Food and Agriculture Organization of the United Nations

Lessons from two decades of **tilapia** genetic improvement in Africa

GENETICS IN AQUACULTURE
A CASE STUDY

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Contents

1. Introduction

1.1 The overall status of aquaculture breeding programmes in Africa

African aquaculture has increased in importance since the beginning of the twenty-first century due to dwindling yields from capture fisheries and the success that aquaculture has had in Asia and Egypt. Nile tilapia (*Oreochromis niloticus*) is one of the major cultured fish in the world after carps (FAO, 2020). In Africa, Nile tilapia dominates total production from aquaculture, followed by *Clarias gariepinus* (African catfish). However, for a fish that is indigenous to Africa, it is remarkable that Egypt is the only African country among the top ten producers of this species in the world. Nile tilapia contributes nearly 70 percent of all fish farmed in Egypt (GAFRD, 2017, 2019). Nile tilapia dominates production, although several other species of tilapia are farmed in Africa including *O. mossambicus*, *O. andersonii*, *O. esculentus*, *O. aureus*, *O. shiranus*, *O. spirulus* and *Coptodon zillii*. Red tilapia, an introgressed farmed type between Nile tilapia and *O. mossambicus* (Mozambique tilapia), is also widely farmed. The popularity of Nile tilapia is attributed to its ability to feed on various diets, rapid growth, tolerance of a wide range of culture conditions, good consumer acceptance, ease of breeding and wide availability to farmers (Pullin, 1991; Pullin *et al.*, 1991; Charo-Karisa *et al.*, 2006). In Africa, Nile tilapia is either cultured in monoculture or in polyculture with African catfish in semi-intensive manure-fertilized earthen ponds with supplementary feeding (Charo-Karisa *et al.*, 2006; El-Sayed, 2008). A major achievement in the breeding of Nile tilapia was the development of the Genetically Improved Farmed Tilapia (GIFT), developed by WorldFish (earlier known as the International Center for Living Aquatic Resource Management, ICLARM). GIFT was developed at the end of the 1980s through a breeding programme that was based on the procedures used in Norway for its salmon breeding programme.

Following the highly successful economic performance of the GIFT, which was formed by interbreeding multiple farmed types of Nile tilapia from Africa and Asia, an interest in establishing local breeding programmes in Africa was incentivised. Several reasons made it necessary for African governments to take this path: (i) the recognition, in the Nairobi declaration (Gupta *et al.*, 2004), that the introduction of non-native species or improved farmed types can result in "*a clear risk of escape into the wild, and possible negative impacts on biodiversity*" and that such concerns should be addressed; (ii) the desire of some African governments to use their own indigenous species and farmed types rather than the already selectively bred Nile tilapia; and (iii) potential support for capacity building in genetic improvement programmes.

1.2 The GIANT programme

Egypt, Ghana, Kenya, Malawi and Zambia were the first countries in Africa to undertake selective breeding programmes in line with the GIFT technology, in every case with the support of WorldFish and its partners. GIFT technology protocols have been applied in the development of the Genetically Improved Abbassa Nile Tilapia (GIANT) strain in Egypt. GIANT has been at the centre of Egypt's success with tilapia and its rapid aquaculture production expansion. The technology has also been applied to *O. shiranus* in Malawi, the three spotted tilapia (*O. andersonii*) in Zambia, the Akosombo strain of Nile tilapia in Ghana (Trinh *et al.*, 2021) and a Nile tilapia Breeding Programme in Kenya (Omasaki *et al.*, 2016).

The purpose of this case study is to review the GIANT breeding programme in Egypt and to share experiences and lessons that would help in the establishment and implementation of similar breeding programmes in Africa and elsewhere.

2. Creating a well-managed breeding programme

Breeding programmes are expensive to run and require long-term commitment of significant human, infrastructural and financial resources.

2.1 Establishing and implementing an effective aquaculture breeding programme

The main steps in establishing a breeding programme include deciding the suitable structure and scheme to be followed. This will be determined by considerations of the biological characteristics of the target species, the traits of greatest commercial importance, the on-growing environment, and an examination of the market to see if it is large enough and valuable enough to warrant the required investment. A well-managed and effective breeding programme must therefore consider the aspirations of consumers, stakeholders and government and how the current and future demand for the species in a particular country or region might be supplied. These considerations determine the amount of funding and funding mechanisms required, the necessary human resource capabilities and facilities, and the required planning and policy direction. A good programme has to manage government and stakeholder expectations in terms of (i) expected response to selection; (ii) ability to provide a realistic implementation timeline, and (iii) delivery of benefits to the industry through an appropriate dissemination strategy.

It is important that the improved farmed type reaches target farmers when they are adequately prepared to receive, utilize and benefit from using the improved seed. The breeding protocol must consider the range of farming environments available and the preferred traits (e.g. the harvest size preferred by consumers). A functional system must also be in place to disseminate the genetically improved farmed type from the breeding centre (breeding nucleus) to a large number of fish farmers through a series of broodstock multiplication centres (BMCs) and hatcheries. In addition, a feedback mechanism that enables staff at the breeding nucleus to receive opinions, complaints and data from the users is essential. The users include hatchery owners, farmers, consumers, funding organizations and, where applicable, the general public. Different players in the value chain often demand improvement of different fish traits. For example, while farmers prefer fast-growing farmed types to reduce production costs, hatcheries prefer fish that have high reproductive capacity and survival to maximize the number of fingerlings for the seed market. It is thus also important to consider the presence of correlated responses among traits in the programme.

The necessary steps in the development of a selection programme are listed in Section 2.2. These steps may be fewer or greater in number than those listed, depending on the availability of baseline information and the development level of the national aquaculture sector.

2.2 Timeline and drivers

The timeline and main steps required for a tilapia breeding programme (and common to most breeding programmes) are as follows:

- **First year:**[1]
  - preparing a breeding concept note and popularizing it amongst donors, industry players and government;
  - planning and describing the culture environment of the target species and the dissemination system;
  - carrying out consumer preference and market studies, and determining selection traits, as well as constructing or renovating the facilities as necessary.

- **Second and third years:**
  - collecting the founding broodstock from hatcheries (i.e. individuals of genetically improved or unimproved farmed types) and/or from the wild;
  - disease screening, including quarantine;
  - genetic/morphological characterization of collected individuals and farmed type performance comparison (based on an analysis of traits of importance to stakeholders) across a range of culture environments in order to determine which farmed types or farmed type combination to bring into the breeding programme and the potential importance of genotype by environment interactions;
  - developing and applying a selection index based on weighting of trait importance when selection is for more than one trait and predicted response to selection.

- **Fourth year:**
  - founder stock (G_0) production;
  - selection of the best performing fish as parents of G1.

1 This time may need to be longer due to the specific circumstances of the initiator.

- **Fifth year:**
  - G_1 production, selection of best performing fish (including estimation of response to selection or genetic gain, which is undertaken by the institution responsible for the breeding programme);
  - on-farm studies to determine performance under actual farm conditions.
- **Sixth year:**
  - G_2 production;
  - estimation of response;
  - on-farm studies.
- **Seventh year:**
  - G_3 production and dissemination of G_2 to BMCs;
  - estimation of response;
  - on-farm studies.
- **Eighth year:**
  - G_4 production and dissemination of G_2 to farmers;
  - estimation of response;
  - on-farm studies;
  - dissemination of G_3 to BMCs.
- **Ninth year:**
  - production of $G_{5;}$
  - dissemination of G_4 to BMCs and G_3 to hatcheries;
  - estimation of response;
  - on-farm studies.
- **Tenth year:**
  - production of $G_{6;}$
  - dissemination of G_5 to BMCs;
  - on-farm studies.
- **Nth year:**
  - production of $G_{(n-4)}$ and dissemination of $G_{(n-5)}$.

The steps described above assume the presence of well-trained staff with sufficient incentives and the availability of the necessary hatchery facilities. If the facilities are not in place they will need to be constructed or renovated by the end of the first year. Ideally, each hatchery should receive a new generation of broodstock every three years since the broodstock may otherwise become too large. In turn, the breeding nucleus should release each selected generation to multiplication centres. However, due to cost and logistical considerations, not all generations produced at the breeding nucleus get disseminated.

Continuous awareness building is essential throughout the selective breeding process. This should be followed by the training of farmers, hatchery managers and feed producers on the requirements of the improved fish as well as on best management practices for their culture.

The benefits of a breeding programme require time to be delivered. Long-term planning, and the availability of dedicated financial and human resources, are keys to success. Publicly funded breeding programmes also need high-level political support.

3. The Egyptian experience

3.1 From conception to successful implementation

The concept of the GIANT programme was mooted as part of the establishment of the WorldFish Centre at Abbassa, Abou Hamad, Egypt in 1998, and was aimed at producing a strain that could succeed in a range of African environments. The programme started in 1999 following collection of the original stocks from wild and hatchery populations in different locations in Egypt: Zawia, Maryout, Aswan and Abbassa (Rezk *et al.*, 2002; Charo-Karisa *et al.*, 2005). The fish were kept separate in ponds until the breeding programme started in 2002 when the base population was formed. In this year, two lines of selection were started from the same base population utilizing two different culture environments: (i) a high-input line that received supplementary feeds and were stocked at a fish density of $2/m^{-2}$ and (ii) a low-input line grown in fertilized ponds with no feeding and stocked at $1/m^{-2}$. The two lines were managed by WorldFish and Wageningen University respectively. The purpose was to evaluate genotype by environment interactions and to be able to advise on suitable environments for selection. These two culture systems were intended to cover the range of farming environments used for tilapia in Egypt and throughout the region.

In 2006, the first reports of response to selection were published for the low-input line (Charo-Karisa *et al.*, 2006). Response estimates for the high input line were published in 2009 (Rezk *et al.*, 2009). The first and only dissemination occurred in 2012 when the 9th generation of the high-input line was released to BMCs and hatcheries.

3.2 Collaborative structure/partnerships of the programme

The breeding programme was a collaborative effort amongst various institutions and funding organisations. It was conducted from 2000 onwards by ICLARM (now WorldFish) at the Regional Centre for Africa and West Asia, Abbassa, Egypt. Funding came from several donors including, the CGIAR Research Programme on Fish and Livestock, the Embassy of Switzerland through the STREAMS project, EC/IFAD Cooperation and the Government of Egypt. In addition to funding, the Government of Egypt provided laboratory space and pond facilities to undertake the breeding programme with land hived off from the Central Laboratory for Aquaculture Research (CLAR). WorldFish also worked closely with Wageningen University, James Cook University, and the Roslin Institute of the University of Edinburgh.

3.3 Public and private sector participation

The participation of both public and private sectors was a paramount factor in the success of the programme. In addition to the direct support from the Government of Egypt, some government institutions such as CLAR were involved in the dissemination of the improved strain. This was carried out by mobilizing farming communities and participating in the best practice training of farmers and hatchery managers. Public and private BMCs and hatcheries were recruited through Memorandums of Understanding (MoUs) to supply fingerlings in different regions of the country.

The BMCs received broodstock directly from WorldFish Abbassa free of charge, only arranging their own transportation. In turn, BMCs produced the mixed sex broodstock which they sold to hatcheries (mostly privately-owned).

On-farm studies were undertaken by the private sector and publicly owned farms. These were dependent on an understanding that the farmer would treat the fish as instructed by the WorldFish and CLAR trainers, use their own inputs, and that pond management and data would be collected to improve the breeding programme. The fingerlings were provided free of charge and limited pond preparation support was given where necessary. This model did not return any proceeds of the sale of broodstock to the breeding nucleus at WorldFish Abbassa and this affected the ability to consistently produce new generations and undertake country-wide dissemination of the improved strain.

3.4 Brief description of the breeding programme

The base population was obtained from all possible diallel crosses between the fish from the four collection sites. In the initial mating a total of 86 sires and 115 dams were used. A mating design in which each male was to be sequentially mated to two females without the option for repeated spawning of females was used, in order to produce paternal half-sibs. Mating pairing was done at random. However, due to difference in size between males and females, larger females were matched with larger males to avoid mortalities caused by aggressive male behaviour. In addition, inbreeding was minimized by avoiding the mating of related fish such as full-sibs and half-sibs.

Typically, the production of each generation began just at the end of spring when the water temperature was above 20 °C. The male was first placed in a nylon fine-meshed breeding hapa with one ready-to-spawn female. Originally the hapas were designed for one male and one female only. When spawning was verified in one of the hapas, the female was left to continue maternal care but the male was placed in a different hapa with another female to produce half-sibs. This led to a longer spawning season lasting 2-3 months which made the common environmental effect very high.[2] To avoid a prolonged spawning season, the male and female fish were initially kept separately for 12 weeks before mating began. However, even with this arrangement, synchronizing spawning[3] remained a challenge. Therefore, the breeding programme was modified in subsequent generations to use larger hapas that could hold two females and one male and the premaxillae of the males were trimmed to reduce incidences of female mortality due to male aggression. This system gave better spawning results and comparable half-sibs produced by both females spawning simultaneously.

2 Common environment effect refers to factors causing similarity among full-sibs, e.g. size of eggs, care of the mother, and effect of the hapa in which they are reared.

3 Desirable to ensure all fry were of approximately the same size and age.

The full-sib families produced were nursed in hapas for a month and numbers were reduced randomly to about 100 fry per family in a process known as thinning; this enabled the reduction of further hapa environmental effects. No selection occurred at this stage. The fry were nursed in the hapas until they reached a mean size of 2–5 g, at which size they could be tagged. The extra fry were maintained as backup and discarded only after their cohorts were evaluated and selection candidates identified and reproduced. Furthermore, spawning and fry rearing prior to tagging were conducted in fine-mesh hapas inside concrete tanks. A polyethylene cover over a heating and aeration unit were used to maintain suitable water temperature and quality. This increased the number of facilities required and the financial resources needed to purchase the feeds for rearing the backup fish.

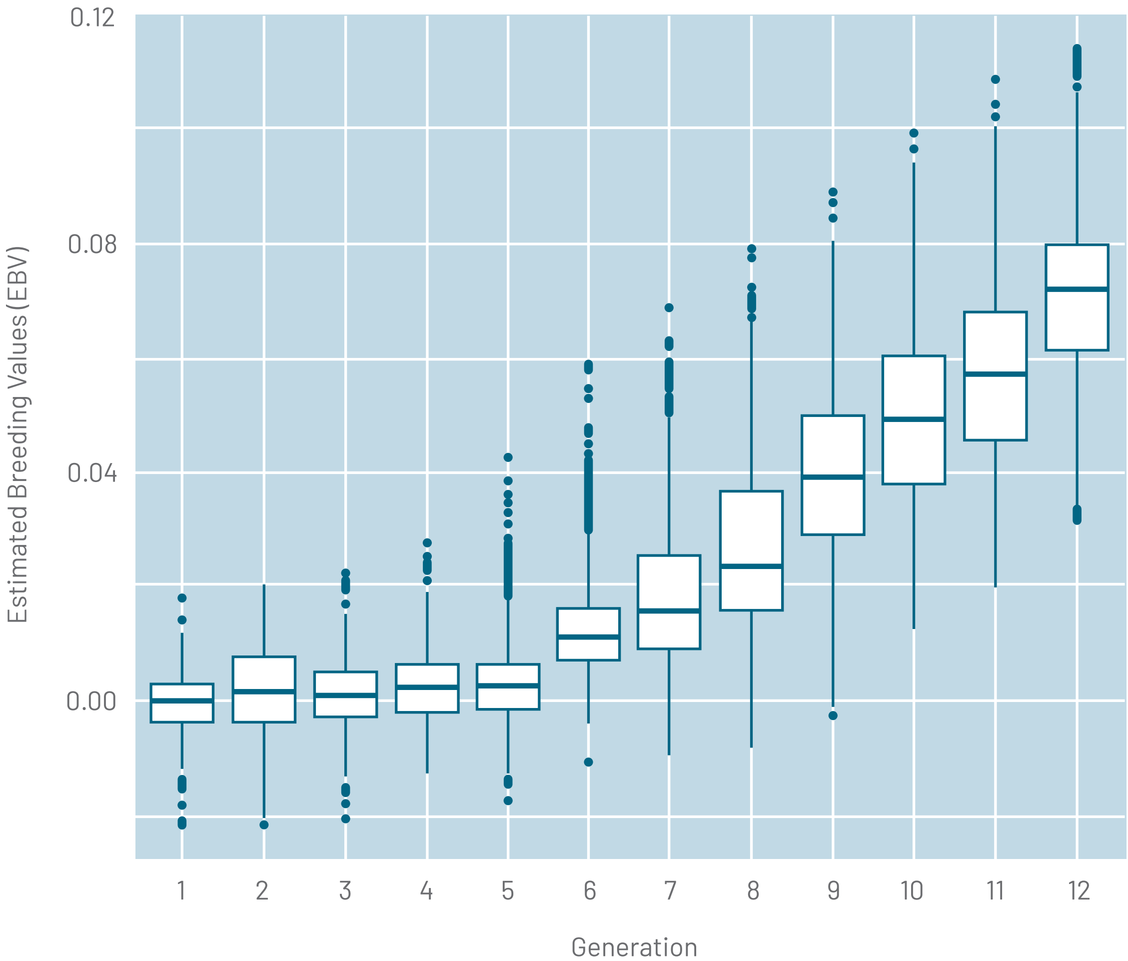
Prior to evaluation in communal ponds, a number of the fingerlings from each family were tagged using Floy® fingerling tags (FloyTag & Manufacturing Inc.®, Seattle, United States of America). After tagging (Figure 1), the fish were kept in their respective hapas for two days to recover from handling and tagging stress. A total of 20 tagged individuals per family were randomly chosen and individually weighed. These were stocked in a 1 000 m^2 earthen pond for communal evaluation for about 8 months, including an overwintering period. For each fish, spawning, stocking and harvesting dates, initial and harvest weight, sex of the fish, and pond number were recorded. Survival was recorded as the proportion of fish from each respective full-family that were alive at harvesting.

Figure 1. Fingerlings tagged with Floy Tags

3.5 Dissemination

Each year, a new generation of tilapia was produced, the pedigree updated, fish performance recorded and analysed, and the genetic gain estimated from the estimated breeding values (EBVs). Figure 2 shows that the response estimates were progressively larger after each generation. The response was clearly substantial as early as the third generation, G_2 (Charo-Karisa *et al.*, 2006) but it was not until the 8th generation that a decision to release the fish was contemplated. This occurred when a donor project became available to undertake this activity. As a step towards release of the improved strain to farmers, its performance was evaluated against other commercially available farmed types. The 8th generation of GIANT was evaluated against the Kafr El Sheikh strain, which was the most commonly farmed commercial type under pond aquaculture in Egypt.

Figure 2. Estimated Breeding Response (EBV) to selection in the Genetically Improved Abbassa Nile Tilapia breeding nucleus across 12 generations



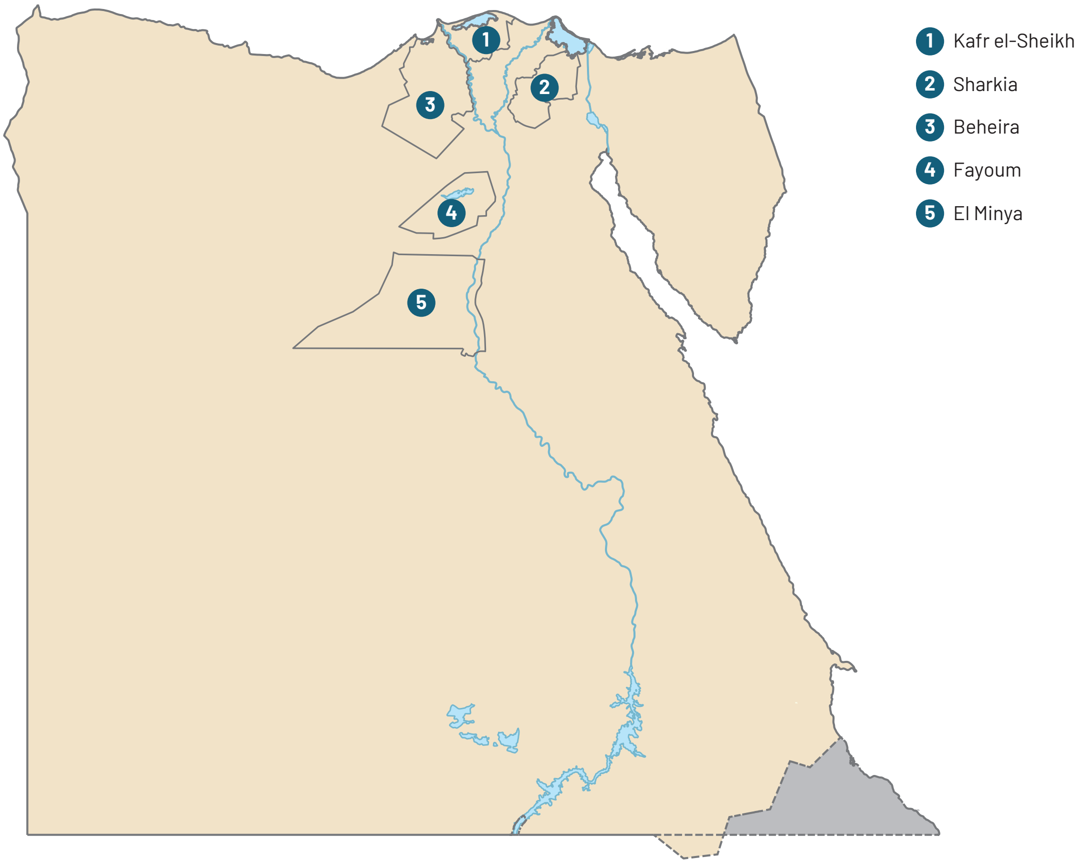
Note: Box plots indicate the mean, standard deviation and range of EBV per generation

Source: Author's own elaboration

With the results indicating a growth superiority for GIANT of ~ 30 per cent for generation 8 compared to the commonly used commercial farmed type Kafr El Sheikh, WorldFish disseminated GIANT strain "G_9" to about 2 000 fish farms in the Egyptian aquaculture sector through a series of BMCs and hatcheries (Dickson *et al.*, 2016). The BMCs were supplied with mixed-sex fry in July 2012, which were on-grown and transferred to breeding systems within the BMCs at the start of the 2013 season. In turn, the hatcheries produced 10.8 million monosex fry that were sold to 93 fish farms in 2013 and 2014.

As a part of the dissemination process, a value chain analysis was undertaken among hatcheries and feed producers. Best management practice training was also provided to the 2 400 fish farmers who were targeted to benefit from the release of the faster-growing strain. The improved strain had reached about 500 fish farms in selected regions of Kafr El Sheikh, Beheira, Sharkia, El Minya, and Fayoum Governorates by 2014 (Figure 3).

Figure 3. Map of Egypt showing governorates where GIANT was disseminated



Map conforms to United Nations Geospatial. 2012. Map of Egypt. United Nations. Cited 19 January 2023. https://www.un.org/geospatial/content/egypt

During the lifetime of this breeding programme, it was only G_9 that was released to farmers; this may have limited the impact of the programme given that by 2020, G_{15} had been produced. Lack of funds inhibited the studies and community mobilisation that are essential for the collection of field data. In turn, this limited analysis of the performance of the improved strain. This highlights the need for developing a robust and long-term dissemination plan early in the programme and providing the necessary resources to support this plan.

Another factor that became necessary to address was the need to synchronize the provision of fry and fingerlings from hatcheries to farmers at the beginning of the on-growing season. Before the dissemination of fish from Abbassa to the BMCs began, the breeding cycle typically occurred in summer (July to October). However, the farmers wanted fingerlings to be ready at the beginning of summer (April-May) to maximize the growing season. Therefore, the breeding nucleus, multiplication centres and hatcheries had to innovate. Warmer underground water, greenhouses and water heaters were used to maintain water temperatures suitable for spawning and growth during winter. At the breeding nucleus, increased warmer temperatures and early finalization of tagging procedures ensured that fish stocking into earthen outdoor ponds for on-growing and overwintering could be harmonized with on-farm conditions. Plans to increase cold tolerance levels were not fruitful due to initially low heritability for cold tolerance trait (Charo-Karisa *et al.*, 2005).

3.6 Achievements and challenges

The accomplishments of the GIANT breeding programme and associated activities in Egypt are summarized as follows:

- Good performance of the breeding programme achieved a 30 percent improved growth rate compared to other commercial strains. (This was less than expected compared to GIFT and may be attributed to introgression with *O. aureus* as noted by Nayfa *et al*., 2020).
- Overall, fish farmers who stocked GIANT had significantly higher average fish sales (USD 5567 /ha) than those who stocked commercial strains (USD 5192 /ha) in all governorates (Ibrahim *et al*., 2019).
- The farmers that received the improved breeds were provided with training on Best Management Practices, which led to increased production efficiency and farm profits.
- The project produced at least three PhDs and several MSc graduates.

- Scientific publications documenting the processes for future reference.
- Environmental gains and reduced emission of greenhouse gases were achieved.
- Positive feedback and demand for the improved fish among farmers was generated.
- Impact of the breeding programme on target farmers using improved strains was documented (STREAMS project report [DBA, 2019]).
- There was strong support from the host country.

The main challenges that slowed down full implementation of the programme were as follows:

- An insufficient number of experts handling the programme following the passing away of the pioneer geneticist. This led to a hiatus in the programme until a replacement was identified which caused some loss of accuracy in the estimation of genetic parameters.
- Lack of funding leading to gaps in production of further generations.
- Difficulties in planning a nationwide dissemination programme due to lack of facilities and sufficient financial resources.
- Lack of proactive decision making (bureaucratic tendencies) leading to disillusionment among donors and government.
- Inadequate release of new generations of the improved strain, an opportunity cost to farmers and the country.
- Absence of a self-sustaining revenue generation model which would have allowed for the proceeds of the sale of fingerlings to be returned to the breeding nucleus to provide dissemination and research support.
- Negative publicity from disgruntled farmers and hatcheries that could not participate in the dissemination.
- Weak collaboration with farmers leading to failure of some on-farm trials.
- High cost of biosecurity because the site is on a bird migration route.
- Difficulties in timing of the spawning season in hatcheries due to the winter season and the need for ready-to-stock fish at the beginning of spring. This forced hatcheries to incur extra energy costs in warming hatchery water to enable them to meet the highest demand at the beginning of on-growing season.

4. New genetic improvement initiatives in Africa

The Egyptian experience has motivated a number of breeding programmes aimed at the utilization of indigenous species of tilapia. Some countries, such as Ghana and Kenya, have focused on Nile tilapia while others have begun programmes for local tilapia species, such as *O. andersonii* in Zambia and *O. shiranus* in Malawi.

Zambia's tilapia genetic improvement programmes started as a subcomponent of the Zambia Enterprise Development Project (ZAEDP). This project aimed to stimulate a viable aquaculture subsector in Zambia in order to promote economic diversification, food security and sustainable employment generation. These are central priorities of the Government of Zambia. The debate on choosing the species to farm in Zambia between the non-native Nile tilapia and the native three-spotted tilapia (*O. andersonii*) had been on-going for a long time. Comparative growth trials were conducted to provide evidence to support the decision on species choice. As Nile tilapia was already being commercially farmed in Lake Kariba, it was decided to limit its spread rather than eradicate it from the country and to develop Zambian aquaculture based on *O. andersonii* for the rest of the country. Part of the objective of the ZAEDP was to "clean up" Nile tilapia from hatcheries and farms in parts of the country. It was considered that this decision would help to conserve the native species and to keep *O. niloticus* away from the upper reaches of the Zambezi and Kafue River systems where *O. andersonii* is endemic (Gopalakrishnan, 1988). The Zambian *O. andersonii* breeding programme was undertaken with funding from the African Development Bank. Collaborating institutions included WorldFish, the Department of Fisheries and the Citizens Economic Empowerment Commission (CEEC).

On the other hand, the Malawi programme was initiated as part of the project "Transfer of GIFT Technology from South East Asia to Sub-Saharan Africa and Egypt" supported by WorldFish, Japan and the United Nations Development Programme. There was no evidence of involvement of many local stakeholders within the country; the project depended entirely on donor funding. Currently, the programme is funded through an African Development Bank funded Sustainable Fisheries, Aquaculture Development and Watershed Management project.

5. Lessons learnt from the Egyptian experience

Several lessons from the experience of Egypt can be applied in other genetic breeding programmes in Africa and beyond:

- A well thought out dissemination plan is necessary at the inception of the breeding programme to ensure timely release of broodstock and fingerlings to hatcheries and farmers. The breeding nucleus should be connected to a series of BMCs selected from amongst national aquaculture research stations and private sector hatcheries.
- There is a need for early communication and the signing of MoUs with farmers to ensure on-farm studies are supported by stakeholders.
- A minimum level of facilities are needed before the initiation of a breeding programme; these should include a quarantine facility at the nucleus centre, breeding facilities and testing facilities.
- Screening any broodstock that is sourced from outside the breeding nucleus is essential to ensure that the incoming fish are free from pathogens.
- There is a need to establish a strong capacity building programme in BMCs.
- It is necessary to build local capacity to undertake the breeding programmes. Both Zambia and Malawi depend on expertise from WorldFish. The COVID-19 pandemic made it impossible for WorldFish experts to travel, resulting in delays in carrying out the breeding programmes and related analyses.

- Establish biosecurity measures in the breeding nucleus and the BMCs handling the genetically improved fish. An outbreak of Tilapia Lake Virus at the breeding programme in Zambia necessitated broodstock testing.
- Ensure that the facility does not already suffer from flooding or is at future flooding risk. Although the Abbassa facility did not suffer serious floods in the hapas used, a single occurrence would have had the potential to cause the fish to escape or get mingled and cause the failure of the programme. The design of the breeding facility should ensure no floods can occur.
- Work with organized clusters/cooperatives to obtain feedback and create demand for the improved breed.
- Put in place a long-term dedicated funding basket for the programme and embed income generation and sustainability within it.
- Management of human resources is key to the continuation of the programme. Therefore, appropriate remuneration and incentive schemes (housing, schools and social amenities) and succession planning for the scientists involved should be considered to ensure full-time care for the breeding programme.

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African aquaculture has increased in importance since 2000 due primarily to dwindling capture fisheries and its demonstrable success in Egypt, which is the only African country among the world's top ten producers of Nile tilapia (*Oreochromis niloticus*).

This case study provides an overview of tilapia breeding programmes in Africa with a main focus on the Genetically Improved Abbassa Nile Tilapia (GIANT) breeding programme in Egypt.

The main steps for establishing a tilapia breeding programme are described, together with the specific lessons learnt in Egypt.

This case study was prepared by
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