Hindawi
Aquaculture Research
Volume 2024, Article ID 1341858, 21 pages
https://doi.org/10.1155/2024/1341858

Review Article

Towards Sustainability in Seed Supply for African Catfish, *Clarias gariepinus* (Burchell, 1822) Culture in Kenya: Lessons from Asian Catfishes Industry

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Received 11 August 2023; Revised 9 February 2024; Accepted 12 March 2024; Published 25 March 2024

Academic Editor: Pravesh Kumar

The culture of African catfish, *Clarias gariepinus*, is constrained by the high mortality of fry, occasioning a shortage of high-quality seeds for stocking by farmers. Asia, a continent with many success stories for aquaculture, leads in farmed production of some catfishes, a diverse group of 37 different families. Globally, the culture of catfishes ranks fifth in global farmed finfish production. Globally, Vietnam leads in the production and export of farmed striped catfish, *Pangasianodon hypophthalmus*, with 1,400,000 tonnes produced annually from about 7,000 hectares. Similarly, China farmed the non-native Channel catfish, *Ictalurus punctatus*, into the major crop, with a current annual production of 250,000 tonnes. On the contrary, *C. gariepinus*, the main farmed catfish species in Africa, records low annual yields, with 240,000 tonnes for the whole continent. This paper explores the factors behind the high production of *P. hypophthalmus* and *I. punctatus* in Vietnam and China, respectively, and draws lessons for *C. gariepinus* farmers in Africa. Specifically, the use of differentiated hatchery and nursery husbandry practices was critical in boosting seed production, quantity, availability, and distribution for expanding the culture of *P. hypophthalmus* in Vietnam. Improvement of fish species through well-designed genetic improvement programs helped China substantially increase production of *I. punctatus*. For both species, intensive fish production, as well as the adoption and implementation of suitable policies, increased seed production from hatcheries in both countries. These are discussed as some of the factors that spurred catfish production in the two Asian countries. We argue that if these are adopted by farmers in Africa, they could help improve the production of farmed *C. gariepinus* on the continent for food and nutrition security as well as generation of livelihood for local communities.

1. Introduction

1.1. Background Information on African Catfish, Clarias gariepinus Fisheries. Despite the diversity and global distribution of catfishes, landings of this group of fishes from many fisheries of the world are largely small-scale, behind cod, salmonids, cichlids, and carps [1]. Catfishes comprise a total of 37 families [2, 3]. These are distributed in major lakes, including the Great Lakes of Africa [4], rivers [5, 6], reservoirs [7], and swamps [5, 8], where they serve as important food resources for local communities. Catfishes are also important in the functioning of aquatic ecosystems, where most serve as predators. In most of these fisheries, however, exploitation of catfishes is still artisanal, with low annual landings, due to various reasons. In Lake Victoria, for instance, a decline in native fish species due to overfishing [9] and the impact of the non-native *Lates niloticus* through predation [10] reduced the populations of catfishes, making their exploitation artisanal. Additionally, habitat destruction through pollution and invasive species, such as the water hyacinth, *Eichhornia crassipes* [11], makes the exploitation of catfishes by fishermen difficult, occasioning reduced landings. On the other hand, habitat fragmentation through damming [7, 12] and the growth of papyrus at river mouths affect the breeding biology of some catfish species, since brooders migrating upstream for spawning are unable to navigate through the papyrus at river mouths or dykes of the dams. Similarly, after hatching by brooders upstream, fry or fingerlings have to migrate back to the lake for suitable nursery and feeding grounds. However, this migration is often difficult, where river mouths are overgrown with papyrus, which blocks the entry of the fry or fingerlings to the lake [12]. This exposes the juveniles to predation, reducing the numbers and effective recruitment to the stock. Reclamation of swamps for agriculture, tourism, and other domestic needs [8] reduces suitable habitats for catfishes and threatens critical species like the small-sized clariid catfishes (smooth head catfish *Clarias liocephalus* (Boulenger, 1898), Alluaud's catfish *C. alluaudi* (Boulenger, 1906), Snake catfish *C. theodorae* (Weber, 1897)) that form important biodiversity and food resources for local communities [13]. Similarly, intensification of agriculture in high agricultural potential areas, and increased human settlement and related anthropogenic activities lead to siltation of aquatic habitats, most of which are inhabited by catfishes, threatening catfish resources in reservoirs, which form part of the species exploited on a small scale [14].

These factors imperil the future reliance on natural populations of catfishes for human food. Furthermore, it is well documented that capture fisheries globally have stagnated, declined, and/or collapsed [15], and there was a need to increase aquaculture production to bridge the gap in fish supply. Generally, aquaculture is recognized as the fastest-growing animal food-producing sector globally [16] and has the greatest potential in meeting the increasing demand for fish. In Africa, freshwater-farmed finfish production is dominated by the Nile tilapia, *Oreochromis niloticus*, and African catfish, *C. gariepinus*. Although *O. niloticus* is the main farmed species in most African countries except Nigeria and Uganda, each species has its unique challenges in culture. In the spirit of diversifying farmed species on the continent, each of the two is generally promoted for their ability to meet food and nutrition security among local communities and reduce exploitation pressure on natural fisheries resources [17].

1.2. Initial Research Efforts on the Culture of African Catfish, C. gariepinus in Africa. Following the identification of *C. gariepinus* as a suitable species for aquaculture in Africa during the early stages of the history of fish culture on the continent [18], several research efforts were undertaken to enhance the production of the species. Notable among these were the field trials under the Food and Agriculture Organization of the United Nations (FAO) projects in the Central African Republic, Republic of Congo Brazzaville, Kenya, Ivory Coast, Nigeria, and Ghana [19]. Additional work was undertaken by the Department of Technology and Fisheries Science of Rhodes University, South Africa; the Department of Aquaculture and Inland Fisheries of Wageningen University, The Netherlands; Department of Zoology, Utrecht University, The Netherlands; as well as the Kinneret Limnological Laboratory of Israel; under different projects [19]. The studies involved pond construction, artificial propagation techniques, hatchery establishment and operations, diets, diseases and disease control, economic feasibility of catfish culture, seed production and nursery, reproduction, and growth [20], backed by practical development in skills [19]. Development of enhanced practical skills was boosted by sending some African students and officers on short practical courses in Norway, the United Kingdom, Netherlands, Belgium, Israel, and the Aquaculture Research and Development Center in Port Harcourt, Nigeria.

These efforts stimulated the development and establishment of *C. gariepinus* culture in many African countries in the 1970s and 80s. In Kenya, for instance, a total of 30,000 ponds were established in the 1970s in the western part of the country (the former Western and Nyanza Provinces) alone [21], mainly stocked with *C. gariepinus* and tilapias. These efforts were subsequently boosted by government intervention under the rural development fund, which supported the establishment of more ponds across the country in the 1980s [22]. Although these interventions represented a real boost for the culture of *C. gariepinus* in Africa, many farmers faced high mortality of fry and fingerlings [23], which generally led to a shortage of seed for stocking ponds. Therefore, as the lifespan of the projects ended, many farmers in different countries could not cope with the challenge of mortality of fry and inadequate availability of seed and subsequently abandoned their ventures. Consequently, *C. gariepinus* production in Africa slumped in the 1990s, safe for a few countries like Nigeria and Uganda. However, there was a renewed interest in *C. gariepinus* culture on the continent from the 2000s, driven by diverse factors. In East Africa, for instance, demand for *C. gariepinus* rose due to the use of fry as live bait for catching Nile perch, *L. niloticus* in Lake Victoria using long lines and hooks [24]. Declining catches from the capture fisheries and increased availability of trained manpower to support extension service for farmers, backed by increased research activities [25], also fueled demand for farmed *C. gariepinus* in the region.

Increased availability of trained manpower in the region arose from various projects operating on Lake Victoria, such as the Haplochromis Ecology Survey Team, spearheaded by the University of Leiden, the Netherlands; Lake Victoria Environmental Management Programme, Lake Victoria Research Programme, which sponsored the training of Africans at MSc and PhD degrees levels in Fisheries Management at European Universities (notably Leiden, Hull, and Bangor). Similarly, scholarship programs of specific countries, such as the Commonwealth Scholarship helped train Africans at the University of Stirling (Institute of Aquaculture), while the Netherlands Scholarship Programme (NUFFIC) sponsored Africans to train in Fisheries science at Wageningen University. The Belgian Development Cooperation, through the Flemish Inter-University Council, supported the training of African students for a Master's degree in Aquaculture, especially at Ghent University, Belgium. Through these initiatives, the hatchery at Sagana Fish Culture Farm received technical support from the Belgian government in the mid-1990s, which helped renovate the hatchery for improved seed production. This was followed by the relocation of the United States Agency for International Development supported project (Pond Dynamics Aquaculture) on aquaculture development and training from Rwanda to Kenya. The project was based at Sagana Fish Farm, as a collaboration between the Kenya Fisheries Department, Moi University, and Auburn University (USA). Manpower from these programs helped improve fisheries management, and establishment of hatcheries to support aquaculture (including propagation and nursery of Clarias fry for seed) as an option for reducing exploitation pressure on the Lake Victoria fishery. Research efforts focused on the poor survival of larval stages of the species [26], and the same problem was identified in the 1970s as the main challenge to Clarias culture on the continent [27].

1.3. Challenges to the Culture of African Catfish C. gariepinus in Africa. Farmed production of *C. gariepinus* across the African continent is constrained by poor survival of fry [26]. This is a long-standing challenge to the practice, having been identified in the initial trials of *C. gariepinus* culture of the 1970s and 80s [23, 28–30]. Poor survival of fry limits the availability of adequate numbers of seeds for use by farmers to expand their aquaculture enterprises. Mortality of 32.5%–99.8% of the total batch of fingerlings purchased and stocked by farmers occurs [23, 31], and consequently, farmers become disillusioned and abandon their enterprises [32].

1.4. Causes of Mortality in Farmed C. gariepinus Seed. During egg incubation, a batch of eggs may fail to hatch due to contamination of the facilities in the hatchery with bacteria, viruses, and fungi [33], because the pathogens or parasites clog the eggs and prevent fertilization of some of the eggs or suffocate eggs by surrounding them to prevent exposure to dissolved oxygen, or even extract nutrients from eggs, interfering with development. This reduces the number of hatchlings from a given batch of fertilized eggs under incubation despite the high fecundity of the species. The presence of pathogens in fry nursery units causes mortality of fry [34] through irritation, stress, and disease. Mortality of fry during nursery further reduces the actual number of fingerlings available for sale to potential farmers, occasioning a critical shortage of seed. However, due to cannibalism, big-sized catfishes, either in culture or brood stock ponds, may cannibalize each other, especially if the feeding regime is not optimal. This reduces the number of fish in ponds, disillusioning farmers due to losses at harvest. General husbandry practices by many farmers also inadvertently cause mortality of the fish at different stages of growth. For instance, diets and feeding practices for larvae at the hatchery are critical for the survival of the fish. Considerable challenges in the nutrition of larvae emerge at the onset of exogenous feeding after absorption of the yolk sac [35]. This is because larvae require live feeds at this stage, yet different farmers use different live and dry feeds of varying quality and nutritional composition.

The use of live feeds that are unsuitable, of poor nutritional quality, or even dry feeds of poor composition, unsuitable sizes, and digestibility [36] leads to high mortality of larvae. Small-scale farmers of *C. gariepinus* often use dry diets such as maize bran as starter feeds for larvae and fry [36]. This is because such feeds are cheaper and so affordable for resource-poor farmers. However, these are of poor nutritional quality (crude protein content of only 13.3% compared to Artemia nauplii of 74% and fish meal of 55% crude protein) [36] and poor digestibility [36], and consequently cause poor survival of larvae and fry. Similarly, larvae require optimal feeding frequency, usually around six times daily, to ensure satiation. Inadequate feeding frequency leads to mortality of larvae, either directly through hunger [37] or through cannibalism among siblings. In the early stages of growth, larvae or fry have very rapid growth under good nutrition. So, a few larvae in the batch that command higher feeding ability quickly become bigger than their siblings and begin to cannibalize smaller larvae in the batch [36]. This reduces the number of larvae and, subsequently, seed availability.

Formulating appropriate diets for fingerlings is even more complicated [37], because of the desire to replace expensive sources of animal protein, such as fish meal, with plant-based protein sources. Often, farmers overcome this by utilizing ingredients for plant protein [37] instead. Usually, a variety of plant matter is incorporated as ingredients for plant protein in order to enhance the profile of amino acids in the formulated diets [38]. This increases the nutritional suitability of the diets. However, most plant materials contain anti-nutritional factors (ANFs), which inhibit the digestibility and bioavailability of nutrients in the fish's digestive system [39]. Such feeds are not suitable for *C. gariepinus* fingerlings and lead to mortality. However, different processing methods may ameliorate the ANFs, but these are costly.

C. gariepinus at hatchery and nursery units generally require optimal rearing temperature for survival and growth. Temperature ranges of 25−33°C are recommended for rearing *C. gariepinus* larvae and fry, with 28°C being the optimal and preferred temperature [40, 41] for higher survival. Larvae and fry maintained at lower temperatures of 22°C suffer higher mortalities [40]. Temperature is critical for metabolism, and it appears to be an important factor in the growth and survival of *C. gariepinus* fry. At the hatchery, a higher temperature seems necessary to stimulate active feeding, which impacts both the growth and survival of fry. In many African countries, *C. gariepinus* hatcheries are open air, with no control of temperature, which often drops to lower levels at night and leads to the mortality of fry. Small-scale farmers operate small hatcheries, where temperature is not controlled because of limited resources and the scale of operations, and so report higher mortality of fry and fewer seeds available for stocking and or sale to other farmers. Similarly, while many endowed farmers now establish nursery units for *C. gariepinus* fry in greenhouses, temperatures in the greenhouse often decrease at night and may cause fry mortality unless supplemental heat is used at night.

While husbandry practices (feeding, predation, temperature control), body physiology, and disease pathogens and parasites seem to influence the survival of *C. gariepinus* larvae and fry at hatcheries, characteristics and management of brood stock used at the hatchery may play an even bigger role in larval and fry survival. In a recent study, it was suggested that the use of poor-quality brood stock of mixed ancestry may be a contributory factor in the poor survival of fry [42]. In Kenya, the development of *C. gariepinus* culture from around 2,000 involved a complex transfer of brood stock and seed across the country. Seed was moved from Sagana Fish Culture Farm in Central Kenya, the main fish seed production center at that time, to western Kenya for on-farm trials [25]. Around the same time, seed was moved to Uasin Gishu in the Rift Valley from Sagana at the onset of the Pond-Dynamics Aquaculture project [32]. But from 2003, with the construction of the Moi University Fish Farm, *C. gariepinus* seed was distributed widely from here to the Lake Victoria basin to support renewed interest in Clarias culture and supply live baits for use in the Lake Victoria *L. niloticus* longline fishery. Due to poor documentation, the origin of the initial *C. gariepinus* brood stock at both Sagana station and the Moi University Farm was not known, although studies showed that the stock at Sagana station had multiple sources [32]. Around the same time, several farms under the Lake Basin Development Authority, as well as private farms, were revived and developed, as sources of seed. Fish from these farms and or Lake Victoria were used to restock Lake Kenyatta in Lamu at the Kenyan coast [43], many miles away from the Lake Victoria basin.

Often, such translocations cause cross-breeding or inter-population hybridization [44], which increases the fitness of the fish through heterosis or hybrid vigor. These benefits are realized in both hatchery-reared and natural fish populations, and this strategy is commonly applied by hatcheries whose brooders suffer loss of fitness [42, 44]. Hybrid vigor also accrues from the hybridization of different species. The non-native African catfish, *C. gariepinus*, introduced into Thailand in 1987 from the Lao PDR, has faster growth rates and higher resistance to diseases than the native *C. macrocephalus* and *C. batrachus* [45], whose flesh is of better quality and taste. Therefore, male *C. gariepinus* is hybridized with female *C. macrocephalus* and the hybrid is used in aquaculture [46] due to its faster growth rate, higher tolerance to diseases, environmental variability, and better flesh quality and taste [45]. Better attributes of the hybrid result from hybrid vigor, which helped spur annual farmed Clarias production in Thailand to 20,000 tonnes in the early 1990s [46]. *C. gariepinus* is also reported to hybridize with *C. anguillaris* in the Senegal River basin [47], and a mixture of *C. gariepinus* populations affects the survival and persistence of natural populations [43].

However, the benefits that accrue from hybrid vigor are only transient in both farmed and natural fish populations and species, since the vigor hardly lasts beyond F1 generation [44]. This is because the hybrid or crossbreed loses the ability to adapt to local conditions [48], or coadapted gene complexes associated with the parents are broken down [49, 50] [44]. Therefore, the hybrid or crossbreed loses fitness through outbreeding depression [51, 52], which may occur in F1 or later hybrids [44]. In Clarias species, the loss of fitness may be expressed as reduced survival [45, 53, 54] and informs the threat of the non-native Dutch strain of *C. gariepinus* on native populations in South Africa [53] and the ban of *C. gariepinus* in Bangladesh [55].

Furthermore, individual hatchery operators often collect both male and female *C. gariepinus* brooders from natural habitats or neighboring farms to increase the numbers at the hatchery, because a male is always sacrificed during artificial propagation for milt to fertilize the eggs, while the number of females may reduce due to cannibalism. Such collection exercises are often indiscriminate, without regard to the boundaries or drainage basins of the species or population. This increases the frequency with which a female brooder is reused to generate offspring in the next generation. This leads to inbreeding, which if persisted in the population, causes inbreeding depression and the reduction of fitness due to mating between relatives [44]. Mating between relatives increases homozygosity for a particular trait [56], and the reduction in fitness is expressed as poor growth and survival of the fish.

In many African countries, the supply and distribution of fish seed is motivated more by the economic gains made by the sale, without regard to safeguarding the purity of the fish species based on the species boundaries within which it is naturally distributed. Therefore, seed for a given species are moved across river basins, and even across countries, due to porous borders and limited understanding of the species range among extension workers, farmers, and government regulatory authorities. This leads to a mix-up of species and populations, prejudicing the purity and integrity of species, and this negatively impacts the unique traits of a given fish species or population. Overall, therefore, it becomes difficult to ascertain the origin and exact species of the brood stock used by farmers in artificial propagation, which affects the quality of progeny [42]. Furthermore, brooders whose origin is uncertain often are sources of transmission of parasites and disease pathogens to hatcheries and nursery units, which increase the mortality of fry [34] or lower the hatching rates of fertilized eggs [57], reducing the availability and quality of seed.

2. The Culture of Catfishes in Asia as a Success Story

2.1. Seed Propagation for P. hypophthalmus (Sauvage, 1878). The migratory Sutchi (Striped or Tra) catfish, *P. hypophthalmus* (Sauvage, 1878) of the Mekong is one such species of catfish, whose current aquaculture production exceeds landings from capture fisheries [58] and commands a high global market demand [59]. Overexploitation of natural populations, use of illegal fishing gears by fishermen, habitat modification through damming for hydropower production and irrigation, deforestation, and decline in water quality [60] are some of the factors that influenced the decline of natural populations of *P. hypophthalmus* in the Mekong. The decline of landings of the species from capture fisheries of the Mekong occasioned the establishment of a vibrant aquaculture enterprise in the Mekong delta of Vietnam [61], quickly distinguishing the species as an important export commodity (Figure 1) of high demand in 136 countries [64].

The rapid growth of the *P. hypophthalmus* culture industry, at an average of 37% increase annually, saw annual tonnages hit an average of 1,400,000 MT by 2011 (Figure 1), with a turnover value of US$ 1.85 billion and employing 221,535 people [64]. Of these, 105,535 people were directly employed in fish production, comprising seed production,

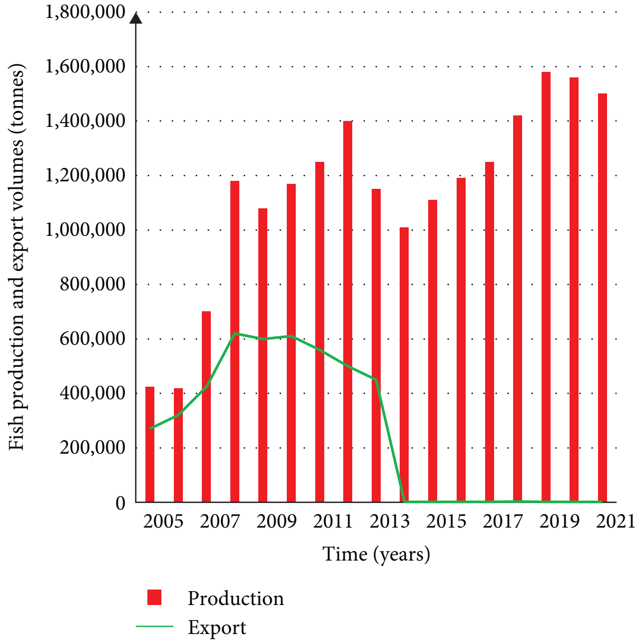

Figure 1: Total tonnage of farmed *Pangasianodon hypophthalmus* produced in and exported by Vietnam, 2005–2021. There was a rapid increase in annual production from about 2005, mainly due to intensive production to meet demand from increasing export markets. Exports of the commodity rose steeply between 2005 and 2008, before a decline from 2009, mainly because of antidumping laws in the USA against Vietnamese *P. hypophthalmus*. There was a steep decline in export volumes from 2013, ranging from 1,186 to 2,261 tonnes annually between 2014 and 2021, mainly because of declining markets and a drop in prices by up to 35%. Source: [15, 59, 62, 63].

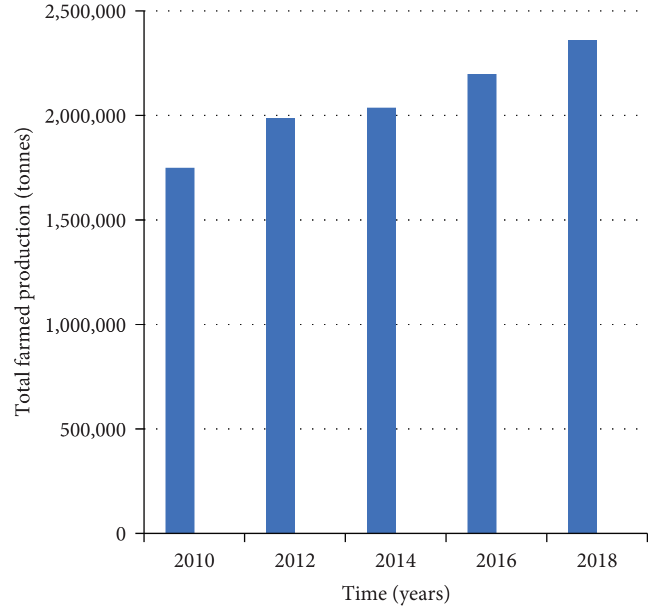

Figure 2: Global production of farmed striped catfish, *P. hypophthalmus* 2010–2018. Intensification of production and use of technology, high-quality seeds produced from hatcheries, commercial diets, and processing of the product using global quality control systems commercialized the industry. Global annual production was averaging 2.4 million tonnes from China, Thailand, Cambodia, Myanmar, Lao PDR, Vietnam, and Bangladesh. A large proportion of this came from Vietnam, with many farmers utilizing the large Mekong Delta of Vietnam. Adopted from Ouma and Barasa [3].

nursery and distribution, and grow-out systems, while 116,000 people worked directly in fish processing factories [65]. Although the species is cultured in several Asian countries (China, Thailand, Cambodia, Myanmar, Lao PDR, Vietnam, and Bangladesh) with a total annual production of 2,400,000 metric tonnes (Figure 2), Vietnam is the lead producer, contributing about 58% of the total annual production (Figure 2). In order to guarantee production to meet the global demand for *P. hypophthalmus* fillets, Vietnamese authorities invested heavily in seed production [66] to ensure farmers had a sufficient supply of high-quality seeds.

2.2. Channel Catfish, I. punctatus (Rafinesque, 1818). As a similar success story, China established a vibrant aquaculture industry of the Channel catfish, *I. punctatus* (Rafinesque, 1818) in the country after the importation of the species in the 1980s. Following the successful development and implementation of artificial propagation of the species for seed production in 1997, farmed production rose rapidly, hitting 248,000 tonnes by 2013 [67] (Figure 3). This rapid rise in production was due to a high demand for the fish product in many parts of the country [71]. Like the *P. hypophthalmus* of Vietnam, this demand stimulated heavy investment in production, especially seed availability for use by farmers, and increased employment opportunities for locals [71]. This saw a steep rise in annual production between 2003 and 2010, peaking at 238,564 tonnes in 2009 (Figure 3), before a slight decline in 2011 [68], and a steady rise to 250,000 tonnes annually, before shooting to 295,671 tonnes in 2019 [68] (Figure 3). Both local demand and the export market fueled increased production of the species. The steep rise in annual production between 2003 and 2008 (Figure 3), the industrialization phase of *I. punctatus* in China, was favored by the trade war between the USA and Vietnam over imports of *P. hypophthalmus*, which were restricted under the antidumping laws [69]. Therefore, China took advantage of these restrictions to increase production of *I. punctatus* (Figure 3) to take up the market in the USA [72] (Figure 3), which is still the leading importing country for Chinese *I. punctatus* [72]. Over the same period, export volumes rose from 6,000 tonnes to a high of 17,074 tonnes annually in 2008 [72] (Figure 3), then declined to 16,993 tonnes in 2009 and subsequently stabilized at below 10,000 tonnes annually (Figure 3). The increase in export volumes in 2007–2009 was driven by the increased number of processing factories for the species across the country [73]. By 2019, export volumes were 3.50% of the total annual production, with the USA being the lead importing country [72], followed by the Democratic Republic of Congo (DRC), Republic of Congo Brazzaville, Cameroon, Equatorial Guinea, Central African Republic, Singapore, Thailand, and Costa Rica [72].

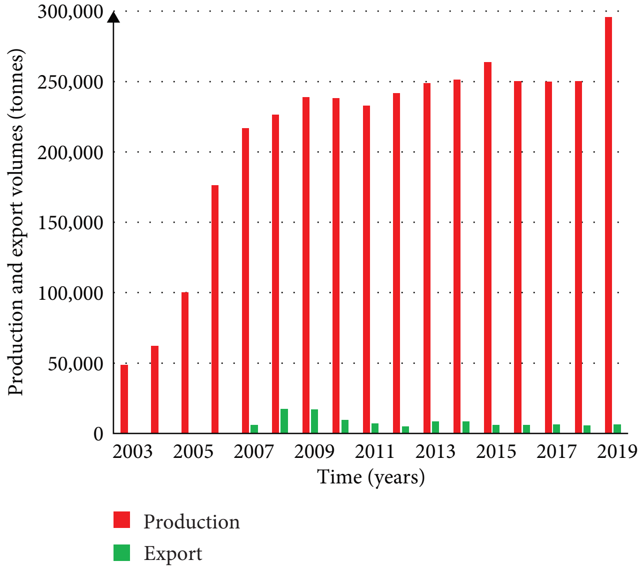

FIGURE 3: Annual production and export volumes of farmed channel catfish, *I. punctatus* production in China, 2003–2019. Source: [68]. Annual production rose sharply between 2003 and 2010, before stabilizing at around 245,000 metric tonnes for about 5 years, then rose above 250,000 tonnes. While commercial production of the species in China started around 2003, substantial export for the species started around 2007 and peaked in 2008–2009, because of the market opportunities arising from the ban on Vietnamese *P. hypophthalmus* exports to the USA by the anti-dumping Laws of 2003 [69]. Source: [70].

These two species, together with *C. gariepinus* (Burchell, 1822), are the most important catfish species in aquaculture [74], contributing largely to the total global production of 5.06 million metric tonnes of farmed catfishes in 2016. However, unlike *P. hypophthalmus* of Vietnam and the non-native *I. punctatus* of China, which are success stories of aquaculture in Asia, farmers of *C. gariepinus* in most African countries are highly vulnerable, because seed availability is often a challenge. Even where a farmer is able to access and purchase a sufficient number of seeds, high mortality often occurs in ponds [19, 32]. This causes losses to farmers, creates disillusionment, and is responsible for the stifled growth of Clarias culture in most African countries after growth trials in ponds in the 1970s. The species is also invasive and predatory [75], and this may have restricted its importation to some countries, such as China, in the 1970s in order to protect native fish species [76].

However, its good attributes for aquaculture, such as fast growth rate and high dress-out content [77, 78], favored its widespread translocation, often through deliberate human effort, flooding, and escape from aquaculture facilities [78]. Also, weak laws and regulations such as the PRC Domestic Animals Epidemic Prevention Regulation, 1983, and the PRC Animal and Plant Quarantine, 1992 [79] only enforce quarantines to control the spread of diseases but do not restrict the importation of non-native fish species into China. Therefore, *C. gariepinus* was imported into China from Egypt and the Central African Republic in 1981 (Wang & Cheng, 1990) [80]. Widespread cultivation of the species was adopted in South China, where farmers were motivated by the higher prices of *C. gariepinus* compared to the native *C. fuscus* [79]. Due to faster growth and higher resistance to diseases compared to the native *C. macrocephalus*, *C. gariepinus* was imported to Thailand in 1988 [46]. The two are hybridized to give an offspring of higher growth and disease resistance, which currently constitutes 80% of farmed Clarias production in Thailand [54]. These examples illustrate the suitability of *C. gariepinus* in aquaculture, and production of the species in Africa could be increased substantially if the key challenges were addressed adequately.

2.3. Seed Propagation of C. gariepinus (Burchell, 1822). Artificial propagation of *C. gariepinus* at hatcheries is a well-developed, routinely practiced, and documented procedure [31], the same technological advancement that drove rapid growth in farmed production of *P. hypophthalmus* and *I. punctatus* of Asia. Detailed procedures of the technique are reported by several studies [19, 27, 30]. Incubation of fertilized eggs is done in diverse units, depending on the ability of the hatchery. These include outdoor concrete tanks, earthen ponds, or indoor glass tanks (aquaria). In order to increase hatch rates, indoor units are often installed in greenhouses, where optimal temperatures are attained naturally. In the absence of a greenhouse, indoor units are often fitted with thermostats powered by solar or electricity. Requisite optimal temperatures for egg incubation range from 27 to 30°C [81], where hatching is successfully accomplished in about 24 hr. However, for outdoor units or where the temperature is not optimal, hatching lasts more than 24 hr [81].

Fertilized eggs (stripped from a gravid female and fertilized with milt from a male) are transferred onto a substrate on which they attach and put into the incubation unit. Several types of substrates are used by different farmers, including kakabans (strings of sisal twine, nylon, or sackcloth), roots of water hyacinth, and egg trays (netting material mounted on some frames) [82]. Usually, a substrate holds a large number of eggs, which hatch successfully as long as optimal temperature and aeration are maintained during incubation. Newly hatched fry have a yolk sac, a mass of nutritious food material, on which the fry feed [83], and so the fry remain in the incubation unit for one more day after hatching, during which the yolk sac is completely absorbed. Immediately, the yolk sac is absorbed, and fry is transferred to the nursery unit, where they are fed on live feeds, since their digestive system is not yet developed. Live feeds are nutritious and easy to digest and include the brine shrimp (*Artemia nauplii*), yeast, and plankton [84]. This requires the production of these feeds for adequate and reliable supply by, for instance, hatching the shrimp from cysts and culturing plankton in ponds enriched with organic manure. Fry are stocked in the nursery units at a density of 100 m^{-2} [19], where they are reared for 5 weeks [27], although higher stocking densities of 250 m^{-2} is practiced by experienced hatchery or nursery operators [19]. The length of time the fry are reared in the nursery can be reduced to 3–4 weeks to reduce cannibalism, but they are maintained on live feeds for the first 2 weeks before dry feeds are introduced slowly. High feeding frequency, often up to six times daily, is required to ensure satiation and reduce cannibalism. Dry feeds should be of high quality (35%–40% crude protein) to increase both growth and survival rates [35, 36], and these can be freshwater atyid shrimp-formulated diets and catfish starter diets [35]. From the nursery, fingerlings are transferred to grow-out units, which may be outdoor earthen ponds, indoor tanks, or raised ponds. Grow-out units, especially ponds, are limed and fertilized to boost natural feeds for the fish, and the fish are fed on dry diets of high quality (30%–35% crude protein). Stocking density in grow-out units is 10 fingerlings m^{-2} [19].

2.4. Lessons for African Catfish C. gariepinus Culture Industry in Africa. A global culture of catfishes is dominated by *C. gariepinus*, *P. hypophthalmus*, and *I. punctatus* [3], belonging to three different families: Clariidae, Pangasiidae, and Ictaluriidae, respectively. Each of the three species has a high fecundity and high growth rate and achieves a large size in grow-out units. It also exploits a diverse range of food materials, attributes that make them excellent species for aquaculture. In this regard, *P. hypophthalmus* and *I. punctatus* are iconic examples of success stories for aquaculture production, where they have been recruited to aquaculture. Cultured *P. hypophthalmus* is best captured in the Mekong delta of Vietnam, which became a success story in about a decade of sustained enterprise by farmers in a small geographical area [85]. Between 1997 and 2007, annual production rose from 683,000 metric tonnes, of which 90% was exported as processed fillets [86], earning US$645 million. Similarly, the culture of *I. punctatus* in China recorded phenomenal growth in a decade, reaching 248,000 metric tonnes in 2013 [67] (Figure 3).

On the contrary, farmed production of *C. gariepinus*, the main cultured catfish species in Africa, is low. In 2006, for instance, the average annual production on the continent was 300,000 tonnes, valued at US$400 million [87]. At that time, a total of 30 countries globally were producing more than 100 tonnes annually [87]. Total farmed production in Africa is variable [2], mainly due to poor reporting in many African countries. Lead producers of the species on the continent are Nigeria, Uganda, Ghana, Egypt, and Kenya [70] (Figure 4), and production peaked in 2015 with a total annual tonnage of 246,476 metric tonnes [88], which dropped to less than 200,000 tonnes in 2020 [15]. (Figure 4). Farmed *C. gariepinus* production in Malaysia was 50,000 tonnes in 2015, valued at US$ 51,271 [89]. This low production of *C. gariepinus* in Africa is mainly attributed to the inadequate availability of high-quality seeds for use by farmers in stocking their ponds for commercial production, due to the high mortality of fry or fingerlings [26]. Despite tremendous research efforts in addressing these challenges [3], the shortage of high-quality seed for use by farmers still persists in many African countries due to the poor survival of fingerlings. Here, we draw parallels in the culture of *P. hypophthalmus* and *I. punctatus* that would be useful for increasing the production of *C. gariepinus* in Africa, if implemented. Measures for producing adequate and high-quality

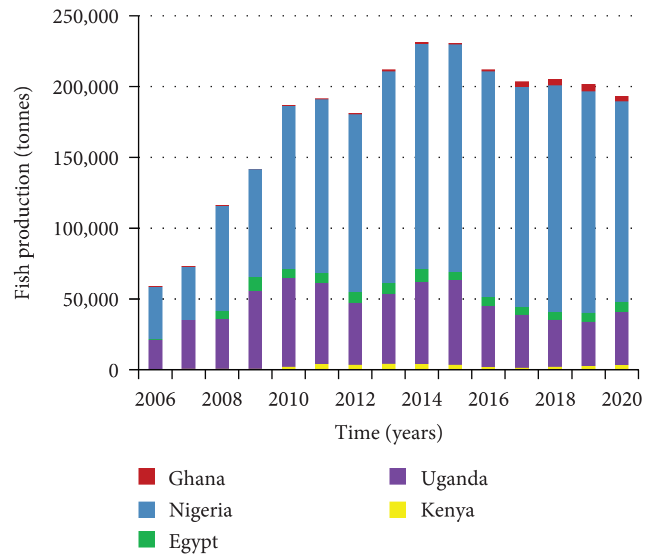

Figure 4: Annual farmed *Clarias gariepinus* production in five lead producers of the species in Africa (Nigeria, Uganda, Ghana, Egypt, and Kenya), 2006–2020. Source: [15]. Production peaked around 2014 and 2015, with total production below 250,000 tonnes, and has been declining since.

seed, fish improvement programs, intensive fish production, larval nutrition, as well as policy issues are discussed in the context of how they spurred the production of *P. hypophthalmus* and *I. punctatus* in Asia and the potential for driving adequate seed production for commercial *C. gariepinus* aquaculture in Africa.

2.5. Production of Adequate and High-Quality Seed. The phenomenal increase in farmed production of *P. hypophthalmus* and *I. punctatus* in Vietnam and China, respectively, was initiated by developing, perfecting, and disseminating artificial propagation skills to all hatcheries in the countries [90] to ensure that seed production was not dependent on natural populations. This was an important step, since, for *P. hypophthalmus*, Cambodian authorities had banned the harvesting of seeds from the Mekong by farmers [59, 90] for use in stocking ponds. Prior to the ban and development of artificial propagation techniques, fry, and fingerlings for stocking were mainly collected from natural populations of the Cambodian waters at the confluence of the Bassac, Mekong, and Tonle Sap rivers [91]. Following the breakthrough with artificial propagation techniques, adequate numbers of seeds for farmers were ensured by increasing the number of hatcheries across Vietnam [66]. These ranged from small scale to a large one, with different levels of operations. In total, 93 hatcheries were developed, which helped increase seed production to 813 million [66], produced in 29 cycles of fry annually [92]. These developments in the culture of *P. hypophthalmus* mirrored those for *I. punctatus* culture in China, starting with the development of artificial propagation techniques for the species and the expansion of hatchery production operations to meet the demand for high-quality seeds [71]. Similarly, most of the hatcheries used large-sized brooders for spawning, since fecundity is directly related to the size of brooders. Therefore, the number of seeds obtained or expected from a single batch of spawning brooders was high, contributing to the adequacy of seed supply. All these developments parallel those implemented for *C. gariepinus* culture in Africa. In Kenya, for instance, the number of hatcheries for *C. gariepinus* propagation rose from about 5 to 29 in 2010 through the implementation of the government-funded National Fish Farming Enterprise Productivity Program of 2009–2012 [93]. This number has since increased, with the devolution of the aquaculture subsector to county governments countrywide from 2013, as a new level of governance under the new Constitution of Kenya 2010. Several county governments with visionary leadership have since established new hatcheries to support seed production for commercial aquaculture in their jurisdictions. More efforts are needed to establish fish hatcheries in many African countries to support the production and supply of an adequate number of seeds to farmers for commercial aquaculture.

In order to increase the quality of fry for aquaculture enterprises in Vietnam, most hatcheries maintained a large number of brooders at the hatchery, from which suitable spawning pairs were selected. For *P. hypophthalmus*, most hatcheries kept 350–29,200 fish as brooders [66]. A large population of brood stock of high genetic variation is desirable to maintain the genetic quality of the offspring [94], i.e., the ability of the hatchlings to meet the purpose for which they are bred: fast growth rate, high survival, and fecundity in culture. Therefore, for *P. hypophthalmus*, the high number of brooders maintained at hatcheries was sufficient enough to assure high-quality offspring. This is a practice that *C. gariepinus* hatchery operators in Africa need to adopt and internalize to help generate fry of higher quality and, therefore, increase the survival of fry. However, for the benefits of a large sample size of brooders to be realized, farmers also need to source for and use brooders of pure strain and of high genetic variation. Brood stock of higher genetic variation imparts higher vigor to offspring [44], while a larger population of brooders minimizes the frequency with which a given brooder is reused for spawning to give the next generation of fry [56]. This reduces inbreeding, which would otherwise lower the fitness of fry. To be able to keep a large number of brooders at the hatchery, *C. gariepinus* farmers need to invest more in ponds or tanks for holding the brooders, optimal feeding strategies to avoid cannibalism, ensure adequate, clean, and reliable water supply, control parasites and disease pathogens among brooders, and control predators, including potential thefts of the fish in ponds. These are husbandry practices that control mortality or decline in numbers of the fish reared at the hatchery level to avoid population bottlenecks that otherwise lower the genetic variation of the fish.

Population bottlenecks result from founder effects, disease out-breaks, and deterioration of water quality in fish-holding units, since all these would cause fish mortality [95]. One way Kenyan farmers could address these is by specialization in the stages of *C. gariepinus* growth, similar to the differentiation in seed production and management of farmed *P. hypophthalmus* in the Mekong delta, Vietnam [66]. Seed production comprised of the hatchery and nursery (fry and fingerling units carried out by different farmers), with each of these being performed by different farmers who then sold their products to grow-out farmers. This enabled specialization by farmers who easily adopted better management practices (BMPs) that were used to manage diseases and environmental variability in the culture units [66]. Since for every artificial propagation of *C. gariepinus* at the hatchery, a male brooder is sacrificed to provide milt to fertilize the eggs, a deliberate attempt should be made to add more males to the brood stock frequently, for availability during the next time they are required for artificial propagation. The number of females should also be kept high in order to avoid frequent reuse of a certain female. If additional brooders are collected from natural ecosystems such as rivers, reservoirs, or lakes, care should be taken to ensure the strain collected is the same as that for the brood stock already at the hatchery, in strict compliance with regulations on interbasin transfers of fish. The collection of a different strain of *C. gariepinus* would lead to the mixing of different gene pools, which affects the gene pool of the strain initially at the hatchery. This causes out breeding depression [44], expressed in poor production, such as reduced survival of fry. A large number of brood stock population maintains the quality of fry because it increases genetic variation at a locus for a given trait [96].

Seed production units for *P. hypophthalmus* are well differentiated and specialized, generally composed of hatchery, nursery, and grow-out units, each with a distinct ownership and management [66]. The hatchery comprises brood stock ponds, the hatchery unit itself, earthen fry ponds, and earthen nursery ponds. Fish seeds from the hatchery unit are sold to the nursery unit, which is composed of earthen fry ponds and earthen nursery ponds. Fish seeds from the nursery unit are sold to the grow-out unit, which comprises on-stream and on-canal ponds and reared to marketable size [66]. In each of these clearly defined units, the fish seeds are reared under BMPs, minimizing impacts on the environment, while optimizing conditions for fast growth and survival and controlling the environmental variables to ensure the safety and quality of the product. In order to address the challenge of poor survival of *C. gariepinus* seed, it would be desirable to adopt the differentiated system of fish seed production and development for *P. hypophthalmus* so that each unit is specialized to handle only a certain stage of the seeds. This way, it will be easier to employ suitable husbandry practices such as optimal temperature conditions for egg incubation and fry nursery units, optimal feeding regimes, disease control, as well as selection and grading of fry, to avoid cannibalism that reduces survival.

2.6. Improvement of Fish for High-Quality Seed. The high quality of the seed is also maintained by continuous genetic improvement of the fish. This is achieved by selective breeding so that the breeding pair used to generate seeds for stocking in ponds is one that has been selected [97] for the desired trait, such as growth, survival, or fecundity. In order to increase cultured production of *I. punctatus* in the USA, genetic improvement of the species started early in the 1980s, with studies on genetic diversity [98, 99] and selective breeding [100]. These efforts helped raise seed production from 500 million annually by 2003 to the total required amount of 2 billion [99], and this is estimated to have reached 2.6 billion by 2019 [101]. Following the rapid growth of *I. punctatus* culture in the 1980s in China, the quality of germ plasm was quickly eroded, expressed as reduced growth rate and disease resistance [102]. This was due to a small number of brooders at hatcheries, the long generation time of the fish, and high inbreeding levels [103]. This forced the authorities to establish breeding programs for better strains [71].

To facilitate effective breeding programs for better quality and quantity of seed, the authorities constructed the National Genetic Breeding Center for Channel catfish [102]. The breeding efforts gave rise to the JiangFeng No. 1 strain [71], with a faster growth rate (22.1%–25.3% greater than nonimproved strains). Breeding efforts were also boosted by the China Catfish Institute, which was established in 2004 to undertake research on all aspects of Catfish [102]. Studies in the USA report single nucleotide polymorphisms for harvest weight and residual carcass weight [104], as well as improved efficiency of selection using estimated breeding values (EBVs) and genomic EBV [104] for *I. punctatus* in the USA. Similarly, linkage groups with quantitative trait locus for disease resistance have been mapped in the species [105], and studies are underway to identify genes associated with disease resistance [105]. These concerted research efforts on genomic selection have contributed to increased production of *I. punctatus* in the USA, with a current annual production of 164,000 tonnes [106]. Although China is not currently applying genomic selection in *I. punctatus* culture, adoption of this technology could help increase annual production from the current tonnage of 300,000 tonnes [106] substantially. Additionally, in the USA, the production and use of hybrid *I. punctatus* fingerlings and other improved lines of *I. punctatus* helped increase and intensify farmed *I. punctatus* production [107]. Recommendations on the need to develop a continental or regional improvement program for *C. gariepinus* in Africa were made in 2007 [108]. Following this, and the already established need and desire to increase seed production of the species from hatcheries and or farms [17, 109] for income, livelihoods, and as a strategy to conserve natural populations of the species, studies on genetic characterization of *C. gariepinus* have been undertaken over the last decade [32, 42, 43, 110–113]. Although these studies focused on populations from East and West Africa, they report genetic variation in the species that is high enough to support the development of a genetic improvement program for *C. gariepinus*. Implementing a continental or regional genetic improvement program for the species would help increase seed production. Adoption of the genetically improved farmed tilapia (GIFT) strain by farmers, for instance, helped increase sustainable seed production by 68% and 46% in the Philippines and Thailand, respectively, by 2003 [114]. The most important factor in a genetic improvement program for a fish species is to develop a base population of high genetic variation for the trait of interest, which would not be eroded in just a few generations of selection in aquaculture, best exemplified by the development of the GIFT strain [115]. Therefore, advanced studies could build on the molecular studies so far undertaken on *C. gariepinus* in Africa, applying genomics to map commercially important traits such as survival and growth rate in suitable populations of *C. gariepinus* to support breeding efforts for higher survival of offspring.

Studies of heritability and response to selection give insights into whether mass selection of the species would help improve a farmed fish species [116]. If these two parameters are high for a species, then it is possible that selection would help improve the species for the trait of interest. It is possible to expect a genetic gain from selective breeding. Due to high values of heritability and response to selection in *I. punctatus* in the USA, growth rate, survival, and feed conversion ratio (FCR) were improved significantly in selected populations relative to nonselected fish [116]. Response to selection in three strains of domesticated *I. punctatus* ranged from 54 to 73 g, while realized heritability ranged from 0.24 ± 0.06 to 0.50 ± 0.13 [116], demonstrating the ability of mass selection to improve the growth of the species. Early studies on the species involved selection for rapid growth and helped identify populations of the species suitable for important traits such as growth and survival [100, 117]. These studies stimulated research in selective breeding and the general improvement of *I. punctatus* in the USA and were replicated in China after the importation of the species in 1984. Recent studies report the first genetic improvement program for *C. gariepinus* in Thailand, with additive genetic variance for the species laying the foundation for genetic improvement [118]. Thailand is one of the Asian countries with a fairly well-developed Clarias culture industry and has an annual production of 150,000 metric tonnes [119] of the hybrid, which constitutes more than 80% of Clarias farmed in Thailand [120]. Related to this, moderate heritability has been reported for the species [121], showing the possibility of additive genetic variance for the species, which could be exploited for genetic gain to improve growth traits for the species. Genetic parameters have been established for growth traits [118], as well as reproductive traits in *C. gariepinus* [121]. Although low values of heritability for reproductive traits for the species were recorded [121], these enabled the study of genetic gain in the species or the response to selection, which could be improved upon in subsequent generations. A good selection response of 10.37% was reported in the species [122], although heritability for growth was low (0.128−0.129) and may affect the response to selection in generations [122]. This selection response was similar to those reported in other commercially important catfish species: 5.8%–20.0% per generation in *I. punctatus* [116] and 9.3% per generation in *P. hypophthalmus* [123]. Therefore, if well-designed and sustained, a genetic improvement program for *C. gariepinus*, coupled with good husbandry practices, is likely to help reduce the challenges that stifle its culture in Africa.

2.7. Intensive Production of Fish. Despite numerous studies on the effect of stocking density on survival among farmed catfishes, it is not yet clear if higher stocking density would

Table 1: Production characteristics for larvae to fry and fry to fingerlings for farmed striped catfish, *P. hypophthalmus* in the Mekong delta, Vietnam.

Parameter	Production period	
	Larvae to fry	Fry to fingerling
Stocking density (/m^2)	60–8,000	500–800
Stocking density (/m^3)	200–7,000	25–583
Culture period (days)	20–45	20–120
Harvest (millions of fish/farm/year)	0.04–1,800	0.02–60,000
Harvest yield (millions of fish/ha/crop)	0.3–4.65	0.25–1.3
Mean size of fish (cm)	0.5–8.5	1.2–20

Adopted from de Graaf and Janssen [19] and Gisbert et al. [130].

favor the survival of catfish in culture. Results showed that the effect of stocking density on fish survival may be specific to the culture system used [124], fish species being cultured [125], or dependent on the stage of fish, for instance, fingerlings of *C. gariepinus* [126] or *C. gariepinus* fry [126]. Generally, some studies report a favorable effect of higher stocking density on the survival of cultured *C. gariepinus* [126] due to the ability of the fish to breathe atmospheric oxygen when the arborescent organ becomes fully developed [127]. Due to this, a number of studies recommend stocking *C. gariepinus* at high densities of 9–15 fry per m^2 [126, 128]. Obviously, more studies are required to clearly understand the effect of stocking density on the survival of farmed *C. gariepinus* fry, fingerlings, or grow-out fish. However, if stocking density positively influences survival, then farmers need to intensify production at each of the stages of fish growth, similar to the intensification of *P. hypophthalmus* and *I. punctatus* that consequently increased the harvest dramatically, within a short period. Such intensification would increase the availability of seeds for stocking, as well as the total harvest of mature fish after a reasonable grow-out.

Executed on a very small area of about 6,000–7,000 ha in a single location of the world [129], the culture of *P. hypophthalmus*, an iconic industry in all aspects, produces about 200–400 t^{-1} ha^{-1} crop [129] (Table 1), the highest production for any primary production sector globally [59]. Grown in southwestern Vietnam in the Mekong delta, the culture of *P. hypophthalmus* also represents the highest level of intensification [59], with annual growth in production sustained at 37% between 2003 and 2008 [87]. The practice transformed from the use of cages to earthen ponds, with a typical pond being 4–4.5 m deep with regular water exchange from the river. Part of the intensification stems from the vertical integration of the production system, with hatchery, fry to fingerling, and grow-out operations being carried out independently [129] (Table 1) by different players in different locations [59], but each of the units complements the other. This makes it easier for respective operators to follow and adhere to laid down best management practices, with an eye on the highest possible production, to feed and tap in to the expanding export market. Most of the farmers are organized into clusters [66], which makes it easier to disseminate new technology or any relevant information, make bulk purchases of inputs for the cluster, benefit from possible reduced prices, and reap from favorable prices and markets. The produce from respective farmers is easily pooled together as a cluster to reap from the economies of scale. Similarly, operating as a cluster helps in cost-effective methods of disease control, since it is possible for a cluster of farmers to keep a certain level of hygiene and avoid practices that are environmentally unfriendly. This helps farmers adhere to quality standards for the product, which ensures the quality and safety of the produce [59]. These are very important measures that contribute to the suitability of *P. hypophthalmus* as an export commodity, since almost all of the produce from this industry is destined for the export market [129]. A similar mode of a cluster of farmers was adopted in Kenya during the implementation of the National Fish Farming Enterprise Productivity Programme [93], implemented between 2009 and 2012, with farmers grouped together based on the location. It was easier for the farmers to be supplied with inputs and training on modern techniques of fish production. There is a need to revive this cluster system for *C. gariepinus* farmers to boost production.

Record keeping is ensured by all farmers. This helps to track production in terms of quantities and quality, as well as pricing of the product, costs of inputs, profitability of the enterprise, and market trends over a period of time. Similarly, record keeping is quite crucial in the breeding of the fish, because it helps farmers to track the number of brooders, the productivity of each brooder, and other desirable traits such as growth rate. In this regard, a farm that has excellent records for the enterprise is able to mount an effective selective breeding program using pedigrees that increase the output and profitability of the enterprise. Due to these factors, combined with an expanding export market, seed production is a vibrant venture in the farmed *P. hypophthalmus* of Vietnam to support grow-out systems. In 2008, for instance, a total of over 60 billion seeds were produced [66], well in excess of the 52 billion that was required for 2008 [92]. In order for *C. gariepinus* farmers in Africa to increase seed production to support sustainable farmed production, the adoption of similar measures will be crucial, as well as capacity building for extension agents and farmers on genetic management of brood stock [66].

3. Larval Nutrition

Generally, feeding is the single most costly practice in the culture of finfish, demonstrating the importance of supplementary feeding for farmed fish. Furthermore, the importance of feeding for successful aquaculture enterprises is reflected in the fact that the fish must be fed daily. It is applicable to all the systems under which the fish are reared or the fish improvement program being implemented to increase farmed fish production. Balanced nutrients for farmed fish are crucial because they enhance the growth of the fish, improve immunity, and hence overall fish health, fecundity, and reproduction, as well as enhance the nutritional profile of the fish [131]. This increases the suitability for use as human food [131]. The rapid rise in production of the iconic *P. hypophthalmus* of Vietnam and the non-native *I. punctatus* of China was also partly driven by optimum nutrition for all stages of the farmed fish. For instance, high quantities of seed production for *P. hypophthalmus* were achieved by stratification into specialized operations of hatchery, nursery, and grow-out units [66]. These increased efficiency of production through the adoption of BMPs, with farmers for respective units, for instance, using the best quality of diets, specific for differential growth stages of fish. Naturally, farm-formulated diets were often of better quality and cheaper than commercial diets; more hatchery operators used farm-formulated diets than those using commercial diets [66] to feed their fish. A high feeding ratio of up to 10% body weight of fish was also maintained by most hatchery operators [66] and ensured that the fish were well-fed for high growth and survival rates. For grow-out units, most farmers used commercial diets [85], with average crude protein content of 25.8%. However, farm-formulated diets incorporated vitamins, probiotics, prebiotics, and premixes [132] to enhance the palatability, digestibility, pelletization of feed, and immunity of the fish. Throughout the development of the *I. punctatus* culture in China, research into the optimization of efficient and high-quality feed production was maintained [71]. Current high production of the species in China is supported by nutritionally balanced diets [71], incorporation of enzymes, such as phytase [133], carnitine [134], and fermented herbal extracts [135], to enhance feed digestibility and immunity of the fish. The quality of eggs is also called oocyte developmental competence, the ability of the egg to be fertilized and develop into a normal embryo [131]. An egg of good quality will survive at the different stages of embryonic development and will, therefore, influence the survival of the larvae. This underscores the importance of brood stock nutrition, since the quality of nutrients available to brooders is transferred to the eggs to improve the quality. Brood stock maintained under high-quality nutrients, such as the inclusion of n-3 highly unsaturated fatty acids, show a higher ability for reproduction, and the quality in terms of survival and growth of larvae is much higher [136]. For *C. gariepinus*, brood stock fed with suitable diets increased reproductive performance and the growth and survival of larvae [137]. A higher specific growth rate (SGR) of 0.87% and relative growth rate of 135.25% are reported in *C. gariepinus* larvae from brood fish fed at 5% body weight compared to larvae from brooders fed at a lower level of a high-quality diet of 40% crude protein [138]. The fish fed at 5% body weight also had higher fecundity and survival [138]. Similarly, *C. gariepinus* fry fed on a 35% crude protein diet showed higher SGR, survival, and better FCR than the fry fed on 30%, 28%, and 25% crude protein diets [139].

C. gariepinus brooders fed diets with curcumin and thyroxine hormone supplementation spawned eggs of higher quality and generally showed higher reproductive performance that positively impacted the survival of larvae [140]. As a phenolic compound, curcumin is a hepatoprotective [140], increasing the functioning of the liver, especially in vitellogenesis that produces vitellogenin [141], a substance that increases reproductive potential in fish by increasing egg yolk content [136, 140]. Eggs with a high amount of yolk sac ensure improved embryogenesis and adequate nutrition for the hatchlings, which positively impacts the growth and survival of such hatchlings [140]. Similarly, curcumin contains phytoestrogens, which enhance the expression of antioxidant genes in hepatocytes [142], and this boosts the synthesis of vitellogenin [141, 142]. Coupled with curcumin, thyroid hormone creates synergy in reproductive activity in fish: the synthesis of estradiol by granulose cells of the thyroid hormone [143]. Estradiol hormone then stimulates the expression of vitellogenin genes in hepatocytes, which then induce the production of vitellogenin [140], which is transported to oocytes under the influence of thyroxine. Also, the thyroid hormone enhances the availability of intracellular energy required for vitellogenesis. Therefore, these two compounds are essential in the reproduction of fishes, and for *C. gariepinus*, they help increase vitellogenin, triglycerides, and the diameter of spawned eggs, whose overall effect is improved embryogenesis [140]. Hatchlings from such eggs would be of higher quality and probably of higher survival and growth. Therefore, supplementation of feeds for larval *C. gariepinus* with these compounds plus other related substances is crucial in improving the reproductive performance and quality of larvae. However, there is a need to test these hypotheses, in order to add these additives in feed formulation for *C. gariepinus* larvae to enhance survival.

4. Feed Additives

Feed additives are substances added in trace amounts to a diet or feed ingredient for their beneficial effects. Generally, feed additives are grouped into four categories: technological additives, e.g., preservatives, antioxidants, emulsifiers, and acidifiers [144]. These are added to diets to preserve the nutritional characteristics of the feed prior to giving to the fish or animal. This group of additives helps to improve feed quality by reducing ANFs, microbes, and rancidity, improving dispersion of ingredients, and feed pelleting. Sensory additives, such as flavors and colorants, improve the quality of feeds by improving the taste, color, and general palatability to attract fish for consumption of the diet. Nutritional additives include vitamins, amino acids, and trace elements, while zootechnical additives, such as digestibility enhancers, generally improve the digestion of feeds ingested by the fish [144].

Feed additives improve the feed quality and thus enhance the health performance and feeding efficiency of the fish [145]. They increase anti-oxidation, immune-stimulation, and probiotics for health and growth promotion, as well as improving water quality [145]. Natural feed additives are used in aquaculture species as alternatives for disease prevention [146]. Due to their importance, feed additives have been applied in diets for different farmed fish species to improve growth, health, and efficiency, and these benefits have been demonstrated in the growth, survival, and body composition of *C. gariepinus* fingerlings [146]. Studies report a much more beneficial effect of combining probiotics and medicinal plants in diets of farmed fish and livestock [147], and these could be new research frontiers on innovative and sustainable strategies of dietary formulations to improve growth and survival in *C. gariepinus* fry.

Generally, immuno-stimulants are currently used increasingly as alternatives to antimicrobial agents in aquaculture, because they enhance fish growth and survival [148] by boosting nonspecific immune response in fish, while helping avoid antibiotic resistance by pathogens [148]. Herbal products are especially useful in this regard, since they serve as antistressors, appetizers, tonics, antimicrobials, and immuno-stimulants. For instance, supplementation of diets with feed additives garlic, *Allium sativum*, devilweed, *Chromolaena odorata*, and waterleaf, *Talinum triangulare* increased the growth and survival of *C. gariepinus* against bacteria [148]. The positive effect of these additives on the growth of the fish could result from their ability to improve the deliciousness, digestion, and nutrient absorption of the diets [148]. Supplementation of diets with *Echinacea purpurea* and *A. sativum* [149] and green tea (*Camellia sinensis*) and amla-fortified [150] have a similar positive effect on the growth and yield of *O. niloticus*, while Phyllathus emblica-formulated diets enhanced the growth of *O. mossambicus* [151]. On the other hand, the additives increased the survival of *C. gariepinus* because of boosting the immunity of fish against pathogens (bacteria and fungi). It is thought that the additives achieve this function by serving as immuno-stimulants, enhancing both innate and adaptive immune responses of *C. gariepinus* [148] due to bioactive compounds. Therefore, in order to increase the growth and survival of *C. gariepinus* on the continent, farmers need to increase the use of phytobiotics as additives by incorporating these in feeds. Phytobiotics are especially important because they boost the innate immunity of fish, are cheaper than antibiotics and more environmentally friendly, with minimal residual and side effects, and have been proven effective in boosting the growth and survival of rainbow trout [152].

In order to address cannibalism among a batch of *C. gariepinus*, especially larval stages, additives that reduce aggression and cannibalism among siblings should be incorporated into diets. Larvae-fed live feeds such as Daphnia reduce aggression and cannibalism, because this negative behavior and energy is directed toward pursuing mobile live feeds [153]. The efficacy of live feed in reducing cannibalism is further enhanced by mixing it with micronematodes of the Panagrellus sp. family. This is because of the increased protein–fat ratio [154] and the secretion of additional proteolytic enzymes by the nauplii, which enhance food absorption in larvae [155]. Supplementation of diets with L-tryptophan, an amino acid that secretes serotonin, is one of the powerful ways of reducing cannibalism in *C. gariepinus* and other fish species [156]. Serotonin increases the serotoninergic activity of the brain [157], which inhibits aggression among the fish, social subordination caused by dominance hierarchy, lowers the level of cortisol in serum, thereby reducing stress among the fish, effectively reducing cannibalism [157]. Additionally, L-tryptophan additive increases food ingestion and utilization, as well as boosts the immunity of the fish [157], important factors in countering mortality through infection and cannibalism [156]. More studies on suitable additives for *C. gariepinus* diets able to reduce cannibalism and increase survival, FCR and utilization are required to effectively address cannibalism in farmed populations.

5. Probiotics

Probiotics are live microorganisms capable of protecting animals and plants from pathogenic microbes when administered in adequate amounts [158]. Probiotics confer the health benefits to host individuals by improving the immunity and the gut microbiota of the host. For *C. gariepinus*, studies show that probiotics play an important role in the growth, survival, and feed utilization, when incorporated in adequate amounts in diets. For instance, larval *C. gariepinus* fed on diets with probiotics show higher survival and PER than those fed on Artemia only [159]. Similarly, larvae fed Artemia showed higher SGR and weight gain than those maintained on probiotics. However, among diets of probiotics, larvae fed mixtures of different probiotics (lactic bacteria, *L. acidophilus*, *L. bulgaricus*, and *S. thermophilus*, embedded g^{-1} in dry white edible starch) reported higher survival and PER than those fed on diets of single probiotic species (*Saccharomyces cerevisiae*) only [160]. Similar studies in Indonesia testing the effect of probiotics on the survival and growth performance of *C. gariepinus* fingerlings report higher survival, daily weight gain, SGR, and FCR by fingerlings fed on diets and reared in water supplemented with probiotics (mixture of *Bacillus subtilis* and Lactobacillus sp.), compared to controls [160].

Related studies also suggested better growth and survival of *C. gariepinus* fed with probiotics compared to controls [161]. These studies seem to suggest that higher survival, growth rate, and feed utilization efficiency of first-feeding larvae and fingerlings of *C. gariepinus* could be attained by using probiotics in different mixtures as diets and could help increase seed availability. The positive effects of probiotics on the growth, survival, and feed utilization efficiency of fish are achieved through diverse mechanisms, such as increasing the number and diversity of microbial community inside the gastrointestinal tract of the fish, improving the immunity of the fish, stimulating enzymatic microbial activity, inhibiting and or killing pathogens in the water medium, which increases the health of the fish, and increasing digestibility of feeds improves FCR [159, 160].

6. Policy Issues

In order to increase the farmed production of *P. hypophthalmus*, the Vietnamese authorities put in place measures to address environmental, social, technical, and economic factors influencing the sustainability of the industry. Key challenges facing the industry included the use of locally caught native fish for feed of farmed *P. hypophthalmus*; the impact of effluent from ponds on the surrounding environment; the application of chemicals and antibiotics; and competition for land [162, 163]. Generally, the authorities encouraged farmers to use a combination of farm-formulated and commercial diets, as well as the adoption of alternative ingredients to develop their own feeds for the farmed fish [66]. These reduced the exploitation of natural populations of fish for use in formulating diets, so that natural fish populations are exploited only for human food, especially for the rural people. In order to minimize the impacts of wastewater effluents on the Mekong, water from ponds was directed to other farms, such as rice paddies and horticulture units, to improve agricultural production. Similarly, prior to stocking ponds, lime was always applied as a husbandry practice, to control pathogens as well as increase water alkalinity to support primary productivity.

In the aftermath of the decline of indigenous fish species of Lake Victoria due to various factors [9, 10, 17], many hatcheries have been built, and efforts to increase production of *C. gariepinus* seeds from hatcheries made in East Africa [24, 109, 164]. This is a strategy to enhance the conservation of indigenous fish species of the basin by reducing exploitation pressure. However, many hatcheries face challenges that reduce their efficiency in seed production. These include high costs of electricity, raw materials such as ingredients for feed, and equipment such as tanks, thermostats, and pipes. Governments in Africa need to waive or reduce taxes on such items in a deliberate attempt to encourage hatchery operations for *C. gariepinus* seed production. Power tariffs should particularly be reduced and supply enhanced to make power availability more reliable and cost-effective, so that hatchery operations such as egg incubation are not disrupted by power failure.

As a leading aquaculture-producing country in the world, the single most important factor that has fueled China's phenomenal growth in aquaculture is policy and law on the development and regulation of aquaculture [165]. For instance, the Fisheries Law of the People's Republic of China was adopted in 1986 [166], helping to guide the growth of aquaculture by shifting from marine and inland capture fisheries to aquaculture [165]. This was followed progressively by policies supporting improved quality and efficiency of fish products rather than quantity of production [165]. In order to accelerate the development of fish seed production for commercial aquaculture, the Administrative Regulations on Aquaculture Fingerlings were adopted in 2001 and revised in 2005 [167]. These regulations helped shift from the use of natural fish seed collected from natural habitats to that propagated on farms and hatcheries. Additionally, the regulations helped refine artificial propagation techniques, dissemination and effective guidance of farmers on the same by a vibrant extension service [165].

All these efforts were boosted by the official focus on aquaculture development and growth through the policy of reform and opening up, in which the country encouraged zero growth in fishing production and a ban on summer fishing, leading to the aquaculture dominance policy of the 1980s and 90s [168]. Under this policy, the government progressively shifted focus from capture fisheries to aquaculture. This enabled heavy investment in breeding centers for respective farmed species, including *I. punctatus*, the development of improved and cost-effective feeds utilizing raw materials that are less environmentally destructive and not in competition with food materials for humans, control of diseases and pathogens, the introduction of quality control systems across the value chains for respective species, as well as market research to boost the export market for respective species. In this regard, the government established aquaculture industrial zones showcasing modern technology and innovation in fish breeding, artificial propagation, husbandry, disease control, product safety and quality control, processing, and marketing [169], which served as model learning centers for farmers of respective species.

Consequently, the number of fish seeds of all freshwater-farmed fish species increased from 59.51 billion in 1981 to 1.252 trillion in 2019, while the number of marine fish fry increased from 167 million in 1996 to 11.44 billion in 2019 [170]. Production of such high quantities of seed was further facilitated by the construction of the aquaculture seed industry systems. These included the construction of breeding and genetics centers for the genetic improvement and breeding of aquatic species, the establishment of aquaculture introduction centers for new species, refurbishing original aquatic breeding farms for the protection of native species with good characteristics and breeding of high-quality parental fish, integration of genomic selection in selective breeding of farmed species, effective dissemination and extension service, adoption of best practices in seed production, wide adoption of improved strains and artificial propagation techniques by farmers, which spurred commercial production [171, 172]. For species like *I. punctatus*, the Chinese authorities established the China Catfish Institute to handle diverse aspects of the species, such as marketing, quality control of germplasm, and fillets of mature fish.

It is clear that heavy investment by the Governments of Vietnam and China was instrumental in the rapid growth of *P. hypophthalmus* and *I. punctatus* farmed production. In order to increase the quality and quantity of seeds for Clarias aquaculture, African Governments need to develop suitable policies to guide investment in and development of Institutions for the breeding and multiplication of seeds, demonstration centers for the learning of farmers, as well as boosting public extension service. Such policies should be clear on the qualifications of extension staff to be recruited, the numbers of staff required per unit area or number of farmers, facilitation of extension staff to reach farmers, and frequent refresher courses for the staff. Except for a few African countries such as Egypt, Nigeria, Uganda, Kenya, Malawi, Zambia, and South Africa, which have a fairly well-established aquaculture industry, most countries on the continent have no aquaculture facilities, and those that have coastlines or inland water resources still rely heavily on capture fisheries for fish supply, despite dwindling landings.

But even for those few that have tried to develop the aquaculture industry, facilities are often generalist, and not specialized for certain fish species. It is important for African countries to try and establish species-specific facilities, so that the production of species like *C. gariepinus* is increased and the value chain is improved. Although many aquaculture development projects were established in different countries such as Central African Republic, Nigeria, Ghana, South Africa, and Kenya by the FAO, African Union, and the WorldFish [19], these did not have much impact on *C. gariepinus* production and were not sustained, for lack of qualified staff and adoption and support by respective governments.

In Kenya, the promulgation of the new Constitution of Kenya 2010 necessitated the merging of several organizations and the creation of new ones in the Agriculture sector, as per the provisions and clauses of new laws and policies. For instance, the Kenya Animal Genetics Resources Centre (KAGRC) was created by the conversion of the former Central Artificial Insemination Station (CAIS). KAGRC is mandated to produce, preserve, and conserve animal genetic materials (semen, embryos, tissues, and live animals) and rear breeding sires for the provision of high-quality, disease-free semen to meet the national demand and for export. This is the closest the establishment of specialist Institutions for breeding has come in Kenya, and although the Center is charged with animal genetic material, it is still limited to livestock and has so far not handled fish genetic material. Although the main Institution charged with fisheries and Aquaculture research in Kenya has fish multiplication and research centers, none of these are species-specific.

Following the promulgation of the Constitution of Kenya 2010, the Fisheries industry in Kenya has undergone several changes, involving the creation of new laws and Institutions to regulate and oversee specific functions for the growth of the industry. This transformed the Kenya Fisheries Department from one governed only by the Fisheries Act Cap 378 to two components currently: the State Department of Fisheries and Blue Economy (SDFBE) and State Agencies (Table 2). The SDFBE handles policy issues affecting the Fisheries industry, while different legislation has created a total of five State Agencies to handle different specialized functions to improve the efficiency and growth of the fisheries industry. Although specialization created by these institutions is not yet to a level where an institution solely handles matters for a specific fish species as it happens currently in China, it represents a step in the right direction for Kenya. This specialization, albeit at its current limited level, could be built upon in the future to address species-specific matters.

In particular, institutions of higher learning that train personnel for the fisheries and aquaculture industry in African countries should be well equipped with facilities for fish hatchery, nursery, and grow-out, so that trainees obtain practical skills in modern aquaculture technology to help them serve farmers efficiently and effectively when recruited as officers. This requires substantial investment by governments. China and Vietnam have highly specialized universities, offering fisheries and aquaculture or oceanography degree programs [88, 173] with well-equipped laboratories, and most of the students' fees are covered by governments [174]. Also, in Vietnam, students are often attached to public Institutions to learn and acquire practical skills before they complete their degree programs [175]. In China, students benefit from strong University–Industry linkages that allow them to spend time in industry for practical skills, and newly recruited extension workers are trained at well-equipped field training centers for staff [118]. Currently, African Institutions Training Fisheries experts are few, and some offer these as short courses, or those offering degree programs, do so only for a few years, and then the program closes [176] due to limited facilities, qualified personnel, and financial support for students. According to [177], out of 329 Institutions in 10 countries within the Great Lakes of Africa region that offer academic programs in aquatic sciences, only 23% offered specialized programs in Aquatic sciences, with the rest offering nonspecialized programs such as general Ecology, Environmental Sciences, and Natural Resource Management. Drawing from the strategy of specialization applied by China in the growth and development of aquaculture, there is a need for African countries to develop and mount degree programs that are specialized in Aquaculture, especially at the postgraduate level of study. This specialization should also cut across research institutions in fisheries and aquaculture that absorb the graduates. In this regard, certain centers of the research institutions should be specialized in certain farmed fish species, so that they are manned by specialists for the species.

7. Conclusions

Artificial propagation of *C. gariepinus* is well developed and routinely performed by many hatcheries and farms in Africa where the species is cultured, but requires improvements, such as BMPs, in order to match the procedures for *P. hypophthalmus* and *I. punctatus* in Asia. Specifically, *C. gariepinus* farmers and hatchery operators need to specialize in different stages of seed production: egg incubation, larval rearing, nursing of fingerlings, and grow-out units. Specialization allows individual operators to understand the challenges of a given stage of propagation or rearing and, therefore, improve the management of the respective stages of the seed. Farmers specialized in a specific stage of seed production will also form groups of cooperative societies for the specific stage to help in marketing of the seed, as well as procurement of inputs more cost-effectively. This should be supported with a vibrant extension service provided by well-trained and motivated extension agents. To ensure continuous training of extension officers, training centers for in-service staff should be established and staffed well. At each of the stages for seed production and grow-out, proper nutrition for the fish should be adopted to improve growth and survival. Improvement of the species, using technologies such as selective breeding, should be supported, in order to realize the immense benefits associated with selective breeding. This is crucial, since the technology has helped improve the production of other fish species substantially, yet it has never been implemented for *C. gariepinus* in Africa.

Table 2: The new state agencies running the Kenya fisheries and aquaculture sector, created under the new laws of Kenya to improve the management and development of fisheries resources.

Agency	Relevant legislation	Risks	Main function
State Department of Fisheries and Blue Economy	Executive order number 1/2016 on organization of government	As a single agency, Kenya Fisheries Department was unable to effectively manage, regulate, and develop Fisheries and Aquaculture in Kenya due to outdated Fisheries Act cap 378, with limited budgetary support from the Exchequer for the sector	Policy matters affecting the fisheries industry
County Governments	Transition to Devolved Governments Act 2012	Limited public participation and ownership in food production systems and ineffective public extension service	Aquaculture development and production
Kenya Fisheries Service (KeFS)	Fisheries Management and Development Act 35 of 2016	Conservation, management, development, and regulation of the Fisheries and Aquaculture in Kenya were challenging under the Kenya Fisheries Department, with a single Act	A corporate body for fisheries regulation and law enforcement for sustainable conservation, management, and development of Kenya's fisheries and aquaculture resources
Kenya Fish Levy Trust Fund (KFTLF)	Section 28 of Fisheries Management and Development Act of 2016	Inadequate financing of the fisheries sector, making it difficult to achieve sustainability for important activities	To provide sustainable supplementary funding for activities on management, development capacity building, awards, and urgent mitigation for the sustainability of the fisheries resources
Kenya Fish Marketing Authority (KFMA)	Fisheries Management and Development Act 35 of 2016	Inability to attract new and more lucrative markets, including export markets for Kenyan Fish and fish products	A corporate body to market fish and fisheries products from Kenya
Kenya Fish Industries Corporation (KFIC)	Legal Notice No. 214 of the State Corporations Act 2018	Lack of spirit of entrepreneurship, value addition, manufacturing, and industrialization of the Kenyan fisheries sector, which reduces efficiency and profitability	To exploit fishery resources in the Kenya fishery waters and high seas by promoting the establishment and efficiency of businesses engaged in fishing and fishing-related activities
Kenya Coast Guard Service (KCGS)	Kenya Coast Guard Service (KCGS) Act 11 of 2018	Security of Kenyan fisheries resources, both inland, and marine, is a challenge, leading to illegal, unregulated, and unreported fishing, with some of these activities using destructive gears	Deployed in territorial waters to enforce maritime security and safety, pollution control, protect marine and fisheries resources, and prevent trafficking of illegal and prohibited items and products

The State Department of Fisheries and blue economy is the overall management institution, and the state agencies are charged with specific functions and jurisdiction.

Data Availability

Data sharing is not applicable to this manuscript because we did not generate and analyze own data.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

James E. Barasa wrote the original draft of the manuscript, and Don Felix Ouma replotted the graphs.

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