Inês Maria Cortez Vital

Development of sustainable diets for community-based aquaculture

UAlg
UNIVERSIDADE DO ALGARVE

Universidade do Algarve
Faculdade de Ciências e Tecnologia

2021

Inês Maria Cortez Vital

Development of sustainable diets for community-based aquaculture

Master's degree in Aquaculture and Fisheries:
Specialization in Aquaculture

Thesis supervision:

Dr. Cláudia Aragão (Centre of Marine Sciences - CCMAR/ Universidade do Algarve)

Dr. Sofia Engrola (Centre of Marine Sciences - CCMAR)

UAlg
UNIVERSIDADE DO ALGARVE

Universidade do Algarve

Faculdade de Ciências e Tecnologia

2021

Development of sustainable diets for community-based aquaculture

Declaração de autoria de trabalho

Declaro ser a autora deste trabalho, que é original e inédito. Autores e trabalhos consultados estão devidamente citados no texto e constam da listagem de referências incluída.

Inês Maria Cortez Vital

Acknowledgements

Em primeiro lugar, quero agradecer à Doutora Cláudia Aragão e à Doutora Sofia Engrola pela disponibilidade em me guiar neste processo e por terem partilhado o seu conhecimento na área de nutrição animal e conselhos que irei levá-los para o resto da minha vida.

Um obrigado a todas as pessoas do Aquagroup, especialmente ao Miguel Cabano e à Rita Colen por todo o apoio, conhecimento e por me terem aturado durante este percurso.

A todos os meus amigos, alguns estando longe, que me apoiaram e ajudaram até ao fim deste ano. Especialmente, à Joana pelo apoio constante e pelos conselhos.

Por fim um muitíssimo obrigado à minha família, especialmente aos meus pais, que sem eles não teria a oportunidade de seguir o meu sonho a quilómetros de casa.

Abstract

Developing countries in Eastern Africa, like Mozambique, do not have high economic power and are overdependent on natural resources, which causes ecosystems degradation. Community-based aquaculture with adequate low-cost diets is an important alternative or supplementary income generating activity to minimize these impacts. Tilapias have high potential for this, due to some of their characteristics, such as fast growth and resistance to stress and diseases. Therefore, the aim of this Thesis was to evaluate in Nile tilapia (*Oreochromis niloticus*) juveniles fed a diet formulated with local ingredients, from a Mozambican community, the growth performance, feed efficiency protein retention and nitrogen balance. A growth trial was performed using two diets, a commercial-like diet (CTRL) and a diet formulated with the local ingredients (EXP). Each diet was tested in triplicate tanks with 50 fish for 64 days. At the end of the trial, fish were sampled for growth performance and whole-body composition analysis. Fish fed with the EXP diet had significantly lower growth performance and feed utilization than fish fed the CTRL diet. Whole-body-protein composition and nitrogen losses were similar between treatments. The results obtained in this study showed that the diet with local ingredients could be viable in a community-based aquaculture in earth ponds.

Keywords: Nile tilapia, community-based aquaculture, sustainability, nutrition

Resumo

Os países subdesenvolvidos na zona Este de África, como Moçambique, têm baixo poder económico, níveis de educação baixos e são extremamente dependentes dos recursos naturais, o que faz com que haja uma degradação dos ecossistemas. Atualmente, a aquacultura é o setor de produção animal em maior crescimento. Alguns estudos já descreveram que há um grande potencial para a aquacultura em África e que esta poderá contribuir para um maior poder económico de alguns dos países. Contudo, a contribuição de África para a aquacultura mundial é muito pequena, sendo o segundo continente com menor produção em aquacultura. Os fatores que contribuem para a falta de sucesso no desenvolvimento da aquacultura em África são a fraca qualidade das larvas e das rações, a falta de conhecimento técnico e uma má infraestrutura do mercado. Além disso, a falta de financiamento, quando o suporte por parte de grandes empresas ou governos estrangeiros cessa, leva a que a maior parte dos projetos de aquacultura colapsem. A farinha de peixe é a principal fonte proteica das rações em aquacultura porque tem um excelente perfil de aminoácidos, alto valor proteico, elevada palatibilidade, ausência de antinutrientes e é uma boa fonte de ácidos gordos, vitaminas e minerais. Com o constante crescimento da aquacultura, o preço da farinha de peixe tem vindo a aumentar e a sua disponibilidade a diminuir. A aquacultura em comunidades poderá ser uma boa alternativa ou atividade suplementar para gerar maior poder económico e menor dependência dos recursos naturais marinhos. Nas últimas duas décadas, têm sido desenvolvidos projetos em aquacultura para melhorar a vida destas comunidades e promover a conservação da biodiversidade marinha. Deste modo, é importante encontrar dietas alternativas, formuladas com ingredientes locais aproveitados de sobras da alimentação das comunidades e das plantações. Alguns estudos identificaram que a redução da farinha de peixe através da incorporação de produtos ou ingredientes locais nas dietas pode reduzir os impactos ambientais e o seu custo. A tilápia do Nilo (*Oreochromis niloticus*) é um peixe omnívoro, amplamente distribuído em África, nomeadamente no Botswana, em Moçambique, na Zâmbia, e no Zimbabué. É uma espécie adequada a este tipo de aquacultura devido aos seus atributos, tais como crescimento rápido, boa aceitação de rações artificiais, alimentação a um baixo nível trófico, resistência ao stress e às patologias. Como resultado, a produção global de tilápia do Nilo cresceu de 0.5 milhões de toneladas nos anos 90 para 6.03 milhões de toneladas em 2018, sendo a terceira espécie mais produzida no mundo. Assim, o objetivo desta tese foi avaliar a performance do crescimento, a eficiência alimentar e a utilização da proteína em juvenis de tilápia do Nilo alimentados com uma dieta com ingredientes locais de uma comunidade moçambicana. Os ingredientes locais incluíram folhas de mandioca e moringa, amendoins, milho, mapira, mandioca e feijões pweri, jugo e nhimba. Assim, foi realizado um ensaio de crescimento no Centro de Ciências do Mar, na Universidade do Algarve, num sistema de recirculação em aquacultura. Neste ensaio foram usadas duas dietas isolipídicas e isoenergéticas, uma comercial (CTRL) e uma formulada com os ingredientes locais (EXP). Cada dieta foi testada em triplicados (n = 50 peixes/tanque) durante 64 dias e os peixes foram alimentados à mão até à aparente saciedade, três vezes por dia. Durante o ensaio, diariamente, a temperatura, o oxigénio dissolvido na água, o pH e a mortalidade foram registados. Para monitorizar o crescimento, ao fim de 27 dias, os peixes foram pesados após anestesia ligeira. No final do ensaio, os peixes amostrados foram mortos por anestesia letal, pesados e medidos para determinação do crescimento e amostras foram recolhidas para análise da composição proximal. Todos os dados foram analisados estatisticamente através de um teste *t*, depois de serem submetidos a testes de normalidade e homogeneidade da variância. Os peixes alimentados com a dieta EXP tiveram um crescimento e uma eficiência alimentar significativamente menor do que os peixes alimentados com a dieta CTRL. O pior crescimento e eficiência alimentar poderão ter sido devidos à baixa digestibilidade da proteína ou a um perfil de aminoácidos desequilibrado na dieta experimental. Para além disso, no início do ensaio os peixes alimentados com a dieta EXP ingeriram menores quantidades de alimento do que os peixes alimentados com a dieta CTRL, sugerindo que a dieta EXP poderá ter uma menor palatibilidade. Este facto poderá também ter contribuído para a menor eficiência alimentar. Já foi demonstrado que a digestibilidade da proteína da folha de cassava é baixa, podendo esta ser causada por fatores antinutricionais, nomeadamente taninos e cianeto de hidrogénio, ou por conter proteína que não se encontra disponível à ação dos enzimas digestivos. Doses subletais de cianeto de hidrogénio presentes nas dietas podem desencadear processos de desintoxicação e, por sua vez, aumentar os requisitos de metionina. A metionina é um aminoácido que se encontra em quantidades menores na dieta EXP do que na dieta CTRL. Outra hipótese, é o facto de o tanino formar moléculas complexas com a proteína que não podem ser digeridas pelos peixes. No final da experiência, a retenção de proteína e o conteúdo proteico dos peixes não foram significativamente diferente, sugerindo que ambos os tratamentos utilizaram de igual forma a proteína presente nas dietas. Os índices hepatossomático e viscerossomático não apresentaram diferenças significativas, o que sugere que ambos os tratamentos utilizaram de igual forma os lípidos presentes nas dietas. A quantidade de azoto ingerida e o seu ganho foram significativamente menores nos peixes alimentados com a dieta EXP do que nos peixes alimentados com a dieta CTRL. As perdas de azoto entre os tratamentos não foram significativamente diferentes. No entanto, pôde-se verificar que os peixes alimentados com a dieta EXP perderam uma percentagem maior de azoto ingerido comparado com os peixes alimentados com a dieta CTRL. Apesar de ter havido um menor crescimento e eficiência alimentar, os resultados deste estudo demostram que a dieta com ingredientes locais poderá ser viável numa aquacultura com tanques de terra, onde iria ocorrer o efeito da fertilização, que irá dar origem a alimento natural. De forma a poder tirar mais conclusões sobre esta dieta seria necessário fazer um ensaio da digestibilidade dos nutrientes e dos aminoácidos. Também, seria interessante analisar a composição proximal de cada ingrediente local presente na dieta experimental e aferir a existência de fatores antinutricionais que possam interferir com a digestão e absorção dos nutrientes da dieta.

Palavras-chave: tilápia do Nilo, aquacultura, sustentabilidade, nutrição

Abbreviations

CBA – community-based aquaculture

cm – centimeter

DGI – daily growth index

DM – dry matter

FAO – Food and Agriculture Organization

FBW – final body weight

FCR – feed conversion ratio

g – grams

h – hours

IBW – initial body weight

kg – kilogram

L – liter

mg – milligrams

MMT – million metric tons

N – nitrogen

NGO – non-governmental organization

ºC – degrees Celsius

PER – protein efficiency ratio

RAS – recirculating aquaculture system

Tt - thousand tonnes

USD – united states dollar

VFI – voluntary feed intake

WG – weight gain

Index

List of Figures

List of Tables

1 Introduction

1.1 The dimension and importance of the aquaculture

Currently, aquaculture is the fastest growing animal food production sector in the world that contributes to answer to the significant increase in demand for seafood (FAO, 2018, 2020; Ng and Romano, 2013a). World aquaculture production of farmed animals grew on average at 5.3 percent *per* year in the period of 2001-2018 (Figure 1) (FAO, 2020).

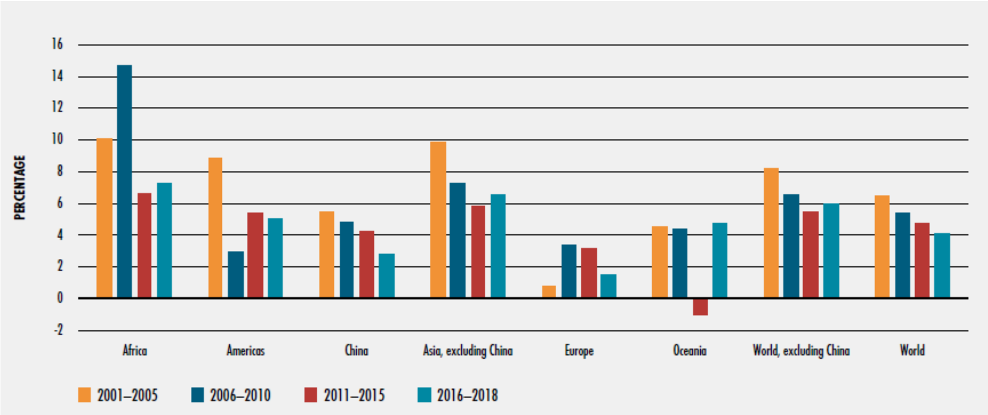

Figure 1 Annual growth rate of aquaculture production of farmed aquatic animals' quantity in the new millennium (FAO, 2020).

In 2018, aquaculture reached an historic production record of 114.5 million tonnes in live weight (Figure 2) (FAO, 2020). The total production of aquatic animals was 82.1 million tonnes, representing 46 percent of total world fish production, and with an estimated value of USD 250.1 billion. In 2018, aquaculture fish production was dominated by finfish (54.3 million tonnes, USD 139.7 billion), molluscs (17.7 million tonnes, USD 34.6 billion) and crustaceans (9.4 million tonnes, USD 69.3 billion) (FAO, 2020). In Table 1 are presented the 10 most produced finfish species in aquaculture.

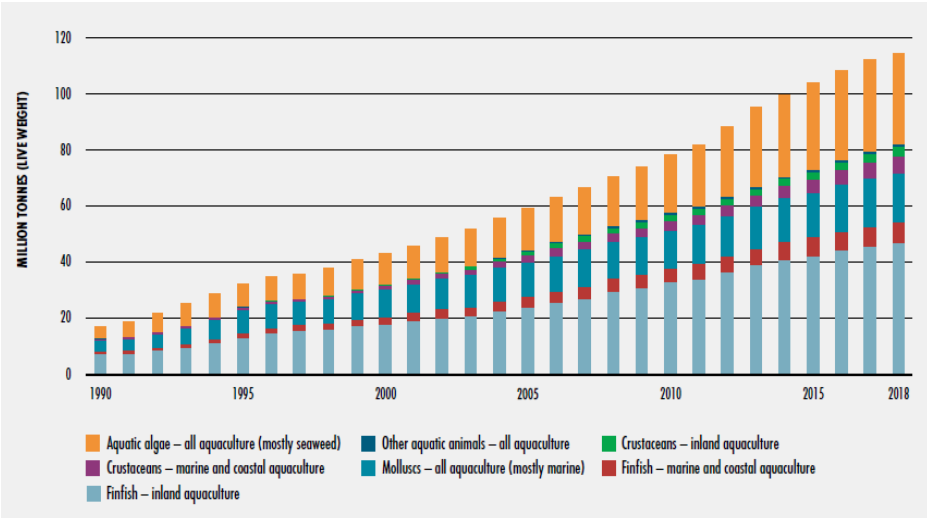

Figure 2 World aquaculture production of aquatic animals and algae, 1990-2018 (FAO, 2020).

Table 1 Ten most produced finfish species in the world (FAO, 2020).

Common Name	**Scientific name**	**Aquaculture production (thousand tonnes)**
Grass carp	*Ctenopharyngodon idellus*	5 704.0
Silver carp	*Hypophthalmichthys molitrix*	4 788.5
Nile tilapia	*Oreochromis niloticus*	4 525.4
Common carp	*Cyprinus carpio*	4 189.5
Bighead carp	*Hypophthalmichthys nobilis*	3 143.7
Catla	*Catla catla*	3 041.3
Atlantic salmon	*Salmo salar*	2 435.9
Stripped catfish	*Pangasianodon hypophthalmus*	2 359.5
Roho labeo	*Labeo rohita*	2 016.8
Milkfish	*Chanos chanos*	1 327.2

Aquaculture production is dominated by Asia, with 89 % of the global total production in the last 20 years. China is the biggest producer of farmed aquatic food of the world, with a production of 47559.1 thousand tonnes (Tt), followed by India (7066.0 Tt), Indonesia (5426.9 Tt), Vietnam (4134.0 Tt), and Bangladesh (2405.4 Tt) (FAO, 2020). Africa (2195.9 Tt) is the second continent to contribute less to the world global aquaculture production, despite its high demand for fish and high aquaculture potential (FAO, 2020; Moyo & Rapatsa, 2021).

1.2 Nile Tilapia (*Oreochromis niloticus*)

Nile tilapia (Figure 3) is a perciform fish that belongs to the family Cichlidae, genus *Oreochromis*. It is widely distributed in Africa, mostly in Zambia, Botswana, Zimbabwe, Mozambique, and South Africa (Bereded et al., 2021; Moyo & Rapatsa, 2021). It is a freshwater omnivorous species, that prefers to live in shallow waters (Ng & Romano, 2013b; Rakocy, 2009). Feeds on algae, aquatic plants, small invertebrates, detritus and associated bacterial films (Bereded et al., 2021). They are "mouthbreeders", where the female incubates fertilized eggs in her mouth cavities (El-Sayed, 2006). Under natural conditions, sexual maturity is reached at a size of 20-30 cm (150-250 g) (El-Sayed, 2006; Graaf et al., 1999). However, in captivity under stressful environmental conditions, tilapia mature at smaller sizes of 8-13 cm (20-50 g) (El-Sayed, 2006; Graaf1 et al., 1999).

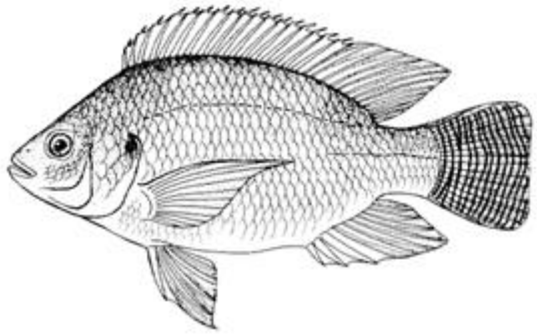

Figure 3 Scientific illustration of Nile tilapia (*Oreochromis niloticus*). Source: FAO Available in: http://www.fao.org/fishery/culturedspecies/Oreochromis_niloticus/en)

Nile Tilapia is one of the most important farmed species in the world (Abdel-Ghany et al., 2021; Teodósio et al., 2020), due to their many attributes, such as, fast growth, tolerance to a wide range of environmental conditions, resistance to stress and disease, ability to reproduce in captivity, feeding on low trophic levels and acceptance of artificial feeds immediately after yolk-sac absorption (Abdel-Ghany et al., 2021; El-Sayed, 2006). As a result, global tilapia production grew from less than 0.5 million metric tons (MMT) in the early 1990s to 6.03 MMT in 2018 (FAO, 2021).

1.3 Factors affecting tilapia aquaculture in Africa

It has already been reported that there is high biophysical potential for aquaculture in Southern Africa (Figure 4) (Aguilar-Manjarrez & Nath, 1998). Also, most of the governments in Southern Africa consider aquaculture development the main solution to poverty alleviation (Moyo & Rapatsa, 2021). However, the contribution of Southern Africa for global aquaculture production is very small (Moyo & Rapatsa, 2021). The factors that contribute for the lack of success in aquaculture development in Africa are the production systems, the species for culture, the poor quality of seed and feed, the lack of technical advice and the poor market infrastructure (Brummett et al., 2008; Moyo & Rapatsa, 2021).

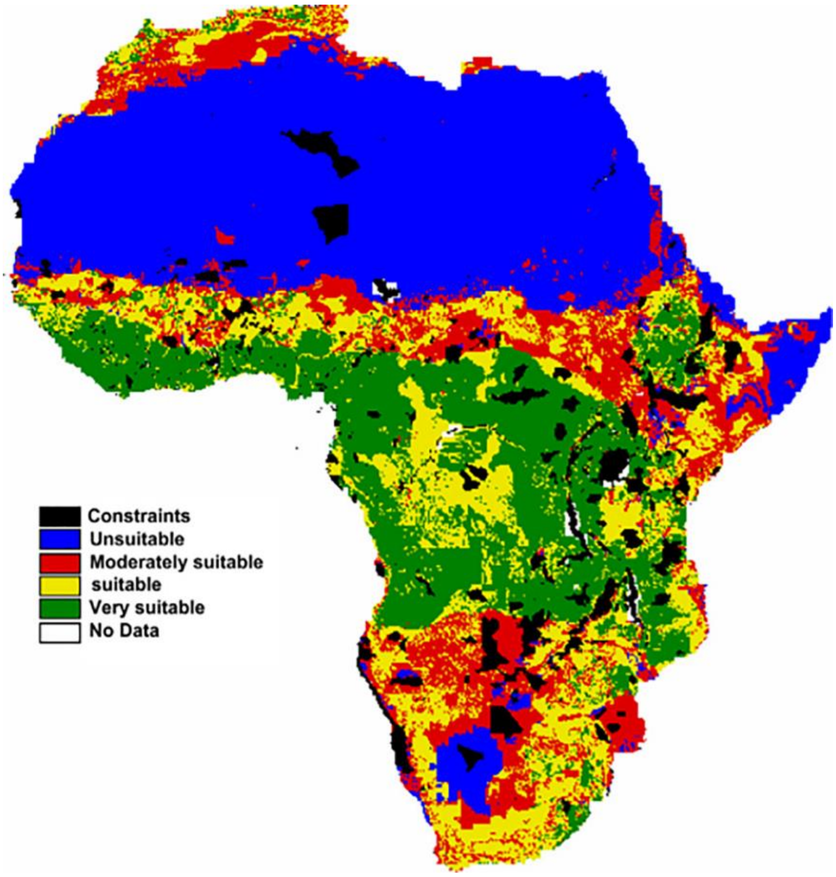

Figure 4 GIS assessment potential for small scale/artisanal aquaculture in Africa (Moyo and Rapatsa, 2021)

In Southern Africa, tilapia aquaculture production systems range from earthen ponds to recirculating aquaculture systems (RAS) (Moyo & Rapatsa, 2021). Earthen ponds have high water consumption and low productivity, are cheap and easy to build but difficult to manage (Abdelrahman & Boyd, 2018; Moyo & Rapatsa, 2021). Most of the ponds in Southern Africa are in unsuitable areas because fish farming is a secondary activity and most of them are backyard ponds. Only the ponds where farmers have donors are in suitable areas and well designed (Moyo & Rapatsa, 2021). RAS technology has low water consumption, which makes a good option for areas with water scarcity in Southern Africa. However, these systems are expensive and difficult to manage. Also, in RAS fish require a complete diet which is usually expensive (Moyo & Rapatsa, 2021).

Mozambique tilapia (*Oreochromis mossambicus*) is the most cultured tilapia species in Southern Africa, despite its slow growth rate in comparison to Nile tilapia (Moyo & Rapatsa, 2021). This slow growth could be attributed to bad hatchery management practices which result in poor genotypic quality (Moyo & Rapatsa, 2021). Most countries out of Africa that culture tilapia use improved strains that have been selectively bred (Brummett et al., 2008). However, in Southern Africa unimproved strains are mostly used, which results in slow growth and early maturity ages (40% lower performance than wild fish) (Brummett et al., 2008; Moyo & Rapatsa, 2021).

Most of the feed used in Southern Africa is imported, at a high cost (IDC/Urban-Econ, 2015; Moyo & Rapatsa, 2021). Fishmeal is the main protein source in carnivorous and omnivorous fish diets because it has an adequate amino acid profile and high palatability, and it is a great source of essential fatty acids, minerals and vitamins (Campos et al., 2018; Gatlin III et al., 2007; Teodósio et al., 2020). However, due to its constant price rise and questionable environmental sustainability, is essential to find new protein sources for diet formulation (Campos et al., 2018; Teodósio et al., 2020). Studies using life cycle assessment showed that reducing fishmeal through the incorporation of locally produced products/ingredients or even from by-products can decrease aquafeed environmental impact and feed cost (Campos et al., 2018; Moyo & Rapatsa, 2021). There have been already some studies on the inclusion of local ingredients in fish diets to substitute fishmeal. Replacement of fishmeal by kikuyu grass with the incorporation of Natuzyme (an enzyme that improve the digestion and absorption of nutrients in the gastrointestinal tract) had successful results and made the production of tilapia more profitable (Hlophe & Moyo, 2014; Hlophe-Ginindza et al., 2016). Replacement of fishmeal with mopane worm meal resulted in high growth rates and good feed conversion ratio in tilapias, and was suggested that there is high potential for higher economic returns (Rapatsa & Moyo, 2017).

Due to their high demand, in most of the countries in Southern Africa, tilapias are imported from China (Moyo & Rapatsa, 2021). Also, there is lack of financial support, which leads to lack of fish feed availability, its quality, and acquisition of high quality fingerlings (Moyo & Rapatsa, 2021). One of the reasons for lack of support may be because some post-colonialism aquaculture projects collapsed when the donor support came to an end (Moyo & Rapatsa, 2021). Another key constraint is poor market infrastructure as mentioned above. Bad roads, police harassment, absence of storage facilities and unsanitary market stall are limitations for producers to get fair prices for their fish (Brummett et al., 2008).

1.4 Community-based aquaculture

Community-based aquaculture (CBA) is an alternative or supplementary income generating activity that aims to improve livelihoods and food security of poor coastal communities (Ateweberhan et al., 2018; Beveridge et al., 2013). CBA reduces dependence on natural resources, promotes biodiversity conservation and can improve local economies and food security, by diversifying livelihoods and providing new skills (Béné et al., 2016; Brummett et al., 2008; Diana, 2009; Troell et al., 2014). CBA projects have expanded throughout much of the tropical and subtropical coastal developing countries, with diverse species being farmed, employing a wide range of techniques models and partnerships (Ateweberhan et al., 2014, 2018).

Coastal communities in Eastern Africa, like Mozambique, are among the poorest in the world (Cinner, 2009, 2011; Cinner et al., 2012). In these communities, education and technical skills are very low and they have no formal rights to the marine resources on which they depend (Ateweberhan et al., 2018). Due to direct human activities such as overfishing or unsustainable coastal development, as well some extreme thermal events, marine resources in this region have shown signs of significant overexploitation and suffered from habitat degradation (Burke et al., 2011; Cinner et al., 2012; Maina et al., 2008). This trend is expected to continue, due to the population increase in this region, as well as more frequently extreme climatic events (Ateweberhan et al., 2014, 2018).

In the last two decades, CBA projects have been developed in many parts of Eastern Africa with the objective to improve livelihoods of the poor communities, to promote conservation of the marine biodiversity through creation of marine reserves and to alleviate fishing pressure (Ateweberhan et al., 2018). This has resulted in a dynamic and cross-cutting sector, bringing together communities, research institutions, NGOs, and business partnerships in a broad range of scientific, technical, and business disciplines (Troell et al., 2011).

1.5 Objective

This work aims to evaluate juvenile Nile tilapia performance when fed diets produced with local ingredients from a Mozambican community. Nile tilapia will be used as a model, due to logistics and availability constraints in Europe. To evaluate fish performance and environmental impact, the following parameters will be analysed: growth performance, feed intake and utilization, fish composition, protein retention, and nitrogen balance.

2 Methodology

2.1 Growth trial

This experiment was conducted at Centre of Marine Sciences (CCMAR), at University of Algarve (Faro, Portugal). Nile tilapia juveniles with an average body weight of 0.5 g were acclimatized to the new rearing facilities in a recirculating aquaculture system (RAS) and fed a commercial diet.

Juveniles were reared in 100 L-cylindrical tanks in a RAS. The system was equipped with a mechanical filter, a biological filter, and a UV sterilizer. Daily, temperature (25.5 ± 0.5 ºC), dissolved oxygen (DO) in water (96.5 ± 2.7 % saturation), pH (8.4 ± 0.2) and fish mortality were monitored. The concentration of ammonia and nitrites were monitored weekly or more frequently if necessary and maintained at 0 mg/L. Photoperiod was natural (October until December, 37°02'34.9"N 7°58'15.6"W).

Six homogenous groups of 50 Nile tilapia juveniles with a mean initial body weight of 0.71 ± 0.12 g were stocked at an initial density of 0.4 kg/m3. Twenty fish from the initial stock were euthanized by lethal anaesthesia (1.5 ml/L of phenoxyethanol), measured, and weighed individually, and stored at -20 ºC for analysis of whole-body composition. Triplicate tanks were randomly assigned to one of the two dietary treatments (CTRL, EXP). Fish were fed to visual satiety by hand, three times a day (9h30, 12h30, 16h00), and apparent feed intake was recorded daily for 64 days. To monitor growth and feed utilization, fish from each tank were bulk weighed under moderate anaesthesia (0.5 ml/L of phenoxyethanol) after 28 days of experimental feeding.

At the end of the trial, each tank was bulk-weighed and 5 fish from each tank were euthanized by lethal anaesthesia, individually weighed, and measured, and pooled together and frozen at -20 ºC for subsequent analysis of whole-body composition. Three additional fish from each tank were euthanized with lethal anaesthesia (1.5 ml/L of phenoxyethanol), individually weighed, and liver and viscera were collected and weighed for analysis of somatic indexes. All samples were collected after 24 h of fasting.

2.2 Experimental diets

For this experiment two isolipidic and isoenergetic diets were formulated. The control diet (CTRL) was a commercial-like diet for Nile Tilapia, with soybean meal and other plant ingredients (74.7%) as main protein sources. Fishmeal and poultry meal were also used as protein sources. The experimental diet (EXP) was formulated considering the possibilities and conditions of the communities. In this diet, levels of soybean meal and fishmeal were reduced, and poultry meal was abolished. The local ingredients were used as protein and lipid sources. As protein sources peanut, cassava leaf, beans, corn, sorghum, moringa leaf and cassava were used. As lipid source, soybean oil was substituted by palm oil. To simulate the natural feed present in the earth ponds, insect meal was added to the EXP diet. Samples from each diet were collected and analysed for proximate composition. The detailed formulation and proximate composition are presented in Table 2. The amino acid profile of each experimental diet is presented in Table 3. All the experimental diets were formulated, manufactured, and extruded at SPAROS, Lda. (Olhão, Portugal).

Table 2 Formulation and proximate composition of the Control (CTRL) and the experimental (EXP) diets (%).

Ingredients	**CTRL (%)**	**EXP (%)**
Fishmeal	7.50	2.50
Poultry meal	7.50	0.00
Insect meal	0.00	2.50
Soybean meal	25.00	10.00
Rapeseed meal	7.75	0.00
Sunflower meal	7.75	0.00
Wheat bran	10.00	0.00
Rice bran full fat	10.00	0.00
Corn Meal	14.23	0.00
Cassava leaf	0.00	13.25
Moringa leaf	0.00	1.00
Cassava root	0.00	1.00
Jugo bean	0.00	11.20
Peanut	0.00	14.00
Nhimba bean	0.00	9.50
Pweri bean	0.00	13.25
Corn	0.00	9.68
Sorghum	0.00	6.00
Vitamin & Mineral Premix	1.00	1.00
Mono-calcium phosphate	0.40	0.00
Binder (guar gum)	1.50	1.50
L-Lysine HCl	0.15	0.00
L-Threonine	0.20	0.00
L-Tryptophan	0.05	0.00
DL-Methionine	0.45	0.00
Yttrium oxide	0.02	0.02
Soybean oil	6.50	0.00
Palm oil	0.00	3.60

Proximate composition (as fed basis)		
Crude protein, %	30.65	21.12
Crude fat, %	11.00	10.50
Ash, %	7.20	4.30
Moisture, %	7.20	7.30
Gross energy, MJ kg^{-1}	20.17	19.96

Table 3 Amino acid profile (mg AA/g DW) of the Control (CTRL) and the experimental (EXP) diets.

Amino acid	CTRL	EXP
Arginine	32.6	19.9
Histidine	9.8	5.9
Lysine	20.9	13.2
Threonine	17.3	8.3
Isoleucine	15.1	10.1
Leucine	24.7	17.7
Valine	17.4	12.0
Methionine	12.9	3.0
Phenylalanine	19.9	15.6
Cystine	2.9	1.6
Tyrosine	18.0	15.1
Aspartic acid + Asparagine	25.9	19.2
Glutamic acid + Glutamine	47.2	32.8
Alanine	16.4	10.2
Glycine	22.3	11.3
Proline	17.6	10.2
Serine	16.5	11.2
Taurine	0.9	0.0

2.3 Proximate composition

Before analysis, whole-body fish samples from each tank were pooled together and all samples (whole-body and diets) were finely ground. Diets and whole-body fish samples were freeze-dried before protein and amino acid analysis. Proximate composition analysis of the diets and whole-body fish was done in triplicates by the following methods: dry matter by drying at 105ºC for a 24h period, ash by incineration in a muffle furnace at 550ºC for 12h and crude protein (N×6.25) using an elemental analyser (Elemental Vario El III).

Total amino acid profile from diets samples were determined by ultra-high-performance liquid chromatography (UPLC) on a Waters Reversed-Phase Amino Acid

Analysis System, using norvaline as an internal standard. Samples were pre-column derivatised with Waters AccQ Fluor Reagent (6-aminoquinolyl-N-hydroxysuccinimidyl carbamate) using AccQ Tag method (Waters, USA) after acid hydrolysis (HCl 6 M at 116 °C for 48 h in nitrogen-flushed glass vials). Amino acids were identified by retention times of standard mixtures (Waters) and pure standards (Sigma-Aldrich). Instrument control, data acquisition and processing were achieved by the use of Waters Empower software.

2.4 Calculations

Growth performance, feed utilization and nitrogen balance were calculated as follows:

- Weight gain (%) = 100 x (FBW – IBW) / IBW, where IBW and FBW are the initial and final body weights, respectively
- Daily growth index (DGI) = 100 x [($FBW^{1/3}$ – $IBW^{1/3}$) / days]
- Hepatosomatic index (HSI %) = 100 x (liver weight / body weight)
- Viscerosomatic index (VSI %) = 100 x (viscera weight / body wight)
- Feed conversion ratio (FCR): apparent feed intake / weight gain (g), where weight gain (g) is: final body weight – initial body weight
- Daily voluntary feed intake (VFI, % / day): 100 x (apparent feed intake / ABW / days), where ABW is average body weight: (final body weight + initial body weight)/2
- Protein efficiency ratio (PER): weight gain (g) / crude protein intake
- Protein retention (% intake): 100 x [(final body protein content – initial body protein content) / (protein intake)].
- Daily nitrogen intake (mg / kg / day): nitrogen intake / ABW / days.
- Daily nitrogen gain (mg / kg / day): (final body nitrogen content – initial body nitrogen content) / ABW / days.
- Daily nitrogen loss (mg / kg / day): daily nitrogen intake – daily nitrogen gain.

2.5 Statistical analysis

Data are expressed as means ± standard deviation. All data expressed as a percentage were arcsine transformed previously to statistical analysis. Normality and homogeneity of variances were checked previously. When normality was met, data were subjected to a Student's *t* test; if not, a Mann-Whitney *U* test was performed. All statistical tests were performed using RStudio software version 3.6.1.

.

3 Results

3.1 Growth performance and feed utilization

Final body weight, final body length and condition factor are presented in Figure 5. Final body weight and length in fish fed the EXP diet (1.98 ± 0.79 g; 4.81± 0.60 cm) were significantly lower ($p < 0.05$) than in fish fed the CTRL diet (9.78 ± 3.31 g; 8.12 ± 1.09 cm). There were no significant differences in the condition factor between the dietary treatments ($p > 0.05$).

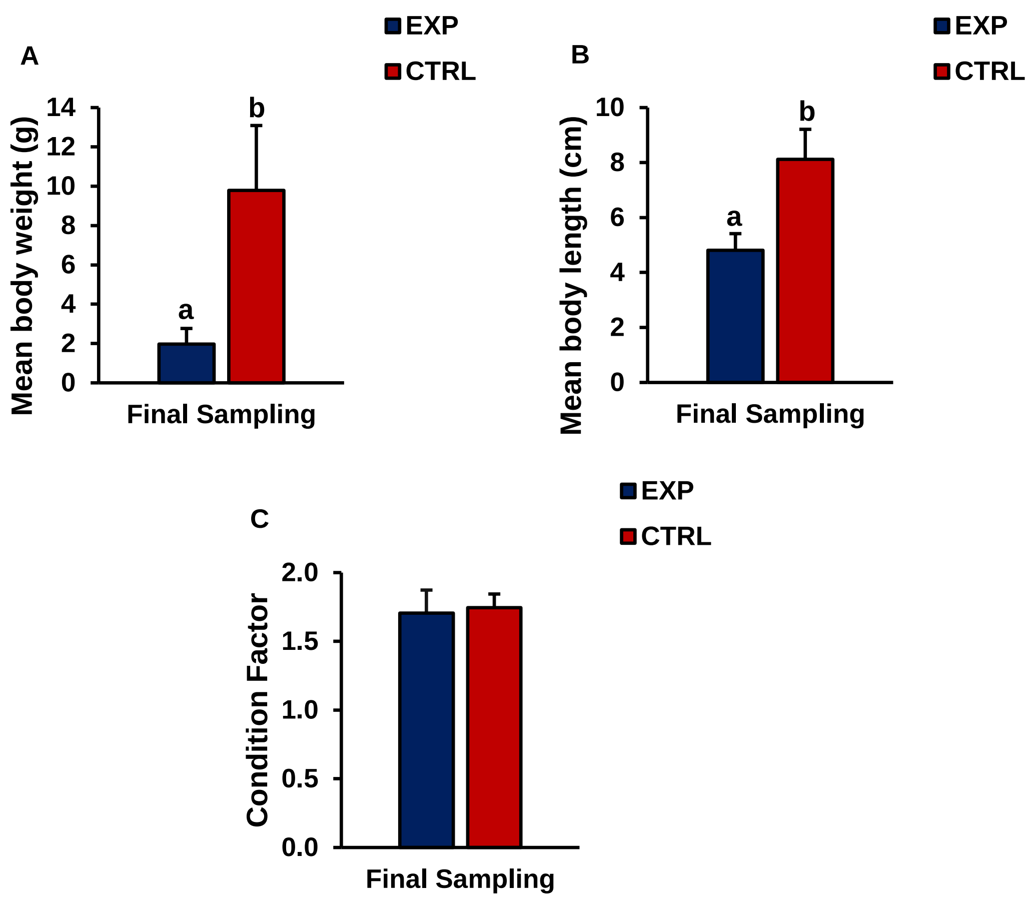

Figure 5 A – Final body weight; **B** – Final body length; and **C** – Condition factor of Nile tilapia juveniles fed the Control (CTRL) or the Experimental diet (EXP) for 64 days. Values are presented as means ± standard deviation ($n = 8$). Bars with different letters differ significantly ($p < 0.05$); (Initial body weight: 0.77 ± 0.10 g, initial body length: 3.6 ± 0.3 cm; initial k: 1.71 ± 0.68).

Survival, weight gain and daily growth index (DGI) are presented in Figures 6 to 8. Survival (Fig. 6) was not influenced by the different dietary treatments ($p > 0.05$). In the two samplings that occurred during the experimental period, weight gain (Fig. 7) and DGI (Fig. 8) of fish fed the EXP diet were significantly lower than fish fed the CTRL diet ($p < 0.05$).

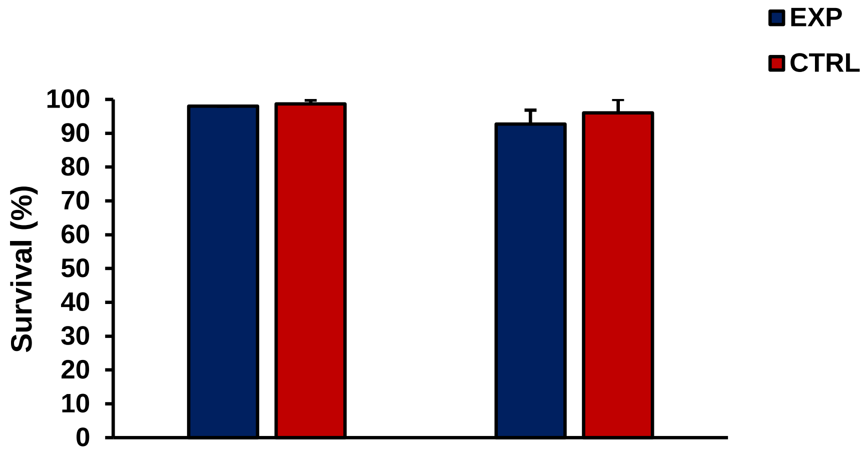

Figure 6 Survival of Nile tilapia juveniles fed the Control (CTRL) or the Experimental diet (EXP) for 28 (intermediate sampling) or 64 days (final sampling). Values are presented as means ± standard deviation ($n = 3$). Absence of letters indicate no significant differences ($p > 0.05$).

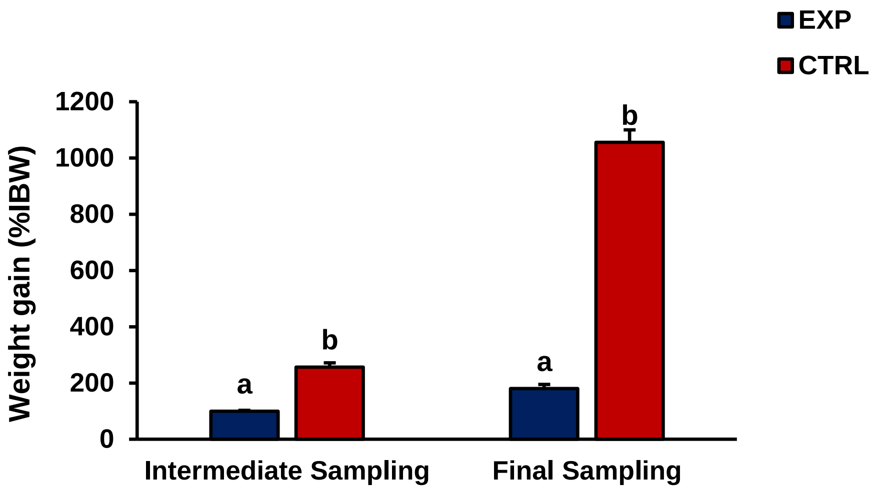

Figure 7 Weight gain of Nile tilapia juveniles fed the Control (CTRL) or the Experimental diet (EXP) for 28 (intermediate sampling) or 64 days (final sampling). Values are presented as means ± standard deviation ($n = 3$). Bars with different letters indicate significant differences ($p < 0.05$) at each sampling period. IBW = initial body weight.

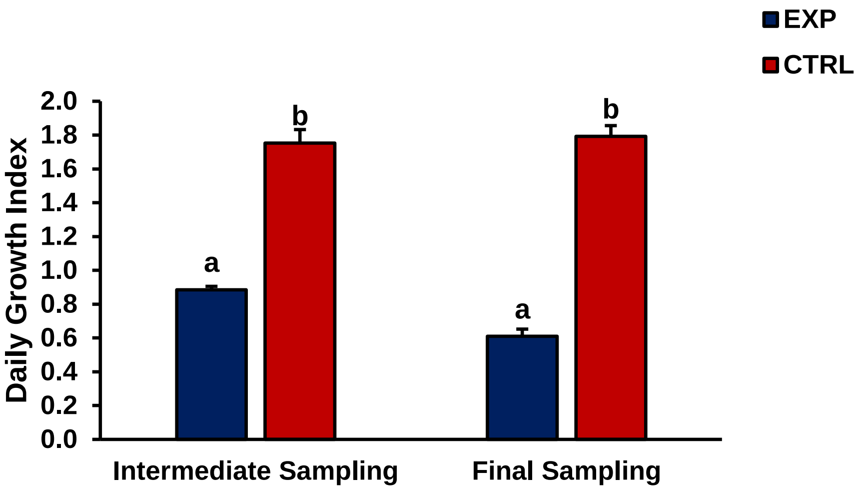

Figure 8 Daily growth index (DGI) of Nile tilapia juveniles fed the Control (CTRL) or the Experimental diet (EXP) for 28 (intermediate sampling) or 64 days (final sampling). Values are presented as means ± standard deviation (n = 3). Bars with different letters indicate significant differences ($p < 0.05$) at each sampling period.

Daily voluntary feed intake, feed conversion ratio (FCR) and protein efficiency ratio (PER) are presented in Figures 9 to 11. At the intermediate sampling, daily voluntary feed intake in fish fed the CTRL diet was significantly higher than in those fed the EXP diet (Fig. 9). At the end of the experiment, there were no significant differences in the daily voluntary feed intake and the valued ranged from 2.80 ± 0.11 %/day to 2.86 ± 0.03 %/day ($p > 0.05$). FCR in fish fed the EXP diet was significantly higher than in fish fed the CTRL diet, in the two samplings that occurred during the experimental period (Fig. 10). There were no significant differences at the intermediate sampling, regarding PER ($p > 0.05$; Fig. 11). However, at the end of the experiment, fish fed the CTRL diet showed a significantly higher PER than those fed the EXP diet ($p < 0.05$).

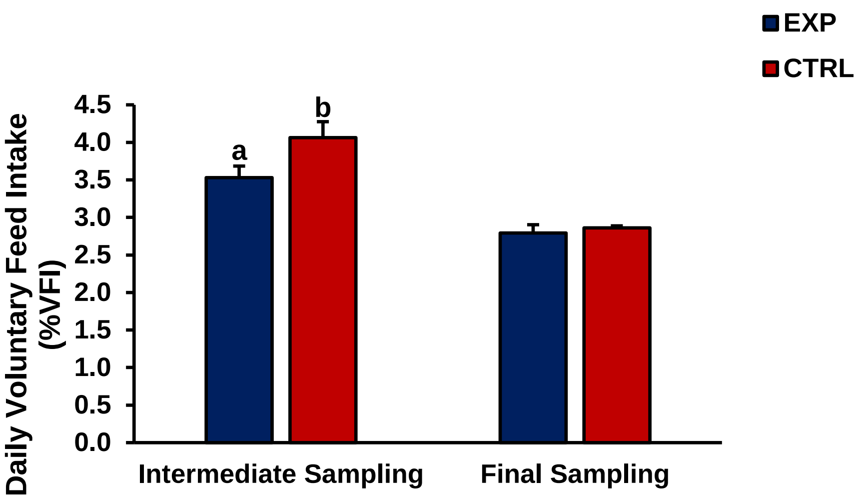

Figure 9 Daily voluntary feed intake of Nile tilapia juveniles fed the Control (CTRL) or the Experimental diet (EXP) for 28 (intermediate sampling) or 64 (final sampling) days. Values are presented as mean ± standard deviation (*n* = 3). Bars with different letters indicate significant differences ($p < 0.05$).

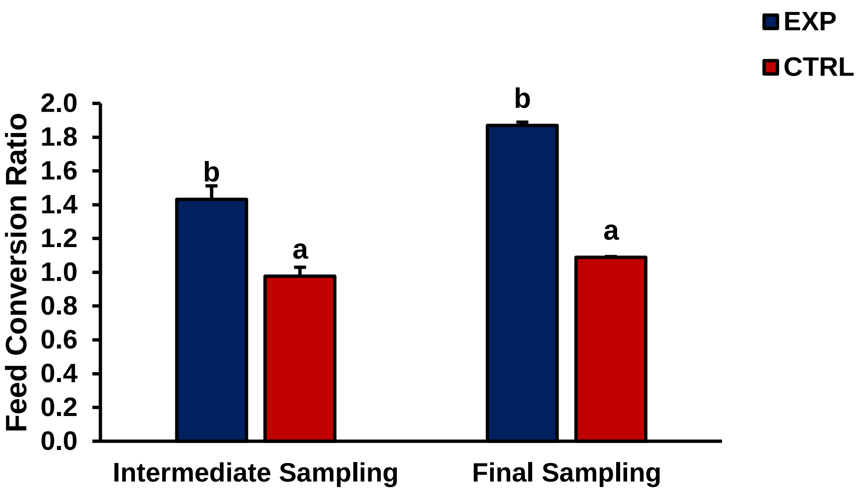

Figure 10 Feed conversion ratio of Nile tilapia juveniles fed the Control (CTRL) or the Experimental diet (EXP) for 28 (intermediate sampling) or 64 (final sampling) days. Values are presented as means ± standard deviation (*n* = 3). Bars with different letters indicate significant differences ($p < 0.05$) at each sampling period.

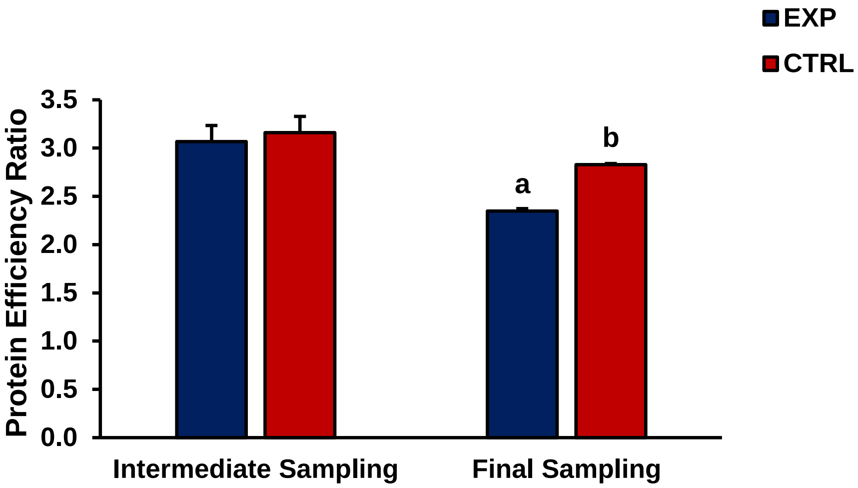

Figure 11 Protein efficiency ratio of Nile tilapia juveniles fed the Control (CTRL) or the Experimental diet (EXP) for 28 (intermediate sampling) or 64 (final sampling) days. Values are presented as mean ± standard deviation (*n* = 3). Bars with different letters indicate significant differences ($p < 0.05$).

Hepatosomatic index did not had significant differences and ranged from 0.67 ± 0.34 to 1.01 ± 0.58. Viscerosomatic index did not have significant differences and ranged from 9.00 ± 1.06 to 9.86 ± 1.00.

Table 4 Hepatosomatic and viscerosomatic indexes of Nile tilapia juveniles fed the Control (CTRL) or the Experimental diet (EXP) for 64 days.

	EXP	CTRL
HSI, %	1.01 ± 0.58	0.67 ± 0.34
VSI, %	9.86 ± 1.00	9.00 ± 1.06

Values are means ± standard deviation (*n* = 3). Absence of letters indicate no significant differences ($p > 0.05$).

3.2 Whole-body fish composition and nutrient retention

Whole-body fish composition values are represented in Table 5. Dry matter content values were higher in fish at the end of the experiment; on the other hand, ash and crude protein values were lower. Fish fed the CTRL diet showed higher ash values than those fed the EXP diet ($p < 0.05$). For dry matter and crude protein, there were no significant differences at the end of the experiment between treatments ($p > 0.05$).

Table 5 Proximal composition of Nile tilapia juveniles fed the Control (CTRL) or the Experimental diet (EXP) at the beginning and at the end of the experiment (64 days).

	Initial	EXP	CTRL
Dry matter (DM), %	18.9 ± 0.6	25.6 ± 1.6	25.9 ± 0.6
Ash, % DM	3.9 ± 0.0	3.1 ± 0.3 [a]	3.5 ± 0.1 [b]
Crude protein, % DM	63.1 ± 2.3	56.1 ± 3.3	57.0 ± 1.4

Values are means ± standard deviation (*n* = 3). Different letters within a row indicate significant differences ($p < 0.05$).

Apparent protein retention is represented in Figure 12. There were no differences between treatments in protein retention at the end of the experiment ($p > 0.05$).

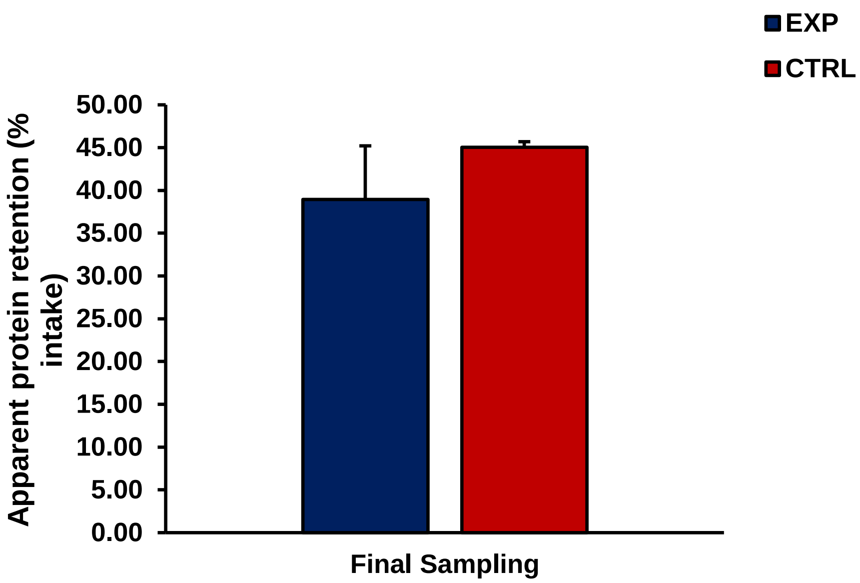

Figure 12 Apparent protein retention of Nile tilapia fed the Control (CTRL) or the Experimental (EXP) diets for 64 days. Values are presented as means ± standard deviation (*n* = 3). Absence of letters indicate no significant differences ($p > 0.05$).

Daily nitrogen intake and daily nitrogen balance are represented in Figures 13 and 14. Daily nitrogen intake and daily nitrogen gain in fish fed the EXP diet was significantly lower ($p < 0.05$) than in fish fed the CTRL diet. For daily nitrogen loss there were no significant differences ($p > 0.05$).

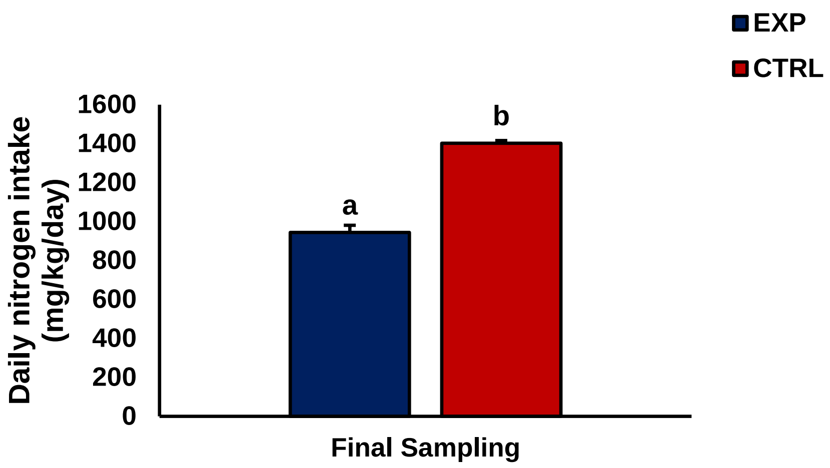

Figure 14 Daily nitrogen intake of Nile tilapia fed the Control (CTRL) or Experimental (EXP) diets for 64 days. Values are presented as means ± standard deviation (*n* = 3). Bars with different letters differ significantly ($p < 0.05$).

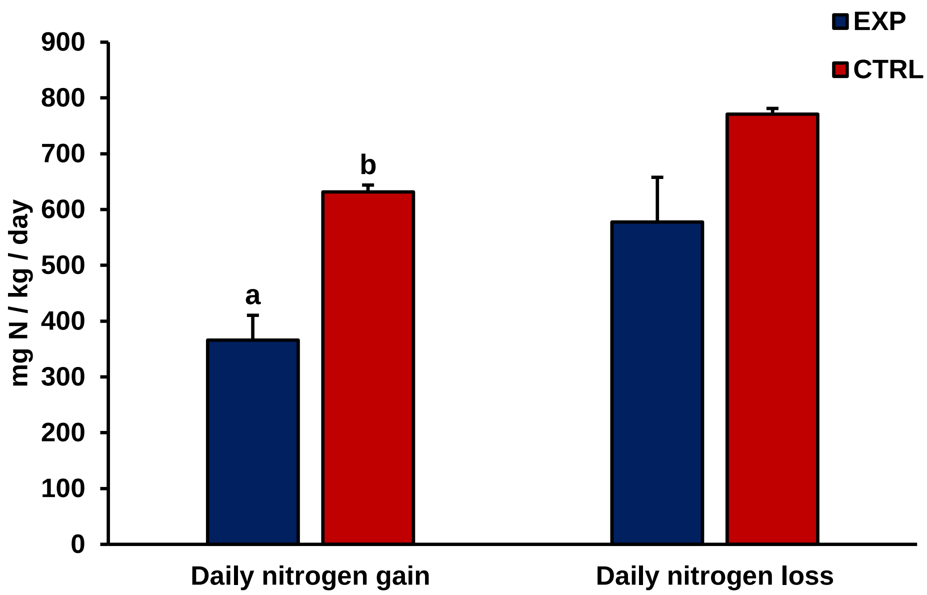

Figure 13 Daily nitrogen balance in Nile tilapia juveniles fed the Control (CTRL) or the Experimental (EXP) diet for 64 days. Values are presented as means ± standard deviation (*n* = 3). Bars with different letters differ significantly ($p < 0.05$).

4 Discussion

Community-based aquaculture is important in the production of food on undeveloped countries, with poor and isolated communities. Most of the fish feed in these countries are imported at a high cost, as already mentioned, which makes important to search and develop diets that can be made with local ingredients by the communities. Some of the local ingredients used as main protein sources included in the EXP diet have already been studied such as, peanut (Silva et al., 2017), cassava (Madalla et al., 2016; Ng & Wee, 1989; Wee & Ng, 1986), corn (Khalifa et al., 2018), and nhimba beans (Olivera-Castillo et al., 2011).

Peanut meal (PNM) is a by-product of the extraction of oil from peanuts, it is usually used to replace soybean meal in diets and has high protein content, varying from 40.1 to 50.9%. However, its protein quality is considered inferior to soybean meal, due to an imbalanced amino acid profile, specifically arginine and lysine (Batal et al., 2005). Silva et al. (2017) tested the dietary effect of different levels of PNM on growth performance of Nile tilapia (13.4 g), concluding that PNM may be added up to 11.7%, without affecting growth performance, feed efficiency and body composition. In the present work, the EXP diet had a higher inclusion of peanut (14%) that were not processed as in Silva et al. (2017) and soybean meal inclusion was reduced to 10%, which may have resulted in lower fish growth and feed utilization. It is also important to note that in this work fish were smaller than in the work of Silva et al. (2017).

Cassava can be divided into two types: roots, a good energy source, and foliage, a good protein source (Ng & Wee, 1989). Cassava root is rich in carbohydrates that may have a protein-sparing effect, which makes it a good and low-cost choice to include in diets of herbivorous/omnivorous fish to reduce the use of fishmeal (Carvalho et al., 2012; Wee & Ng, 1986). The protein content of the cassava leaves varies from 17.8% to 34.8% (Ravindran, 1992). The amino-acid profile is similar to the profile of soybean meal, the only exception is the deficiency of sulphur containing amino acids (Eggum, 1970). However, cassava leaves present a high content of antinutritional factors, hydrogen cyanide (HCN) and tannins. Wee and Ng (1986) tested different levels of cassava root meal inclusion (15%, 30%, 45%, 60%) in diets for Nile tilapia. In that study, it was reported that increased levels of dietary cassava root meal led to a better growth performance and feed utilization. Also, in all experimental tanks, phytoplankton growth occurred due to the fertilization of uneaten feed and faeces. Ng and Wee (1989) tested the nutritive value of cassava leaf meal as a dietary protein source in diets for Nile tilapia. In their work, it was not possible to include 20% of cassava leaf meal without affecting growth. However, they emphasize the fact that the experiment was done in an indoor clear water RAS, which may impair growth performance, since in an outdoor system the growth could be better due to the fertilization effect, as pointed out in previous studies (Wee & Ng, 1986). More recently, Madalla et al. (2016) tested the effect of diets with the inclusion of cassava leaf meal on growth performance of Nile tilapia, concluding that griding sun-dried leaves presented low levels of HCN and its inclusion should be less than 15% of dietary protein. Cassava root and cassava leaf inclusions in this work were of 1.0% and 13.3%, respectively. Although, the inclusion of cassava leaf was lower than in previous studies, it was also less processed, leading to similar results in terms of growth and feed utilization and to a better retention of protein (Madalla et al., 2016; Ng & Wee, 1989).

Wet milling of corn separates the kernel into starch, oil, corn gluten meal and corn gluten feed. High demand for ethanol and high fructose corn syrup, made of starch, increased the production of corn gluten meal (Wu et al., 1995). Wu et al. (1995) studied the incorporation of corn gluten meal in tilapia diets, containing 32 and 36% protein from corn and soybean meal, respectively, with and without fishmeal and soy lecithin. They concluded that is possible to use corn gluten meal in a fishmeal well balanced amino acid diet for tilapia, and that the growth performance was better compared to a commercial diet without corn. Wu et al. (2000) tested the growth performance and sensory characteristics of tilapia fed diets with 21-35% of corn gluten meal, high-lysine corn, full-fat soybean meal, and synthetic amino acids with and without fishmeal. The authors concluded that the growth performance of fish fed diets with corn gluten meal was equally good compared to those fed with a commercial diet containing fishmeal. In the present work, the EXP diet had a lower inclusion of corn (9.68 %) that was not processed. Unprocessed corn has lower protein content, which may have resulted in lower growth and feed utilization than previous studies (Wu et al., 1995, 2000).

Nhimba beans (*Vigna unguiculata*) are considered a good source of protein (CP: 21.4%, Olivera-Castillo et al., 2011). However, they contain several antinutritional factors. The whole seeds can contain tannins, phytates, trypsin inhibitors and lectin (Olivera-Castillo et al., 2011; Siddhuraju & Becker, 2007). Olivera-Castillo et al. (2011) studied the potential of nhimba beans, raw and processed, as a partial substitute of fishmeal in diets for Nilie tilapia fry (0.43 g). In the present work, growth and feed utilization were worse, despite the EXP having similar inclusion levels of nhimba beans (9.50 %). In Olivera-Castillo et al. (2011) results were higher probably due to high inclusion levels of fishmeal (52.8 %) and not using soybean meal as protein source in the diets.

In the present work, at end of the growth trial, mean body weight and length, WG and DGI of fish fed the EXP were significantly lower than fish fed the CTRL diet. In addition, fish fed EXP diet had a lower growth performance when compared with the data from previous studies with similar fish sizes (Abdel-Tawwab et al., 2010). It is important to note that, the protein content in CTRL (30.65% CP) and EXP (21.12% CP) diets was below the nutritional requirement (35-50% CP) of Nile tilapia fry (~ 0.5 g) (Abdel-Tawwab et al., 2010; Balarin & Haller, 1982). It should be notice that the EXP diet was as optimized as possible based on the resources of the Mozambican communities. This may have impaired growth performance, especially in the EXP treatment. However, regarding the condition factor and survival there were no significant differences, which means that in both treatments fish grew proportionally in the same way, indicating that although using local ingredients from communities and a lower dietary protein content the EXP diet meets the minimal requirements, ensuring fish survival and growth.

Fish fed the EXP diet and fish fed the CTRL diet did not show any significant differences in daily voluntary feed intake, at the end of the experiment. However, in the middle of the experiment (intermediate sampling) daily voluntary feed intake in fish fed the EXP was lower than fish fed the CTRL diet. This suggests that the EXP diet have lower palatability than the CTRL diet. Also, growth may have been affected by the need to adapt to the EXP diet. In further studies the CTRL diet should have less fishmeal or poultry meal due to their high palatability (Dawson et al., 2018; Hernández et al., 2010). Fish fed the EXP diet had a significantly higher FCR than fish fed the CTRL diet, which means that fish fed the EXP diet need more feed to grow the same as the CTRL treatment. The cause for a higher FCR may be the low feed intake in the first 27 days observed in fish fed the EXP diet. However, these results are still positive, since fish fed the CTRL diet had better results and fish fed the EXP diet had similar results when compared with previous studies with the same size-range (Abdel-Tawwab et al., 2010). Fish fed the EXP diet had a significantly lower PER than fish fed the CTRL diet. Which suggests that fish fed the EXP were less efficient using dietary protein that fish fed the CTRL diet at the end of the experiment. These results are not in agreement with previous studies, where it was implied that PER decreases with increasing levels of dietary protein, even when it is below the requirement (Abdel-Tawwab et al., 2010). The cause for a lower PER may be the lower protein intake in fish fed the EXP diet, that was a consequence of the lower feed intake in the first 27 days and of the low dietary protein content of the EXP diet.

Viscera and liver are important fat storage tissues (Cabral et al., 2013). There were no significant differences between both treatments in HSI and VSI. HSI values were lower than in other studies with similar dietary protein levels (Abdel-Tawwab et al., 2010), which suggests that fish used efficiently the dietary lipids.

Whole-body protein content was not significantly different between treatments. Also, protein retention in fish fed the EXP diet was not significantly different than in fish fed the CTRL diet. These results indicate that fish from both treatments were equally efficient in using dietary protein from the diets and that fish quality was similar.

At the end of the experiment, daily nitrogen intake was significantly lower in fish fed the EXP diet than fish fed the CTRL diet, which may have been due to the low feed intake in fish fed the EXP diet. Also, daily nitrogen gain was significantly lower in fish fed the EXP diet than fish fed the CTRL diet. These results, emphasize the poor growth and feed utilization. Daily nitrogen losses were not significant between treatments, but it is possible to conclude that fish fed the EXP diet (61.05 %) lost more of their nitrogen intake than fish fed the CTRL diet (54.97 %). Higher nitrogen losses are linked to low dietary protein digestibility or a higher protein catabolism (Abdel-Tawwab et al., 2010; Teodósio et al., 2020), due to dietary amino acid imbalances. The EXP diet has much lower content of all amino acids in comparison with the one from the CTRL diet, especially methionine and arginine.

The lower growth performance, feed and protein utilization of fish fed the EXP diet are probably a consequence of low protein digestibility, of the sub-lethal doses of hydrogen cyanide or of the low content of methionine and arginine. The apparent digestibility of cassava leaf and peanuts in Nile tilapia has already been studied, being low cassava leaf and high in peanuts (Tram et al. (2011). The low protein digestibility of cassava leaf could be due to various reasons. Of the total protein present in cassava meal only 85% is true protein and the remaining is non-protein nitrogen (Ravindran, 1993), which tilapias are incapable of utilizing (Madalla et al., 2016). Also, a large quantity of protein in cassava leaves is bound to neutral-detergent fibre condensed tannins, making it unavailable to digestive enzymes (Reed et al., 1982). Sub-lethal doses of hydrogen cyanide may trigger detoxification processes that tend to increase the demand for methionine (Madalla et al., 2016), which is one of the amino acids that have lower content in the EXP diet .

In summary, the EXP diet could be viable in an outdoor system due to the fertilization effect, as already mentioned (Ng & Wee, 1989; Wee & Ng, 1986). To understand better if the EXP diet would be viable for a community-based aquaculture, it would be recommended to do further experiments on growth, feed utilization, and essentially in nutrient and amino acids digestibility.

5 Conclusions

This work showed that the diet with local ingredients impaired the growth performance and feed utilization of Nile tilapia, without affecting its quality. Nevertheless, in a community-based aquaculture context, where it is used in earth ponds and it could occur the fertilization effect, this diet could be good option because it ensures the survival and growth, although more slowly. Community-based aquaculture may improve the community life quality by giving access to a higher protein intake, and in the case of production surplus, the community may sell the fish and gain access to other commodities.

It is important to note that information about some of these ingredients are scarce or non-existent. To understand better the reason for some of the negative effects, further studies on growth, feed utilization and especially on nutrient and amino acids digestibility are necessary. It would be interesting to analyse the composition of some local ingredients separately to understand if they have antinutritional factors not reported to date.

References

Abdel-Ghany, H. M., Salem, M. E.-S., Ezzat, A. A., Essa, M. A., Helal, A. M., Ismail, R. F., & El-Sayed, A.-F. M. (2021). Effects of different levels of dietary lipids on growth performance, liver histology and cold tolerance of Nile tilapia (*Oreochromis niloticus*). *Journal of Thermal Biology*, *96*, 102833. https://doi.org/https://doi.org/10.1016/j.jtherbio.2020.102833

Abdel-Tawwab, M., Ahmad, M. H., Khattab, Y. A. E., & Shalaby, A. M. E. (2010). Effect of dietary protein level, initial body weight, and their interaction on the growth, feed utilization, and physiological alterations of Nile tilapia, *Oreochromis niloticus* (L.). *Aquaculture*, *298*(3), 267–274. https://doi.org/https://doi.org/10.1016/j.aquaculture.2009.10.027

Abdelrahman, H. A., & Boyd, C. E. (2018). Effects of mechanical aeration on evaporation rate and water temperature in aquaculture ponds. *Aquaculture Research*, *49*(6), 2184–2192. https://doi.org/https://doi.org/10.1111/are.13674

Aguilar-Manjarrez, J., & Nath, S. (1998). A strategic reassessment of fish farming potential in Africa. In *CIFAA. Technical paper*. FAO.

Ateweberhan, M., Hudson, J., Rougier, A., Harris, A., Jiddawi, N., & Msuya, F. E. (2014). Community based aquaculture in the Western Indian Ocean: Challenges faced and lessons learned. *Blue Ventures Conservation*, *44*(0), 48. https://blueventures.org/publication/community-based-aquaculture-western-indian-ocean-challenges-faced-lessons-learned/

Ateweberhan, M., Hudson, J., Rougier, A., Jiddawi, N. S., Msuya, F. E., Stead, S. M., & Harris, A. (2018). Community based aquaculture in the western Indian Ocean: challenges and opportunities for developing sustainable coastal livelihoods. *Ecology and Society*, *23*(4). https://doi.org/10.5751/ES-10411-230417

Balarin, J. D., & Haller, R. . (1982). The intensive culture oftilapia in tanks, raceways and cages. In J. F. Muir & R. . Roberts (Eds.), *Recent Advances in Aquaculture* (pp. 265–356).

Batal, A., Dale, N., & Cafe, M. (2005). Nutrient Composition of Peanut Meal. *J. Appl. Poult. Res*, *14*, 254–257. https://doi.org/10.1093/japr/14.2.254

Béné, C., Arthur, R., Norbury, H., Allison, E. H., Beveridge, M., Bush, S., Campling, L., Leschen, W., Little, D., Squires, D., Thilsted, S. H., Troell, M., & Williams, M. (2016). Contribution of Fisheries and Aquaculture to Food Security and Poverty

Reduction: Assessing the Current Evidence. *World Development*, *79,* 177–196. https://doi.org/https://doi.org/10.1016/j.worlddev.2015.11.007

Bereded, N. K., Abebe, G. B., Fanta, S. W., Curto, M., Waidbacher, H., Meimberg, H., & Domig, K. J. (2021). The Impact of Sampling Season and Catching Site (Wild and Aquaculture) on Gut Microbiota Composition and Diversity of Nile Tilapia (*Oreochromis niloticus*). In *Biology* (Vol. 10, Issue 3). https://doi.org/10.3390/biology10030180

Beveridge, M. C. M., Thilsted, S. H., Phillips, M. J., Metian, M., Troell, M., & Hall, S. J. (2013). Meeting the food and nutrition needs of the poor: the role of fish and the opportunities and challenges emerging from the rise of aquaculture. *Journal of Fish Biology*, *83*(4), 1067–1084. https://doi.org/https://doi.org/10.1111/jfb.12187

Brummett, R. E., Lazard, J., & Moehl, J. (2008). African aquaculture: Realizing the potential. *Food Policy*, *33*(5), 371–385. https://doi.org/https://doi.org/10.1016/j.foodpol.2008.01.005

Burke, L., Reytar, K., Spalding, M., & Perry, A. (2011). Reefs at Risk Revisited. In *Defenders* (Vol. 74, Issue 3). http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3150666&tool=pmcentrez&rendertype=abstract

Cabral, E. M., Fernandes, T. J. R., Campos, S. D., Castro-Cunha, M., Oliveira, M. B. P. P., Cunha, L. M., & Valente, L. M. P. (2013). Replacement of fish meal by plant protein sources up to 75% induces good growth performance without affecting flesh quality in ongrowing Senegalese sole. *Aquaculture*, *380–383*, 130–138. https://doi.org/https://doi.org/10.1016/j.aquaculture.2012.12.006

Campos, I., Matos, E., Aragão, C., Pintado, M., & Valente, L. M. P. (2018). Apparent digestibility coefficients of processed agro-food by-products in European seabass (*Dicentrarchus labrax*) juveniles. *Aquaculture Nutrition*, *24*(4), 1274–1286. https://doi.org/https://doi.org/10.1111/anu.12665

Carvalho, P. L. P. F., Silva, R., Botelho, R., M. Damasceno, F., Rocha, M., & Pezzato, L. (2012). Nutritional value of root and leaves of cassava for Nile tilapia. *Boletim Do Instituto de Pesca*, *38*, 61–69.

Cinner, J. E. (2009). Poverty and the use of destructive fishing gear near east African marine protected areas. *Environmental Conservation*, *36*(4), 321–326. https://doi.org/DOI: 10.1017/S0376892910000123

Cinner, J. E. (2011). Social-ecological traps in reef fisheries. *Global Environmental*

Change, *21*(3), 835–839. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2011.04.012

Cinner, J. E., McClanahan, T. R., Graham, N. A. J., Daw, T. M., Maina, J., Stead, S. M., Wamukota, A., Brown, K., & Bodin, Ö. (2012). Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. *Global Environmental Change*, *22*(1), 12–20. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2011.09.018

Dawson, M. R., Alam, M. S., Watanabe, W. O., Carroll, P. M., & Seaton, P. J. (2018). Evaluation of Poultry By-Product Meal as an Alternative to Fish Meal in the Diet of Juvenile Black Sea Bass Reared in a Recirculating Aquaculture System. *North American Journal of Aquaculture, 80*(1), 74–87. https://doi.org/10.1002/naaq.10009

Diana, J. S. (2009). Aquaculture Production and Biodiversity Conservation. *BioScience*, *59*(1), 27–38. https://doi.org/10.1525/bio.2009.59.1.7

Eggum, B. O. (1970). The protein quality of cassava leaves. *The British Journal of Nutrition*, *24*(3), 761–768. https://doi.org/10.1079/bjn19700078

El-Sayed, A.-F. M. (2006). *Tilapia culture* (A. F. M. El-Sayed (ed.)). CABI. 277p

FAO. (2018). *The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals*. FAO. 210p

FAO. (2020). *The State of World Fisheries and Aquaculture 2020. Sustainability in action.* https://doi.org/https://doi.org/10.4060/ca9229en 206p

FAO. (2021). *Global Aquaculture Production 1950-2019*. http://www.fao.org/figis/servlet/TabLandArea?tb_ds=Aquaculture&tb_mode=TABLE&tb_act=SELECT&tb_grp=COUNTRY

Gatlin III, D. M., Barrows, F. T., Brown, P., Dabrowski, K., Gaylord, T. G., Hardy, R. W., Herman, E., Hu, G., Krogdahl, Å., Nelson, R., Overturf, K., Rust, M., Sealey, W., Skonberg, D., J Souza, E., Stone, D., Wilson, R., & Wurtele, E. (2007). Expanding the utilization of sustainable plant products in aquafeeds: a review. *Aquaculture Research*, *38*(6), 551–579. https://doi.org/https://doi.org/10.1111/j.1365-2109.2007.01704.x

Graaf, G. J., Galemoni, F., & Huisman, E. A. (1999). Reproductive biology of pond reared Nile tilapia, *Oreochromis niloticus* L. *Aquaculture Research*, *30*(1), 25–33. https://doi.org/https://doi.org/10.1046/j.1365-2109.1999.00295.x

Hernández, C., Olvera-Novoa, M. A., Hardy, R. W., Hermosillio, A., Reyes, C., & González, B. (2010). Complete replacement of fish meal by porcine and poultry by-product meals in practical diets for fingerling Nile tilapia *Oreochromis niloticus*: digestibility and growth performance. *Aquaculture Nutrition*, *16*(1), 44–53. https://doi.org/https://doi.org/10.1111/j.1365-2095.2008.00639.x

Hlophe-Ginindza, S. N., Moyo, N. A. G., Ngambi, J. W., & Ncube, I. (2016). The effect of exogenous enzyme supplementation on growth performance and digestive enzyme activities in *Oreochromis mossambicus* fed kikuyu-based diets. *Aquaculture Research*, *47*(12), 3777–3787. https://doi.org/https://doi.org/10.1111/are.12828

Hlophe, S. N., & Moyo, N. A. G. (2014). Replacing Fishmeal with Kikuyu Grass and Moringa Leaves: Effects on Growth, Protein Digestibility, Histological and Haematological Parameters in *Clarias gariepinus*. *Turkish Journal of Fisheries and Aquatic Sciences*, *14*(3), 795–806. https://doi.org/10.4194/1303-2712-v14_3_22

IDC/Urban-Econ. (2015). Research into the potential for the production, processing and export of tilapia for the Southern African market. In *Final Report* (p. 122).

Khalifa, N. S. A., Belal, I. E. H., El-Tarabily, K. A., Tariq, S., & Kassab, A. A. (2018). Evaluation of replacing fish meal with corn protein concentrate in Nile tilapia *Oreochromis niloticus* fingerlings commercial diet. *Aquaculture Nutrition*, *24*(1), 143–152. https://doi.org/https://doi.org/10.1111/anu.12542

Madalla, N., Agbo, N., & Jauncey, K. (2016). Evaluation on ground-sundried cassava leaf meal as protein source for Nile Tilapia, *Oreochromis niloticus* (L) juvenile's diet. *Journal of Agriculture and Veterinary Sciences*, *15*, 1–12.

Maina, J., Venus, V., McClanahan, T. R., & Ateweberhan, M. (2008). Modelling susceptibility of coral reefs to environmental stress using remote sensing data and GIS models. *Ecological Modelling*, *212*(3), 180–199. https://doi.org/https://doi.org/10.1016/j.ecolmodel.2007.10.033

Moyo, N. A. G., & Rapatsa, M. M. (2021). A review of the factors affecting tilapia aquaculture production in Southern Africa. *Aquaculture*, *535*, 736386. https://doi.org/https://doi.org/10.1016/j.aquaculture.2021.736386

Ng, W.-K., & Romano, N. (2013a). A review of the nutrition and feeding management of farmed tilapia throughout the culture cycle. *Reviews in Aquaculture*, *5*, 220–254. https://doi.org/10.1111/raq.12014

Ng, W.-K., & Romano, N. (2013b). A review of the nutrition and feeding management of farmed tilapia throughout the culture cycle. *Reviews in Aquaculture*, *5*(4), 220–254. https://doi.org/https://doi.org/10.1111/raq.12014

Ng, W. K., & Wee, K. L. (1989). The nutritive value of cassava leaf meal in pelleted feed for Nile tilapia. *Aquaculture*, *83*(1), 45–58. https://doi.org/https://doi.org/10.1016/0044-8486(89)90059-8

Olivera-Castillo, L., Pino-Aguilar, M., Lara-Flores, M., Granados-Puerto, S., Montero-Muñoz, J., Olvera-Novoa, M. A., & Grant, G. (2011). Substitution of fish meal with raw or treated cowpea (*Vigna unguiculata* L Walp, IT86-D719) meal in diets for Nile tilapia (*Oreochromis niloticus* L.) fry. *Aquaculture Nutrition*, *17*(2), e101–e111. https://doi.org/https://doi.org/10.1111/j.1365-2095.2009.00739.x

Rakocy, J. E. (2009). *Oreochromis niloticus (Linnaeus, 1758)*. Cultured Aquatic Species Fact Sheets. www.fao.org/tempref/FI/DOCUMENT/aquaculture/CulturedSpecies/file/en/en_niletilapia.htm

Rapatsa, M. M., & Moyo, N. A. G. (2017). Evaluation of Imbrasia belina meal as a fishmeal substitute in Oreochromis mossambicus diets: Growth performance, histological analysis and enzyme activity. *Aquaculture Reports*, *5*, 18–26. https://doi.org/https://doi.org/10.1016/j.aqrep.2016.11.004

Ravindran, V. (1992). Preparation of cassava leaf products and their use as animal feeds. *FAO Animal Production and Health Paper*, *95*, 111–125.

Ravindran, V. (1993). Cassava leaves as animal feed: Potential and limitations. *Journal of the Science of Food and Agriculture*, *61*(2), 141–150. https://doi.org/https://doi.org/10.1002/jsfa.2740610202

Reed, J. D., McDowell, R. T. E., van Soest, P. J., & Horvath, P. R. J. (1982). Condensed tannins: A factor limiting the use of cassava forage. *Journal of the Science of Food and Agriculture*, *33*(3), 213–220. https://doi.org/https://doi.org/10.1002/jsfa.2740330302

Siddhuraju, P., & Becker, K. (2007). The antioxidant and free radical scavenging activities of processed cowpea (*Vigna unguiculata* (L.) Walp.) seed extracts. *Food Chemistry*, *101*(1), 10–19. https://doi.org/https://doi.org/10.1016/j.foodchem.2006.01.004

Silva, R., M. Damasceno, F., Rocha, M., Sartori, M. M., Barros, M., & Pezzato, L. (2017). Replacement of soybean meal by peanut meal in diets for juvenile Nile tilapia, *Oreochromis niloticus*. *Latin American Journal of Aquatic Research*, *45*, 1044–1053. https://doi.org/10.3856/vol45-issue5-fulltext-19

Teodósio, R., Engrola, S., Colen, R., Masagounder, K., & Aragão, C. (2020). Optimizing diets to decrease environmental impact of Nile tilapia (*Oreochromis niloticus*) production. *Aquaculture Nutrition*, *26*(2), 422–431. https://doi.org/https://doi.org/10.1111/anu.13004

Tram, N. D. Q., Ngoan, L. D., Hung, L. T., & Lindberg, J. E. (2011). A comparative study on the apparent digestibility of selected feedstuffs in hybrid catfish (*Clarias macrocephalus* × *Clarias gariepinus*) and Nile tilapia (*Oreochromis niloticus*). *Aquaculture Nutrition*, *17*(2), e636–e643. https://doi.org/https://doi.org/10.1111/j.1365-2095.2010.00813.x

Troell, M., Hecht, T., Beveridge, M., Stead, S., Bryceson, I., Kautsky, N., Ollevier, F., & Mmochi, A. (2011). *Mariculture in the WIO region " Challenges and Prospects "* (Book Series No 11). WIOMSA. 59p

Troell, M., Naylor, R. L., Metian, M., Beveridge, M., Tyedmers, P. H., Folke, C., Arrow, K. J., Barrett, S., Crépin, A.-S., Ehrlich, P. R., Gren, Å., Kautsky, N., Levin, S. A., Nyborg, K., Österblom, H., Polasky, S., Scheffer, M., Walker, B. H., Xepapadeas, T., & de Zeeuw, A. (2014). Does aquaculture add resilience to the global food system? *Proceedings of the National Academy of Sciences*, *111*(37), 13257 LP – 13263. https://doi.org/10.1073/pnas.1404067111

Wee, K. L., & Ng, L. T. (1986). Use of cassava as an energy source in a pelleted feed for the tilapia, *Oreochromis niloticus* L. *Aquaculture Research*, *17*(2), 129–138. https://doi.org/https://doi.org/10.1111/j.1365-2109.1986.tb00094.x

Wu, Y. V., Rosati, R. R., Sessa, D. J., & Brown, P. B. (1995). Evaluation of Corn Gluten Meal as a Protein Source in Tilapia Diets. *Journal of Agricultural and Food Chemistry*, *43*(6), 1585–1588. https://doi.org/10.1021/jf00054a032

Wu, Y. V., Warner, K., Rosati, R., & Brown, P. (2000). Growth, feed conversion, protein utilization, and sensory evaluation of Nile tilapia fed diets containing corn gluten meal, full-fat soy, and synthetic amino acids. *Journal of Aquatic Food Product Technology*, *9*(1), 77–87. https://doi.org/10.1300/J030v09n01_07