, 2014), this could explain the limited aquaponics population. To balance amount of daily fish feed to accommodate plants nutrient needs in a given area of hydroponic culture is often a problem (Lennard, 2012). Mainly because it is difficult, particularly for an ordinary person.

The two empirical nutrient flow aquaponics approaches/models which were developed by James Rakocy in the University of Virgin Island (UVI) from the early 70's and Lennard Wilson as from 2004 show that aquaponic system is the complicated system to operate. Both these approaches agreed with each, in that fish excretion waste and aquaculture waste do not contain sufficient concentrations of phosphorous (P), potassium (K), calcium (Ca) and iron (Fe), as such when one tries to balance one of these nutrients other nutrients, particularly nitrogen become excess, and suggest nutrient supplementation instead of trying to balance nutrient concentrations using fish feed.

There is also a microbial component to aquaponics. This component is possibly the most important because it is usually ignored by most aquaponics operators (Lund, 2014). The microbial component is largely responsible for nitrogen transformation process where ammonium-N is transformed into nitrate-N suitable for plant uptake (Graber and Junge, 2009). This process usually occurs in the biofilter, before nutrient rich solution is pumped into hydroponic culture or in grow beds if inert growth mediums such as gravel are used. This process that allows water to be purified by plants (Buzby and Lin, 2014).

Aquaponics can be very complex and sometimes impossible in this country, because there are lack of expertise (Mchunu et al., 2018). Aquaponics requires a sound simultaneous understanding of two different (morphological and physiological) agricultural ecosystems of fish and plants (Love et al., 2014, 2015). At the same time, there is environmental stress, South Africa is too cool (Bonga and Michael, 2016), average outside environmental condition variables may not support a viable pond aquaculture production. Fish, particularly tilapias species requires an average of 26 ^{o}C, this is not achievable in this country making aquaponics prone failure.

Modeling is the simplified representation of a real system such as aquaponics (Trucano et al., 2006). Models helps to save time and resources by acting as a support tool for planning and decision making (Mabhaudhi et al., 2013). The model aid layperson to optimally use the system with related benefit such as food security and economic productivity (Faber et al., 2011). Hence, if aquaponics decision-making tool is developed and implemented, could be useful resource in this country.

There is insufficient resources and tools to help local aquaponics practisers in this country to make the best decisions for their systems (Mchunu et al., 2018). This study seeks to develop a computer based aquaponics decision-making tool specific to South Africans to help current and new aquaponics practisers.

Materials and Methods

The study followed a mixed method approach, which combined the methods and procedures of quantitative and qualitative data in a single study, using different sources of data. In this context, the study collected data from people who already have an aquaponics in place using a self-administered web-based questionnaire (online survey). And data from the model, observations, key informant face-to-face interviews and secondary literature relevant to the topic in discussion were also used.

The model

Background

A national online survey was conducted in 2016. A total of 44 aquaponics operators responded to the study. The survey results showed a small number of aquaponics systems in this country. The study also revealed a lack of management and production knowledge for these systems among current practisers. The study established the importance of a localised aquaponics decision-making tool for South Africans, and prompted the development of a simple model to promote interest in and the adoption of aquaponics in this country (Mchunu et al., 2018).

The model, shown in flow chart (Figure 1) below was developed, using the Unified Modeling Language (UML), as an easy to use model for early adopters as was suggested. This study acknowledges that, while modeling and model development has great potential to provide for better decision-making to obtain optimum results. However, its use and success is greatly dependent on the acceptability and benefits to the end user/beneficiaries (Thamaga-Chitja, 2008). The Microsoft Excel platform was used as it proved to be user friendly and easily accessible to most South Africans.

The primary data from the online aquaponics survey and a summary of well empirically tested aquaponics production ratios put forward by Rakocy/UVI (1989; 2006; 2007), Lennard (2004; 2012) and FAO (2015) were used to set parameters for this model. The aquaponics production ratios can be adopted and are applicable anywhere in the world. This was useful to the study because it was economically and practically unfeasible for the scope and time of this project to conduct experiments in every province of this country to inform the model. Moreover, the University (University of KwaZulu-Natal) process to conduct studies on animals particularly fish requires a certificate of two year course of fish handling, which was impossible for the, funding, scope and time of the this study.

Model description

The developed model begin with selection of a aquaponics environment currently at or planned to be at. This section consists of three options, namely field, tunnel and greenhouse as defined in Chapter 3 text. When a farmer selects tunnel or field, the model will allow a farmer to select the locality by province, this included specifying different regions within the selected province, this gives an output of how much the temperature need to be adjusted to in winter and in summer. When tunnel is selected, an addition of 5ºC is added to temperature adjustments both for winter and summer. Because when tunnel environment is constructed well, has the capacity of raising the inside temperatures with an average of 5ºC (Boulard et al., 2011). When greenhouse is selected the model does not make locality process available. It was assumed that, in greenhouse conditions, all environmental conditions (wind speed, relative humidity and air temperature) could be fully controlled, including solar radiation. Those assumptions do not hold true in both tunnel and field conditions.

When different plants are selected from the dropdown list, the model search and match plant production ratios, and gives outputs based on the selected plant category, whether it a leafy or fruity. The main model input is the yield selector, in this section a farmer/grower decides how much yield he/she wants to harvest per week. It was also acknowledged and welcomed that some hobby scale may not be interested in yield harvest, however, in the interest of kick-starting, promoting and optimising aquaponics in this country, all model inputs were designed to generate some harvestable yield.

To calibrate different plant types to match with aquaponics production ratios in order for the model to predict the required fish stocking density, daily fish feed and required planting area, it was assumed that the average market size of any individual plant type is 500 g including those that work in bunches like spinach, basil, salad greens, etc. Hence, 25 heads of lettuce translated to 12.5 kg/m^2, in calculation: (25×0.5 kg or 25×500 g/1 000 g = 12.5 kg) also see Table 1 which shows aquaponics production ratios. A similar method was applied to fruity vegetables giving 4 kg/m^2, in calculation: (8×0.5 kg or 8×500 g/1 000 g = 4 kg). The model was designed to predict yield output for the cycle of weekly harvest thereby determine how much plant population will be needed to be in the system. All biochemical parameters were assumed to be at optimum level. The model is designed as dropdown list input function, the green columns in Figure 2 are all inputs and light blue columns are the required and suggested outputs or outcome of the model.

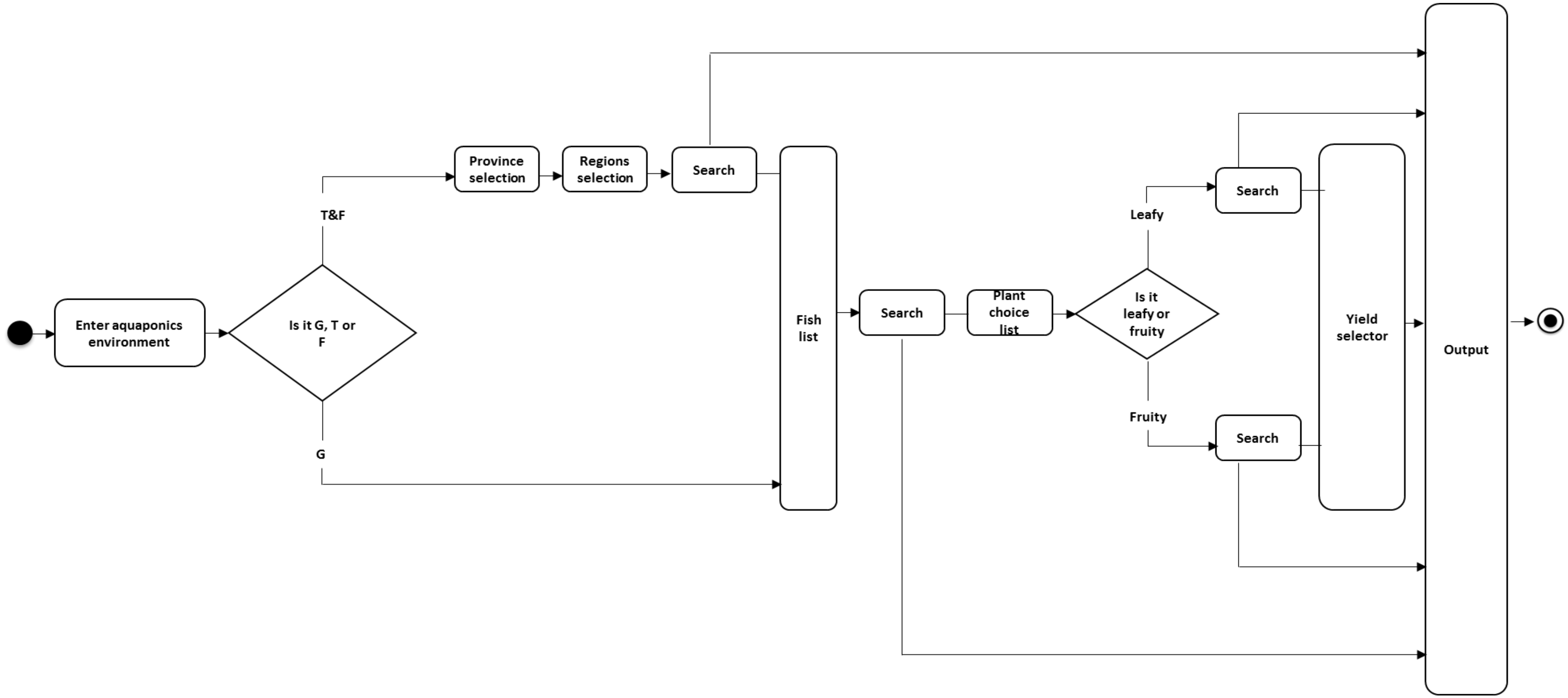

Figure 1 Aquaponic system model design processes flow chart (G stands for Greenhouse, T stands for Tunnel and F stands for Field). The black solid dot represents the beginning of a process or workflow in an activity diagram. The triangle shape represents a decision process and always has at least two paths branching; the pointing arrows present the directions of a process and a decision of a model. The rectangular shape indicates the activities that make up a model process. The circle with solid black dot marks the end state all flows of a process.

Model parameterisation

A plant list generated from the 44 aquaponics operators was categorised as leafy and fruity as per literature (FAO, 2014), and were assigned to specific production ratios as per plant type (fruity or leafy vegetable) (Table 1). The aquaponics production ratios was then used to develop an aquaponics model. The main model parameters are; fish stocking density, daily fish feed and planting area. Equation 1 was used to calculate total quantity of plants seedlings required in the system in order for a farmer(s) to harvest every week. Equation 2 was used to calculate required planting area that will accommodate suggested plant for maximum nutrient removal. Equation 3 was used to calculate the total amount of daily fish feed required to support planting population in aquaponics plant culture. Equation 4 was used to calculate the required fish stocking density to eat fish feed to produce needed nutrients to support plant culture. Fish tank volume size was based on the FAO (2015) ratios that showed that 10 kg/m^3 fish stocking must stocked in 1 000 m^3 for optimal nutrient turn over, and all province and regional temperature was obtained from 2016 South African Weather Service.

Table 1. Empirically developed and tested aquaponics production ratios.

Vegetable category	**Daily Fish Feed (g)**	**Planting density (m^2)**
Leafy vegetables	50-60 (Rakocy, 2007, Lennard 2012) or 40-50 (FAO, 2014 and 2015).	20-25 (Rakocy, 2007; Lennard 2012; FAO, 2014.
Fruity vegetables	80-100 (Rakocy, 2007; Lennard 2012; FAO, 2014.	4-8 (Rakocy, 2007; Lennard 2012; FAO, 2014.

$$25 \text{ heads/weeks} \times 4 \text{ weeks} = 100 \text{ heads in the system} \quad (1)$$

$$25 \text{ heads} = 1 \text{ m}^2\text{, therefore, } 100/25 = 4 \text{ m}^2 \quad (2)$$

$$1 \text{ m}^2 = 50 \text{ g/day}^{-1}\text{, therefore, } 4 \text{ m}^2 \times 50 \text{ g/day}^{-1} = 200 \text{ g/day}^{-1} \quad (3)$$

$$\text{Fish eats 1-2 (\%) of their body weight/ day}^{-1}\text{, therefore,} \quad (4)$$
$$(200 \text{ g/day}^{-1} \times 100 \text{ g})/ 1\text{-}2 \text{ g/day}^{-1} = 10\text{-}20 \text{ kg fish mass}$$

Biofilter area

Biofilter area is a very important part of an aquaponic system because it determines microbial component functioning, which in turn determines the productivity of the aquaponic system by facilitating nutrient turn over and flow in the aquaponic systems. Hence, biofilter area was determined using FAO (2014) ratios from Equations 5 and 6.

$$(g/feed) \times 0.32 \times 0.16 \times 0.61 \times 1.2 = g/ammonia \tag{5}$$

where,

0.32 = g protein is 32% protein in $(g/feed)$,

0.16 = g of nitrogen contained in the protein,

0.61 = g of wasted nitrogen, and

1.2 = each gram of wasted nitrogen, 1.2g of ammonia is produced.

$$\frac{1\ m^2}{0.57\ NH_3} \tag{6}$$

where,

0.57 = g ammonia removal rate by bacteria per day/m^2

Water flow rate

Water circulation is very important in aquaponics because aquaponics by nature are innovative water circulation systems (Khater et al., 2015). As such, water flowrate is the critical aquaponics component that need to be followed and maintained at all times (Wortman, 2015). Water flowrate plays a critical role in facilitating important aquaponics processes such as nutrient flow and turn over which facilitates water purification which aquaponics are well known and adopted for (FAO, 2015). Water flowrate for the model was determined following a ratio that suggest 30-40% water circulation of total fish tank water to be constantly channeled to plant growing area (FAO, 2015).

Recommended method of plant production

There are three mostly adopted methods of plant production in hydroponics, namely; Nutrient Film Technique (NFT), Deep Water Culture (DWC) and Growth Medium Bed (GMB) (Love et al., 2014). The method of plant production of the model was based on Lennard (2012) and FAO (2015). Leafy and fruity vegetables have different nutrient requirement to each other attributed to different plant agronomic orientation in terms of roots, structure and canopy cover (Buzby and Lin, 2014). Most leafy vegetables and herbs can be grown in any method (NFT, DWC or GMB), while most roots and most fruity crops such as tomatoes, cabbage etc perform well in GMB (FAO, 2015).

Recommended temperature adjustments

Most hydroponics plants are suitable to South African climate conditions. The recommended temperature adjustments was based on fish optimum temperatures, because yearly South African average climate conditions are too cool (MacKellar et al., 2014), which could hinder optimum fish production. To determine the summer and winter temperature adjustments required, the average regional winter and summer air temperatures were subtracted from fish optimum temperatures, thereby resulting in the system environmental conditions recommendations being at optimum all the times for fish production. This was done for the field condition option only, if option is tunnel, a 5 ^{o}C was further added into recommended temperature adjustment. This is because summary literature shows that if tunnel environment is constructed well, it could raise air temperature with an average of 5 ^{o}C (Boulard et al., 2011). For the greenhouse option, it was assumed that in the greenhouse environment, all production parameters can be fully controlled hence, outside environmental conditions will not be the factors.

RSA Aquaponics system model		
Input		**Input comments**
Aquaponic Environment	Field	What type of environment would you like your aquaponic system to be at or is at?
Locality	KwaZuluNatal	What is your aquaponic system location by province?
Locality regions	Ukhahlamba-Drakensberg	It is breakdown of selected province by region
Fish selector	Tilapia	What type of fish species you would like to grow in your aquaponic system?
Crop selector	Spinach	What is your aquaponic system crop choice?
Yield selector (kg)	50	Crop yield per week per.
Outputs		**Outputs comments**
Required number of seedlings	2000	Total number of seedlings to be planted in the system in order to harvest rotationally
Required plant growing area (m^2)	20,00	Total planting surface area required to support plant density (FAO and UVI ratios)
Required daily fish feed rate (g day^{-1})	1000	Suggested daily fish feed amount based on FAO and UVI ratios
Required fish stocking density (kg/m^3)	66,7	Suggested fish stocking density based on FAO and UVI ratios
Suggested fish tank size (L)	3333	Suggested fish tank size based on Rakocy and FAO ratios
Required biofilter area (m^2)	34,0	surface area required to mineralise fish waste solids based on FAO ratios
Required flow rate (L/hr)	1333	Water required to flow to your plant growing area based on Rakocy and FAO
Recommended method of plant production	GMB, NFT and DWC	A recommended plant production method based on FAO, Lennard and Rakocy
Winter water temp adjustements (^oC)	20	A recommended winter water temperature adjustment to meet fish optimum temperature
Summer water temp adjustements (^oC)	3	A recommended summer water temperature adjustment to meet fish optimum temperature
Nutrient management, K, Ca and Fe (mg/L)	100, 100 and 7	Levels of limiting nutrients to be achieved for optimum plant yield based on Organic Soil Technology
Required winter fish temp adjustements if it Tunnel (^oC)	N/A	A recommended winter temperature adjustment to meet fish optimum temperature if tunnel housing is used
Required summer fish temp adjustements if it Tunnel (^oC)	N/A	A recommended summer temperature adjustment to meet fish optimum temperature if tunnel housing is used

Figure 2 Aquaponics decision-making tool as it shows aquaponics output recommendations that can be adopted to implement aquaponics when KwaZulu-Natal province, Midlands region, tilapia species, leafy vegetables (spinach) and desired yield of 50 kg/week is selected.

Model simulation

Model simulations was performed using the national aquaponics online survey data and some data from the literature. The online survey data was organised and summarised to create main model input, which was the yield selector. This was performed by using crop yield results from the aquaponics online survey data. The yearly crop yield data from the aquaponics survey for South Africa was regarded as the observed data, data from the survey was transformed until it matched units of the yield selector of the model. The survey crop yield data was based on yearly average yield (kg). This was then divided by individual crop duration and rotation cycle, to determine how much produce (kg) the farmers produced per individual crop rotation. Then, the observed fish stocking density, daily fish feed and planting area data from the online survey were compared with simulated data from the model using different methods of data analysis.

Model evaluation

The goodness of fit of the model was carried out using standard linear equation (Equation 7), coefficient of determination (R^2), Root Mean Square Error (RMSE) and its components (RMSEs and RMSEu) (Equation 8, 9 and 10). The standard linear equation is a mathematical measurement of how close the actual data to the simulated, for a good model fit m should be 1 or more and b = 0 or less. The coefficient of determination R^2 is a statistical measurement of how close the data are to the fitted regression line in the graph and is used when comparing the observed and predicted model output values. The R^2 always falls between within 0 and (100%), where (0%) shows that the model explains none of the variability of the response data around its mean, and (100%) indicates that the model explains all the variability of the response data around its mean, hence, the higher or closer the R^2 to 1, the better the model fits to the measured data.

$$y = mx + b \tag{7}$$

$$\text{RMSE} = (\text{RMSEs} + \text{RMSEu})^{0.5} \tag{8}$$

$$RMSE_s = \left[n^{-1} \sum_{i=1}^{n} (\hat{P}_i - 0_i)^2\right]^{0.5} \tag{9}$$

$$RMSE_U = \left[n^{-1} \sum_{i=1} (\hat{P_i} - \hat{P_i})^2 \right]^{0.5} \tag{10}$$

where, n = the number of observations, and P_i is derived from $P_i = a + b.Oi$ whereby a and b are the intercept and slope, respectively, of a least regression between the predicted (dependent variable) and observed (independent variable) values.

The error based metrics analysis like RMSE, MAE, PRESS and others, offers the most accurate prediction quality (Roy et al., 2016). However, to decide a suitable threshold value for these metrics are usually problematic, for instance, high values of RMSE can be due to presence of small number of high error predictions (Chai and Draxler, 2014; Roy et al., 2016).

Results

After the online survey data was filtered and transformed, most (90%) aquaponics farmers crop production yield output fitted under yield selector of 1 and 2 kg/week/harvest duration of the model input function. This is the lowest model output input. The fit for fish stocking density, fish feed rate and planting area was R^2=0.7477, 0.6957 and 0.4313 respectively (Figure 2, 3 and 4). From the standard linear equation, m= 1.25 and b= -3.06 for fish stocking density, for daily fish feed, m= 0.98 and b= -19.06 and for planting area, m= 0.68 and b= 1.43 (Figure 2, 3 and 4). The RMSE was14 for fish stocking density which deviated by 29 % from observed and simulated, RMSE was 218 for daily fish feed which deviated by 14 % to the observed and simulated data and RMSE was 4 for planting area which deviated by 25 % to the observed (Table 2).

Table 2 Results of RMSE from the observed and simulated aquaponics productions variables.

	Fish stocking density (kg/m^3)	Daily fish feed (g)	Planting area (m^2)
Observed	30	548	7
Simulated	34	518	6
RMSE	14	218	4

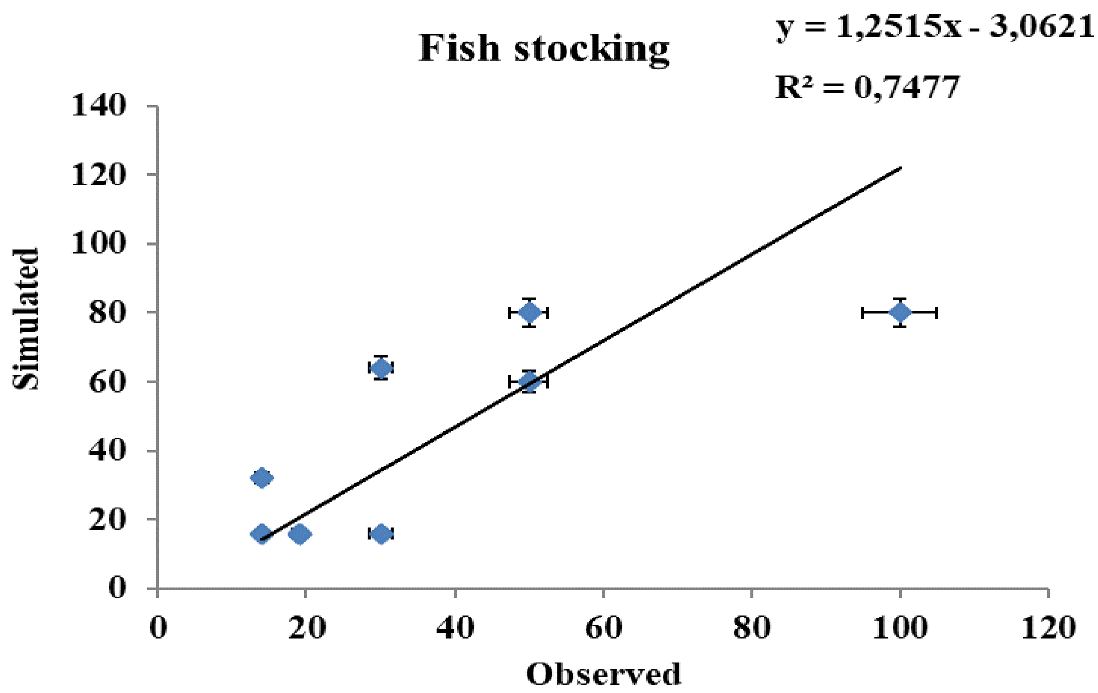

Figure 3 Fish stocking linear relationship between the observed data from the aquaponics online survey and simulated data from the developed RSA aquaponics model.

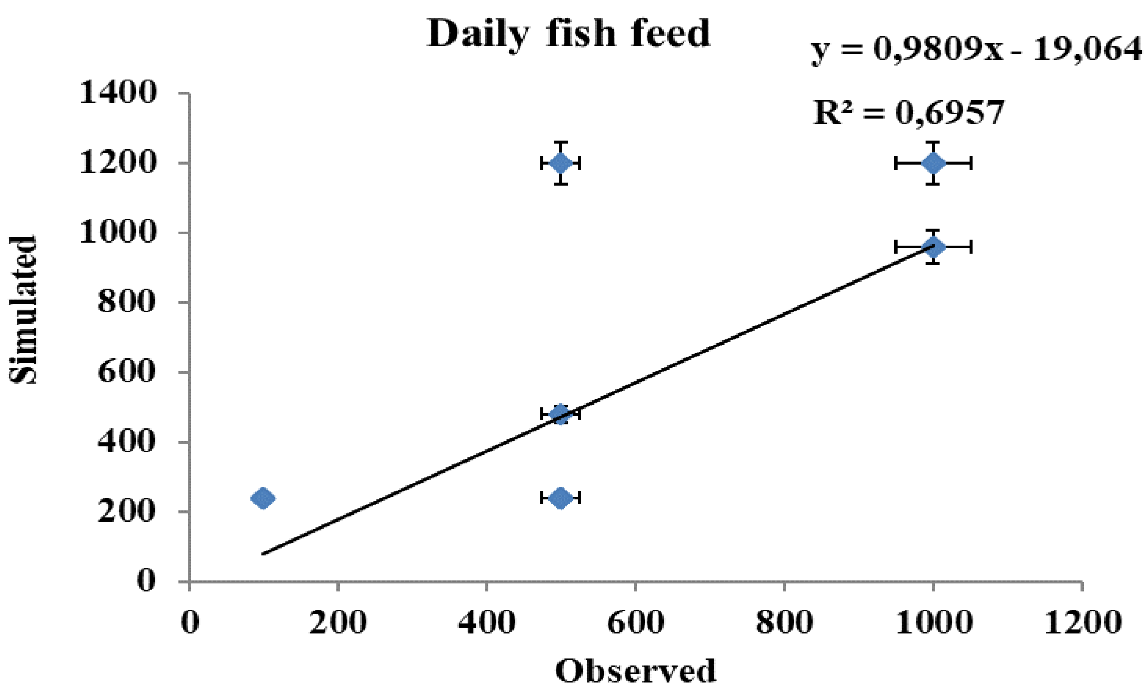

Figure 4 Daily fish feed linear relationship between the observed data from the aquaponics online survey and simulated data from the developed RSA aquaponics model.

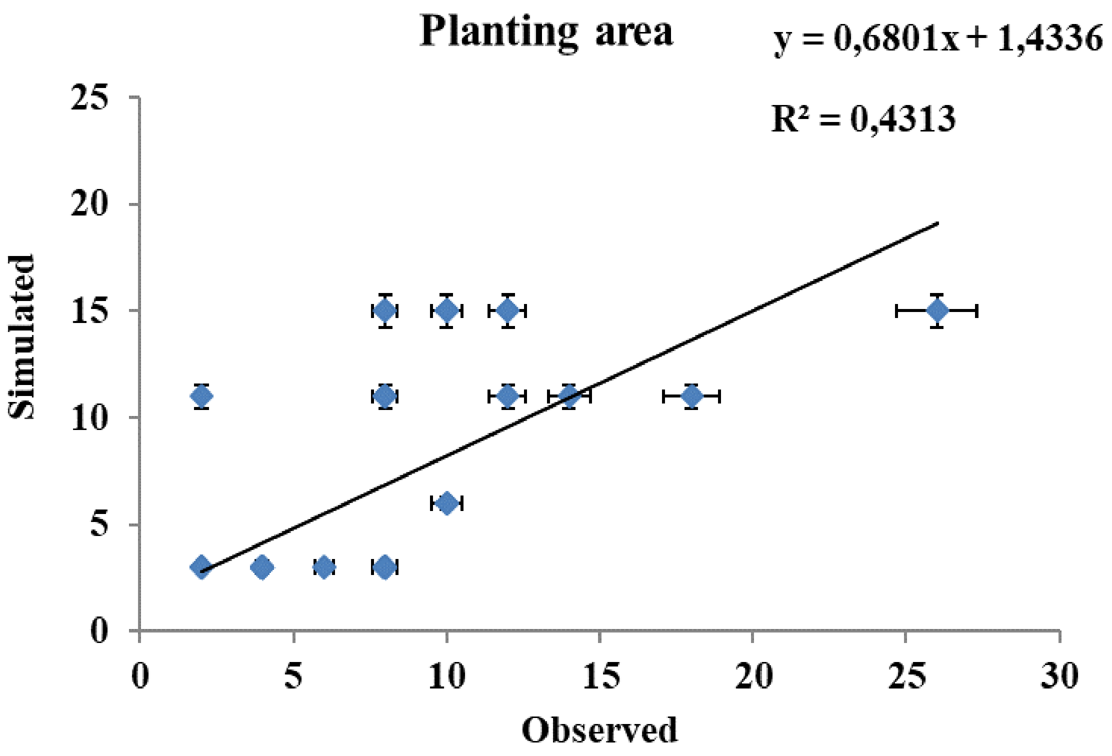

Figure 5 Planting area linear relationship between the observed data from the aquaponics online survey and simulated data from the developed RSA aquaponics model.

Simulations

Pattillo (2016) showed that 1 000 g/fish feed/day =16, 7 m^2, from the online aquaponics calculator, 1 020 g/fish feed/day =17 m^2 (Noodlecode, 2019). In the developed aquaponics model, 1 000 g/fish feed/day = 19 m^2. The result of the model did not differ significantly (*P<0.05*) from others aquaponics models.

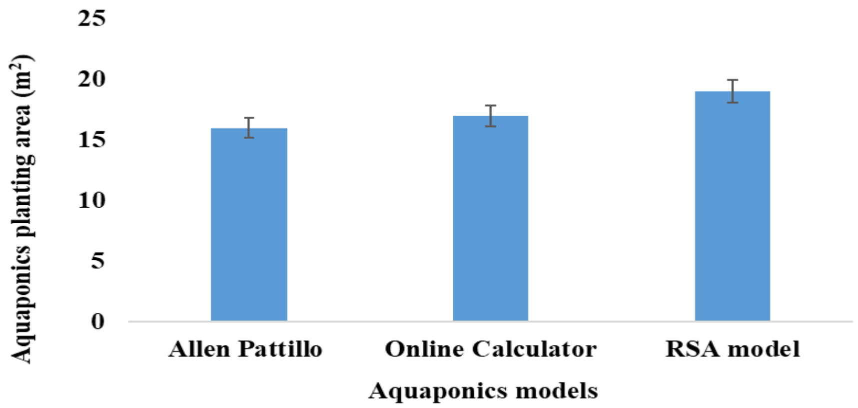

Figure 6 Planting area prediction comparisons using different aquaponics models.

Discussion

The fit of yield to 1 and 2 kg/week, suggest that most local aquaponics are characterised by small systems. This could also suggest that most aquaponics operators in this country produces below optimum capacity. This could be explained by the findings of Mchunu et al. (2018) who showed that most current aquaponics operators do not have sufficient information, data, resources and tools available to obtain maximum yield from their systems. This is also supported by Love et al. (2014 and 2015) international aquaponics survey findings where single response was captured for South. Africa. The results suggest that, aquaponics are indeed emerging practise in this country, hence, it possible to argue that aquaponics in this country are still characterised by production and management errors which results into poor and negative yield production.

The fit of R^2=0.7477 and 0.6957 for, fish stocking density and daily fish feed respectively suggest an acceptable model fit, and the fit of R^2 = 0.4313 for planting area suggest a poor model fit. The closeness of, *m* and *b*, to 1 and 0 respectively for, fish stocking density and daily fish feed suggest an acceptable model fit. For planting area, *m* and *b*, was not close 1 and 0 respectively and suggest a poor model fit. Similarly, the poor model fit is attributed to negative yield production and emerging nature of aquaponics in this country. The current aquaponics decision making tool can be used to rectify this.

Similarly, the RMSE of 14 for fish stocking density which deviated by 29 % from observed and simulated, RMSE of 218 for daily fish feed which deviated by 14 % to the observed and simulated data and RMSE of 4 for planting area which deviated by 25 % to the observed and simulated data such an acceptable model fit. The poor model fit for planting when using R^2 and linear equation could be attributed to residual errors. The similar predictions between R^2, linear equation and RMSE for fish stocking density and daily fish feed suggest that this model accurately predicts these variables. This could be supported by similar model predictions for aquaponics planting area where different aquaponics model include RSA model were used.

Guidelines for extension officers and farmer support organisations

Agricultural extension service and supports has been shown to be effective in implementing successful innovative development community projects in this country (Faber et al., 2011).

Hence, extension support will need to be adopted if these systems are implemented for the first time. To use the model effectively extension officers or development agencies will need to have or understand the following:

- Aquaculture background, to keep fish safe and healthy by making sure that all fish production parameters particularly, pH, dissolved oxygen and water temperature in order for fish to convert all fish feed into needed waste by plants in hydroponic culture.
- Microbiology background, to make sure that conditions required for transformation of ammonium nitrogen into nitrate nitrogen are provided for. This is because waste produced from the water tank is in ammonium form and needs to be transformed into nitrate for plants to absorb in the hydroponic culture. This is a very important component of an aquaponic system because it determines the nutrient turn over and nutrients available for plants as well as the water quality for fish in the fish tank. In the absence of this component, the whole system could collapse.
- Hydroponic background, to understand plant nutrient requirement and different aquaponics plant categories, because this model is very sensitive to plant categories. Leafy vegetables have a significantly different nutrient requirement and planting density than fruity vegetables. One mistake could lead to a significant outcome thus affect budget and resource efficiency, hence an extension officer should be able to quickly notice if something is wrong before model output is taken into consideration.
- Meteorology background, in order to be able give better advise to farmers, particularly small-scale farmers about what type of aquaponic system materials and instruments to use to achieve optimum climate variables (relative humidity, air temperature and water temperature), because South Africa is too cool for optimum fish production.
- Spreadsheet background to be able use the model to calibrate, verify and validate the model according to different farmer's scenarios.

Conclusion

The main objective of this study was to develop an aquaponics decision-making tool for South African. The main research question was, can aquaponics decision-making tool really make aquaponics easy for a layperson? And the hypothesis was, aquaponics decision-making tool, if developed and implemented, can predict aquaponics yield production. The developed model was able to predict the main aquaponics system variables, namely, fish stocking density, daily fish feed and required planting area. The model is an easy use because in inputs function are designed as a dropdown list and implemented in Microsoft excel which has proven to be user friendly and ready available for everyone in this country. However, Extension support service will need to be employed if these systems are to be implemented for the first time in this country. Even though this study used the well-tested aquaponics ratios, empirical experiments will need to be conducted to calibrate and validate the model.

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4. AQUAPONICS PRODUCTION SIMULATIONS USING THE AQUAPONICS DECISION-MAKING TOOL

Accepted in African Journal of Food, Agriculture, Nutrition and Development

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ABSTRACT

Aquaponics have related food and nutrition security benefit that are important for this country (South Africa). The aim of this study was to apply aquaponics decision-making tool to provide potential aquaponics production data and information for South Africa. This study was designed as 2×3×3 factorial study giving 18 interactions. Because aquaponics are the production of fish and crops concurrently, therefore yield production had two levels- fish and crop, fish stocking density had three levels- low, optimum and higher and aquaponics scale of production had 3 levels- hobby, subsistence and commercial scale. The summary of data of aquaponics variables from the literature was used as optimum level, lower and higher levels were based on experimental design. Yield production (kg) of both fish and plants increased significantly ($p<0.05$) as fish stocking density was increased. In hobby scale, plants yield was higher than fish yield in all levels of fish stocking density, the plant-fish yield (kg) was 40-33, 80-67 and 150-133 respectively. In subsistence scale, fish-plant yield (kg) was 240-200, 300-267 and 400-333 respectively. In commercial scale, fish-plant yield (kg) was 600-533, 1 100-1 000, 1 500-1 333 respectively. Daily fish feed increased significantly with increase in fish stocking density across all scale of aquaponics production (hobby<subsistence<commercial). In hobby scale, at low fish stocking, 0.65kg feed produced 1 kg fish, at optimum, 0.65kg feed produced 1 kg fish and at higher fish stocking, 0.37kg feed produced 1 kg fish. In subsistence scale at low fish stocking density, 0.38kg feed produced 1 kg fish, at optimum level, 0.63kg feed produced 1 kg fish and at higher level, 0.65kg feed produced 1 kg fish. In commercial

scale, in low fish stocking, 0.64kg feed produced 1 kg fish, at optimum, 0.63kg feed produced 1 kg fish and at higher fish stocking, 0.64kg feed produced 1 kg fish. Plant culture have more yield output than fish culture in all aquaponics scale of production. Hobby scale produced the lowest yield than subsistence than commercial scale of production. Hobby scale practise could not produce sufficient yield to support human subsistence. Fish feed closely mirrored yield production. Lower fish stocking density maybe adopted in subsistence scale. Higher fish stocking density maybe adopted in commercial scale. Fish feed could become an economic sustainability constrain in aquaponics production, particularly in a developing country like South Africa. Water availability and quality effects on yield was not determine especially in African context.

Key word: Fish stocking density, Yield production, Fish feed, Planting area

INTRODCTION

Aquaponics is the innovative production of fish and crops concurrently in one system [1]. The dual production of fish and vegetables at the same time, allows for food diversity, which is essential for food and nutrition security. Placing aquaponics among potentially important strategies to address food and nutrition insecurities in South Africa[2]. Fish is a significant source of protein, essential amino acids, and vitamins, which are important for food security [3]. Even in small quantities, fish can improve dietary quality by contributing essential amino acids often missing or underrepresented in vegetable based diets [4]. In addition to proteins, fish and fish oils are a significant source of omega three fatty acids which are important for normal brain development particularly during pregnancy and in infants [5]. As such, aquaponics can, if developed, implemented for and owned by local people, address food insecurity problems in Africa, particularly in South Africa. [6] .

However, the two empirical nutrient flow aquaponics approaches/models which were developed by James Rakocy in the University of Virgin Island (UVI) from the early 70's and Lennard Wilson as from 2004 shows that aquaponics systems are complicated systems in nature, particularly to design and operate. Both these approaches agreed with each, in that fish excretion wastes and aquaculture wastes do not contain sufficient concentrations of phosphorous (P), potassium (K), calcium (Ca) and iron (Fe) to support plant culture. As such, when one tries to balance one of these nutrients other nutrients, particularly total nitrogen become excess resulting in potential toxicity, particularly for fish. Thus suggested a nutrients supplementation programme instead of trying to balance nutrient concentrations using fish feed.

There is also a microbial component to aquaponics. This component is possibly the most important because it is usually ignored by most aquaponics operators [7]. The microbial component is largely responsible for nitrogen transformation process where ammonium-N is transformed into nitrate-N suitable for plant uptake [8]. This process usually occurs in the biofilter, before nutrient rich solution is pumped into hydroponic culture or in grow beds if inert growth mediums such as gravel are used. This process allows water to be purified by plants in order for a clean water to be recirculated back in the fish tank to sustain fish well-being [9]. This is the heart of an aquaponic system, as such, if this component is ignored, could result in system failure or collapse which will affect heathy food production suitable for human subsistence. [9]. If aquaponics is to be adopted as a poverty alleviation tool in South Africa, optimum yield production for human subsistence will need to be determined. A national aquaponics survey in South Africa has established the lack of knowledge, information and skills required operate aquaponics systems [10].

Aquaponics production and profitability are affected by a number of variables, the more important of which are; fish stocking density; water volume in the fish tank; quantity of daily fish feed, type of crop cultured and the planting area [10] . Fish play a critical role in nutrient production for plants, and without fish well-being the whole system could also collapse [11], fish stocking density needs to be carefully calculated and managed. Fish stocking density is influenced by type of fish species cultivated and surface area available for fish culture [12]. Tilapias are the most cultivated fish species in aquaponics worldwide including South Africa [13,14]. Nile Tilapia is the most profitable species, but in South Africa, Nile tilapia is prohibited. Tilapias in general are resilient and can survive negative aquaponics scenarios. Tilapias can tolerate a wide range environmental conditions, water temperatures between 8-38 °C, dissolved oxygen as low as 2 mg/L, and nitrate-N level as high as 200 mg/L [15].

All of these factors are however dependent on the scale an aquaponic system. Research makes reference to different scales in aquaponics systems namely, hobby, subsistence and commercial scale. Hobby systems are generally smaller scale and usually have fish stocking density of 10 and 20 kg/m^3 in 500 -1 000 m^3 water volume. In hobby scale production, farming activity is practised with little interest to consume the harvest. Subsistence systems have between 20 and 40 kg/m^3 in 1 000-2 000 m^3. In subsistence level aquaponics systems, farming is practised as a livelihood support system. In commercial scale systems have 100 to 300 kg/m^3 in 4 000 - 50 000 m^3 water volume. In these systems, everything is produced with market sales motive [16]. Correspondingly, yields usually differ across the scales but also within, with differences in environment, market demand and quality usually accounting for the differences [16] .

The main purpose of this study was to provide potential aquaponics production data and information in order to help new aquaponics operators and government to have more knowledge about this developing sector in South Africa. This was done through the application of the aquaponics decision-making tool using fish stocking density as the main variable. The results of the study will assist in promoting the aquaponics concept and informing policy makers in this country.

MATERIALS AND METHODS

Study area

The study was conducted in the Republic of South Africa (RSA) (30°.55′95″S, 22°.93′75″E). South Africa is bordered by the Atlantic Ocean on the west and the warm Indian Ocean on the east. This gives the country its comfortable yearly average temperatures of 0^oC (Figure 1), and the abundant biodiversity in the range of fish and plants which South Africa is popularly known for [17] .

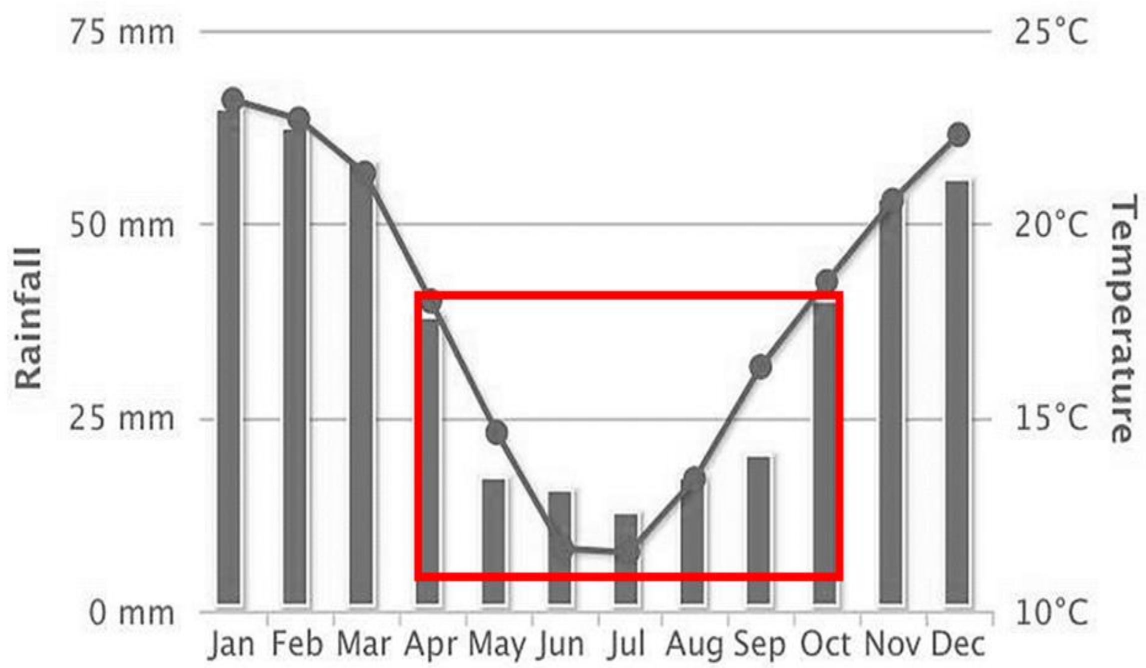

Figure 1: South Africa average yearly climate variables of 2019 as it relate to rainfall and air temperature trends which could affect aquaponics production in South Africa' particularly in winter as indicated by red square in the figure above. Fish particularly tilapias requires an average of 28 to 30 °C for optimum economic production throughout the production cycle [27].

Model description

The developed decision-making tool start with selection of an aquaponics environment. This section consists of three options, namely field, tunnel and greenhouse. Tunnel refers to the aquaponics that are housed in environments covered by polyethylene sheet which are designed to allow minimum and maximum effect of: wind spend, solar radiation, relative humidity and air temperature, by automatic evaporative cooling method, facilitated by wet walls and cooling fans. Greenhouse is the aquaponics environment where all environmental conditions (solar radiation, wind spend, air temperature and relative humidity) are fully controlled to suit any species in any given time of the year and field production refers to aquaponics that are completely exposed to the outside environmental conditions (solar radiation, wind spend, air temperature and relative humidity) with zero control.

When a farmer selects tunnel or field, the model will allow a farmer to select the locality by province, this included specifying different regions within the selected province, this gives an output of how much the temperature needs to be adjusted to in winter and in summer. When tunnel is selected, an addition of 5°C is added to temperature adjustments both for winter and summer. Because when tunnel environment is constructed well, has the capacity of raising the inside temperatures with an average of 5°C [18]. When greenhouse is selected the model does not make locality process available. It was assumed that, in greenhouse conditions, all environmental conditions (wind speed, relative humidity and air temperature) could be fully controlled, including solar radiation. Those assumptions do not hold true in both tunnel and field conditions.

When different plants are selected from the dropdown list, the model search and match plant production ratios, and gives outputs based on the selected plant category, whether it a leafy or fruity. The main model input is the yield selector, in this section a farmer/grower decides how much yield he/she wants to harvest per week. It was also acknowledged and welcomed that some hobby scale may not be interested in yield harvest; however, in the interest of kick-starting, promoting and optimising aquaponics in South Africa, all model inputs were designed to generate some harvestable yield.

To calibrate different plant types to match with aquaponics production ratios in order for the model to predict the required fish stocking density, daily fish feed and required planting area, it was assumed that the average market size of any individual plant type is 500 g including those that work in bunches like spinach, basil, salad greens, etc. Hence, 25 heads of lettuce translated to 12.5 kg/m^2, in calculation: (25×0.5 kg or 25×500 g/1 000 g = 12.5 kg) also see Table 1 which shows aquaponics production ratios. A similar method was applied to fruity vegetables giving 4 kg/m^2, in calculation: (8×0.5 kg or 8×500 g/1 000 g = 4 kg). The model was designed to predict yield output for the cycle of weekly harvest thereby determine how much plant population will be needed to be in the system. All biochemical parameters were assumed to be at optimum level. The model is designed as dropdown list input function, the green columns in Figure 2 are all inputs and light blue columns are the required and suggested outputs or outcome of the model.

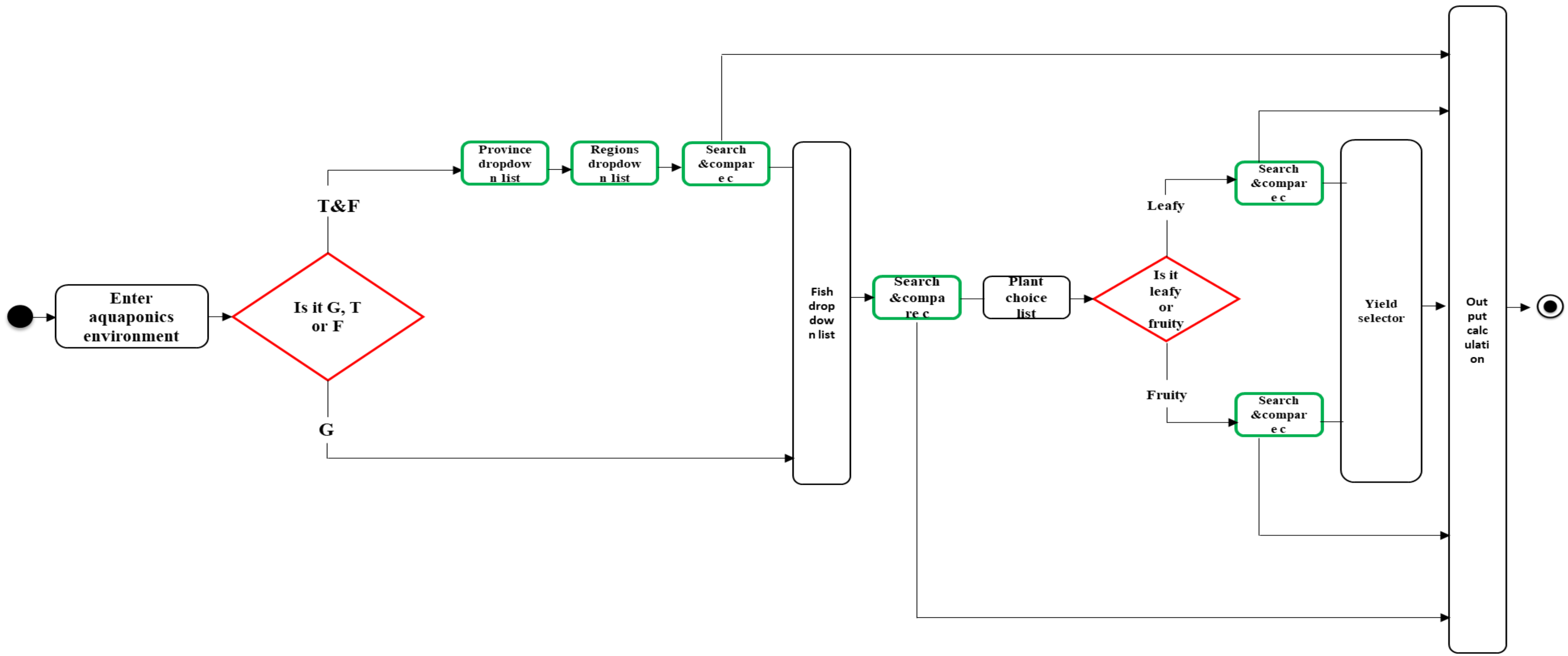

Figure 2: Aquaponics system model design processes flow chart with red and green highlighted part showing the most important part of the model, G stands for Greenhouse, T stands for Tunnel and F stands for Field). The black solid dot represents the beginning of a process or workflow in an activity diagram. The triangle shape represents a decision process and always has at least two paths branching; the pointing arrows present the directions of a process and a decision of a model. The rectangular shape indicates the activities that make up a model process. The circle with solid black dot marks the end state all flows of a process.

Model parameterisation

A plant list data generated from the 44 aquaponics operators using the online survey was categorised as leafy and fruity as per literature and were assigned to specific production ratios as per plant type (fruity or leafy vegetable) (Table 1). The aquaponics production ratios was then used to develop an aquaponics model. Equation 1 was used to calculate total quantity of plants seedlings required in the system in order for a farmer(s) to harvest every week. Equation 2 was used to calculate required planting area that will accommodate suggested plant for maximum nutrient removal. Equation 3 was used to calculate the total amount of daily fish feed required to support planting population in aquaponics plant culture. Equation 4 was used to calculate the required fish stocking density to eat fish feed to produce needed nutrients to support plant culture. Fish tank volume size was based on the ratios that showed that 10 kg/m^3 fish stocking must be stocked in 1 000 m^3 for optimal nutrient turn over, and all province and regional temperature was obtained from 2019 South African Weather Service.

$$25 \text{ heads/weeks} \times 4 \text{ weeks} = 100 \text{ heads in the system} \tag{1}$$

$$25 \text{ heads} = 1 \text{ m}^2\text{, therefore, } 100/25 = 4 \text{ m}^2 \tag{2}$$

$$1 \text{ m}^2 = 50 \text{ gday}^{-1}\text{, therefore, } 4 \text{ m}^2 \times 50 \text{ gday}^{-1} = 200 \text{ gday}^{-1} \tag{3}$$

$$\text{Fish eats 1 (\%) of their body weight/ day}^{-1}\text{, therefore,} \tag{4}$$
$$(200 \text{ gday}^{-1} \times 100 \text{ g})/ 1\text{g/day}^{-1} = 20 \text{ kg fish mass}$$

Biofilter area

Biofilter area is a very important part of an aquaponics system because it determines microbial component functioning, which in turn determines the productivity of the aquaponics system by facilitating nutrient turn over and flow in the aquaponics systems. Hence, biofilter area was determined using FAO (2014) ratios from Equations 5 and 6.

$$(g/feed) \times 0.32 \times 0.16 \times 0.61 \times 1.2 = g/ammonia \tag{5}$$

where,

0.32 = g protein is 32% protein in $(g/feed)$,

0.16 = g of nitrogen contained in the protein,

0.61 = g of wasted nitrogen, and

1.2 = each gram of wasted nitrogen, 1.2g of ammonia is produced.

$$\frac{1\ m^2}{0.57\ NH_3} \tag{6}$$

where,

0.57 = g ammonia removal rate by bacteria per day/m^2

Water flow rate

Water circulation is very important in aquaponics because aquaponics by nature are innovative water circulation systems [19]. As such, water flowrate is the critical aquaponics component that needs to be followed and maintained at all times [20] . Water flowrate plays a critical role in facilitating important aquaponics processes such as nutrient flow and turn over which facilitates water purification which aquaponics are well known and adopted for. Water flowrate for the model was determined following a ratio that suggest 30-40% water circulation of total fish tank water to be constantly channeled to plant growing area [21].

Recommended method of plant production

There are three mostly adopted methods of plant production in hydroponics, namely; Nutrient Film Technique (NFT), Deep Water Culture (DWC) and Growth Medium Bed (GMB). The method of plant production of the model was based on Lennard (2012) and FAO (2015). Leafy and fruity vegetables have different nutrient requirement to each other attributed to different plant agronomic orientation in terms of roots, structure and canopy cover. Most leafy vegetables and herbs can be grown in any method (NFT, DWC or GMB), while most roots and most fruity crops such as tomatoes, cabbage perform well in GMB.

Recommended temperature adjustments

Most hydroponics plants are suitable to South African climate conditions. The recommended temperature adjustments was based on fish optimum temperatures, because yearly, South African average climate conditions are too cool [22], which could hinder optimum fish production. To determine the summer and winter temperature adjustments required, the average regional winter and summer air temperatures were subtracted from fish optimum temperatures, thereby resulting in the system environmental conditions recommendations being at optimum all the times for fish production. This was done for the field condition option only, if option is tunnel, a 5 ^{o}C was further added into recommended temperature adjustment. Because it is well written that if tunnel environment is constructed well, it could raise air temperature with an average of 5 ^{o}C. For the greenhouse option, it was assumed that in the greenhouse environment, all production parameters can be fully controlled hence, outside environmental conditions will not be the factors.

RSA Aquaponics system model		
Input		**Input comments**
Aquaponic Environment	Field	What type of environment would you like your aquaponic system to be at or is at?
Locality	KwaZuluNatal	What is your aquaponic system location by province?
Locality regions	Ukhahlamba-Drakensberg	It is breakdown of selected province by region
Fish selector	Tilapia	What type of fish species you would like to grow in your aquaponic system?
Crop selector	Spinach	What is your aquaponic system crop choice?
Yield selector (kg)	50	Crop yield per week per.
Outputs		**Outputs comments**
Required number of seedlings	2000	Total number of seedlings to be planted in the system in order to harvest rotationally
Required plant growing area (m^2)	20,00	Total planting surface area required to support plant density (FAO and UVI ratios)
Required daily fish feed rate (g day^{-1})	1000	Suggested daily fish feed amount based on FAO and UVI ratios
Required fish stocking density (kg/m^3)	66,7	Suggested fish stocking density based on FAO and UVI ratios
Suggested fish tank size (L)	3333	Suggested fish tank size based on Rakocy and FAO ratios
Required biofilter area (m^2)	34,0	surface area required to mineralise fish waste solids based on FAO ratios
Required flow rate (L/hr)	1333	Water required to flow to your plant growing area based on Rakocy and FAO
Recommended method of plant production	GMB, NFT and DWC	A recommended plant production method based on FAO, Lennard and Rakocy
Winter water temp adjustements (^oC)	20	A recommended winter water temperature adjustment to meet fish optimum temperature
Summer water temp adjustements (^oC)	3	A recommended summer water temperature adjustment to meet fish optimum temperature
Nutrient management, K, Ca and Fe (mg/L)	100, 100 and 7	Levels of limiting nutrients to be achieved for optimum plant yield based on Organic Soil Technology
Required winter fish temp adjustements if it Tunnel (^oC)	N/A	A recommended winter temperature adjustment to meet fish optimum temperature if tunnel housing is used
Required summer fish temp adjustements if it Tunnel (^oC)	N/A	A recommended summer temperature adjustment to meet fish optimum temperature if tunnel housing is used

Figure 3: Aquaponics decision-making tool as it shows aquaponics output recommendations that can be adopted to implement aquaponics when KwaZulu-Natal province, Midlands region, tilapia species, leafy vegetables (spinach) and desired yield of 50 kg/week is selected

Experimental design and procedure

A summary of the data in the literature and from field visits and observations shows that different scales of aquaponics production can be distinguished. Hobby systems have a fish stocking density of 10-20 (kg/m^3) a nd 500-1 000 (m^3) fish tanks capacity. Subsistence systems have 20-40 kg/m^3 and 1 000-2 000 litre, while commercial scale systems have a stock of 100-300 kg/m^3 and 4 000-50 000 litre fish tanks (Table 2). Based on these variables, aquaponics production experiments were designed. The simulation experiment designs included applying the model to analyse biomass production output, fish stocking density, daily fish feed, planting area and aquaponics scale of production if aquaponics were to be implemented in SA. The study was designed as 2×3×3 factorial study giving 18 interactions.

The three independent variables are: biomass production; fish stocking density and scale of production. Because aquaponics consists of the production of fish and vegetables concurrently, biomass production (yield) has two levels: fish and crop. Fish stocking density has three levels: low, optimum and high and the scale of production variable has three levels: hobby scale, subsistence and commercial scale. The summary of data of aquaponics variables from the literature was used as optimum level, lower and higher levels were based on experimental design. Daily fish feed and planting area variables were analysed as interactions. The interaction included, yield × daily fish feed × fish stocking density × aquaponics scale of production and planting area × fish stocking density.

Assumptions

Because this is a model simulation study, the following were the key assumptions:

- All aquaponics systems are housed in a tunnel environment as per national aquaponics survey results.
- All environmental conditions (air temperature and relative humidity) are optimal.
- Leafy vegetables and tilapia are the selected cultivated aquaponics species as per national aquaponics survey results.
- Mono sex Tilapia was stocked at 50 g weight per fish.
- The method of plant production is deep water culture,
- All leafy vegetables take 4 weeks (1month) to achieve market weight, because all parameters (pH, water quality and water flow rate) are at optimum level.
- Fish are fed 30% protein floating pellet fish feed at 1% body weight, and

- Fish takes 10 months to achieve average harvest weight of 300g,
- The fish growth curved is assumed to be uniform and standard.

Data generation

To determine various aquaponics production in South Africa, data was generated from the aquaponics decision-making tool, by applying the tool to aquaponics production experiment designs. To apply the model, yield selector is the main input function as explained in the model description. Fish stocking density, daily fish feed and planting area are the output from this function. The yield selector function was manipulated until outputs matched the suggested variables of different scales of aquaponics production (Table 1) and those from the experimental design.

Annual fish feed and aquaponics biomass production (fish and plants).

Based on the assumptions, the annual plant yield was 10 months of the assumed fish harvest duration based on the literature. To determine plant yield it was assumed that leafy vegetables takes 4 weeks based on previous research (leafy vegetables can take less than 4 weeks to be harvested if all required nutrients are provided). As such, 4 weeks = 1month, calculation; (kg/rotation) × 10 months (average fish harvest) = Annual plant yield (kg). To determine annual total fish yield, fish stocking was divided by 50g of the assumed fish stocking weight to determine how many fingerlings are in the stocking density (kg/m^3). The number of fingerlings was multiplied by the assumed fish harvest weight (300 g).

Analysis

Data analysis for the experiments was carried out using the General Linear Model; Repeated Measures using the Genstat 18 Statistical Package was used to compare treatment means and the interactions. Statistical significance was determined at the 5% probability level.

RESULTS AND DISCUSSION

Yield and scale of production

There were significant differences ($p<0.05$) observed in the annual yield production (kg/year) between plants and fish within different levels of fish stocking densities, low, optimum and high, within hobby scale production. Plants yield was higher than fish yield in all levels, the plant-fish yield (kg/year) was 40-33, 80-67 and 150-133 respectively (Figure 4). In subsistence scale of production, the yield of fish and plants differed significantly *($p<0.05$)* at all level of fish stocking density, low, optimum and high, plants had higher yield than fish, the plant-yield yield (kg/year) was 240-200, 300-267 and 400-333 respectively (Figure 5). In commercial scale, yield (kg/year) of fish and plants did not differ significantly within low and optimum fish stocking density, was 600-533, 1 100-1 000 respectively, however, at high level of fish stocking density, plants and fish differed significantly *($p<0.05$)*, plants had higher yield than fish, plants-fish yield was 1 500-1 333 respectively (Figure 6). In all scales of aquaponics production, the yield of plants was higher than the yield of fish. The yield production of both fish and plants increased significantly ($p<0.05$) as the fish stocking density was increased across all the scales of production. However, hobby scale produced the lowest yield output than subsistence and commercial scale of production.

The low yield output in hobby scale production relative to subsistence and commercial, suggest a yield limitation in hobby scale production. This could mean hobby scale production may not produce yield to support household livelihood. This is acceptable and understandable and can be explained by the nature of hobby scale practice that, in such operations the operator is not really interested in the harvest as much as in the bioprocesses. The significantly higher plant yield than fish at low, optimum and higher level of fish stocking density suggest that all levels can be adopted to obtain food production from these systems. However, even though all level results in the increased yield of plants than fish, higher levels of fish stocking density could result in elevated water quality cost [22,23]. Because the more fish in the fish tank you have the more fish solids excretion waste and the higher is the cost to remove solids in bulk, because more electricity and bigger pump will be required to circulate the water more often. Solid removal is crucial practise in aquaponics because, when solids dissolves in water it results in low system pH (from nitrification process), low dissolved oxygen and increased fish disease risk and all this could results into system collapse and significantly reduced yield.

The significantly higher biomass production of plants than fish in higher level of stocking density than low and optimum levels suggest that higher level of fish stocking density is more profitable than low and optimum densities. This also explain why some aquaponics models could not be applicable to commercial systems, because not one model works for all in this practise. The increase in yield production as fish stocking increased was expected because the more fish you have in the fish tank the more nutrients required by plants you can generate resulting in more nutrients availability [24].

The higher plant yield as compared to that of fish across the different scales of production may be explained by species rotation in both enterprises. Leafy vegetables take less than four weeks if the system is operating at optimum, as leafy vegetables are better at absorbing nutrients. In addition, they require less agronomic attention such as air temperature modification than fish [24]. Fish on the other hand take an average of 10 months to be harvested. However, it must be noted that, optimum fish production is mostly achieved at optimum environmental conditions. The condition that allows for an optimum fish production are; dissolved oxygen between 5-10 mg/L, water temperature kept at 28^{o}C, pH between 6-7 and nitrate-N must be below 100 mg/L. Nile tilapia is the most cultivated aquaponics fish species in the world because. Nile tilapia production is not allowed in this country (South Africa), which could affect optimum and viable aquaponics production in South Africa if aquaponics are developed and implemented. The higher plant yield than fish is also supported by Thorarinsdottir (2015) where she reported that aquaponics mass balance calculations, typically, the plant biomass output should be 7-10 times the fish biomass output. In practice, this is equivalent to 4 kg of plants to 1 kg of fish [25]. Similarly, this is achievable with a sound aquaponics management. The main aquaponics production parameters are pH, water temperature, concentration of macro- and micronutrients, air temperature, dissolved oxygen in water and light (25).

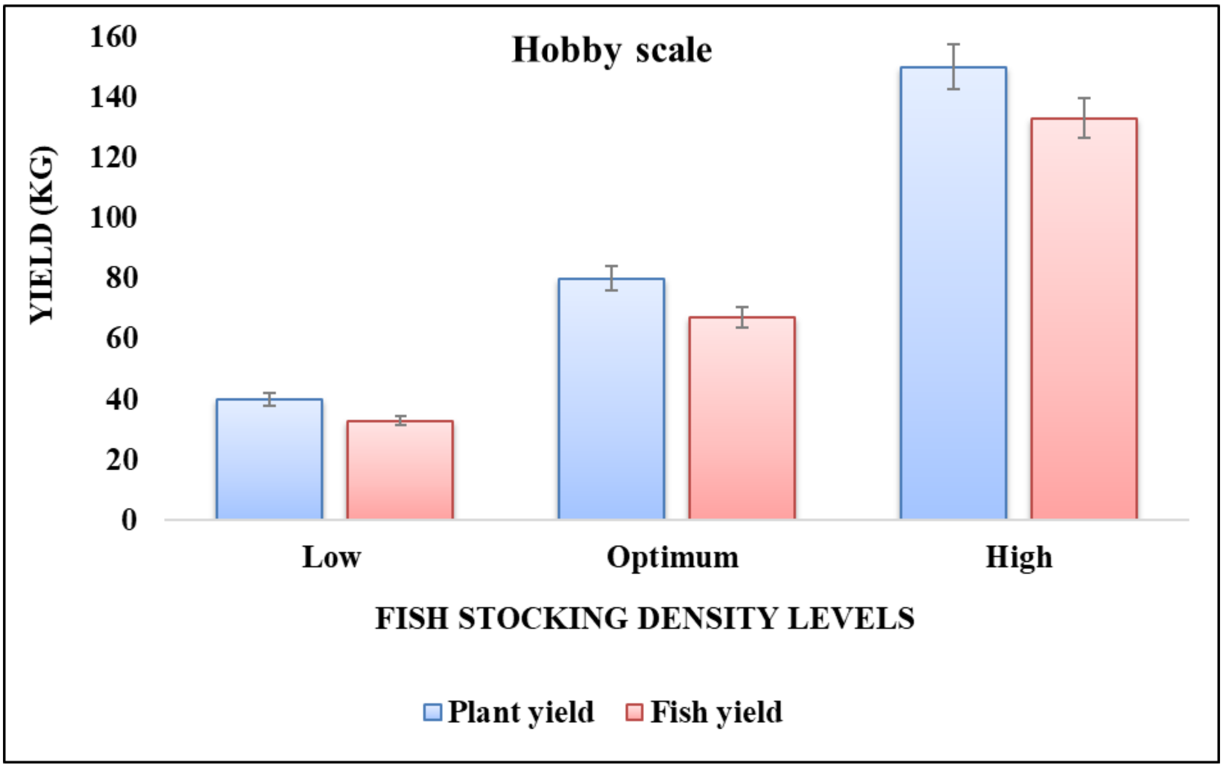

Figure 4: Comparison of fish and plant yield production against different level of fish stocking density in a hobby aquaponics system, low refers to low stocking density than optimum, optimum refers to the ideal fish stocking density and high refers to the higher stocking density than optimum.

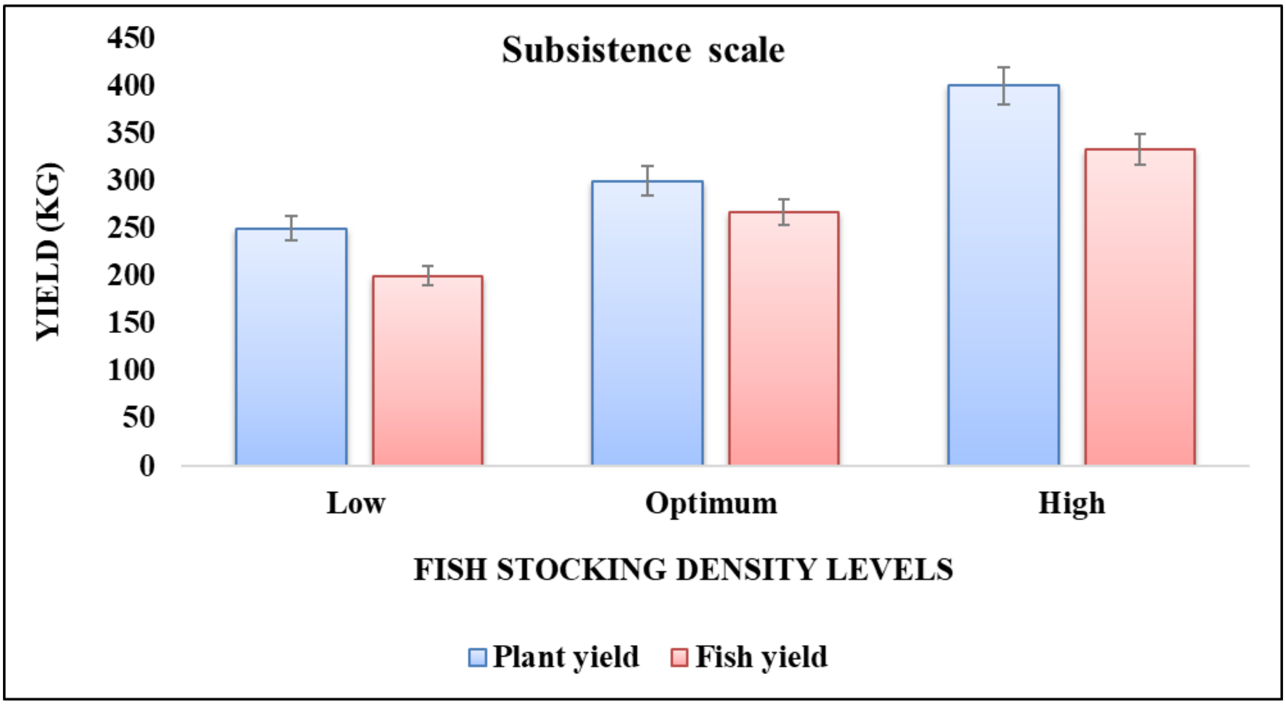

Figure 5: Comparison of fish and plant yield production against different level of fish stocking density in a subsistence aquaponics system, low refers to low stocking density

than optimum, optimum refers to the ideal fish stocking density and high refers to the higher stocking density than optimum.

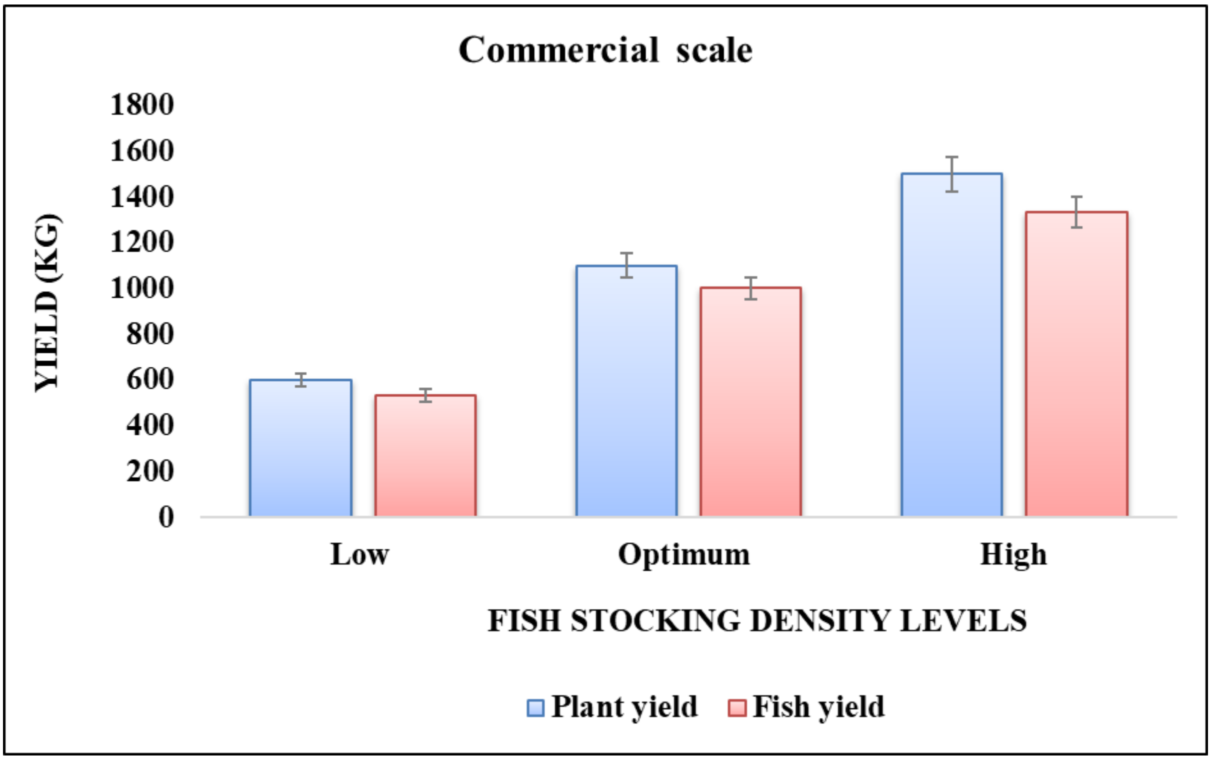

Figure 6: Comparison of fish and plant yield production against different level of fish stocking density in a commercial aquaponics system, low refers to low stocking density than optimum, optimum refers to the ideal fish stocking density and high refers to the higher stocking density than optimum.

Total yield, daily fish feed, planting area and scale of production

Total yield production and daily fish feed differed significantly (*p<0.05*), yield production was higher than fish feed applied. However, fish feed closely mirrored yield production across all levels of fish stocking density in the hobby scale production (Figure 7). In hobby scale, total yield output (kg/year) and fish feed required (kg/year) at low fish stocking density was 37-24 (0.65kg feed to produce 1 kg fish). Was 74-48 (0.65kg feed to produce 1 kg fish), at optimum fish stocking density, while at higher fish stocking density was 242-90 (0.37kg feed to produce 1 kg fish). In subsistence scale of aquaponics production, total yield (kg/year) and fish feed (kg/year) differed significantly (*p<0.05*) (Figure 8). Total yield and fish feed was 225-85 (0.38kg feed to produce 1 kg fish), at low fish stocking density was 284-180 (0.63kg feed to produce 1 kg fish) at optimum level and was 367-240 (0.65kg feed to produce 1 kg fish), at higher fish density. Like in the hobby scale of production, fish feed closely mirrored yield production across all levels of fish stocking density in commercial scale of production (Figure 9). Total yield (kg/year) and fish feed (kg/year) was 567-360 (0.64kg feed to produce 1 kg fish), at low fish stocking density, was 1 050-660 (0.63kg feed to produce 1 kg fish), at optimum fish stocking density and was 1 417-900 (0.64kg feed to produce 1 kg fish), at higher fish stocking density. Fish feed increased significantly ($p<0.05$) as fish stocking density was increased across aquaponics scale of production (hobby, subsistence and commercial). Hobby scale used less fish feed than subsistence and commercial scale of production. In terms of planting area, there were significant ($p<0.05$) differences observed between low, optimum and higher fish stocking density. The planting area increased significantly ($p<0.05$) as fish stocking density increased from low to optimum to higher levels within hobby scale, subsistence and commercial scale of production.

The close margin of fish feed against yield production in hobby and commercial scale suggests that, hobby scale aquaponics operations are not feed efficient, in practise there is no significant yield output for additional fish feed. Again, the nature of the hobby system explains this. The significantly low fish feed required in lower level of fish stocking density while yield (kg/Annum) did not differ significantly between low and optimum level, in the subsistence scale, suggests that low fish stocking density could be adopted to save feed costs while optimum yield is achieved [25]. The significant fish feed increase as fish stocking density and yield increases was welcomed because fish feed is the main source of fish and plants nutrients [25]. However, the close margin of difference between fish feed and yield production across most scale of aquaponics production suggests that significant cost may be channelled toward fish feed, and thus such that fish feed costs could be an constraining factor in developing and implementing sustainable aquaponics systems, particularly in a developing country like South Africa. Fish feed item would need a carefully planning if aquaponics were to be adopted and implemented as a food security solution in this country. Alternatively, none-conventional potential fish feed materials such as locust, worms, duckweed and other sources could be explored to address fish feed cost.

The increase in planting area as fish stocking density was increased suggest that planting area will need to be extended as higher fish stocking density is adopted. This could be explained according to Author(s) [25] that, the more fish stocked the more planting area is required to accommodate high planting density of plants to purify water by taking up nutrients. It may however be appropriate for hobbyists to use lower fish stocking densities because of the related challenges associated with fish stocking density. It is also advisable for hobbyist to adopt as small as possible planting area because building an aquaponics production area is very costly, particularly for countries like South Africa where the majority still live below R 20.00 ($ 1.3 USD) as of 21/08/2019 [26].

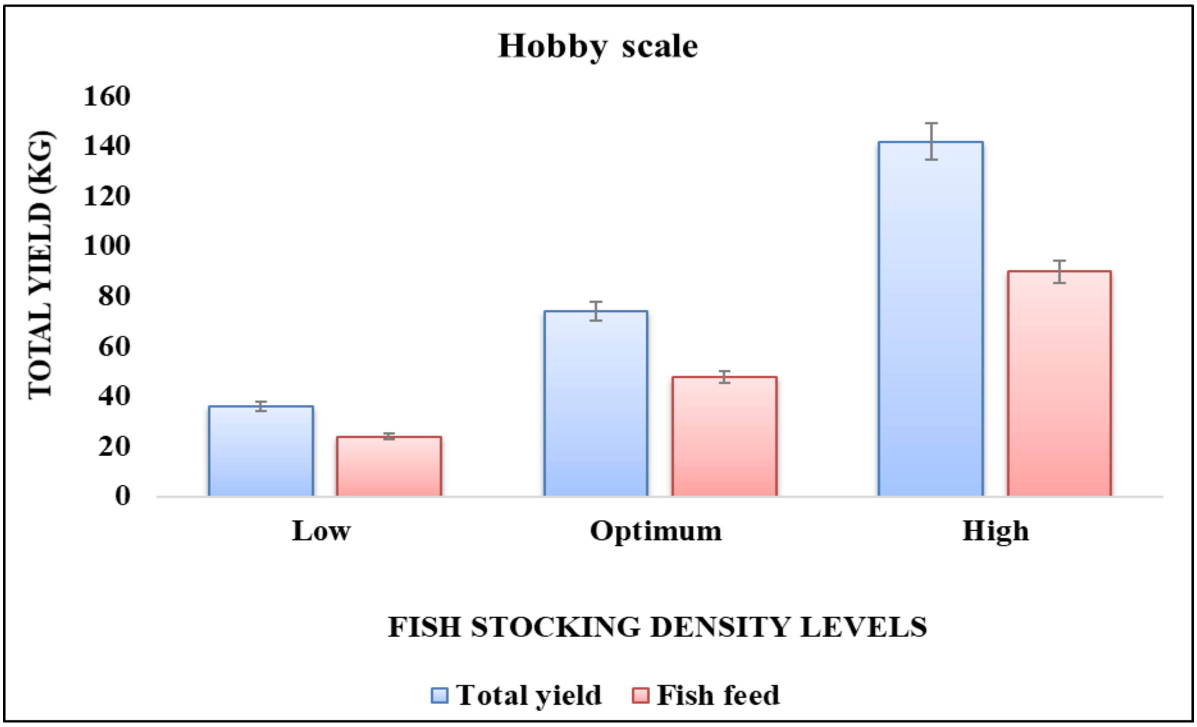

Figure 7: Comparisons of total aquaponics yield with fish feed against different levels of fish stocking density in a hobby aquaponic system, low refers to low stocking density than optimum, optimum refers to the ideal fish stocking density and high refers to the higher stocking density than optimum.

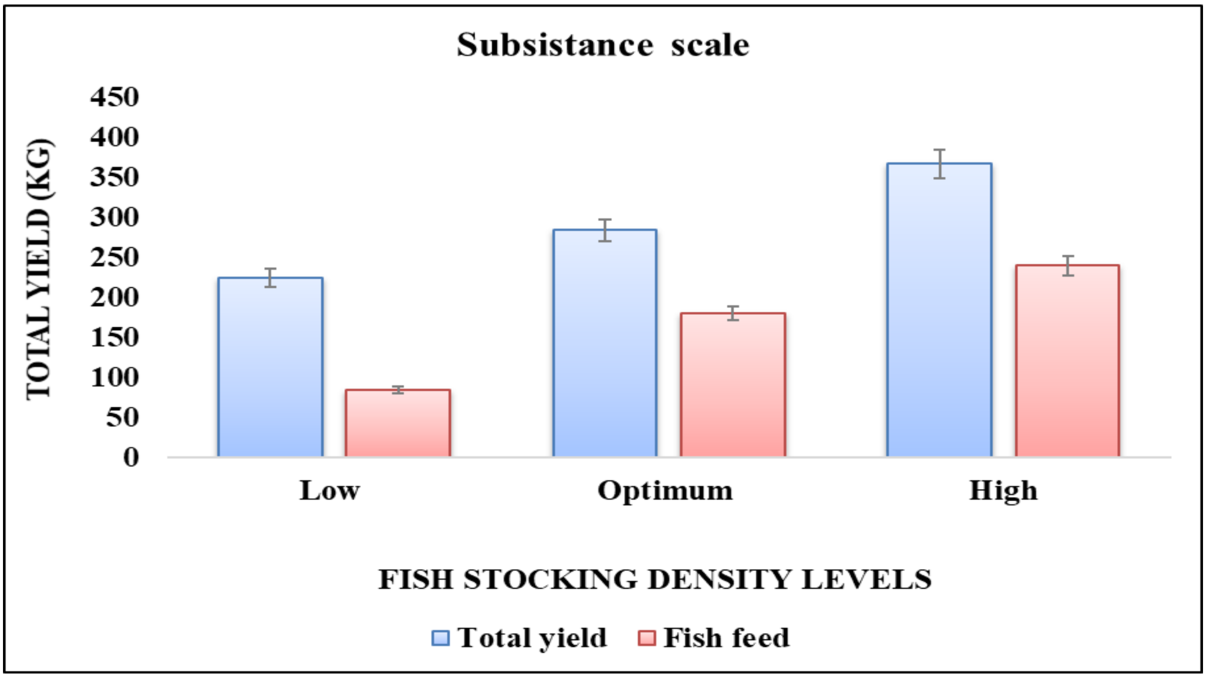

Figure 8: Comparisons of total aquaponics yield with fish feed against different levels of fish stocking density in a subsistence aquaponic system, low refers to low stocking density than optimum, optimum refers to the ideal fish stocking density and high refers to the higher stocking density than optimum.

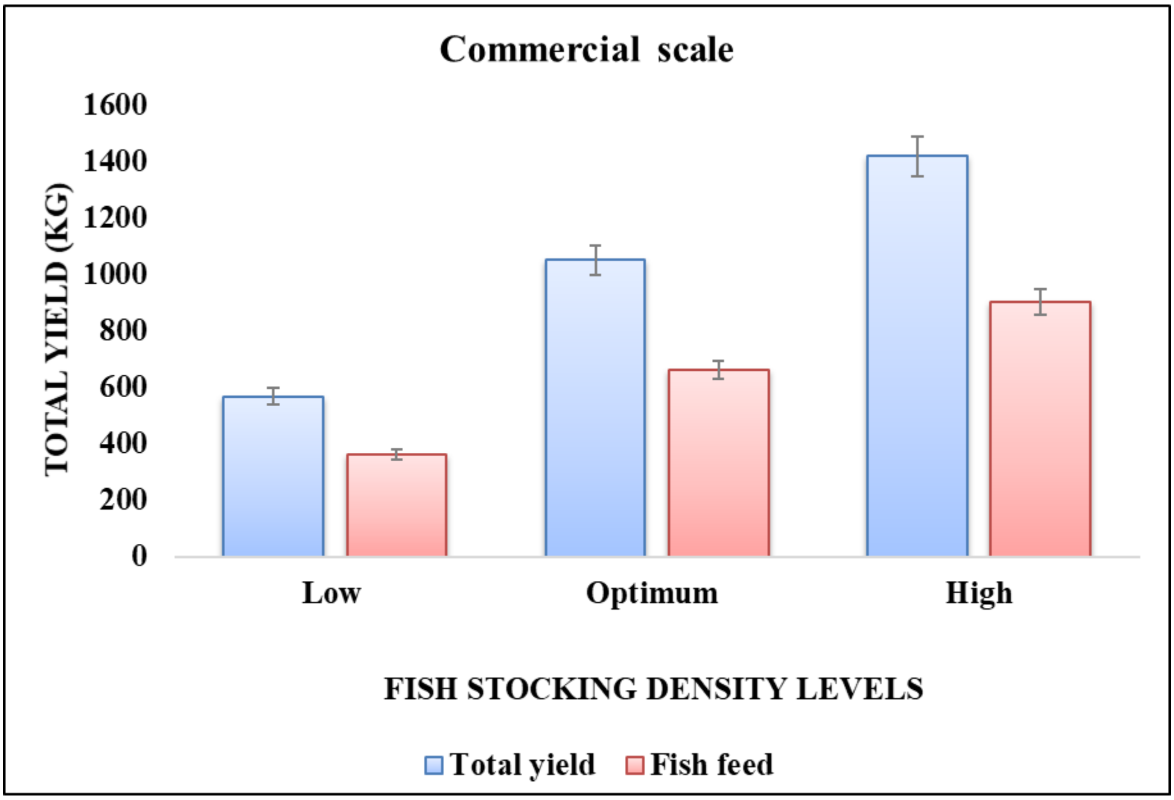

Figure 9: Comparisons of total aquaponics yield with fish feed against different levels of fish stocking density in a commercial aquaponic system, low refers to low stocking density than optimum, optimum refers to the ideal fish stocking density and high refers to the higher stocking density than optimum.

CONCLUSION

The main objective of this study was to apply decision-making tool to determine the potential aquaponics yield production for South Africa in order to have data, to develop and inform aquaponics policies in the country. The objective was achieved because the model was able to predict aquaponics production which was in agreement with empirically recent literature. Plant culture have more yield than fish culture in all aquaponics scale of production. It could be more economical for hobby scale to adopt a small planting area as possible, subsistence scale operators to adopt lower fish stocking density and economic scale to adopt higher fish stocking density. The model was able to generate data to show that, fish feed could become a significant constraint in aquaponics production particularly for a developing country like South Africa. Non-conventional potential fish feed materials such as locust, worms, duckweed and other sources could be explored to address fish feed cost. If aquaponics are adopted in South Africa, government will have to come up with holistic aquaponics policies that will address fish feed constraint. Water availability and quality effects on yield was not determine especially in African context.

Table 1: Empirically developed and tested aquaponics production ratios.

Vegetable category	Daily Fish Feed (g)	Planting density (m^2)
Leafy vegetables	50-60 (Rakocy, 2007, Lennard 2012) or 40-50 (FAO, 2014 and 2015).	20-25 (Rakocy, 2007; Lennard 2012; FAO, 2014.
Fruity vegetables	80-100 (Rakocy, 2007; Lennard 2012; FAO, 2014.	4-8 (Rakocy, 2007; Lennard 2012; FAO, 2014.

Table 2: Aquaponics variables: fish stocking density, daily fish feed and planting area as they relate to different scale of aquaponics production as defined in the text.

Main aquaponics variables	Hobby	Subsistence	Commercial
Fist stocking density (kg/m^3)	10 - 20	20 - 40	100 - 300
Fish tank size (L)	1 000	1 000 – 2 000	4 000 – 50 000

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5. GENERAL DISCUSSION, CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH

This chapter discusses the key finding of this study, thus, componets of this chapter are derived from all chapters including introduction and problem statement. In this chapter, all results are interlinked and used to make conclusion and recommendations.

5.1. General discussion

The greater need to increase food production is in response to the increases in human population, which has resulted in greater use of water and synthetic fertilizer in agriculture. This has allowed deterioration, depletion and instability of agricultural natural nutrient source materials, which is needed for sustainable agricultural production. The quest to address this challenge has resulted in exploration of soilless production systems, particularly aquaponics. Aquaponics are mutual benefiting systems, where fish and vegetables are sustainably produced concurrently, through linking aquacultural fish waste as a natural nutrient source material to grow plants in hydroponic culture in a circulating or decoupled system. In return, plants clean water by taking up most of the total nitrogen to maintain high water quality for fish well-being. Leafy vegetables and tilapia fish are the mostly cultured species in aquaponics worldwide including South Africa. This is also supported by the higher percentage return for these species in the aquaponics online survey. The biology of both these species explains this. Leafy vegetables grow very fast in less than four weeks if all conditions are favourable and provided for, they are good nutrients up takers which enhances an efficient water purification process. In addition, they are cheap to maintain. Similarly, tilapias can tolerate as low as, 9 °C and as high as 38°C water temperatures, pH as low as 2.5, dissolved oxygen as low as 0.1 mg/L, and unionized ammonia concentration of 2.4 mg/L.

Aquaponics has been shown and proven to be an important and suitable agricultural innovation across the world, to address food and nutrition insecurity, water and plant nutrients scarcity. However, aquaponics are still an emerging practice worldwide but particularly in South Africa, Love et al. (2014 and 2015) support this. The primary aim of this study was to develop a decision-making tool (model) that can predict production of various aquaponics setups to provide aquaponics operators with an opportunity to obtain maximum yield from their systems. It was proven by both, higher percent (%) of respondent who did not know what an aquaponics is and fewer (44) aquaponics operators that, indeed aquaponics are not widely practised by many in this country. This suggested that aquaponics in this country are being operated below optimum level.

This was worrisome because aquaponics are shown to have high potential to address water scarcity, food and nutrition insecurity, which this country is currently facing. Furthermore, aquaponics saves water more than conventional agriculture in addition provides a platform for nutrient cycle and opportunity for organic food production, which are all important and needed for this country. Having highly endorsed systems like aquaponics producing below optimum, suggested a crisis for aquaponics and sustainable agricultural development in this country. However, a significant number of youth particularly women showed an interest toward aquaponics. This allows South Africa to have a niche and opportunity to contribute toward United Nations Sustainable Development Goals, if aquaponics could be developed and implemented in this country. The results further suggest that aquaponics could promote youth involvement in agriculture particularly women, thus providing a better opportunity for sustainable aquaponics development.

Models can act as a support tool for planning, decision making and output forecasting. Hence, aquaponics models could make aquaponics simple and easy use system for a layperson. The survey results showed that most aquaponics practisers in this country lack basic management knowledge such as pH and water quality, this is attribute to lack of information disposable to aquaponics operators. However, the development of an aquaponics decision-making tool allows for a better opportunity to kick-start aquaponics in this country, and to obtain a fulfilling yield from these systems. This is supported by validation simulation results from the model which showed that the developed model was able to predict the main aquaponics system inputs, namely, fish stocking density, daily fish feed and required planting area. This is supported by R^2, RMSE and linear mathematical model analysis. The fit of R^2=0.7477 and 0.6957 for, fish stocking density and daily fish feed respectively suggest an acceptable model fit, and the fit of R^2 = 0.4313 for planting area suggest a poor model fit. The closeness of m and b, to 1 and 0 respectively, for fish stocking density and daily fish feed suggests an acceptable model fit. For planting area, m and b, were not close to 1 and 0 respectively which suggests a poor model fit.

Similarly, the RMSE of 14 for fish stocking density which deviated by 29 % from observed and simulated, RMSE of 218 for daily fish feed which deviated by 14 % to the observed and simulated data and RMSE of 4 for planting area which deviated by 25 % to the observed and simulated data such an acceptable model fit. The poor model fit for planting when using R^2 and linear equation could be attributed to residual errors. The similar predictions between R^2, linear equation and RMSE for fish stocking density and daily fish feed suggested that this model accurately predicts these variables. The results are also supported by model simulation studies where the developed model was used to determine the effect of fish stocking density on daily fish feed, planting area and yield production form different scale of aquaponics production. The results were in agreement with recent literature showing that plant biomass production should 4× time more than of fish yield. Furthermore, the simulation results also showed that fish feed could be a constrain in aquaponics development for this country particularly for needy households. This is also supported in recent literature and from aquaponics operators during interviews and focus groups. These research findings should be welcomed because they provide aquaponics practitioners and new entrants with an opportunity and resource to enable better yield production.

5.2. Conclusion

The study therefore concludes that aquaponics has the potential to address food and nutrition security if aquaponics are developed and implemented in this country. Because plants and fish could be produced concurrently as shown by model simulation studies. Policies such as "one home one aquaponic system" and "one school one aquaponic system" could be implemented to further disseminate the concept of aquaponics. In order to increase the knowledge level among starting practitioners because 80% of new respondents did know what an aquaponic system is, but were interested. Along with this policy, fish feed item will need to be carefully discussed and provided for, to avoid system failure associated with fish feed constrain as shown in the simulation studies. Even though the study findings show that aquaponics in South Africa are quite small and few by population and that most of these systems are characterized by small systems, this could be changed and improved significantly particularly if an aquaponics model can be adopted and utilised. However, better support to starting aquaponics entrepreneurs will be important for South Africa in order to stimulate new practitioners. Training and extension support service will need to be employed if these systems were to be implemented for the first time in this country.

5.3. Recommendations and future research

- More studies need to be conducted to produce cheaper fish feed, protein rich interventions such as non-conventional animal protein sources could be explored to determine the potential for fish feed.
- Similarly, to promote aquaponics sustainability in this country, non-conventional plants nutrients sources of Fe, Ca and K which are commonly short in fish feed need to be researched further and be identified in order to minimize inputs costs, this is important in this country because the majority of people still live below R 20 = $ 1.3 a day.
- More research need to be conducted into how traditional knowledge could be integrated with scientific knowledge to effect successful aquaponics development implementation. More studies need to be conducted to measure quantities and forms in which nitrogen is lost from aquaponics system, in order to validate the extent of greenhouse effect.
- More studies need to be conducted to calibrate and validate the RSA aquaponics model. Fish handling certificate need to be applied for two years in advance to avoid study limitations.
- Further studies could be conducted to investigate aquaponics uses in Africa adopting the same study design from this study, but with the series of empirical experiments and data collection to inform scalable aquaponics model suitable for poor, low income and middle class Africans.
- You can continue to follow my aquaponics research output as I have been appointed as an aquaponics manager in an international company which also operate in South Africa. I operates aquaponics in five provinces in this country, Gauteng, Eastern Cape, Northern Cape, Free State and Limpompo. I am also a part time lecturer at the University of KwaZulu-Natal under Local Economic Development project. In these positions, i am responsible for aquaponics operations, research development and implementation. I hold central influential role, which allows me to continue contributing my expertise toward aquaponics development in this country.