ajfand SCHOLARLY, PEER REVIEWED
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
Volume 22 No. 1
February 2022
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

Afr. J. Food Agric. Nutr. Dev. 2022; 22(1): 19040-19061 https://doi.org/10.18697/ajfand.106.19860

AQUAPONICS PRODUCTION SIMULATIONS USING THE DECISION-MAKING TOOL

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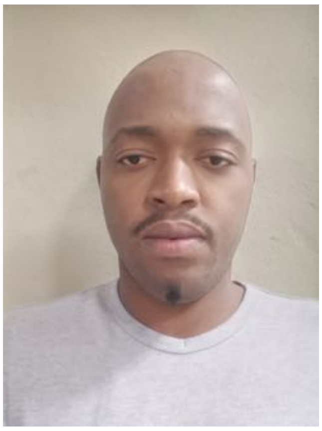

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ABSTRACT

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, 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 constraint 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 words: Fish stocking density, Yield production, Fish feed, Planting area

https://doi.org/10.18697/ajfand.106.19860

INTRODUCTION

Poverty and inequalities have risen with the advent of Covid-19 across the world, particularly in South Africa. 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. Aquaponics have the opportunity 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 will, if properly 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 other, 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, a nutrients supplementation programme was suggested 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. This would adversely affect healthy food production needed 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 collapse [11]. Fish stocking density needs to be accurately calculated and managed. Fish stocking density is influenced by type of fish species cultivated and surface area available for fish culture. Tilapias are herbivorous while catfish and trout are carnivorous species, thereby also influencing protein content in the fish food; carnivorous species requires more protein content than herbivorous species [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 of water. In subsistence level aquaponics systems, farming is practised as a livelihood support system. 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 (Figure 1), and the abundant biodiversity in the range of fish and plants of which South Africa is popularly known for name [17].

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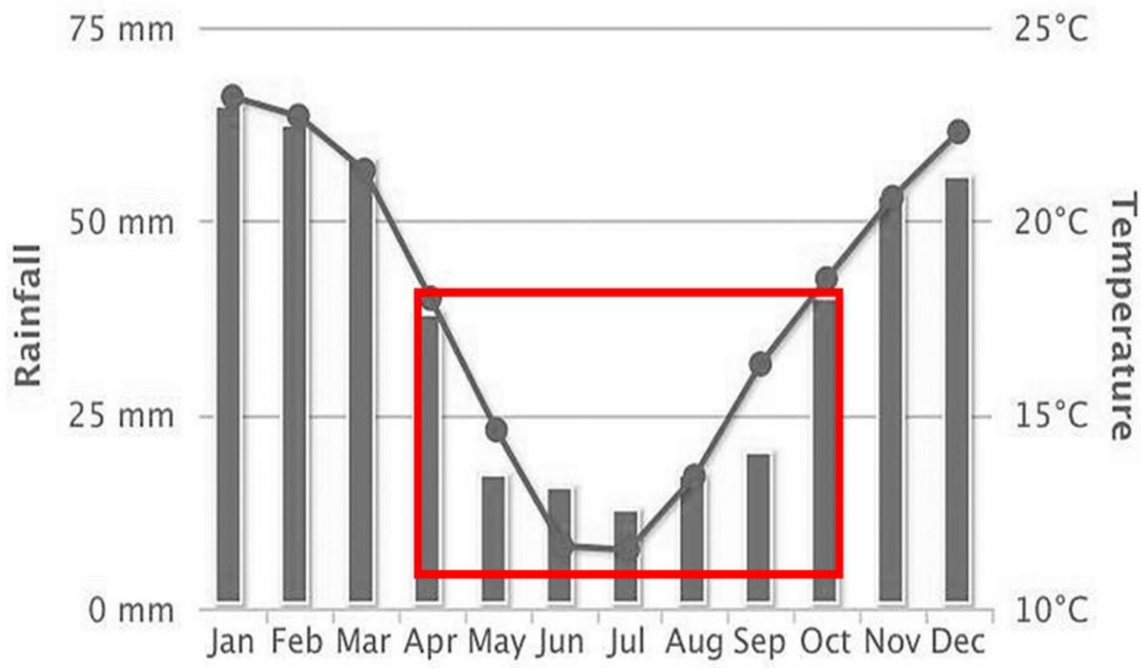

Figure 1: South Africa average yearly climate variables of 2019 [27], as they relate to rainfall and air temperature trends, which could affect aquaponics production in South Africa, particularly in winter as indicated by red square in the figure above. Fish, particularly tilapias, require an average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

Model description

The developed decision-making tool starts with the 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. The field productions refer 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 includes specifying different regions within the selected province, giving an output of how much the temperature needs to be adjusted to in winter and in summer. When tunnel is selected 5^{o}C is added to temperature adjustments, both for winter and summer. When tunnel environment is constructed well, it has the capacity of raising the inside temperatures with an average of 5^{o}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 searches and matches plant production ratios and gives outputs based on the selected plant category, whether it is leafy or fruity. The main model input is the yield selector which enables the farmer/grower to decide how much yield he/she wants to harvest per week. It was also acknowledged and welcomed that some hobby scales 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 and salad greens. 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 determining how much plant population would 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.

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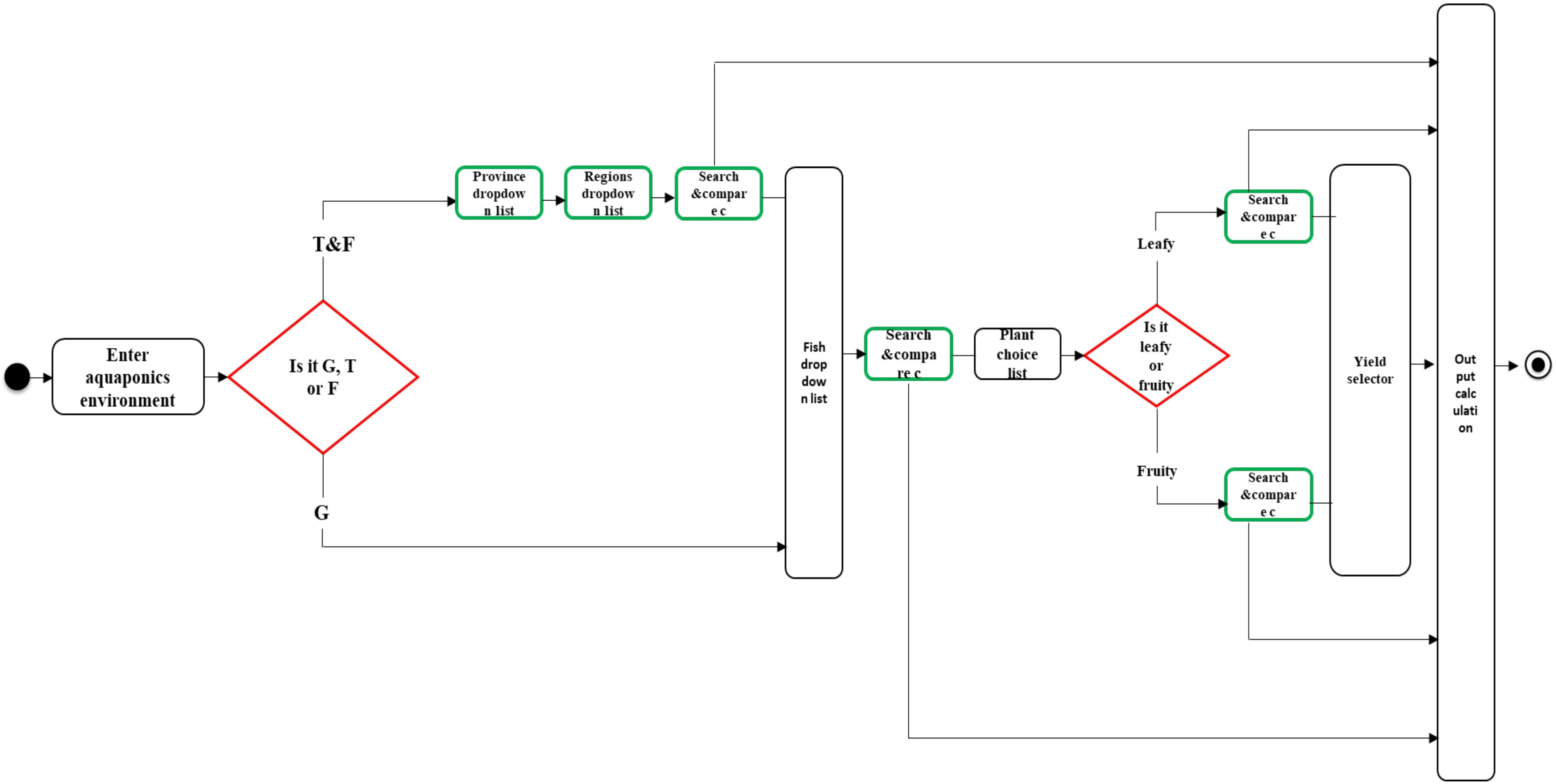

Figure 2: Aquaponics system model design processes flow chart with red and green highlighted part showing the most important part of the model; G stands for Greenhouse; T stands for Tunnel; and F stands for Field). The black solid dot represents the beginning of a process or workflow in an activity diagram. 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

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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 were 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 would 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 the 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.

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

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

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

Fish eats 1 (%) of their body weight/ day^{-1}, therefore, (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.

$$(g/feed) \times 0.32 \times 0.16 \times 0.61 \times 1.2 = g/ammonia \quad (5)$$

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.

$$\frac{1\ m^2}{0.57\ NH_3} \quad (6)$$

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

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Water flowrate

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 and FAO. 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 were 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 required summer and winter temperature adjustments, 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 time for fish production. This was done for the optimal field condition option, if option is tunnel, a 5 ºC 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 ºC. For the greenhouse option, it was assumed that in the greenhouse environment, all production parameters can be fully controlled hence, outside environmental conditions would not be the factors.

https://doi.org/10.18697/ajfand.106.19860

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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 are 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) and 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 were 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 take 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 yields (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 at all levels, the plant-fish yield (kg/year) was 40-33, 80-67 and 150-133, respectively (Figure 4). At the 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). At 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). At 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, the 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 at hobby scale of 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 the 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 levels of fish stocking density suggest that all levels can be adopted to obtain food

https://doi.org/10.18697/ajfand.106.19860

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 costs [22,23]. 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 apparent 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 that could not be applicable to commercial systems because none of the models 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 are required by plants you-generate, resulting in more nutrients availability [24].

The higher plant yields as compared to those 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 conditions that allow for optimum fish production are; dissolved oxygen between 5-10 mg/L, water temperature kept at 28°C, pH between 6-7 and nitrate-N levels that must be below 100 mg/L. Nile tilapia is the most cultivated aquaponics fish species in the world. However, Nile tilapia production is not allowed in this country (South Africa), because it could affect optimum and viable aquaponics production in South Africa if aquaponics is developed and implemented. The higher plant yield than fish is also supported by Thorarinsdottir [25] 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).

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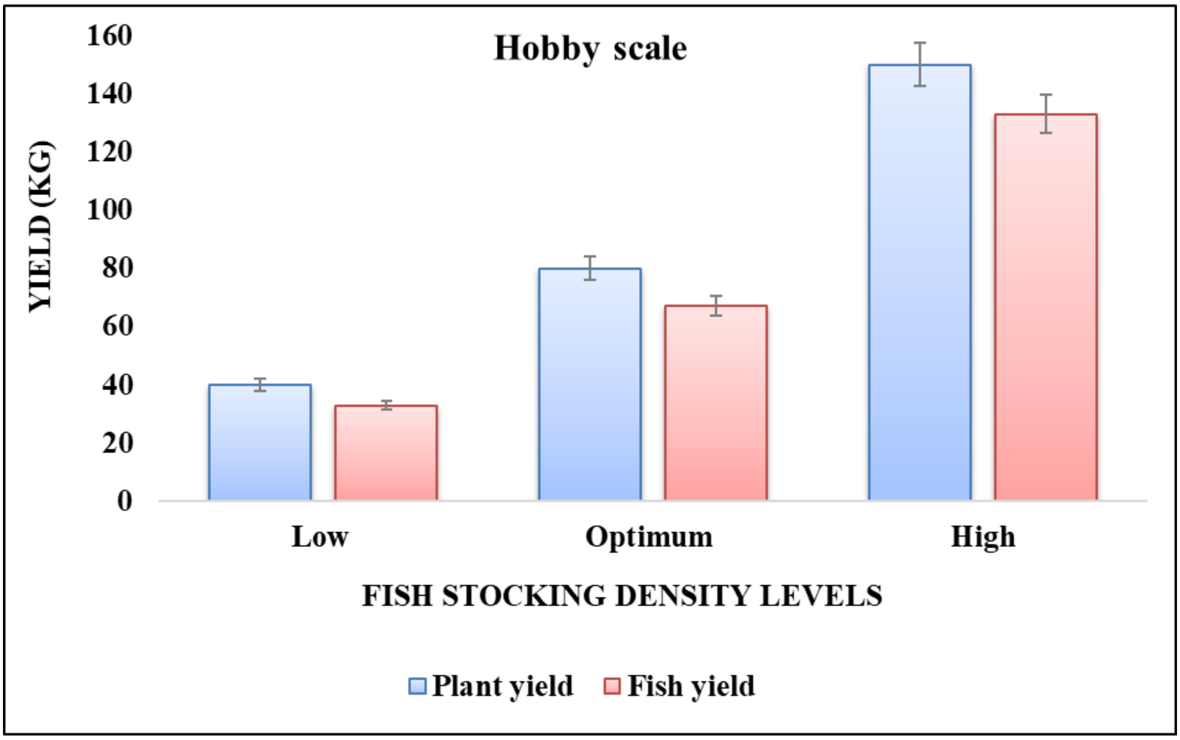

Figure 4: Comparison of fish and plant yield production against different levels of fish stocking density in a hobby aquaponics system; low refers to low stocking density than optimum; optimum refers to the ideal fish stocking density; and high refers to the higher stocking density than optimum

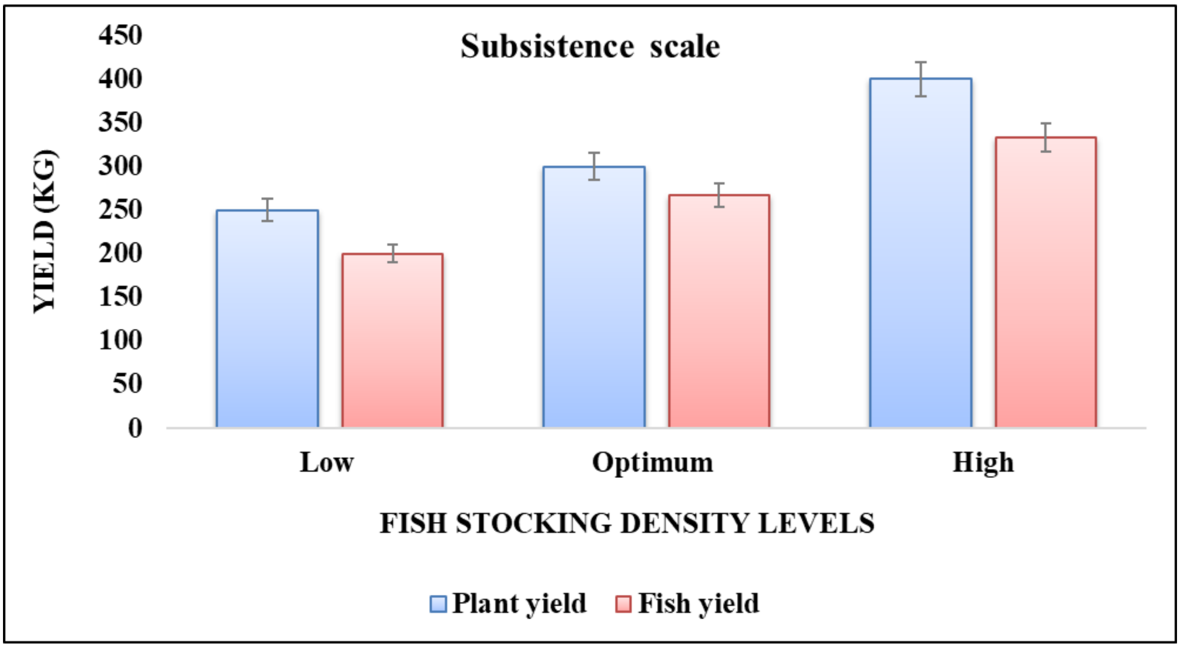

Figure 5: Comparison of fish and plant yield production against different levels of fish stocking density in a subsistence aquaponics system; low refers to low stocking density than optimum; optimum refers to the ideal fish stocking density; and high, refers to the higher stocking density than optimum

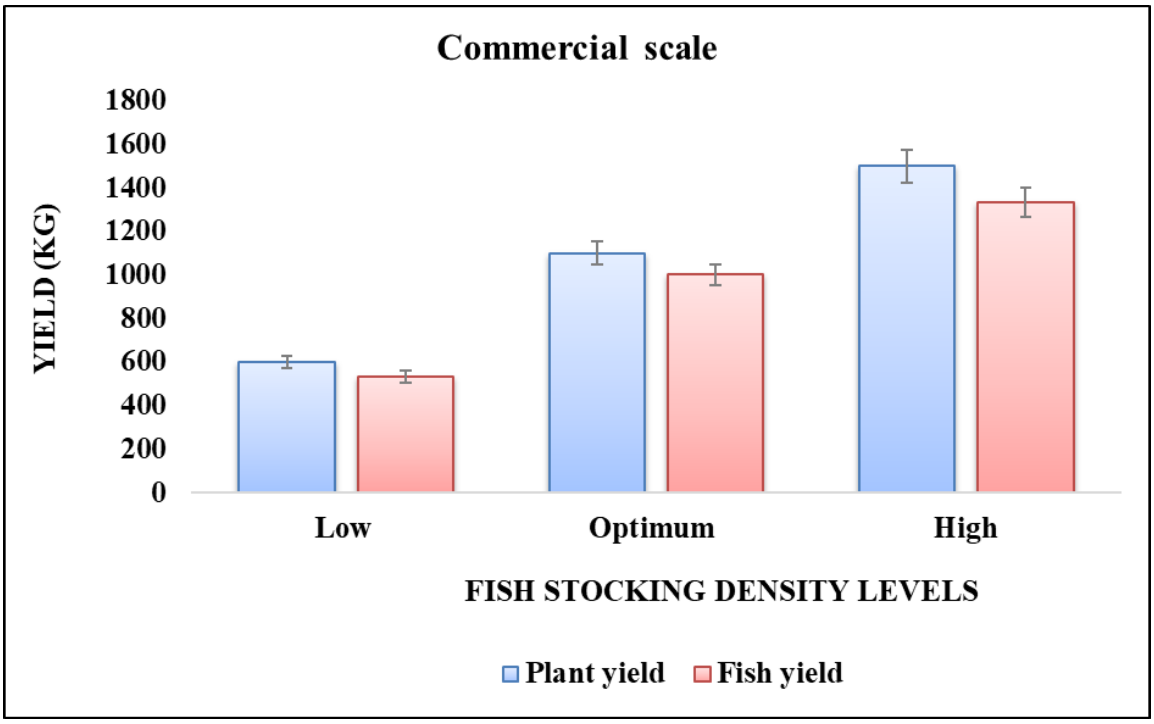

Figure 6: Comparison of fish and plant yield production against different levels of fish stocking density in a commercial aquaponics system; low refers to low stocking density than optimum; optimum refers to the ideal fish stocking density; and high refers to the higher stocking density than optimum

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

Total yield and daily fish feed differed significantly (*p<0.05*). Yield was higher than fish feed applied. However, fish feed closely mirrored yield 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), at optimum fish stocking density was 74-48 (0.65kg feed to produce 1 kg fish) and at higher fish stocking density was 242-90 (0.37kg feed to produce 1 kg fish). At the 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 at 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

ajfand SCHOLARLY, PEER REVIEWED
AFRICAN JOURNAL OF FOOD, AGRICULTURE, NUTRITION AND DEVELOPMENT
Volume 22 No. 1
February 2022
PUBLISHED BY AFRICAN SCHOLARLY SCIENCE COMMUNICATIONS TRUST
ISSN 1684 5374

low, optimum and higher fish stocking density. The planting area increased significantly (*p<0.05*) as fish stocking density increased from low to optimum and 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 and that 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/year) 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~~ a 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 solution to food security in this country. Alternatively, none-conventional potential fish feed materials such as insects, worms, duckweed and other sources could be explored to address fish feed cost.

The increase in planting area as fish stocking density was increased suggests 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 areas 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].

ajfand SCHOLARLY, PEER REVIEWED
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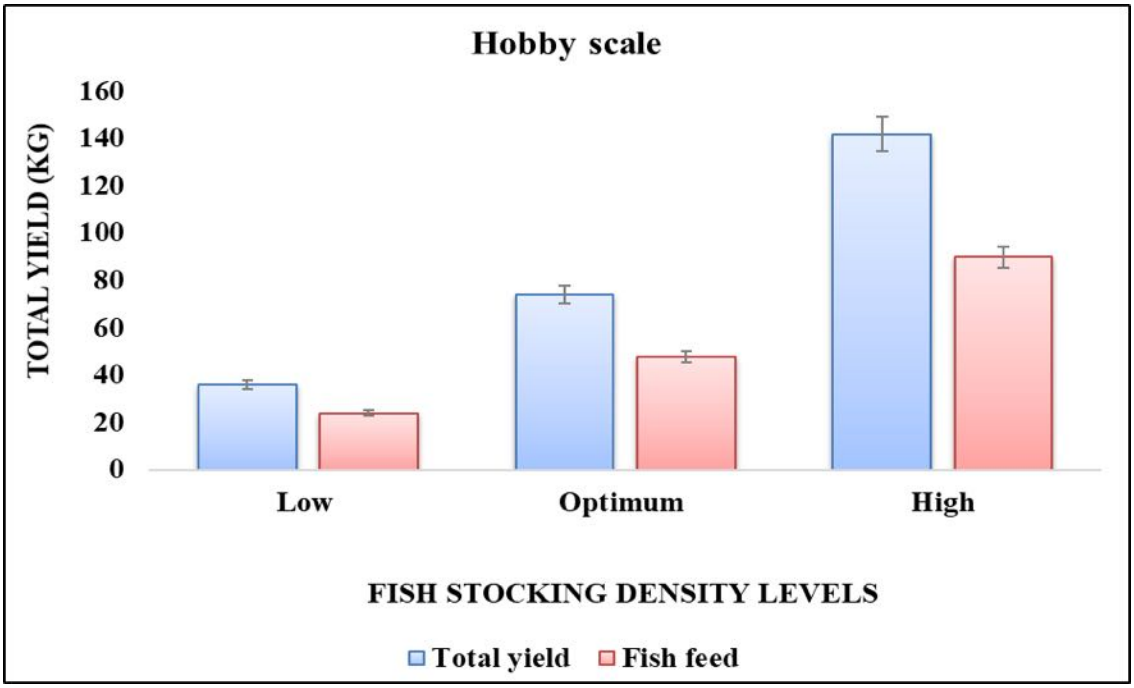

Figure 7: Comparisons of total aquaponics yield with fish feed against different levels of fish stocking density in a hobby aquaponic system; low refers to low stocking density than optimum,; optimum refers to the ideal fish stocking density; and high refers to the higher stocking density than optimum

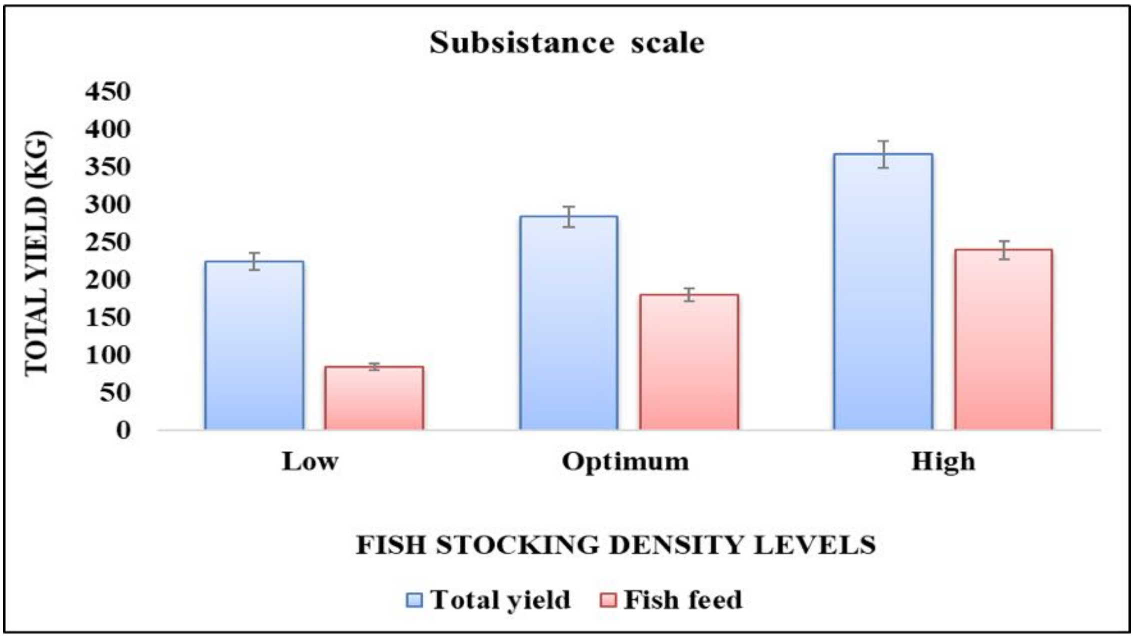

Figure 8: Comparisons of total aquaponics yield with fish feed against different levels of fish stocking density in a subsistence aquaponic system; low refers to low stocking density than optimum; optimum refers to the ideal fish stocking density; and high refers to the higher stocking density than optimum

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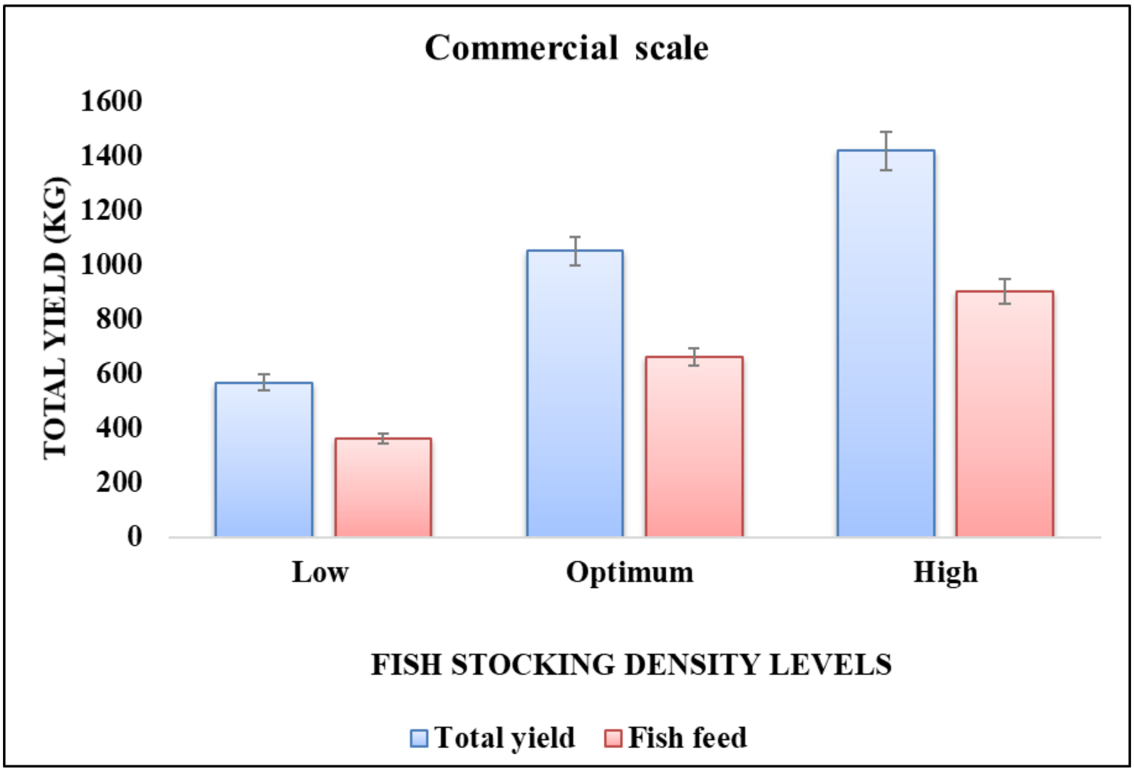

Figure 9: Comparisons of total aquaponics yield with fish feed against different levels of fish stocking density in a commercial aquaponic system~~,~~. Low refers to low stocking density than optimum; optimum refers to the ideal fish stocking density; and high refers to the higher stocking density than 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 empirically with findings in recent literature. Plant cultures have more yield than fish cultures in all aquaponics scale of production. It could be more economical for hobby for the scale to adopt as small planting area as possible. The subsistence scale operators should 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 insects, worms, duckweed and other sources could be explored to address fish feed cost. If aquaponics were adopted in South Africa, government would have to come up with holistic aquaponics policies that address fish feed constraints. There is a need to determine water availability and quality effects on yield, as this was not determined, especially in the African context.

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Table 1: Empirically developed and tested aquaponics production ratios

Vegetable category	Daily Fish Feed (g)	Planting density (m^2)
Leafy vegetables	40-50 [11,21,24].	20-25 [11,21,24].
Fruity vegetables	80-100 [11,21,24]	4-8 [11,21,24].

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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