Tanzania Journal of Science 45(3): 355-371, 2019 ISSN 0856-1761, e-ISSN 2507-7961


# The Need of a Structured Tilapia Breeding Program in Tanzania to Enhance Aquaculture Production: A Review

**Redempta A Kajungiro [1,2], Levinus L Mapenzi[3,4], Christer S Nyinondi[1,3], Anna Norman Haldén[6], Aviti J Mmochi[3], Mwita Chacha [2], Matern SP Mtolera[3], Hieromin A Lamtane[5], and Dirk Jan de Koning[1*]**

*[1]Department of Animal Breeding and Genetics, Swedish University of Agricultural Sciences, P. O. Box 7023, Uppsala, Sweden.*
*[2]Department of Aquatic Sciences and Fisheries Technology, University of Dar es Salaam, P. O. Box 60091, Dar es Salaam, Tanzania.*
*[3]Institute of Marine Sciences, University of Dar es Salaam, P. O. Box 668, Zanzibar, Tanzania.*
*[4]Department of Biology, University of Dodoma, P. O. Box 338, Dodoma, Tanzania.*
*[5]Department of Animal, Aquaculture and Range Sciences, Sokoine University of Agriculture, P. O. Box 3004, Morogoro, Tanzania.*
*[6]Department of Biomedical Sciences and Veterinary Public Health, Swedish University of Agricultural Sciences, P. O. Box 7084, Uppsala, Sweden.*
**Corresponding author; e-mail address: dj.de-koning@slu.se*
*E-mail addresses of co-authors: srahmy40@yahoo.co.uk (Kajungiro); mwitachacha@udsm.ac.tz (Chacha); avitimmochi@gmail.com (Mmochi); mtolera@ims.udsm.ac.tz (Mtolera); christer.simon@yahoo.com (Nyinondi); levinus@yahoo.com (Mapenzi); hlamtan@suanet.ac.tz (Lamtane)and anna.norman-halden@slu.se (Haldén)*

## Abstract

Breeding programs are crucial for boosting productivity and increase sustainability of aquaculture. Over years, Tanzania has witnessed fluctuation in its capture fisheries production from 320,900 to 375, 535 and back to 362,595 metric tonnes in the years 2000, 2005 and 2016, respectively (URT 2016). The declining trend in fish production has made fish supply in the country unstable and conversely, increased the demand for fishes to about 730,000 metric tonnes in 2017. However, the local aquaculture production has not increased accordingly. Tanzania is importing fish mainly from Asia to meet its increased demand. In 2017, a total of 2,055,721 kg of frozen tilapia were imported from China and Mozambique (URT 2017). The introduction of exotic fish species in Tanzania should be carefully managed because introduced species have many negative impacts on the indigenous species. Tanzania should have a moderate scale tilapia breeding program that will produce good quality fingerlings at affordable prices for smallholder fish farmers. The availability of reliable good quality fingerlings is key to improve aquaculture production in the country. Among 17 existing hatcheries, only 12 hatcheries are active; however these hatcheries are not performing well due to low investment and technology, leading to the production of low quantity and quality fingerlings. The need for a structured sustainable Tilapia breeding program with bio secured and reliable hatcheries to enhance aquaculture production in Tanzania is put forward in this review.

**Keywords:** Aquaculture, Breeding programs, Nile tilapia, Local strains.

## Introduction

Aquaculture is an important sector which contributes to food security and income generation (FAO 2018, Rothuis et al. 2014), poverty reduction and provide nutritional benefits in developing countries (Allison 2011). Since the late 1980s, capture fishery production has not changed much (Figure 1) while aquaculture continues at an increasing trend contributing 47% of total global fish production (FAO 2018). Globally, aquaculture has become the major food production responsible for supplying fish for human consumption (FAO 2018). Aquaculture in Tanzania is mainly practiced at small scale in earthen ponds (Shoko et al. 2011), largely in extensive and semi-intensive farming systems. Inland fresh water aquaculture, dominated by mainly tilapia species such as Nile tilapia (*Oreochromis niloticus*) (Figure 2) while other common fish species cultured include African catfish (*Clarias gariapinus*). The number of earthen fish ponds for catfish and tilapia have increased from 24,302 in 2017/2018 producing 14,800 tonnes to 26,445 fish ponds in 2018/2019 producing 18,081.6 tonnes with the addition of fish production from 408 fish cages in lakes (L. Victoria and L. Tanganyika) and ponds (Malambo) (URT 2019). Despite the increase in production but still the supply is low to meet the current demand of 750,000 tonnes of fish in the country (URT 2019).

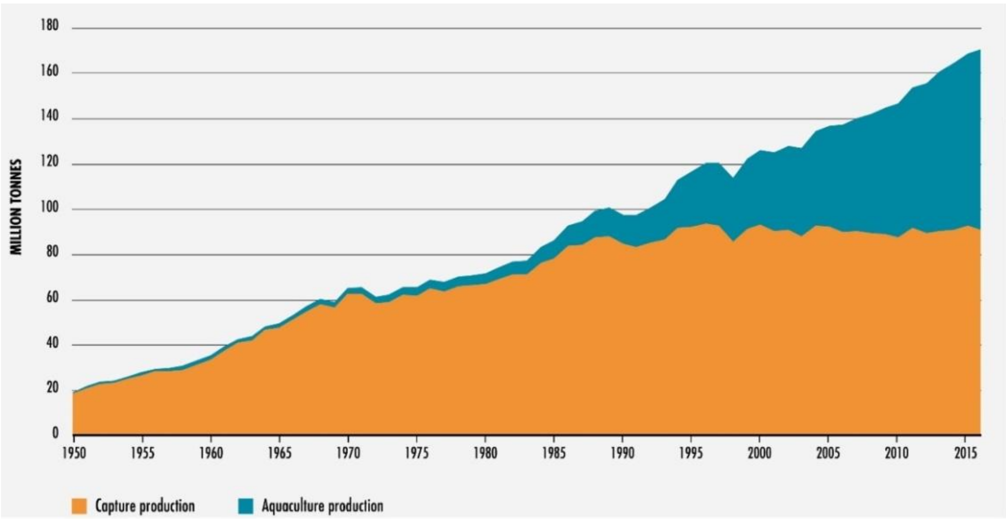


**Figure 1:** The development of global fish production until 2015 (Source: FAO 2018).

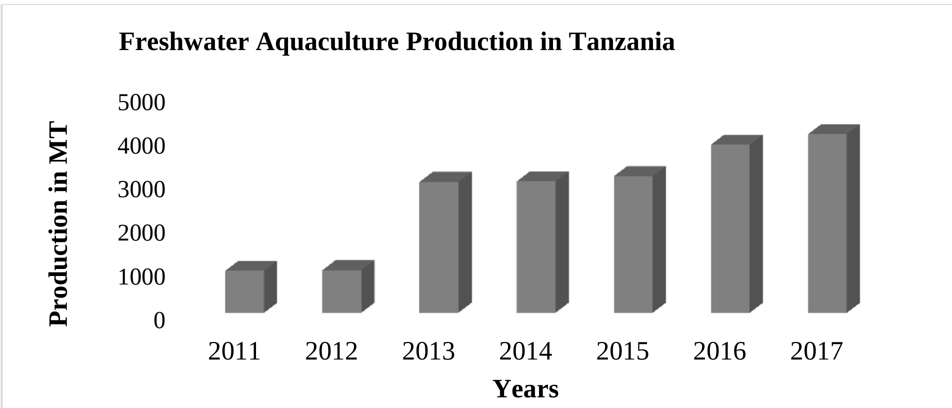


**Figure 2:** Trend of freshwater aquaculture production in Tanzania mainland from 2011-2017 (Source: URT 2017).

With the development of aquaculture in Tanzania, a total of 17 hatcheries have been established, seven public and 10 private owned hatcheries for tilapia, catfish and mariculture production (URT 2019). Catfish and tilapia fingerlings production for both private and public hatcheries have increased from 3,039,775 in 2017/2018 to 6,221,076 fingerlings in 2018/2019 (URT 2019). Mariculture is dominated by mainly seaweeds from Zanzibar islands (Msuya et al. 2016) and the production has increased from 1,197.5 tonnes in 2016/2017 to 1,329.9 tonnes in 2017/2018 (URT 2018). Nile tilapia (*O. niloticus*) is the most important cultured species in Tanzania (Shechonge et al. 2018b). This is because the species has a short generation time, fast growth, tolerance to a wide range of environmental conditions, resistance to stress and disease, ability to reproduce in captivity, and acceptance of artificial feeds right after yolk-sac absorption (Costa-Pierce 2003, Vicente and Fonseca-Al 2013, Ansah et al. 2014). Based on these attributes, the species has been used for breeding programs in other countries and is important for low-input aquaculture production (Ansah et al. 2014). Although Nile tilapia has characteristics which are well-suited for culturing in developing countries, they tend to mature early especially when cultured in ponds and spawn before they reach market sizes (Nkhoma and Musuka 2014). Because of early sexual maturity and high fecundity, they produce large number of small fry that leads to overcrowding and "stunting" where adult fish can sometimes mistakenly be stocked as fingerlings (Shoko et al. 2016). Early sexual maturation has disappointed many fish farmers in Tanzania leading to some farmers, government and private owned hatcheries importing Nile tilapia fingerlings and brood stock from neighbouring countries, i.e., Kenya, Uganda, and Zambia or even further afield from Thailand, believing that they would perform better than native species (Rukanda 2018, Shechonge et al. 2018a). Most of these imports are illegal and put the country at the risk of genetic pollution and introducing diseases.

Aquaculture in Tanzania is currently developing in good pace but still cannot cope with the increase in demand for fish and fish products. Consumers want a good flavoured strain and it has been reported that many consumers prefer red tilapia over Nile tilapia because of fewer problems with off-flavour (Lovshin 2000). Tanzanian consumers are diverse in their preference for all the tilapia features. They prefer fresh, wild, medium (400-600 g) and large (> 600 g) sized tilapia over smoked, farmed, and small (150-400 g) sized tilapia, respectively (Darko et al. 2016). Middle and high-income consumers (and hotels and restaurants) can afford the large sized fish while low-income households cannot (Rothuis et al. 2014). Consumers' preferences for large sized tilapia can be met by improving the quality of farmed strains of tilapia through genetic improvement.

Currently, there are 12 active tilapia hatcheries in the country that are either government (3) or privately (9) owned (Table 1) which produce fingerlings for distribution to the local farmers. For all the visited hatcheries, there were no biosecurity restriction rules and practices to minimize the risk of contamination. Moreover, the capacities of those hatcheries are still inadequate (Table 1) due to low level of investment and limited electric power supply (Rukanda 2018). Additionally, the number of fingerlings produced is lower compared to the demand. The current estimated demand is 40,000,000 fingerlings, yet the supply is still low; about 21,173,226 fingerlings per year (URT 2019). Also, the training and research institutions such as Tanzania Fisheries Research Institute (TAFIRI), Sokoine University of Agriculture (SUA), and Fisheries Education and Training Agency (FETA) serve as fingerling producers and distributers to fish farmers. These centres still face many challenges including the production of poor quality fingerlings due to mixed species and lack of reliable hatcheries, poor government support, and lack of experts in feed formulation and breeding. Feed experts need to know the feed materials, developmental stage of the fish and the nature of the pond (fertilized or unfertilized) before the feed can be formulated. Parent stock and fingerlings have different nutrient requirement, for example fingerlings need higher protein (40-45%) than older fish (Hänninen 2014). Nevertheless, sustainable development of the aquaculture sector requires all potential players to be pro-active and collaborate. These include feed manufacturers, fish farms entrepreneurs, aquaculture experts, and government agencies (Rothuis et al. 2014). Many attempts to improve aquaculture production in Tanzania failed due to poor husbandry, low technology and insufficient long-term funding.

Despite the availability of reliable water from lakes, rivers and 30% of land valued potential for aquaculture (Shoko et al. 2011), Tanzanian aquaculture production is far from optimal. Therefore, a structured breeding program is required to increase food production without further negative impacts to the native germline. Tanzania being a hotspot of biodiversity of about 30 species of tilapia including *O. niloticus* (Di Palma 2017), the importance of having a sustainable aquaculture production as a solution for conserving this diversity cannot be underestimated .

**Table 1:** Number of hatcheries and production capacity per year 2018/2019 in Tanzania

| Owner | Fish species | Hatchery name | Location (District, Region) | | Capacity |
|---|---|---|---|---|---|
| Public | Tilapia | Kingolwira | Morogoro | | 1,200,000 |
| | | Ruhila | Songea, Ruvuma | | 840,000 |
| | | Mwamapuli | Igunga, Tabora | | 120,000 |
| | | | | **Total** | **2,160,000** |
| Private | Tilapia | Ruvu Fish Farm | Bagamoyo, Pwani | | 2,400,000 |
| | | Big Fish | Dar es salaam | | 2,400,000 |
| | | Eden Agri Aqua | Dar es Salaam | | 2,400,000 |
| | | Indian ocean | Kibiti, Pwani | | 1,440,000 |
| | | Jans Aqua | Dar es salaam | | 960,000 |
| | | JUDASA | Dar es Salaam | | 960,000 |
| | | Mpanju Farm | Ilemela, Mwanza | | 1,440,000 |
| | | Shazein | Arusha | | 1,440,000 |
| | | Rofacol | Kyela, Mbeya | | 1,440,000 |
| | | | | **Total** | **14,880,000** |

(Source URT 2019).

**Methodology**

This review was based on literature, field visits and interviews. For the literature, we used published journal articles and reports, government documents such as reports and speech budget from the Ministry of Livestock and Fisheries Tanzania, a desk review, workshops and 'Google Scholar' with the search terms breeding programs, hatchery, tilapia, etc. For the field study, we visited seven hatcheries and 10 fish farms located in Kagera, Mwanza, Kilimanjaro, Mbeya, Dar es Salaam, Morogoro and Pwani regions. During the visits we asked about species cultured, sources of fingerlings, farm productivity, and techniques used to get farmed seeds and farm management practices. For the interview, we interviewed 10 fish farmers, seven hatchery owners, five scientists from training and research institutions and three policy makers from the Ministry of Livestock and Fisheries. Here we wanted to understand the role of the government in fish farming, the knowledge gaps and the challenges encountered.

**Why a Structured Tilapia Breeding Program in Tanzania?**

Tanzania has a high diversity of tilapia species with great ability to interbreed leading to fertile hybrids (Shechonge et al. 2018b). Culturing mixed sex of these species has resulted into slow growth because of early maturity and overcrowding, leading the fish to spawn before reaching market size and harvest weight (Shoko et al. 2016). Some fish farmers depend on the available hatcheries in the country (Table 1) as source of fingerlings while most of them are still collecting fingerlings from the wild, which are of poor quality because they often collect mixed species. This is considered unsustainable for aquaculture development because poor quality fingerlings result into poor harvests. Furthermore, the similarity between different tilapia species at the fingerling stage increases the probability of mixed stocks in production ponds, which may not result into expected profitable production.

Male tilapias are the desired sex for culture because they grow faster (Ferdous et al. 2014), since they divert less energy to reproduction (Phelps and Popma 2000). Pressure from consumers has compelled some producers to practice hormonal sex reversal using 17-α methyl testosterone to produce all-male tilapias. However, hormonal sex reversal is expensive (Shoko et al. 2016) and this has been a challenge to the farmers as they cannot afford to purchase hormones. Moreover, using hormonal treatment requires experts and well established hatcheries to ensure right quantities are applied to fish and to avoid possible impacts on humans and the environment. Also, fish farmers are concerned about fish treated with hormones and consumers' preference (Dergal et al. 2016). Other techniques for controlling mixed sex tilapia have been applied in aquaculture production, such as: polyculture, manual sorting (Forgako 2018) and hybridization (Bartley et al. 2001, Beardmore et al. 2001). Experiments for producing all-male hybrid tilapia production have been done in Tanzania. Mapenzi and Mmochi (2016) reported that hybridization between *O. niloticus* and *O. urolepis hornorum* showed better growth results producing 100% all males. This finding gives the basis for a prospective sustainable tilapia breeding program in Tanzania.

Currently, most cultured species in Tanzania are a mixture of tilapia species and their hybrids (Shechonge et al. 2018b), rather than a pure single species. Therefore, it is difficult to obtain higher production returns from aquaculture because species in practice are unknown so their management is difficult and genetic improvement is impossible. For those reasons, there is a need for developing a sustainable and well-maintained breeding program for aquaculture improvement in the country. A selective breeding program for production of better performing tilapia in Tanzania is important for providing good quality fingerlings and brood stock, aquaculture enhancement, nutritional supply, food security, employment, poverty eradication, and adaptation to impacts of climate change. A breeding program is expected to improve aquaculture production in the whole country by 1) providing a clear understanding of loci affecting the trait of the cultured species using molecular techniques, 2) producing good quality seed from domesticated brood stock and not depending on wild collected seed and brood stock, and 3) good management and proper record keeping for brood stock.

**Consideration for Introductions of Improved Tilapia Strains in Tanzania**

Introduced species, exotic species, alien species, non-native species, and non-indigenous species have the same biological significance (Simberloff 2013). Introduced species mean any species carried and arrived with human assistance out of their natural environments on purpose or accidently

(Vicente and Fonseca-Al 2013). In Tanzania, this is an old practice since Nile tilapia was introduced to the Lake Victoria in the 1950s from Lake Edward for sport fishing and to enhance the declining fisheries (Njiru et al. 2005, Shechonge et al. 2018a). The Nile tilapia, *O. niloticus* is an African cichlid native to the Nile delta, coastal rivers of Israel, and the Niger, Benue, Volta, and Senegal rivers, Chad basin, as well as lakes Tanganyika, Albert, Edward, and Kivu (Trewavas 1983). In Tanzania, Nile Tilapia (*O. niloticus )* is native to Lake Tanganyika (Shechonge et al. 2018a). The introduced *O. niloticus* strain from Lake Victoria has been a species of choice for aquaculture across the country.

Introduced strains can escape in the natural environment and compete for space and food with native species and lead to the extinction and endangerment of native species population (Canonico et al. 2005). Genetically improved Tilapia strains like Genetically improved Farmed Tilapia (GIFT) have been selectively bred for disease resistance (Acosta and Eknath 1998), and are highly resistant to certain diseases. However, GIFT may still carry the diseases (Jansen et al. 2018) when moving from their breeding environment to another area during the dissemination process. Introduction of genetically improved Nile tilapia strains in Tanzania can result into the introduction of new alleles through hybridization. There is evidence of hybridization between native and introduced *Oreochromis* species in different catchments of Tanzania. Examples of such hybridization are found in Lake Victoria catchment where introduced species *O. niloticus* and *O. esculentus* hybridized with native *O. esculentus*, *O. variabilis* and *O. urolepis* (Turner et al. 2017)**.** The situation can result into decline of population size of indigenous species and decrease genetic diversity.

To meet the increased fish demand, fish farmers are considering the introductions of genetically improved tilapia strains as an alternative for providing good quality fingerlings. Private hatcheries owners such as Eden, Big Fish and Mbarali farms stated that wild collected brood stocks and seeds are obstacles to aquaculture development because of mixed tilapia species in the wild, hence preferred to use already improved strains from abroad. Already genetically improved strains such as GIFT from Worldfish Centre in Malaysia, Akosombo strain from Ghana, and Abbasa strain from Egypt have proven to perform better by growing faster than local African tilapia strains (Ansah et al. 2014). Medium to large-scale fish producers are introducing other strains of tilapia fingerlings in Tanzania from neighbouring countries. Surveyed fish farms in Tanzania confirmed importation of tilapia strains such Chitralada strain of *O. niloticus* from Asian Institute of Technology (AIT) in Thailand (Shechonge et al. 2018a), while others imported unknown strains of tilapia from Uganda and Nam Sai Farms in Thailand (Pers. Comm). One farm imported YY-Male Silver (wild type) and red strain of tilapia from Til-Aqua International in Netherlands (Pers. Comm). Whether these introductions are legal with all the required permits and certificates or illegal, they still pose a threat to native species since it is not certain if the introduced strains are pure *O. niloticus*, hybrids, genetically improved strains of Nile tilapia, or other tilapia species.

There is a debate whether a tilapia breeding program in Tanzania should use local species or improved strains. In 2011, Kenya initiated a selective breeding program for Nile tilapia at the National Aquaculture Research Development and Training Centre (NARDTC) in Sagana. The program started with a base population formed from locally available strains (Omasaki 2017). The Nile tilapia breeding program which aimed at improving growth and survival was successful and currently they are at the F7 generation (Nyonje et al. 2018). In Egypt and Ghana, Abbassa and Akosombo strains, respectively were improved from local strains through selective breeding programs (Worldfish Center 2012). Breeding programs for Nile Tilapia in those countries have been successful and can be used as a model for Tanzania to establish a Nile tilapia breeding program.

Before opting for introductions of improved strains in Tanzania to increase the aquaculture production, conservation of indigenous species should be taken into consideration. The use of improved strains from other countries could be a threat to native tilapia populations in Tanzania and can result in reduction of alleles which have great importance for future selective breeding programs (Brummett 2013). At present, there is inadequate information whether pure or nearly pure populations of all native species still exist. Furthermore, it is not known if farmed tilapia species are exotic *O. niloticus*, native tilapia species, hybrids or genetically improved strains. An on-going study in Tanzania on tilapia ecology, genetic diversity and conservation has not yet provided enough information to allow or consider the introductions of new genetically improved Nile tilapia strains in the country.

It should be understood that moving genetically improved strains from their optimal environment for aquaculture to other places can result into negative effects on natural ecosystems and on the growth performance of the strain (Devlin et al. 2015). Environmental changes regulate genes. Differences in the environmental parameters such as photoperiod, temperature and production systems can influence the growth performance of fish and may create the situation known as genotype by environment interaction (G × E) (Bangera et al. 2015). G x E occurs as a result of differences in the responsiveness of individuals to the production environments (Mulder and Bijma 2005). G x E can be exhibited in two forms: re-ranking of individuals and heterogeneity of variances make phenotypic performance in one production environment to differ from other environments (Sae-Lim et al. 2013). Therefore, due to G x E interaction, the introduced genetically improved strains may not perform well in some environments. Luan et al. (2008) reported strong G × E interaction for harvest weight and survival in Nile tilapia GIFT strain cultured in the fresh and brackish water ponds. In the presence of G x E interaction, the breeding program should be optimised for the production environment. If there are different production environments, it may be economically infeasible to have lines specifically targeted for each environment. The best option then is to select the most robust fish that show the lowest G x E. Omasaki et al. (2016) suggested that breeding programs for Nile tilapia must include more sib information from production environments when culturing hormone mediated mono-sex fish for accurate estimation of breeding values.

## Breeding Program

### The concept

The science of applied selective breeding and genetics has contributed greatly to the gradually increase in productivity in animal and plants husbandry (Gjerde and Rye 2010). While in agriculture the high yields are almost entirely based on genetically improved breeds, in aquaculture supply is mainly based on wild population (Subasinghe et al. 2009). Genetic variability of fish held in African hatcheries is reported to be 40-70% less and growth rates 12-40% less than wild stocks (Morissens et al. 1996, Pouyaud and Agnèse 1996, Ambali et al. 1999). Therefore, increased aquaculture production is linked to the genetic quality of the brood stocks available to meet that increasing demand. There are several fish breeding programs that have been successful such as GIFT, Genetically Enhanced Tilapias for Excellence (GET-EXCEL), FAC Selected Tilapia (FaST), GenoMar Supreme Tilapia (GST), Abassa, and Akosombo strain for Nile tilapia (Ponzoni et al. 2008, Ansah et al. 2014), Atlantic salmon (Jonsson and Jonsson 2017); and rainbow trout (Janssen et al. 2015, Sae-Lim and Mulder 2016). However, these programs are yet to sustain the global demand of fish and fish products. Therefore, more breeding programs should be developed, limitations and challenges such as financial resources and human capacity (Ponzoni et al. 2009) facing the successful ones should be explored.

At present, aquaculture is mainly small scale in most African countries and facing many challenges. Developing a tilapia strain like GIFT or one of several other similar lines that grow 40-60% faster than the typical farm populations can make the difference. Currently in Tanzanian fish markets, just like in many other African countries, there are large numbers of imported fish from Asia, mostly China (Olingo 2018, Okai 2019). These imported frozen tilapia outcompete the local tilapia due to their low prices.

In Tanzania, hatcheries are operating without a properly planned breeding program. Poorly managed hatcheries produce poor quality and "stunted" fingerlings as a result of high levels of inbreeding. Most of the hatcheries in Tanzania are privately owned while the government owned hatcheries are not performing well due inadequate infrastructures and limited financial resources from the government.

Before starting up a breeding program, the institutions developing a program in Tanzania should consider the target beneficiaries and the strain(s) they want to improve. A tilapia breeding program in Tanzania should aim at helping fish farmers to develop a fast growing strain with high resistance to environmental stressors and diseases.

**The steps necessary to establish a breeding program**

For any genetic improvement program, the following are some prerequisites:

**Description of the production system**

The production system should be defined, whether it is polyculture, intensive, semi-intensive or recirculating. The breeding program should be tailored to the farming systems being practiced. In Tanzania the production system is mainly semi-intensive mostly done in earthen ponds and currently there are no intensive systems in place.

**Choice of the species or strain**

Species or strains to be used in the breeding program should be known. The local strains can be used to form a base population for the breeding program, for example, *O. niloticus* strain has proved to grow up to 250-350 g in six months when they are not improved (Meiludie 2013). Once they are genetically improved, they can grow even faster. It is therefore recommended to use locally available strains and compare their performance with already improved strains like GIFT. The most important precaution is to use local strains available in the region. The local strains of tilapia or other improved strains with high genetic variations for the traits of interest can be used to form a breeding population.

**Formulating the breeding objectives**

It is important to know the objective of the breeding program since it defines the traits of interest to farmers. Surveyed fish farmers in Tanzania mentioned growth rate to be the most important trait because a faster growing fish will reach harvest weight earlier at lower feeding costs (Gjedrem 2005). Tanzanian fish farmers can choose to start with growth, which contribute to profit and is economically valuable. In the future, growth may be combined with other attributes that affect profit. Growth rate is more correlated with other traits, so that selecting for growth rate can lead to gains in other traits. In many species, growth rate is positively correlated to increase feed conversion efficiency (Ponzoni et al. 2008, Trọng et al. 2013). The other important traits are harvest weight, fecundity and survival rate. It is advised not to include more than six traits in the breeding goal in order to ensure sufficient genetic progress.

**Selection criteria**

Selection traits used need to be checked to ensure that they are in line with the breeding goal. Not all traits in the breeding objective can be measured directly, but correlated traits can be measured instead. For instance, farmers prefer growth rate as an important trait to improve, but in practice we can select for body weight at a given age (at harvest). Furthermore, indicator traits can be selected instead of the traits in the breeding objective. For example length in fish can be used as indicator of weight. Traits used as selection criteria are associated with the traits in breeding objective through genetic co-variances and can be used in estimation of breeding values ( Ponzoni et al. 2006).

**Designation of genetic evaluation**

Genetic evaluation system, depending on heritability of the breeding goal traits, can vary from least costly and most rapid response like mass selection and between family selection to more complex and more costly approaches such as within family selection, combined selection or genomic selection. Mass selection is based on individual phenotypic performance and can be for one or few traits. Within family selection require individual identification and is based on an individual's performance and its relationship with other relatives in the pedigree. Families can be reared in tanks or hapas where inbreeding can be easily controlled. Within family selection is very effective but needs more infrastructures. Combined selection is the best method; more efficient but more expensive (Farias et al. 2017). Selection method which is efficient, with reduced inbreeding and less costly could be applied in the proposed tilapia breeding program in Tanzania.

There can be family based breeding programs at a central location in Tanzania where fish are individually identified, measured, and selected. The breeding generations from this nucleus can be distributed to hatcheries where the genetic variation is maintained, and additional genetic progress can be obtained, using a cohort mating system. Such an approach means that the breeding nucleus can aim for a new breeding generation every few years but it not concerned with the supply of fingerlings to the industry. Likewise, the use of a cohort mating approach at the hatcheries means that their broodstock can act as a back-up for the breeding nucleus. This becomes highly relevant when the nucleus suffers a disease outbreak or other catastrophe that leads to loss of the fish in the nucleus. Also in a scenario where exotic lines are used a brood stock, local hatcheries could maintain a cohort mating system to reduce inbreeding and to reduce the need for import of new improved strains over time.

**Breeding population and mating scheme**

Starting a breeding program with a small population results into uncertain response to selection and potentially a high inbreeding level. With a large population response to selection is high and inbreeding is lower. A base population with large number of fish (more than 200 families) is better for a breeding program in the longer term. Logistics for operation of large number of families is difficult and takes a longer time. With limited infrastructures available in Tanzania, starting a breeding program with 50 to 100 families will be more manageable. The number of families to begin within a breeding program will determine the effective population size. Effective population size is calculated as;

$$\mathbf{Ne = 4(M \times F) \div (M + F)}$$

where Ne = effective population size; M = number of males contributing to the next generation, and F = number of females contributing to the next generation.

Number of parents contributing to the next generation should be ½ Ne. Inbreeding should be avoided as much as possible so large population size will allow adequate number of brood stock to be spawned and decrease a chance of mating relatives.

Mating design depends on the infrastructures available for the breeding program and whether the identification is based on strain, family or individual level. Pair mating scheme is very simple and more common in aquaculture but difficult to manage as many families will be produced and there is a possibility of mating between family members. In a strain comparison experiment, it is of interest to assess the performance of individual lines. Depending on the resources available mating at the ratios of 1:1, 1:2 or 1:3 can be adopted in a proposed tilapia breeding program in Tanzania.

Cohort matings can be used to control inbreeding and improve the efficiency of selection. The population is divided into cohorts depending on the spawning age and size of the fish and selection can be done separately in each cohort (Tave 1999). Fish in each cohort are tagged or can be kept separately in ponds/hapas or tanks. Rotational mating between cohorts can be applied in cohort selection to avoid inbreeding in such a way that females from one cohort mate with the males from another cohort and females and males from one cohort group cannot mate. For year 1 it will be 1->2, 2->3, 3->4 and 4->1 and for the next generation in year 2 it will be 1->3, 2->4, 3->1 and 4->2 with 8 cohorts (Figure 3).

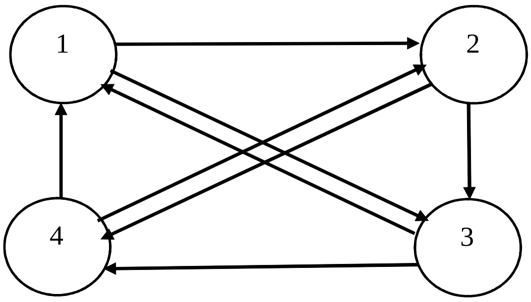


**Figure 3:** Cohort mating. Selected males from one group (cohort) are mated to females from another cohort. The next generation matings are made between different cohorts, thus avoiding inbreeding until all the unique combinations of cohorts have been exhausted.

**Design system for production and dissemination**

The improved strains or species should reach the targeted stakeholders who are fish farmers in Tanzania, hence involvement of farmers in the production system is very important (Eknath et al. 1991). Efforts need to be made to ensure fingerlings with genetic gain are disseminated to the farmers and managed in a way that utilizes their increased genetic potential. A well-organised production flow should be established from the breeding nucleus to reliable, bio-secure, hatcheries that are responsible for multiplication of improved fish strain and dissemination of fingerlings to the fish farmers (Figure 4). Bio-secure brood stock facilities with well-maintained and managed hatcheries must be established for the tilapia breeding program in Tanzania to avoid inbreeding (mating between closely related individuals).

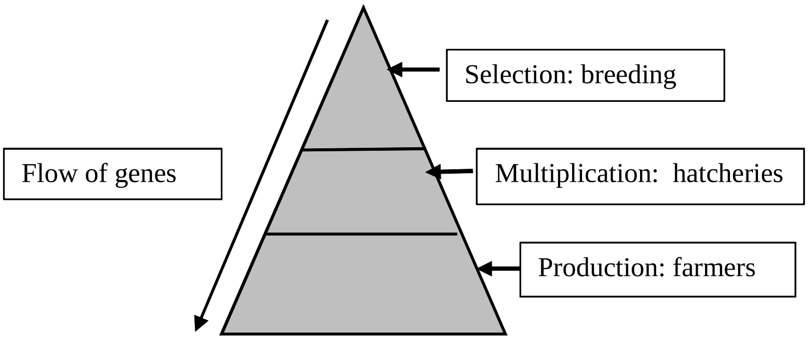


**Figure 4:** Flow of genes from the breeding to the farmers, modified from (Ponzoni 2008).

**Economic and Funding Aspects of Fish Breeding Program**

Fish breeding programs should be seen as investments for sustainable expansion of the aquaculture production and the potential to produce affordable food or other goods for the local community while maintaining their genetic diversity. In most developing countries, development of the breeding programs including livestock is initially made by the government in collaboration with other organizations to enable structure and investments be put in place and on time. Any breeding program must involve farmers at early stages to make sure their needs are taken into account and they provide the support needed for the breeding program to be successful (Philipsson et al. 2006). The size of investment in breeding program differs with species, location, availability of resources, the size of the breeding program and other factors. But all breeding programs require long-term investments with continuous support. This means that the support cannot be paused waiting for funds to be available. That is why it is very important for the governments or equivalent organizations to ensure that they have enough and continuous funds before they start aquaculture breeding programs. It must be noted that even in developed countries, many aquaculture breeding programs are supported by government funds either directly via national breeding programs (like those for rainbow trout and Arctic Char in Sweden) or indirectly via research and development grants to private companies, often in collaboration with research institutions.

**Infrastructure for the Fish Breeding Program**

Infrastructure is an important factor for the development of a fish breeding program. Lack of essential infrastructure is one of the most serious problems facing the development of indigenous breeds in tropical countries (Philipsson et al. 2006). Infrastructure includes a wide range of essential inputs that must be attained for the breeding program to succeed. Such infrastructure and inputs include skilled personnel or trained staff, facilities for breeding, hatching and rearing fish, method and means of recording, dissemination of improved genetic materials, handling and analysis of collected data and decision making bodies (Thien et al. 2001, Ponzoni et al. 2008, Ansah et al. 2014). The lack of an adequate number of people with appropriate training or incentives or institutions to successfully run a breeding program is another potential problem facing the development of indigenous breed in developing countries (Thien et al. 2001, Ojango et al. 2008). Development of a genetically improved fish strain requires highly skilled personnel with different expertise depending on the duties the person will be assigned. Duties may include the development of breeding strategies, designing system for genetic evaluation, reproduction methods, data recording and processing, genetic analysis and estimation of breeding values, monitoring genetic progress, feed analysis and feeding, monitoring of other technical and operational framework including general daily fish management (Ponzoni et al. 2008). For example, to ensure development and success of GIFT projects, WorldFish Center established the International Network on Genetics in Aquaculture (INGA) in 1993 to train scientists in quantitative genetics applied to aquaculture and coordinate national breeding programs in the 13 member countries (Bangladesh, China, Cote d'Ivoire, Egypt, Fiji, Ghana, India, Indonesia, Malaysia, Malawi, Philippines, Thailand, and Vietnam) using the GIFT methodology to genetically improve their indigenous cultured species (Ansah et al. 2014). This has been proven by the success of breeding program developed in those countries such as Abbassa strain in Egypt. Tanzania can follow this example by using the available scientists and researchers or train other scientists in the sectors lacking expertise. Tanzania needs fish genetics experts to expand its knowledge base on fish genetics and breeding and meet aquaculture growing demand in the country. Currently, under the on-going SIDA sponsored project at the University of Dar es Salaam aiming at establishing a breeding program, four PhD students are involved in the project studying genetic purity and diversity of farmed Nile Tilapia strains from Tanzania for future tilapia breeding program. PhD students and supervisors under the project visited World Fish Malaysia for one week training on the GIFT breeding program. The training improved their knowledge on steps needed to establish a breeding program and the required infrastructures. More training and workshops with experts in fish genetics are needed in Tanzania to fill the gaps in quantitative genetics, genomics and selective breeding. In collaboration with Worldfish, the government of Tanzania through the Ministry of Livestock and Fisheries (MLF) are working to enhance aquaculture production in the country. The MLF and Worldfish can consider establishing the suggested breeding program as a means for improving aquaculture production Tanzania.

**Government Policy, Legislation and Plan**

The breeding program should be an important part of the National Fisheries Policy aiming at improving the food and income of a country, region or locality and of fish farmers (Philipsson et al. 2006). This should consider environmental, water and land use policies. Most successful top producers have strong policies, strategies and implementation plans. They have water and land rights, aquaculture mainstreamed into national development plan such as Poverty Reduction Strategic Plans and National Development Strategies (Thorpe et al. 2005). Tanzania can learn from successful breeding programs especially those from the developing countries such Abbassa in Egypt (Dickson et al. 2016) and take the opportunity to scale up aquaculture sector in Tanzania.

**Conclusion and Recommendations**

Sustainable tilapia breeding program and a well-managed hatchery in Tanzania are important for maintaining the purity of tilapia strains, ensure active dissemination of good quality fish seed, and guarantee permanent genetic gain in farmed fish. Establishing a structured tilapia breeding program in Tanzania to increase aquaculture production needs a number of facilities and materials. Therefore, the government should integrate breeding activities with existing farm infrastructures as much as possible. The institution managing a breeding nucleus can produce, multiply and distribute fish seed to the farmers or combined effort of private and government owned hatcheries both can be involved in multiplication and dissemination of fish seed to the farmers.

Clear policies governing the introductions and proper infrastructure need to be in place to avoid escapees to natural environment. Efforts should be made to reduce the import of exotic species, genetically improved strains and other species in Tanzania. Much emphasis should be placed on improving native and locally available species and establishing a sustainable breeding program. Starting a tilapia breeding program with locally available tilapia species can minimize genetic and ecological effects brought by the introductions of exotic strains from other countries thereby protecting indigenous species diversity. Long-term genetic breeding programs should be developed to ensure better performing breeds to reduce the pressure on wild stocks while improving livelihood of fish farmers.

**Acknowledgement**
Many thanks to World Fish Malaysia for hosting us for a one-week training visit on the GIFT breeding program. The writing of this review article was supported by AgriFose2030 (Sweden) and the Swedish International Development Cooperation Agency (SIDA) which are gratefully acknowledged.

**References**

Acosta B, Eknath A 1998 Manual on genetic improvement of farmed tilapia (GIFT) research methodologies.

Allison EH 2011 Aquaculture, fisheries, poverty and food security. *The WorldFish Center Working Papers*, Penang, Malaysia. 2011: 60-65.

Ambali AJD, Doyle RW and Cook DI 1999 Genetic changes in *Oreochromis shiranus* (Trewavas) associated with the early stages of national aquaculture development in Malawi. *Aquacult. Res.* 30(8) : 579–588.

Ansah YB, Frimpong EA and Hallerman EM 2014 Genetically-improved tilapia strains in Africa: Potential benefits and negative impacts. *Sustainability* 6(6) : 3697-3721.

Bangera R, Drangsholt TM, Nielsen HM, Sae-Lim P, Ødegård J, Puvanendran V, Hansen ØJ and Mortensen A 2015 Genotype by environment interaction for growth in Atlantic Cod (*Gadus morhua L.*) in four farms of Norway. *J. Mar. Sci. Eng.* 3(2): 412-427.

Bartley MD, Rana K and Immink JA 2001 The use of inter-specific hybrids in aquaculture and fisheries. *Rev. Fish Biol. Fisher.* 10(3): 325-337.

Beardmore JA, Mair GC and Lewis RI 2001 Monosex male production in finfish as exemplified by tilapia: applications, problems, and prospects. *Aquaculture* 197: 283-301.

Brummett RE 2013 Conservation Economic Growth and the use of Genetically Improved Tilapia in Africa. ISTA10 , *Special Issue* , Washington DC.

Canonico GC, Arthington A, Mccrary JK and Thieme ML 2005 The effects of introduced tilapias on native biodiversity. *Aquat. Conserv.* 15(5): 463–483.

Costa-Pierce BA 2003 Rapid evolution of an established feral tilapia (*Oreochromis* spp.): The need to incorporate invasion science into regulatory structures. *Biol. Invasions* 5(1-2): 71-84.

Darko FA, Quagrainie KK and Chenyambuga S 2016 Consumer preferences for farmed tilapia in Tanzania: A choice experiment analysis. *J. Appl. Aquacult*. 28(3): 131-143.

Dergal NB, Scippo ML, Degand G, Gennotte V, Mélard C and El-Amine AASM 2016 Monitoring of 17α-methyltestosterone residues in tilapia's (*Oreochromis niloticus*) flesh and experimental water after its sex reversal. *Int. J. Biosci.* 9(6): 101-113.

Devlin RH, Sundström LF and Leggatt RA 2015 Assessing ecological and evolutionary consequences of growth-accelerated genetically engineered fishes. *BioScience* 65(7): 685-700.

Di Palma F 2017 *Finding ways to double tilapia production in Tanzania without doing damage*, *THE CONVERSATION* . [Cited 29 January 2018.] Available from URL: http://theconversation.com/finding-ways-to-double-tilapia-production-in-tanzania-without-doing-damage-72099

Dickson M, Nasr-Allah AM, Kenawy D, Fathi

M, El-Naggar G and Ibrahim N 2016 *Improving employment and income through development of Egypt's Aquaculture sector (IEIDEAS) Project*.

Eknath AE, Bentsen HB, Gjerde BJ, Tayamen MM, Abella TA, Gjedrem TR and Pullin RS 1991 Approaches to national fish breeding programs: pointers from a tilapia pilot study. *Naga, the ICLARM Quarterly* 14(2)**:** 10-12.

FAO 2018 *The State of World Fisheries and Aquaculture 2018* - Meeting the sustainable development goals. Rome. www.fao.org/3/i9540en/I9540EN.pdf

Farias T, César J and Silva L 2017 Methods of selection using the quantitative genetics in aquaculture-a short review. *Insights Aquacult. Biotech.* 1: 1-8.

Ferdous Z , Nahar N, Hossen MS, Sumi KR and Ali MM 2014 Performance of different feeding frequency on growth indices and survival of monosex tilapia, *Oreochromis niloticus* (Teleostei: Cichlidae) fry. *Int. J. Fish. Aquat. Stud*. 1(5): 80-83.

Forgako E 2018 Techniques of controlling mixed sex tilapia and the practicability of hormonal reversal in Cameroon. Nations University Fisheries Training Program, Iceland [final project]. http://www.unuftp.is/static/fellows/document/elizabeth16prf.pdf

Gjedrem T and Thodesen J 2005 Selection. In: Gjedrem T (Ed) *Selection and Breeding Programs in Aquaculture*. Springer, the Netherlands, pp. 255.

Gjerde B and Rye M 2010 Design of breeding programs in aquaculture species: Possibilities and constraints. *Aquac. Res.* 192: 181–192.

Hänninen A 2014 *Production and utilization of tilapia feed in Rural Zambia.* Bachelor's thesis, Turku University of Applied Sciences, Finland.

Jansen MD, Dong HT and Mohan CV 2018 Tilapia lake virus: a threat to the global tilapia industry? *Rev. Aquacult.* 11(3): 725-739.

Janssen K, Chavanne H, Berentsen P and Komen H 2015 Rainbow trout (*Oncorhynchus mykiss*)–Current status of selective breeding in Europe. *Aquaculture Europe*, pp.1-12.

Jonsson B and Jonsson N 2017 Maternal inheritance influences homing and growth of hybrid offspring between wild and farmed Atlantic salmon. *Aquac. Environ. Interact.* 9: 231-238.

Lovshin LL 2000 Criteria for selecting Nile tilapia and red tilapia for culture. *Tilapia Aquaculture in the 21st Century. American Tilapia Association and Departamento de Pesca e Aqüicultura*. Rio de Janeiro, Brazil.

Luan TD, Olesen I, Ødegård J, Kolstad K and Dan NC 2008 Genotype by environment interaction for harvest body weight and survival of Nile tilapia (*Oreochromis niloticus*) in brackish and fresh water ponds. *Proceedings from the Eighth International Symposium on Tilapia Aquaculture* 1: 231-240.

Mapenzi L and Mmochi AJ 2016 Role of Salinity on growth performance of *Oreochromis niloticus*♀ and *Oreochromis urolepis urolepis*♂ Hybrids. *J. Aquac. Res. Dev.* 7(6): 431

Meiludie EE 2013 *Comperative evaluation of growth performance and yield of four tilapia species under culture conditions*. PhD dissertation. Sokoine University of Agriculture, Tanzania.

Morissens P, Rognon X and Dembele I 1996 Comparison of growth performance and electrophoretic characteristics of three strains of *Oreochromis niloticus* present in Cote d'Ivoire. *In The Third International Symposium on Tilapia in Aquaculture* 41: 361-367.

Msuya FE, Muumin H and Hamed S 2016 Status of aquaculture in the Zanzibar Islands, Tanzania. *World Aquac.* 47: 25-29.

Mulder HA and Bijma P 2005 Effects of genotype x environment interaction on genetic gain in breeding programs. *J. Anim. Sci.* 83(1): 49-61.

Njiru M, Waithaka E, Muchiri M, Van Knaap M and Cowx IG 2005 Exotic introductions to the fishery of Lake Victoria: What are the management options? *Lake Reserv. Manage.* 10(3): 147-155.

Nkhoma J and Musuka CG 2014 Effect of commercial feed on sexual maturity of two tilapia species (*Oroechromis niloticus* and *Oreochromis tanganicae*). *Int. J. Aquac*. 4: 96-101.

Nyonje BM, Opiyo MA, Orina PS, Abwao J, Wainaina M and Charo-Karisa H 2018 Current status of freshwater fish hatcheries, broodstock management and fingerling production in the Kenya aquaculture sector. *Livest Res Rural Dev. 30, Article #6.* Retrieved 16/9/2018, from http://www.lrrd.org/lrrd30/1/mary30006.html

Ojango JM, Panandam JM, Bhuiyan AK, Khan MS, Kahi AK, Imbayarwo-Chikosi VE Halimani TE, Kosgey IS and Okeyo AM 2008 Higher Education In Animal Breeding In Developing Countries–Challenges and Opportunities. In *The 9th World Congress on Genetics Applied to Livestock Production*.

Okai KE 2019 *Africa's tilapia farmers rise to Chinese challenge*. Cited 21/7/2019 from https://thefishsite.com/articles/africas-tilapia-farmers-rise-to-chinese-challenge.

Olingo A 2018 *Fish imported into East Africa from China fails toxic minerals test.* Cited 21/7/2019 from URL: https://www.thecitizen.co.tz/news/Fish-imported-into-East-Africa-from-China-fails-toxic-/1840340-4899334-biyn7o/index.html

Omasaki SK 2017 *Optimization of breeding schemes for Nile tilapia (Oreochromis niloticus) in smallholder production systems in Kenya*. Doctoral dissertation, Wageningen University.

Omasaki SK, Charo-Karisa H, Kahi AK and Komen H 2016 Genotype by environment interaction for harvest weight, growth rate and shape between monosex and mixed sex Nile tilapia (*Oreochromis niloticus*). *Aquaculture* 458: 75-81.

Phelps RP and Popma TJ 2000 Sex reversal of tilapia. In: Costa-Pierce BA and Rakocy JE (eds.) *Tilapia aquaculture in the Americas*. 2. The World Aquaculture Society, Baton Rouge, pp. 34-59.

Philipsson J, Rege JEO and Okeyo AM 2006 Sustainable breeding for tropical farming systems. In: Ojango JM, Malmfors B and Okeyo AM (Eds.), Animal Genetics Training Resource (version 2). International Livestock Research Institute, Nairobi, Kenya and Swedish University of Agricultural Sciences, Uppsala, Sweden, 1: 25.

Ponzoni RW, Nguyen NH and Khaw HL 2009 Genetic improvement programs for aquaculture species in developing countries: prospects and challenges. In *Proc. Assoc. Advmt. Anim. Breed. Genet* 18: 342-349.

Ponzoni RW, Nguyen NH, Khaw HL, Kamaruzzman N, Hmazah A, Bakar KR and Yee H 2008 Genetic Improvement of Nile Tilapia (*Oreochromis Niloticus*)–Present and Future. *8th International Symposium on Tilapia in Aquaculture*, pp. 33-52.

Ponzoni RW 2006. Genetic improvement and effective dissemination: keys to prosperous and sustainable aquaculture industries. In: Ponzoni RW, Acosta BO and Ponniah AG (Eds.) *Development of aquatic animal genetic improvement and dissemination programs*. WorldFish Center, Penang, Malaysia, pp. 1-6.

Pouyaud L and Agnèse J 1996 Genetic differentiation in several stocks of Sarotherodon melanotheron and Tilapia guineensis from Côte d'Ivoire, Senegal and Gambia. In *The Third International Symposium on Tilapia in Aquaculture* 41: 368.

Rothuis AJ, Turenhout MN, van Duijn A, Roem AJ, Rurangwa E, Katunzi EF, Shoko A and Kabagambe JB 2014 Aquaculture in

East Africa; A regional approach. *Wageningen UR (University and Research centre)*. LEI Report IMARES C153/14| LEI 14-120, pp. 54.

Rukanda JJ 2018 *Evaluation of aquaculture development in Tanzania.* Nations University Fisheries Training Program, Iceland [final project]. http://www.unuftp.is/static/fellows/document/janeth16aprf.pdf

Sae-Lim P and Mulder HA 2016 Selective breeding in aquaculture for future environments under climate change. *Internal project View project OrAqua View project*. In *Proceedings FAO International Symposium on the Role of Agricultural Biotechnologies in Sustainable Food Systems and Nutrition*, Rome.

Sae-Lim P, Kause A, Mulder HA, Martin KE, Barfoot AJ, Parsons JE, Davidson J, Rexroad Iii CE, Van Arendonk JAM and Komen H 2013 Genotype-by-environment interaction of growth traits in rainbow trout (*Oncorhynchus mykiss*): A continental scale study. *J. Anim. Sci.* 91(12): 5572-5581.

Shechonge A, Ngatunga BP, Bradbeer SJ, Day JJ, Freer JJ, Ford AG, Kihedu J, Richmond T, Mzighani S, Smith AM and Sweke EA 2018a Correction to: Widespread colonisation of Tanzanian catchments by introduced Oreochromis tilapia fishes: the legacy from decades of deliberate introduction. *Hydrobiologia* 832(1): 235-253.

Shechonge A, Ngatunga BP, Tamatamah R, Bradbeer SJ, Harrington J, Ford AG, Turner GF and Genner MJ 2018b Losing cichlid fish biodiversity: genetic and morphological homogenization of tilapia following colonization by introduced species. *Conservation Genetics* 19(5): 1199-1209.

Shoko AP, Lamtane HA, Wetengere K, Kajitanus OO, Msuya FE, Mmochi AJ and Mgaya YD 2011 The status and development of aquaculture in Tanzania, east Africa. *Proceedings of the international conference on ecosystem conservation and sustainable development*, Ambo University, Ambo, Ethiopia, pp. 85-97.

Shoko AP, Limbu SM, Mrosso HD, Mkenda AF and Mgaya YD 2016 Effect of stocking density on growth, production and economic benefits of mixed sex Nile tilapia (*Oreochromis niloticus*) and African sharptooth catfish (*Clarias gariepinus*) in polyculture and monoculture. *Aquac. Res.* 47(1): 6-50.

Simberloff D 2013 *Invasive species: what everyone needs to know*. Oxford University Press.

Subasinghe R, Soto D and Jia J 2009 Global aquaculture and its role in sustainable development. *Rev. Aquac.* 1: 2-9.

Tave D 1999 *Inbreeding and brood stock management* (No. 392). Food & Agriculture Organization.

Thien TM, Dan NC and Tuan PA 2001 Review of Fish Genetics Genetics and Breeding Research in Vietnam. *Review Literature and Arts of the Americas*, pp. 91-96.

Thorpe A, Reid C, van Anrooy R and Brugere C 2005 When fisheries influence national policy-making: an analysis of the national development strategies of major fish-producing nations in the developing world. *Marine Policy* 29(3): 211-222.

Trewavas E 1983 *Tilapiine fishes of the genera Sarotherodon, Oreochromis and Danakilia* (No. 878). London: British Museum (Natural History).

Trọng TQ, Mulder HA, van Arendonk JA, Komen H 2013 Heritability and genotype by environment interaction estimates for harvest weight, growth rate, and shape of Nile tilapia (*Oreochromis niloticus*) grown in river cage and VAC in Vietnam. *Aquaculture* 384: 119-127.

Turner G F, Ford A, Genner M J, Ngatunga B P, Shechonge A, Palma, F Di 2017 Edinburgh , Scotland. Genomic approaches to identification and preservation of wild tilapia genetic resources for Aquaculture.

*Eur. Aquacult. Soc. - Meeting Abs.* 3: 2016-2018.

United Republic of Tanzania (URT) 2016 The Tanzania Fisheries Sector: *Challenges and Opportunities, Ministry of Agriculture, Livestock and Fisheries*. Prepared with the support of the Royal Danish Embassy, Dar es Salaam, with technical assistance from MegapescaLda, Portugal, pp. 32.

United Republic of Tanzania (URT) 2017 *Tanzania Ministry of Livestock and Fisheries. Annual Fisheries Statistics Report, 2017.* Dodoma: Government of Tanzania.

United Republic of Tanzania (URT) 2018 *Tanzania Ministry of Livestock and Fisheries. Budget Speech 2018-2019.* Dodoma: Government of Tanzania, July 2018.

United Republic of Tanzania (URT) 2019 *Tanzania Ministry of Livestock and Fisheries. Budget Speech 2019-2020.* Dodoma: Government of Tanzania. [May 2019]

Vicente I and Fonseca-Al CE 2013 Impact of introduced Nile tilapia (*Oreochromis niloticus*) on Non-native Aquatic Ecosystems. *Pak. J. Biol. Sci.* 16: 121-126.

Worldfish Center 2012 *Improved breeding of Nile tilapia leads to productivity gains | WorldFish Press Release, Worldfish*. Cited 23/6/2018 from URL: https://www.worldfishcenter.org/content/improved-breeding-nile-tilapia-leads-productivity-gains.