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REVIEW ARTICLE

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The potential impact of aquaculture on the genetic diversity and conservation of wild fish in sub-Saharan Africa

Mark K. Sanda | Neil B. Metcalfe | Barbara K. Mable

School of Biodiversity, One Health and Veterinary Medicine, University of Glasgow, Glasgow, UK

Correspondence
Mark K. Sanda, School of Biodiversity, One Health and Veterinary Medicine, University of Glasgow, Graham Kerr Building, Glasgow G12 8QQ, UK.
Email: mrksnd127@gmail.com

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Abstract

1. An increasing focus on aquaculture using introduced strains or species poses a serious threat to native wild species in sub-Saharan Africa, yet almost no policies have been enacted or regulations put in place to address this environmental challenge. Aquaculture in these regions has traditionally been conducted on a relatively small scale but is currently expanding rapidly and is projected to continue increasing in the coming decades, with increasing use of genetically improved strains. This expansion is occurring in a region known for its high biodiversity, creating challenges for increasing fish production without damaging wild fish populations. However, few studies have yet assessed the impacts of changes in aquaculture practice on the genetic composition and diversity of wild populations. The use of non-native improved strains for aquaculture could cause competition, gene introgression when there is interbreeding with native populations or species, displacement of species and possible extinction of the native wild populations.
2. After providing historical context on African aquaculture, this review describes the current methods of fish breeding and genetic improvement programmes for the main species of cultured fishes, focusing on the potential conservation impacts of the use of introduced (and selectively bred) farmed species. Existing aquaculture policies, legislation and regulations regarding the import and farming of fish are then compared across the main fish-producing countries. We recommend a regional policy framework considering fish introduction, risk analysis and risk management, human resources development and genetic monitoring that could be drafted into the existing policies to strengthen conservation efforts.
3. We conclude by making recommendations for refining existing regulations and for future research aimed at minimizing the impacts of aquaculture on wild fish populations in sub-Saharan Africa. Aquaculture in this region needs implementation of responsible guidelines to avoid genetic impacts on native populations of high conservation value.

KEYWORDS
aquaculture, catfish, fish breeding, fisheries policy, genetic improvement, species introduction, tilapia

1 | REVIEW APPROACH

This study reviewed how aquaculture, including culture of introduced non-native farmed fish, could genetically impact native wild populations through gene introgression, competition, displacement and extinction. We conducted a literature search on fisheries and aquaculture policies with respect to (i) the history of fish introduction and their impacts in sub-Saharan Africa; (ii) aquaculture practices for commonly cultured species, including breeding programmes implemented; and (iii) escape events and preventive measures. Inferences from well-developed aquaculture countries like Norway, the United Kingdom and the United States were drawn, citing escapes of rainbow trout and Atlantic salmon as guidelines for addressing these problems in sub-Saharan Africa. Reviewed documents, including grey literature on fisheries and aquaculture policy in sub-Saharan Africa, were obtained from the respective governments, fisheries and aquaculture websites and included policy documents not available online that were obtained via email communications with relevant organizations. Online searches on Google Scholar, Web of Science and the University of Glasgow online library used the following keywords: 'fish escape', 'fish introduction', 'fisheries and aquaculture policies in sub-Saharan Africa', 'impact of aquaculture on the genetic diversity of native fish', 'fish breeding programmes in Africa'.

2 | GLOBAL AQUACULTURE PRODUCTION: HISTORY AND STATUS

Aquaculture is believed to have started earlier than 1000 BCE in China, with the common carp (*Cyprinus carpio*) being the first species to be held in captivity for food (Rabanal, 1988). However, aquaculture remained a low-density non-intensive means of rearing fish for many centuries, until the late 20th century, when it started a transition into a modernized intensive form of food production as a result of advances in technology and global information-sharing (Jones, 1987). Progress continues regarding technological developments in culture systems, genetic improvement of species through selective breeding and feed production (Naylor et al., 2021). The most intensive rearing regimes include recirculating aquaculture systems that allow effective economies of scale and result in the highest production per unit area (Ebeling & Timmons, 2012). Recent decades have seen steady increases in the proportion of farmed fish that gain their nutrition from manufactured feeds, rather than from food generated within the water body in which they are living (Naylor et al., 2009). The associated feed industry is witnessing a drastic change, including new technologies such as the biofloc system, which converts nitrogenous waste from feed into microbial biomass that can be immediately used by fish or shellfish harvested and processed into feed ingredients (Avnimelech, 2009; Bossier & Ekasari, 2017; Kuhn et al., 2010). There also have been more gradual changes away from a reliance on marine fishmeal and fish oils and towards plant-based feeds (Naylor et al., 2009; Naylor et al., 2021).

The past four decades have been significant for global aquaculture development, with the sector recording an average annual growth rate of about 8.6% from 1980 to 2012 (FAO, 2014). Fish are an important source of food security and contribute 15% of the total animal protein in human diets globally (Casal, 2006). The increasing human population exerts high fishing pressures on wild fisheries, and there has been a shift to reliance on farmed fish production as an alternative (Ahmed et al., 2019; Naylor et al., 2000). Aquaculture is not, however, without its inherent challenges, which unfortunately are more evident in lower and middle income (LMIC) countries where there has been less investment. Moreover, these countries tend to have greater focus on freshwater aquaculture, which is projected to expand more than cultivation in marine environments (Belton et al., 2020; Zhang et al., 2022). Because many of the problems associated with the expansion of aquaculture relate to its environmental impacts, there is clearly a risk that LMIC countries will experience disproportionate environmental pressures in the drive to increase their production of farmed fish. In this review, we summarize the current state of freshwater aquaculture in sub-Saharan Africa, including its regulation, and provide an assessment of potential environmental risks (with an emphasis on the genetic impacts) and the approaches that could be taken to minimize them. These issues are particularly pertinent to this region given its rich endemic fish diversity and the rapid expansion of aquacultural activities (Lind et al., 2012).

3 | AQUACULTURE DEVELOPMENT IN SUB-SAHARAN AFRICA

Fish farming first started in colonial areas of sub-Saharan Africa in the 1940s and 1950s, with the establishment of aquaculture research stations in the Republic of the Congo, Democratic Republic (DR) of the Congo, Central African Republic, Cameroon, Côte d'Ivoire, Kenya, Madagascar, Uganda, Zambia and Zimbabwe (Brummett et al., 2008). The initial aim was to produce sport and food fishes to supplement the diets of plantation workers (Pouomogne & Brummett, 2004) and was accompanied by substantial investment to support its development (Adeleke et al., 2021; Brummett et al., 2008). The focus was primarily on subsistence-level, pond-based systems (Blow & Leonard, 2007), as few local people could afford the investment needed for intensive large-scale production. Fish production fell and remained low for several decades after these countries became independent from colonial rule, due to the new governments' failure to maintain investment in aquaculture (Pouomogne & Brummett, 2004). In 1975, the Food and Agriculture Organisation of the United Nations (FAO) organized the First Africa Regional Workshop on Aquaculture, to gauge the extent of aquaculture sustainability in the region and to assess the level of support given to the sector by African governments (Coche et al., 1994). Commercial aquaculture was initially slow to develop, with over half of the African countries, including the top producers in the region, like Nigeria, Madagascar and Zambia, reportedly producing less than 100 tonnes of fish annually by 1975 (Moehl & Machena, 2000). African countries south of the Sahara contributed less than 1% to total global aquaculture output over the last decade (Mapfumo, 2022).

The slow growth of sub-Saharan aquaculture has been linked to the lack of a market-driven agenda and governance limitations (Satia, 2011). Production also has been hampered by fish diseases triggered by poor water quality and suboptimal farm management practices (Ragasa et al., 2022). There are very few hatcheries producing fingerlings for other farmers (Anetekhai et al., 2004), and prices of imported, high-quality feed have risen steeply in recent years, with few options for alternative cheaper locally produced feeds. Some countries have been receiving financial aid from the international community to support the development of small-scale commercial aquaculture. For example, the International Fund for Agricultural Development (IFAD) announced in February 2020 a US$ 49 million project in Mozambique aimed at moving the aquaculture sector from a subsistence to a commercial level (Moyo & Rapatsa, 2021). Possibly as a result of such initiatives, production in sub-Saharan Africa has increased markedly in recent decades, with the total production reaching 550,000 tonnes by 2014, mostly consisting of freshwater fishes such as catfishes and tilapias (Subasinghe et al., 2021). While production in Africa is still at a relatively low level overall, it has increased by 9.8% per annum during 2000–2017, faster than the 5.8% world average (FAO, 2019a) and faster than on any other continent (Garlock et al., 2020). In particular, aquaculture growth in sub-Saharan Africa has been on the rise since 2000, with average production increasing by 11% p.a., more than twice the world's average (Ragasa et al., 2022).

Production in terms of quantity of fish produced and financial value is currently dominated by Nigeria, Uganda, Tanzania, Ghana, Zambia, Madagascar, Kenya and Malawi (FAO, 2022). These countries have built aquaculture infrastructures through interventionist programmes such as the National Institute for Freshwater Fisheries Research (NIFFR) in Nigeria, the National Aquaculture Centre in Malawi and the National Aquaculture Research Development and Training Centre in Kenya. These centres serve as research institutes for providing high-quality fish fry and broodstock to local farmers and so have proven pivotal to regional aquaculture development (Jamu et al., 2012).

Successful and profitable aquaculture production relies on the supply of good-quality broodstock and fingerlings (Nadarajah & Flaaten, 2017). There is thus a demand for genetically improved strains that are tolerant to a wide range of environmental conditions, have a good feed conversion ratio, are disease-resistant and are capable of attaining marketable size within the stipulated production period. However, improved strains are in short supply, because the fisheries and aquaculture research institutes responsible for providing good fish eggs and fry have been overwhelmed by farmers' requests and are unable to meet all their demands (Munguti et al., 2014; Shikuku et al., 2021). Broodstock are rarely sourced from the wild, and developing alternative sources of broodstock from wild-harvested stocks are threatened by unsustainable fishing practices. Moreover, seasonality in most rivers and lakes that rely on rain-fed water makes it difficult to find ready-to-breed adults in the wild (Charo-Karisa et al., 2012; Muringai et al., 2022; Ponzoni & Nguyen, 2008).

4 | FISH BREEDING

The African catfish (*Clarias gariepinus*; Family Cyprinidae) and the Nile tilapia (*Oreochromis niloticus*; Family Cichilidae) are among the most important freshwater fisheries and aquaculture species in Africa (El-Sayed & Fitzsimmons, 2023; Munguti et al., 2022; Munguti & Iteba, 2022; Nankinga et al., 2022). The two species have been cultured together under mixed-species (polyculture) farming (Mandal et al., 2014; Shoko et al., 2015). *C. gariepinus* and *O. niloticus* are native to Africa but are now being bred for mass fingerling production following their successful domestication (Ponzoni & Nguyen, 2008). Some of the advantages of *C. gariepinus* over other freshwater fish species include rapid growth rates that result in attainment of marketable size within 6 months (Trofymchuk et al., 2021). Other reasons for their culture include tolerance to a wide range of environmental conditions and good feed conversion rates (Abraham et al., 2018).

The farmed cichlids referred to as tilapias are actually composed of multiple species, notably including *O. niloticus*, *Oreochromis aureus*, *Coptodon zillii* and *Sarotherodon galilaeus*. Nile tilapia (*O. niloticus*) is the most successfully cultured of these species due to its fast-growth, tolerance of harsh environmental conditions and ease of breeding in captivity (Galemoni De Graaf & Huisman, 1999). The WorldFish selective breeding programme for this species has further increased farmers' interests in its culture (El-Sayed & Fitzsimmons, 2023; Henriksson et al., 2017; McAndrew, 2000).

Every successful breeding programme depends on the farmers' ability to select the right broodstock and apply the appropriate techniques to induce reproductive activity and spawning (Moorhead & Zeng, 2010). Because the aquaculture sector in sub-Saharan Africa is dominated by small-scale farmers, they must rely on low-level hatchery technology for fish breeding (Adeleke et al., 2021; Kajungiro et al., 2019). However, minimal or absent regulatory frameworks to control indiscriminate breeding and require confinement pose significant threats to wild populations and can compromise one of the crucial aspects of the breeding objectives, which is to preserve the genetic resources within the species/breed (Farstad, 2018). Farmed tilapias and catfishes are produced in sub-Saharan Africa by very different methods in terms of the techniques involved, hatchery facilities required and levels of investment required (Chaube, 2023). If these processes are unregulated or unsupervised, fish breeders who lack basic genetic knowledge are at risk of making poor breeding decisions that may harm their production stock, as well as native populations and species if the cultured fish escape to the wild.

4.1 | Catfish breeding

Breeding of catfish species (principally *C. gariepinus* and *Clarias anguillaris* and *Heterobranchus bidorsalis*) is induced by hormone treatment (Madu & Offor, 2005). Gravid females, usually at least 9 months old, are obtained from hatcheries and transferred to a holding facility (tanks or ponds), where they are held before breeding. Male *Clarias* become mature when about a year old, but male *H. bidorsalis* take longer to attain maturity (Legendre et al., 1992). The chosen broodstock (*Clarias* spp. or *Heterobranchus* spp.) are starved for 24 h before breeding, after which the female is injected intramuscularly with 0.5 ml/kg ovaprim (Syndel, USA), to facilitate ovulation (Marimuthu, 2019). Injected females are held in a separate pond from the breeding males. At an optimum temperature of 27–30°C, the female will be ready for egg stripping in about 12 h. Eggs are collected into a sterilized bowl; the male is then sacrificed and dissected to collect the milt, which is subsequently used to fertilize the eggs. Fertilized eggs are spread on a fine-mesh net placed on the surface of the breeding pond, which is kept aerated by a continuous flow of water from the inlet until hatching is complete.

Eggs hatch within 24 h, but the free-swimming larvae are sustained by their yolk sac for three days, after which they are fed with shell-free *Artemia* for about 2–3 weeks (Munguti & Iteba, 2022). Catfish are then fed a formulated diet, which comes in various-sized pellets ranging from 0.1 to 9 mm in size.

Catfishes can then be hatched using locally available resources such as bowls, and jerrycans cut in halves and placed outdoors under shade, so that hatcheries can be built with limited resources without a dedicated building. These methods are commonly used by farmers that cannot afford to build a hatchery with modern facilities, such as sophisticated recirculating aquaculture systems.

Producing hybrid catfish is not an uncommon practice among sub-Saharan Africa fish farmers. Hybrids have positive heterosis for growth rate and are potentially able to interbreed with parental species (Senanan et al., 2004). The most commonly farmed hybrids are dubbed 'heteroclarias', an inter-specific hybrid of either *H. bidorsalis* or *Heterobranchus longifilis* and *C. gariepinus* (Bartley et al., 2000). Introgressive hybridization of the genus *Clarias* into the native populations could result in (unrecognized) introgressed individuals (Senanan et al., 2004). This process of introgressive hybridization can result in the loss of genetic diversity or coadapted gene complexes for a species, subspecies or population (Allendorf et al., 2001).

4.2 | Tilapia breeding

Captive breeding of tilapia requires more investment in technology and skills than catfish breeding. Selected male and female broodstock are placed in pairs in the breeding nets (Figure 1). The male will fertilize the eggs laid by the female, but being mouthbrooders, the female then normally collects the fertilized eggs back in her mouth to start the incubation process (Popma & Masser, 1999). This process is altered by the farmer, who collects the eggs and transfers them to a special incubating system in the hatchery, where eggs are commonly held in a jar or column held over a tray, with water flowing into the jar directly from an inlet at a regulated speed. Once hatched, the fry swim from the jar into the tray and remain there until they are sorted and moved to the nursery tanks, where they receive their first meal, which is usually a fine, powder-like formulated feed. Most farmers choose to keep only male tilapia because the growth of females is reduced once they become sexually mature; males thus produce a faster return on the initial investment (Fuentes-Silva et al., 2013). Therefore, all-male populations have been developed using a sex-reversal process (Chen et al., 2018), which involves feeding fry with feed treated with the hormone 17 α-methyltestosterone (MT) (Abucay & Mair, 1997). This provides control of reproduction and prevents the unwanted breeding that leads to overcrowding. For example, the nonsteroidal aromatase inhibitor Fadrozole incorporated into the Nile tilapia feed at 50, 75 and 100 mg/kg dosages produced a population of between 67% and 100% males (Afonso et al., 2001). Similarly, methyltestosterone treatment at a dose of 50 μg/g diet from 8–30 days after hatching resulted in 100% male Nile tilapia (Bhandari et al., 2006). Sex-reversal has been successfully carried out on several species of mouth-brooding tilapias, including *O. aureus*, *Oreochromis mossambicus*, *Oreochromis hornorum* and the red tilapia, which is a diploid interspecific hybrid between *O. mossambicus* and *O. niloticus* (Popma & Green, 1990). The male tilapias grow faster than the females and are desired by farmers; however, sex-reversal does

FIGURE 1 Tilapia broodstock unit in Abeokuta, Nigeria, made with blue mesh netting and installed in an earthen pond in which the fish lay and fertilize their eggs. The female tilapia starts the incubation by carrying the fertilized eggs in her mouth before eggs are collected and transferred to the hatchery where the incubation process is completed.

not guarantee to induce sterility, and males are still capable of breeding with any remaining females to produce viable embryos (Mair et al., 1997). It is also possible to achieve monosex tilapia populations by crossing genetically modified super males with YY sex chromosome and normal females (XX) or genetically feminized males (XY) following oestrogen treatment (Fuentes-Silva et al., 2013).

4.3 | Producing triploid farmed fish as control measure for genetic contamination

Many fish farms in sub-Saharan Africa are vulnerable to fish escapes, often because they lack barriers or screens (an especial problem with earthen ponds—see Figure 2). In this situation, the production of sterile farmed fish would be advantageous for the conservation of wild fish and their gene pool (Chen et al., 2023). Partial or complete sterility can be achieved in farmed fish through the induction of triploidy. This is a chromosomal manipulation process that involves impairing or suppressing the second meiotic division through use of chemicals, heat, pressure or electric shock of the fertilized eggs; the process produces infertile fish that would avoid any genetic impact on the wild population if they escaped (Arai & Fujimoto, 2018; Marx & Sukumaran, 2007; Okomoda et al., 2020; Pradeep et al., 2012). Ploidy manipulations also can be applied to farmed fish to improve their growth and survival (Pandian & Koteeswaran, 1998). The use of triploid fish in aquaculture would negate the problem associated with early sexual maturation and minimize the main genetic concerns potential escapees might pose to wild populations (Farstad, 2018; Iversen et al., 2016). This method has been demonstrated to be effective in *C. gariepinus* using both cold shock and heat shock on fertilized eggs (Marx & Sukumaran, 2007) and also in red hybrid tilapia *O. niloticus* × *O. mossambicus* (Pradeep et al., 2012). Triploidy has long been recommended as one of the best possible solutions for controlling the problem of early sexual maturity and unwanted reproduction in cultured tilapia (Mair, 1993). However, even after decades of inducing triploidy for practical applications in aquaculture, the approach is yet to be utilized at commercial scales in sub-Saharan Africa (Chen et al., 2023). It appears that there is a gap in implementing new and innovative ideas that could potentially benefit the farmers while also protecting the diversity of native species. Most farmers might not be aware of or understand how the triploid technology works, and this lack of awareness may be attributed to ineffective communication, knowledge-sharing and training by fisheries research institutions to local breeders.

FIGURE 2 An earthen pond used for the culture of introduced tilapia with low embankment and poor screen netting material.

5 | INTRODUCTIONS OF NON-NATIVE SPECIES OR IMPROVED STRAINS

The first introductions of non-native fish species to sub-Saharan Africa occurred between the late 1890s and early 1900s, when brown trout (*Salmo trutta*) were introduced from the United Kingdom and France into South Africa, Kenya, Malawi and Zimbabwe (Weyl et al., 2017). The motive surrounding the initial introduction into sub-Saharan Africa of fishes from outside the region was to promote sport fishing, alongside increasing fish production for human consumption (Ogutu-Ohwayo & Hecky, 1991; Weyl et al., 2017). Following their successful breeding in South Africa, brown trout were distributed to neighbouring Swaziland (1915), Lesotho (between 1907 and 1914), Zimbabwe (1907) and Tanzania (1934) (Welcomme, 1988). The period from 1940 to 1950 was an era characterized by unsuccessful rainbow trout (*Oncorhynchus mykiss*) introductions to Congo, Sudan and Zambia (Crawford & Muir, 2008), with its success being linked to unsuitable temperatures, acidic waters, lack of breeding grounds, seasonal droughts and predation (Crawford & Muir, 2008; De Moor & Bruton, 1988). The unsuccessful introduction hindered the establishment of rainbow trout as one of the main aquaculture fishes in sub-Saharan Africa, although South Africa and Kenya have continued to farm both brown and rainbow trout (Stander et al., 2011), but in Kenya, it is still done on only a small scale, constituting 1% of total aquaculture production in 2009 (Munguti et al., 2014). Although both rainbow and brown trout are currently farmed in a number of African countries (Bjørndal & Tusvik, 2019; Du Preez & Lee, 2010; Munguti et al., 2014), their culture in most parts of Africa is yet to become widespread and continues to remain secondary as farmed species relative to *O. niloticus* and *C. gariepinus* (Kaleem & Bio Singou Sabi, 2021; Munguti et al., 2022).

The period between the mid-1950s and late 1970s witnessed the introduction of mainly freshwater farmed fishes both from within and outside the continent of Africa (Brummett et al., 2008; Welcomme, 1986), but cichlids and cyprinids dominated the list of introduced species. For example, Welcomme (1988) documented intentional introductions both within and outside the native range of multiple species, including *Oreochromis andersonii* introduced to Tanzania from Zambia in 1968; *O. aureus* from Israel to Uganda in 1962 and Israel to South Africa in 1976; *O. niloticus* from Egypt to

Madagascar in 1956 and from Israel to South Africa in 1976; and African catfish (*C. gariepinus)* introduced to Cameroon, Congo, Gabon Ivory Coast and Zaire between 1972 and 1973 from the Central African Republic). Other cyprinids (e.g., *Carassius auratus*, *Catla*, *Cirrhinus mrigala*, *Ctenopharyngodon Idella*, *C. carpio*, *Labeo rohita*) also were translocated from India, Indonesia and Israel to Cameroon, Central African Republic, Egypt, Ethiopia, Ivory Coast, Kenya, Mauritius, Nigeria, Rwanda, South Africa, Sudan and Tanzania. The introduction of cichlids was more successful than that of salmonids, a fact that was attributed to their tolerance to variable water quality and ability to survive in both freshwater and marine environments (Canonico et al., 2005).

The most significant recent introduction was selectively bred genetically improved farmed tilapia (GIFT) strain of Nile tilapia. The GIFT tilapia strain was developed from pure native Nile tilapia stocks from Egypt, Ghana, Kenya and Senegal together with commercial experimental strains from Israel, Singapore, Taiwan and Thailand (Pullin et al., 1991). They were first introduced to Africa as a result of the WorldFish Center's official distribution of the strain to the Water Research Institute, Ghana in 2012, solely for research purposes (https://worldfishcenter.org/pages/gift/). GIFT is a strain of *O. niloticus* developed from selective breeding programmes initiated by the International Center for Living Aquatic Resources Management (ICLARM, later re-named WorldFish) in what started as a 10-year (1988–1997) collaborative project with the Institute of Aquaculture Research in Norway (also known as AKVAFORSK), the Philippines National Freshwater Fisheries Technology Research Center of the Bureau of Fisheries and Aquatic Resources, the Freshwater Aquaculture Center of the Central Luzon State University and the Marine Science Institute of the University of the Philippines (Puttaraksar, 2004). Nile tilapia (*O. niloticus*) sourced from wild populations in Egypt, Ghana, Kenya and Senegal as well as farmed populations from Israel, Singapore, Taiwan and Thailand, were used as founding population (Eknath & Acosta, 1998; Yáñez et al., 2020). WorldFish adopted a selective breeding method similar to the Atlantic salmon (*Salmo salmar*) and rainbow trout breeding programmes developed in Norway in the 1970s (Subasinghe et al., 2021). The approach produced improved GIFT with sustained increases in weight-at-age of 10–15% per generation over more than six generations (Dey et al., 2000; Ponzoni et al., 2011). Coupled with the high survival consistently observed in the GIFT strain, the high potential for growth has made it a very attractive genetic resource for aquaculture (Ponzoni et al., 2011). This WorldFish GIFT strain, now in its 20th generation after about 30 years of selective breeding, is transforming aquaculture in sub-Saharan Africa (Trinh et al., 2021).

However, private farms have been importing and breeding the GIFT strain outside of the official dissemination programme run by WorldFish. For example, GIFT farming is currently illegal in Ghana but was detected in a Ghanaian farm following unauthorized introduction (Anane-Taabeah et al., 2019). In Nigeria, it was only in 2022 that the first official agreement was signed between Premium Aquaculture Limited and WorldFish to disseminate GIFT to the country in 2023, but the strain was already present in a number of farms (MKS, pers. obs.). It is a similar situation in Malawi, Zambia, Tanzania and Kenya, where GIFT is becoming an important farmed strain of tilapia (Akongyuure et al., 2015). GIFT is also now widespread in most Southern African countries despite legislation that prohibits their introduction or culture (Moyo & Rapatsa, 2021). This GIFT strain is currently undergoing mass artificial propagation in commercial hatcheries that supply local farmers; these have undoubtedly played an important role in the expansion and transformation of Nile tilapia farming to a more intensive farming system in Ghana, Kenya, Nigeria, Malawi, Zambia, Zimbabwe, Cote d'Ivoire and Uganda (El-Sayed & Fitzsimmons, 2023).

C. gariepinus is another important aquaculture species that is endemic to Africa and found in almost all freshwater systems across the continent (Hecht et al., 1996; Van Steenberge et al., 2020). In the 1970s, Dutch researchers developed an improved strain of *C. gariepinus* that was derived from the native populations from Cote d'Ivoire, Central African Republic, Cameroon and Israel (Holčík, 1991). This strain, known as 'Dutch *Clarias*', was selected for fast growth, body size and fillet quality (Cambray & Van Der Waal, 2006) and was subsequently re-introduced into Africa (Holčík, 1991; Huisman & Richter, 1987; Richter et al., 1987; Welcomme, 1988). There is no record of when the first reintroduction into sub-Saharan Africa was made, but the Dutch *Clarias* is now farmed widely in West Africa (e.g., Cameroon, Ghana, Nigeria), East Africa (e.g., Kenya) and South Africa (Cambray & Van Der Waal, 2006; Iswanto et al., 2015; Williams et al., 2008).

6 | LOCAL GENETIC IMPROVEMENT PROGRAMMES

Several attempts at selective breeding have been made in the past to diversify aquaculture production using native species, based on the recommendation that diversification of species will boost aquaculture (Oboh, 2022) and minimize negative impacts from the introductions of exotic species (Ross et al., 2008). However, most of these efforts are still at an experimental stage. So far, the most successful genetic improvement programme in sub-Saharan Africa has been on Nile tilapia in Ghana, employing WorldFish GIFT methodology. The selective breeding programme was conducted by Ghana's Aquaculture Research and Development Centre of the Water Research Institute to improve the native 'Akosombo' strain of tilapia for farming purposes and achieved a 30% increase in growth performance by the 10th generation (Anane-Taabeah et al., 2019; Trinh et al., 2021). Kenya, Malawi and Zambia (https://www.worldfishcenter.org/pages/gift/) have also carried out successful selective breeding programmes using the GIFT technology (Ansah et al., 2014; Ragasa et al., 2022). For example, the technology was applied to *Oreochromis shiranus* in Malawi, *O. niloticus* in Kenya and the three-spotted tilapia (*O. andersonii*) in Zambia (Trinh et al., 2021).

7 | FISH ESCAPE: IMPACT OF FISH INTRODUCTIONS

Fish escapes from aquaculture can result from equipment failure, handling and transport operations, predator intrusion, storm damage, flooding (in freshwater systems) and other mechanisms (Hine et al., 2010). Reported cases of cultured fish (including *O. niloticus*) regularly escaping from suspended cages and from bankside ponds are a threat to fish biodiversity and the environment (Moyo & Rapatsa, 2021). These escapes have been linked to poor management, leading to dire consequences such as hybridization with indigenous species (Gupta et al., 2004). The threats posed by escapes from fish farms include loss of species diversity, displacement of native fish and challenges to conservation efforts; fish escapes are considered to be a significant factor contributing to the global extinction of endemic species (Gupta, 2002; Latini & Petrere, 2004; Lind et al., 2012; Olden et al., 2007). While not all introduced or escaped fish have an adverse effect on their new environments, many exert ecological, evolutionary and economic impacts (Cucherousset & Olden, 2011). The introduction of farmed fish into the wild thus can be considered a potential ecological catastrophe (Lévêque, 1996). The relative risks posed by farming non-native or selectively bred species are a function of the chances of escape into the wild, and the magnitude of each escape event is determined by the outcomes of interactions with native species (Naylor et al., 2005).

Nile tilapia have been described as an 'aquaculture pest' due to their invasive and aggressive nature, which could negatively impact native populations through dominance in interference competition following an escape (Champneys et al., 2021; Vitule et al., 2009). For example, the introduction of Nile tilapia into important lakes in Brazil led to unpredictably negative consequences, as there was a noticeable decline in native fish production and changes in native population structure (Vitule et al., 2009). In addition, because farmed fishes are usually to some extent genetically altered through inbreeding, hybridization and selective breeding, any escape event could compromise the population structure of the wild fish with which they interbreed, including a reduction of their genetic diversity over several generations (Atalah & Sanchez-Jerez, 2020; Bolstad et al., 2017; Bourret et al., 2011; Glover et al., 2010; Hindar et al., 1991; Miralles et al., 2016). Not only are Nile tilapia, the basis for the GIFT strain, more aggressive than most native cichlid species, they have been known to interbreed with closely related species (Gregg et al., 1998).

Introgressive hybridization of selectively bred escapees with wild individuals may result in offspring with low fitness, posing the risk of outbreeding depression and loss of genetic diversity among wild populations (Ansah et al., 2014). Examples of this type of negative interaction between different tilapia species are provided by cases of interbreeding between introduced Nile tilapia and both native *Oreochromis jipe* (listed by the IUCN in 2006 as critically endangered; Ref. No. 125652) and *Oreochromis leucostictus* in Tanzania (Bradbeer et al., 2019; IUCN, 2022). Repeated hybridization and gene flow between the cultured and wild species (IUCN, 2022) has led to irreversible loss of genetic diversity, reduced environmental adaptability, fitness reduction and potential local extinction of wild populations (Atalah & Sanchez-Jerez, 2020; Bourret et al., 2011; Wringe et al., 2018). Another example of negative effects of escapes has been the displacement of South African native *O. mossambicus* from its habitat following hybridization with introduced *O. niloticus* (Bradbeer et al., 2019; D'Amato et al., 2007; Diedericks et al., 2021). Hybridization between introduced and native species can lead to reduced fitness that may arise from break-up of co-adapted gene complexes, that is, disruption of local adaptations that have evolved within the native species over many generations (Muhlfeld et al., 2009).

WorldFish reported that GIFT strains could have escaped and formed feral populations in the wild or contributed genes to wild tilapia populations in Nigeria, although evidence of the adverse effects of hybridization with native species is yet to be established (Bartley, 2021). The impact of introduced strains on native species is usually difficult to detect at the initial stages of introduction into the wild or escape from farms and might take a while to become apparent (Vitule et al., 2009). However, depending on the extent of the invasion and the vulnerability of the ecosystem being invaded, the loss of diversity at genetic, population, species and community levels can become evident over time (Erarto & Getahun, 2020). Most of these negative impacts are driven by escapes from farms to the wild. For example, a study conducted in Volta Lake, Ghana using mitochondrial and microsatellite DNA markers found admixed individuals from non-native Nile tilapia from two local farms, indicative of interbreeding between the farmed and wild tilapia populations (Anane-Taabeah et al., 2019). In Zambia, introduced farmed Nile tilapia were identified phenotypically around the Itezhi-tezhi Dam and Kafue River, close to the point of introduction. Further genetic analysis confirmed a high degree of introgression involving the introduced Nile tilapia and two native species, *O. andersonii* and *Oreochromis macrochir* (Deines et al., 2014). The Limpopo River of southern Africa serves as an example of the negative effects of the introduction of non-native fish species; pure native *O. mossambicus* has been replaced with red hybrid populations (*O. niloticus* × *O. mossambicus*) throughout the natural range of the native tilapia, and there has been a subsequent loss of genetic integrity since the introduction of *O. niloticus* in reservoirs (Van Der Waal & Bills, 2000).

The risk and impact of fish farm escapes on aquatic ecosystems depends on the farming system employed. With intensive aquaculture now occupying a strategic position within the fisheries sector, cage systems are now being employed in important fishing lakes such as the great East African lakes, where the negative impact of *O. niloticus* escapes on native *Oreochromis variabilis* and *Oreochromis esculentus* has been realized (Wasonga et al., 2017). In 2006, both native species were declared critically endangered by the IUCN (2022) as a result of their hybridization with *O. niloticus*. Important freshwater fish habitats, such as Volta Lake in Ghana and both Badagry Creek and Lagos Lagoon in Nigeria, are witnessing an expansion in cage aquaculture primarily used for rearing Nile tilapia (Asmah et al., 2016). Cage systems have been associated with fish escapes due to multiple causes, including structural failures (e.g., leaky nets), operational errors, damage due to biological causes (e.g., net-biting) and flooding and storms (Jackson et al., 2015). Employing floating net-pen systems in the farming of improved tilapia strains increases the impacts on native populations because fish releases are almost inevitable from such systems, given that cages have direct contact with the external environment, often are not properly maintained and are prone to damage (Azevedo-Santos et al., 2011).

Despite clear evidence of harmful outcomes, current policies for aquaculture management often do not include an assessment of the impacts of introducing non-native species for aquaculture purposes. There are often conflicts of interest between the fish producers, who are the proponents of species introduction, and environmentalists, who are more concerned about biodiversity conservation and sustainability—a problem that is not unique to Africa (Vitule et al., 2009). As with other geographic regions (Allendorf, 1991), in sub-Saharan Africa, these impacts are blurred by the immediate socioeconomic benefits related to food security and poverty reduction which require improved aquaculture productivity (Anane-Taabeah et al., 2019; Ansah et al., 2014). It is often either the case that the impact has not been measured/assessed or the relevant authority does not envision fish escape as a threat to conservation. There is a risk that the absence of evidence for ecological effects could be substituted in management and policy decisions for evidence of the absence of ecological effects (Ansah et al., 2014; Lövei et al., 2012). Holistic policies would call for specific strategies for risk management and clearer communication about potential risks (Arthur et al., 2009; Campbell, 2006; Hallerman, 2008).

8 | RISK ASSESSMENT AND RISK MANAGEMENT

With growing interest in sub-Saharan Africa related to the use of non-native species for aquaculture as a means to ensure food security and as a source of livelihood (Ansah et al., 2014), it is important to measure the risk factors associated with potential threats to native species. A good risk assessment model assists in decision-making when considering the introduction of new species and provides a means of assessing the ecological risk posed by the further spread of those introduced fish that are already present (Rowe & Wilding, 2012). The introductory stage of a risk assessment in this context should take into consideration whether the species is highly domesticated or cultivated for commercial use; can become naturalized where introduced; has invasive relatives; can reproduce across a wide environmental range; has a history of introduction outside its native range in other places; has the potential to out-compete native species; and/or hybridizes naturally with native species (Copp et al., 2005). Lind et al. (2015) provide an in-depth analysis of different risk assessment methodologies in their study of risk analysis in aquaculture based on the outcomes of the Workshop on Risk Assessment Methodologies and Tools for Aquaculture in sub-Saharan Africa. The risk assessment should be designed to include risks associated with changing the genetic composition and genetic diversity of wild populations, such as can arise from introgression, and through competition with introduced species or strains (Hallerman, 2008). Although there will be inherent uncertainty related to risks associated with incomplete information on species distributions (Copp et al., 2005), important considerations for risk management include consistency in methodology, use of stakeholder consultation and application of high levels of stringency (Arthur, 2008). Risk analysis, therefore, makes available to stakeholders detailed information on potential risk factors and their causes (Andersen et al., 2022). Applying such precautionary approaches and involving the relevant stakeholders is always a good starting point before deciding to introduce a new species outside its native range (Bartley, 2021).

Conducting risk analysis before any introduction is made will be beneficial to the conservation goal of maintaining the genetic integrity of populations and minimize the transfer of different genetic stocks (Reantaso, 2001). Risk management weighs policy alternatives, in consultation with all interested parties, by considering the risk assessment and seeks the means to reduce either the likelihood of the exposure to hazard or the consequences of harm being realized following exposure (Sumner et al., 2004). It is conducted in two stages: risk identification, where the risks are measured and analysed, and risk treatment, where decisions are made on the next course of action (Sethi, 2010).

9 | CURRENT AQUACULTURE POLICIES AND LEGISLATION IN SUB-SAHARAN AFRICA

Global aquaculture has been associated with controversial issues regarding on resource management, policy and regulations (Anderson et al., 2019). It is therefore the responsibility of individual governments to adopt a framework that follows the Food and Agriculture Organization of the United Nations Guidelines for Sustainable Aquaculture (UNFAO, 2022); the guidelines apply principles of genetic management to domesticated aquatic resources, so as to facilitate the implementation of policies, laws and regulations that will promote environmentally friendly, technically feasible and socially responsible aquaculture. A policy that works and drives sustainable fish production, preventing or regulating activities that could pose threats to species conservation, needs to be based on realistic expectations (Brummett et al., 2008). A good effective policy, for example, would manage the negative impact of escaped GIFT tilapia on other tilapia populations realized through hybridization and genetic introgression (Lind et al., 2015), but such policies are currently not in force in most sub-Saharan countries, which are yet to promulgate and implement policies to address genetic concerns associated with aquaculture activities. Current fisheries and aquaculture policies in most of sub-Saharan Africa were either enacted or reviewed between 2000 and 2015, to address the present-day challenges associated with fish farming while fostering the growth of the aquaculture industry; these are described below for each major country and are summarized in Table 1. Aquaculture has been recognized in the sub-Saharan fisheries policies as a viable means towards achieving food security means; however, these legislative documents have not clearly addressed the impact of introducing non-native fishes as farmed species, particularly as regards the risk of escapes and the potential impact of aquaculture fish in the event of an escape.

9.1 | South Africa

An exception to policies failing to address the problems of aquaculture discussed above is South Africa, which has one of the best-developed environmental policies and implemented legislation in sub-Saharan Africa. The South African Department of Environmental Affairs (DEA) National Environmental Management: Biodiversity Act 2004 (https://www.gov.za/sites/default/files/gcis_document/201409/a10-04.pdf) mandates guidelines on the introduction of species and considers the potential genetic impact and adverse effects of such species on wild populations (DEA, 2014). This Act also provides a framework for deciding the aquaculture sites where such introductions can occur. South Africa's Alien and Invasive Species Regulations 2014 provide the general rules on monitoring, control and eradication plans for invasive species, while the National Aquaculture Policy Framework 2013 addresses general aquaculture issues, including decision-making, management and regulation. The Act promotes the management and conservation of both non-native and translocated native species. Likewise, a permit for the introduction of species considered to be alien or invasive can be issued only upon fulfilling the requirements that adequate risk assessment and risk management measures have been taken by the applicant to prevent escape. The policy addresses prohibitive measures by ensuring that any planned introduction must have been found to have negligible or no invasive potential. The section of the National Aquaculture Policy Framework on norms and standards for sustainable aquaculture takes into consideration area-wide planning and zoning, including risk assessments as well as the requirement to obtain permits before farmed fish can be sold. The South African government has identified protected areas considered unsuitable for aquaculture, so as to prevent the introduction of invasive alien species either from farms, conservation projects or angling (Ellender & Weyl, 2014).

9.2 | Nigeria

The Nigeria Fisheries Act, 2014, is the policy document regulating fisheries and aquaculture activities in the country. It provides the framework for the conservation, management and development of marine fisheries, inland fisheries, aquaculture and related matters. The Act requires that an individual importing live fish into the country or introducing species into any inland water must obtain written permission from the Minister of Agriculture, under which the Federal Department of Fisheries operates (Act, 2014). The culture of non-native genetically improved strains is allowed under such licences. The Minister or Commissioner could issue a licence to an individual intending to establish a fish farm with a surface area greater than 1 hectare and at sites close to natural waters where fish escape is likely to occur. Any business or experimental operation involving aquaculture activities, including the processing of aquaculture products, requires the written permission of the relevant authority (Act, 2014). However, even with recurring cases of fish farm escapes in Nigeria, the country is yet to consider reporting escape events, a monitoring measure that would help the authority build a database of the causes and measures that can be taken to prevent future reoccurrences. Given that this danger to native fish species may not always be clear to the farmers, sensitization exercises to explain the section of the Fisheries Act on escapes would be beneficial over the long run in support of the management of wild fish populations. Likewise, reviewing the policy to include the conservation genetics of wild fish species could support actions to reduce the risk of population depletion, introgression of non-native gene pools and species extinctions.

9.3 | Tanzania

In Tanzania, the National Fisheries Policy of 2015 was implemented to address major concerns with aquaculture, including management and control of aquatic resources, knowledge of the fisheries resource base, processing and marketing, research development, extension services, manpower and aquaculture development (http://faolex.fao.org/docs/pdf/tan168881.pdf). This policy is an update on the previous National Fisheries Sector Policy and Strategy Statement of 1997 and identifies challenges within the sector that should be addressed through policy reform (Mwaijande & Lugendo, 2015). The document highlights the potential seriousness of fish escapes, including the surveillance, monitoring and control of fish escapees (URT, 2015). Given that the introduction of Nile tilapia in Tanzania led to the displacement of indigenous tilapia species now considered critically endangered, as highlighted above, stringent measures to prevent future reoccurrence starting with risk assessment and risk management measures before introducing non-native species and setting up a fish farm should be a focal point of the country's policy on aquaculture. However, there is no obligation to report any suspected escape to the relevant authority, a measure employed in countries such as Norway and Scotland that have well-developed fisheries and aquaculture industries, so as to learn and take actions to prevent future escape (Jackson et al., 2015; Thorvaldsen et al., 2015). Mandatory reporting would help assess of the scale of overall escape events and likely causes and would inform development of guidelines to monitor the risks of escapes in the future (Jensen et al., 2010).

9.4 | Kenya

Fisheries and aquaculture activities in Kenya are regulated by the Kenyan Fisheries Services. One of their mandates is to regulate and

TABLE 1 Summary of fisheries and aquaculture policies in those sub-Saharan African countries that are the biggest producers of farmed fish, together with details of introduced tilapia strains, tilapia breeding programmes and native species that are known to be impacted by these activities.

Country	Legislation	Conservation strategy on fish introduction	Introduced strains	Fish escape	Breeding programme	Native species under threat
Ghana	a. The Fisheries Act of 2002 b. Fisheries Regulations of 2010	Prohibition of non-native genetically improved fish culture in cages.	GIFT	Not addressed	Akosombo tilapia genetic improvement programme	*Oreochromis mossambicus*, *Oreochromis niloticus* (Anane-Taabeah et al., 2019)
Kenya	Fisheries Act 2012	i. Farmers need Fish Mover's Licence for live fish movement ii. Stocking of fish species that were hitherto not present in a water body is prohibited by law	GIFT and *Oreochromis leucostictus*	Not available	Selective breeding programme of tilapia	*Oreochromis variabilis*, *Oreochromis esculentus* (Wasonga et al., 2017).
Malawi	National Fisheries and Aquaculture Policy 2016	Use of native species and improved strains of the indigenous species for biodiversity conservation	GIFT	Not addressed	Selective breeding programme of tilapia	*Oreochromis karongae*, *O. mossambicus* (Nzohabonayo et al., 2017)
Nigeria	Fisheries Act 2014	Written permission from the Minister is required to import into Nigeria any live fish introduced into any inland water system	GIFT from Thailand, Egypt, the Netherlands, and Ghana; Dutch *Clarias*	Licence is required from the Minister or Commissioner to establish farms with a surface area of more than one hectare where the escape of farmed fish into the fisheries waters is likely to occur	None	Potential genetic impact on *Oreochromis aureus*, *Sarotherodon melanotheron* and *Sarotherodon galilaeus* (Bartley, 2021)
South Africa	Alien and Invasive Species Regulations, 2014 National Aquaculture Policy Framework 2013 National Environmental Management: Biodiversity Act, 2004	Provides guidelines on the genetic management of domesticated stocks including genetically improved organisms in terms of protecting the natural biodiversity	Tilapias and other cichlids	Not addressed	None	*O. mossambicus* (D'Amato et al., 2007)
Tanzania	National Fisheries Policy of 2015	Not available	*O. niloticus*	The Government conducts surveillance to monitor and control fish escapees	None	*O. esculentus*, *Oreochromis jipe* and *Oreochromis korogwe* (Bradbeer et al., 2019)
Uganda	National Fisheries Policy 2004	Regulate import and export of fish and fisheries product	GIFT	Not addressed	None	*O. niloticus* and *O. leucostictus* (Diedericks et al., 2021)
Zambia	National Fisheries and Aquaculture Policy 2023	Provide for restrictions of the importation of fish	GIFT	Not addressed	Selective breeding of tilapia	Introgression with native *Oreochromis andersonii* (Brummett et al., 2008)

Abbreviation: GIFT, genetically improved farmed tilapia.

promote the genetic improvement of farmed fish. The Fisheries Act 2012 guides overall fisheries activities, including aquaculture (https://infotradekenya.go.ke/media/Fisheries%20Act%20CAP%20378.pdf). The Act prohibits the import, export and movement of fish from one water body to another unless the person possesses a permit. A special licence is required for collection of broodstock for breeding purposes. However, priority is given to researchers who might want to collect fish for scientific research, breeding or educational purposes. The current law is in place to regulate the introduction and movement of live fish within the country, but there are no measures to address questions related to fish escape and how it should be reported. The Act fails to provide remedial measures like tracing fish escapes and regulation of facilities like cages installed in natural lakes to raise farmed fish by ensuring that they meet standard requirements to minimize escapes. The Act is also not specific on how to deal with the impact of farmed fish on wild populations, a highly relevant topic since GIFT is now being cultured in Kenya (Munguti et al., 2022) and could be a threat to native species in the event of an escape.

9.5 | Ghana

The Fisheries Act of 2002 (Act 625) is the main legislative instrument that governs the practice of aquaculture in Ghana. Section 60 of the Act stipulates that a licence obtainable from the Fisheries Commission is required before setting up any aquaculture project (Awity, 2005; Ghana, 2002). In 2008, Ghana enacted new regulations to augment research capacity to bridge the gap between national fish demand and supply over the medium term (MoFAD, 2015). They subsequently drafted a Fisheries and Aquaculture Sector Development Plan (2011–2016), which outlined the steps taken to implement the Policy, followed by a Marine Fisheries Management Plan (Ameyaw et al., 2021). The Ghanaian authorities prohibit the culture of GIFT in Lake Volta and also mandate that an environmental risk assessment be conducted before installing cages in the lake (Blow & Leonard, 2007). However, there is evidence of farmers producing non-native GIFT in the lake and other aquaculture sites (Anane-Taabeah et al., 2019), which defeats the purpose of the law that prohibits such activities. Good policy and legislation on managing fish escape must be accompanied by regular supervision, while ensuring that penalties are enforced on offenders. Only then will proper actions be taken to manage risk, including the reporting of escape events to the relevant authority.

9.6 | Uganda

While Uganda is one of the leading fish producers in sub-Saharan Africa, its fisheries and aquaculture industries have been beset with problems due to weak legal, institutional and policy frameworks. To address these challenges, the Ugandan authority implemented the National Fisheries Policy 2004 to increase sustainable fish production through properly managing capture fisheries, promoting aquaculture and reducing post-harvest losses (Mugambwa et al., 2021). This policy also provides regulations for the import and export of fish and fisheries products (http://extwprlegs1.fao.org/docs/pdf/uga201565.pdf). The guidelines only highlight how to regulate the introduction of live fish, but because non-native farmed strains have found their way into Ugandan fish farms, there is a need for the authorities to introduce guidelines and also punitive measures to ensure that where it is prohibited, no such strains are being cultured. Likewise, addressing technical standards for aquaculture facilities and reporting escapes would help prevent future escapes and enable the government to take swift action to minimize the impacts.

9.7 | Zambia

Zambia's current principal legal framework for regulating fishing-related activities and aquaculture is the National Fisheries and Aquaculture Policy 2023. This new policy is an update of the previous Fisheries Act No. 22 of 2021 and the Fisheries Regulation No. 24 of 2012 (Shula & Mofya-Mukuka, 2015; Zambia, 2012). The National Fisheries and Aquaculture Policy addresses the issue of illegal introductions of non-native species, poor management of fish breeding areas and measures to prevent translocation of non-native species to the wild environment; the species that it covers include *O. niloticus*, *Cherax quadricarinatus* (redclaw crayfish) and *C. carpio* (common carp). The major challenge of the policy is low compliance due to inadequate personnel to enforce the law (https://www.mfl.gov.zm/wp-content/uploads/2023/06/NATIONAL-FISHERIES-AND-AQUACULTURE-POLICY.pdf). With the thriving *O. niloticus* production industry in Zambia posing a possible threat to native *O. andersonii* (Basiita et al., 2022), there is a need for the implementation of import and movement controls (Ellender et al., 2014).

9.8 | Malawi

In Malawi, the policy document guiding the management of the fisheries resources prior to 2016 was the National Fisheries and Aquaculture Policy of 2001 (Malawi, 2001). The need for more inclusive management and conservation to promote sustainable utilization of aquatic resources and income generation led to the development of a new National Fisheries and Aquaculture Policy (https://faolex.fao.org/docs/pdf/mlw190922.pdf) in 2016. This policy addresses more aquaculture-related activities, with an emphasis on the use of native species and improved strains derived only from indigenous species (Ministry of Agriculture, Irrigation and Water Development, 2016). However, with the GIFT now available in Malawi, provisions need to be made in the law or implementing regulations made to strengthen the National Fisheries and Aquaculture Policy of 2006 to address cases of fish escapes. Conducting risk assessments and requiring risk management measures before establishing a farm intended for the culture of non-native species such as GIFT (Lind et al., 2015) would minimize the future impact of escapes. It is also important to integrate mandatory reporting of fish escapes to enable early tracking by the relevant authority. Farmers producing non-native species need proper orientation to the dangers of fish escapes and the roles they can play to minimize the risks that escapes pose to fish conservation.

9.9 | Summary of legislative deficiencies

It is clear that the existing legislation and regulations relating to aquaculture in the relevant countries of sub-Saharan Africa do not effectively safeguard the conservation of wild fish species. In addition to a general failure to consider the risks of fish introductions, there are few regulations on the import of non-native species and genetically improved strains. There is also a lack of policies on facilities monitoring, technical assessment of cages and nets holding the fish, educating farmers on the risk of escapes, reporting every escape as soon as it occurs and implementing consequences for violating existing regulations. Fish escape is taken seriously in countries with long histories of intensive aquaculture such as Norway and Scotland, where escaped farmed Atlantic salmon have been reported to negatively impact wild salmon populations (Thorstad et al., 2008). Lessons can be learned from both countries, where reporting fish escapes as soon as they occur is mandatory (https://lovdata.no/dokument/LTI/forskrift/2022-08-22-1484). Introducing technical assessments of facilities and ensuring that individual farmers have the professional competence to help prevent escapes of fish from aquaculture facilities, as applied in the new Norwegian policy review (NYTEK23, 2022), would be a major boost to the genetic conservation of native wild fish populations in sub-Saharan Africa. Aquaculture policies across sub-Saharan Africa must be designed to take into account aquatic genetic resource conservation in order to protect the declining wild fish populations already threatened by unsustainable fishing practices and environmental change.

10 | RECOMMENDATIONS FOR REGIONAL POLICY FRAMEWORKS

Having highlighted some of the threats that fish introduction can cause to native wild populations, it is therefore important that the relevant authorities enact policies that follow guidelines such as those that the Commission on Genetic Resources for Food and Agriculture mandates for promoting the sustainable use of resources for food security and human well-being (FAO, 2019b). In order to minimize future risks from the introduction of non-native farmed fish, we suggest that a holistic policy centred on the conservation of aquatic genetic resources should incorporate the following recommendations:

i. Risk assessments should be conducted as a precautionary approach to estimate the likelihood of contamination of the genetic pool of wild fish following exposure to farmed fish, and risk management measures should be in place to minimize the impacts in the event of escapes (Hallerman, 2008).
ii. Genetic diversity indicators, including numbers of species, geographical distributions of native species and DNA-based monitoring, should be combined with information on the locations of fish farms sites when considering the risks posed by farming introduced species (FAO, 2019b; Hoban et al., 2020).
iii. The farming of non-viable monosex or sterile triploid stocks should be considered in sites where escapes are likely (e.g., outdoor ponds with no barriers) (Mair et al., 1997).
iv. Aquaculture sites should be regularly monitored to ensure the compliance and implementation of the enacted policies.
v. Farmers and fishers should receive training in genetic resource management and conservation, provided by Government fisheries and aquaculture research institutions (FAO, 2019b).
vi. There should be a greater emphasis on capacity building and investment in research and development, so as to monitor genetic resources and anticipate the effects of any proposed introduction of non-native fish species or strains (Allendorf, 1991).

11 | RECOMMENDATIONS FOR FUTURE RESEARCH AND POLICY DEVELOPMENT

Aquaculture involving production of non-native species is a potential threat to wild fish conservation. The impacts of farmed fish on wild populations can therefore only be minimized if relevant authorities adopt risk assessment and management strategies that will reduce the number and impact of escapees. Thorstad et al. (2008) recommended that the first management action is to understand the causes, circumstances and sources of fish escape to identify relationships between particular culture technologies, techniques and site locations and escapes. We provide a summary of the common features of aquaculture activities that lead to fish escapes in Table 2, along with suggestions for how either the probability of escapes or their impact can be reduced. Dealing with uncertainties posed by fish farms that could threaten the genetic diversity of native species requires adopting best management practices, which includes setting up minimum standards in terms of policy, choice of cultured species quality of rearing facilities and implementation of effective confinement. Ensuring the conservation of native wild fish genetic diversity in this era of rapid aquaculture development should be a priority. Hybridization between farmed and wild species can be controlled only if hybrids involving genetically improved strains stocked in the farms are non-viable.

Currently, there is limited information on the genetic diversity of native fish species in sub-Saharan Africa. Efforts aimed at conserving fisheries genetic resources must address this knowledge gap and place greater emphasis on research development in applied population genetics in the various country's fisheries and aquaculture policy documents. There is a need to investigate species distributions and conduct more research on genetic monitoring of the population

TABLE 2 Features of aquaculture activities that influence the likelihood of fish escape and the mitigation strategies that could be put in place to regulate these events, including potential minimum requirements a farm must have to comply with these strategies.

Aquaculture feature	Mitigation strategy	Minimum requirement
Introduction of non-native fish species	a. Establishing biosecurity measures and ethical guidelines on fish introduction and preventing illegal introduction through regulation. b. Establishment of protected areas where farmed fish must not be cultured, so as to prevent escapes from farms into native waters of conservation importance.	i. Conduct a risk assessment and management analysis to investigate the genetic and ecological impact of the prospective species. The goal is to reduce the introduction risk to the bare minimum. ii. An Act or decree regulating aquaculture fish introductions, covering both translocations within a country from one water body to another and introductions that transcend political borders. iii. Up-to-date database for introduced fish and stocking destinations.
Culture facilities	a. Farms must have effective screens or physical barriers to prevent escapes. b. Cages must be made from reliable materials to withstand attacks from fish predators and heavy storms without degradation. c. The use of recirculating aquaculture systems (RAS) to minimize fish escape. d. Public education and farm monitoring programmes.	i. Facilities must be certified suitable for the culture of non-native species, so as to minimize negative interactions with native species. ii. The freshwater Fish Invasiveness Screening Kit (FISK) risk assessment method to be used to evaluate invasion risks and classify fish under threats of invasion (Almeida et al., 2013, Marr et al., 2017).
Species/strains	Use of sterile populations such as triploid fish that lack the ability to reproduce, so eliminating the risk that escaped farmed fish can hybridize with native species (Muir & Howard, 1999).	Establishing and stocking in farm exclusion zones and implementing higher biosecurity measures (Thorstad et al., 2008, Xu et al., 2022).
Escape reporting	Documentation of the nature, scale and timing of any farm escapes	Provide information to farmers on the appropriate channel to report escape events for early detection (Wasonga et al., 2017). Requirement for immediate reporting of the situation, with any remedial actions taken.

structure of native species, as this is the best approach to detect interbreeding between farmed and native species (D'Ambrosio et al., 2019).

As a supporting approach, Lind et al. (2012) recommended a combination of geographical zoning, environmental risk analysis and molecular characterization approaches as the best overall strategy to minimize potential genetic contamination from farmed fish to wild populations. WorldFish has developed detailed guidelines for using GIFT; these were presented at the Workshop on Risk Assessment Methodologies and Tools for Aquaculture in Sub-Saharan Africa and adopt the principle of responsible introduction before transferring the strain to any country (Lind et al., 2015). While implementation of these guidelines and regulating the introduction of farmed fish is the responsibility of the individual countries, which must ensure that effective policies are in place to address the potential threats of fish introduction to the conservation of their native wild populations, there also should be consideration of cross-border regulations for countries that share water bodies.

12 | CONCLUSIONS

In conclusion, most of the top fish-producing sub-Saharan African countries have policies and legislation that clearly outline the importance of the conservation of fish species so as to increase fish production and provide households with an inexpensive source of protein (Table 1). However, these policies omit key details and alone do not ensure effective outcomes, because government competence is judged by the effective implementation of these policies (Mugambwa et al., 2021). If responsible aquaculture practices are to be adopted across sub-Saharan Africa, there is a need for the implementation of policies enshrined in the fisheries and aquaculture legislation. Some sub-Saharan countries, like Nigeria, Ghana, Tanzania and Zambia, have updated their fisheries and aquaculture legislation to address the present-day challenges while increasing fish production, and Nigeria and Tanzania have recognized the need to address fish escapes. However, more effort needs to be placed on implementation and surveillance, as well as a more specific focus on understanding genetic impacts on wild populations.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

ORCID

Mark K. Sanda https://orcid.org/0000-0002-0210-0959

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