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Meet the editor

Dr. Muhammed Atamanalp is a professor at the Fisheries Faculty, Atatürk University, Turkey. He has nearly ninety SCI papers to his credit, most of them on aquatic toxicology. He is a specialist in water pollution, fish physiology, and the toxic effects of newly synthesized compounds on aquatic organisms.

Contents

Preface

Aquaculture is one of the fastest-growing food industries worldwide. In this sector, the most important factors determining the species to be cultivated are the climate and water conditions. In addition to the increase in the number of cultivated species, the rate of production has increased with the development of technologies.

Seafood has an important place in meeting the protein needs of people. Catfish represent one of the largest groups of freshwater fishes, with more than 2000 species, and every year more are discovered and classified. This species has a cosmopolitan distribution and is an important group due to their use as ornamentals, food fish in aquaculture, research animals, and for sport fishing.

This book discusses the latest developments in catfish research, production, and usage.

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Section 1

Catfish - General Information

Chapter 1

Successes and Challenges of Catfish Farming in the Small-Scale Industry in Southern Africa

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Abstract

This chapter summarizes the successes and challenges of catfish farming in the small-scale industry in Southern Africa. Given that capture fisheries have been declining steadily over the years in many countries, aquaculture is generally expected to grow to meet demand. However, catfish production in most Southern African countries is low. This is despite the region having the most suitable temperature for the culture of freshwater fish species. In Southern Africa, catfish farming is one of the most important components of inland aquaculture, and it is mainly dominated by the small-scale sector. Production in the small-scale sector is affected by several constraints, which affect the profitability of the sector. These challenges include, among others, quality of production systems, supply of quality fingerlings, feeds, management of diseases, education and training of farmers, marketing and development of products, access to finance, research capacity, extension services, and, to some extent, regulatory frameworks and policies. The chapter proposes interventions that are needed to improve the production of catfish in Southern Africa. For instance, there is a need for the small-scale sector to move from intensive to advanced culture systems, such as recirculating aquaculture systems and integrated aquaculture systems, such as aquaponics, in order to boost catfish production.

Keywords: freshwater aquaculture, diseases, production systems, integrated aquaculture, systems, feeds

1. Introduction

Clarias gariepinus (African sharptooth catfish) (Burchell, 1822) is one of the most widely cultured fish species in Southern Africa [1]. Farmers prefer this species because of its favorable characteristics, such as tolerance of adverse environmental conditions, fast growth rates, and resistance to diseases [2]. Its ability to feed on a variety of food items, such as fish, insects, phytoplankton, zooplankton, macrophytes, and detritus, also makes it an attractive species to farm [2, 3]. South Africa is the largest catfish producer in Southern Africa [4]. The Department of Agriculture, Forestry and Fisheries' Aquaculture Year Book shows that catfish production in South Africa has been increasing steadily since 2012 [4]. The industry is dominated by the small-scale industry and is projected to create employment for the youth and women. In South Africa, catfish is considered a high-value commodity and is consumed by almost 50% of the rural population.

Zambia is also one of the countries in Southern Africa where catfish culture has been growing rapidly. In Malawi, Zimbabwe, and Mozambique, catfish culture has been growing slowly, but it is expected to increase in the future due to donor organizations, and government interventions. However, these countries are doing relatively well in tilapia farming compared to South Africa. There is very low catfish production in Lesotho and eSwatini, which could be attributed to a lack of national aquaculture strategies to drive production in these countries. Catfish culture in Namibia has been at a developmental phase since the 1990s, but there is a potential to grow the industry. Overall, the production data from these countries shows that despite significant investments and the development of favorable policies in the catfish industry, there are still several major challenges hindering the sustainable expansion of this sector. This is despite Southern Africa being one of the most suitable regions for freshwater aquaculture development. Various reports have shown that Southern Africa has high biophysical potential for freshwater aquaculture [5]. These challenges include, among others, types of production systems currently being used, limited supply of quality fingerlings, availability of high-quality feeds, management of diseases, education and training of farmers, marketing and development of products, access to finance, research capacity and extension services, and to some extent regulatory framework and policies. The aim of this chapter is to look at the successes and challenges of catfish farming in the small-scale aquaculture in Southern Africa.

2. Challenges affecting catfish farming in Southern Africa

2.1 Feed inputs

The availability of quality and cheaper feeds is one of the major constraints facing catfish farmers in Southern Africa. The aquaculture industry in Southern Africa largely depends on manufactured feeds, which uses highly priced ingredients, such as fishmeal. This exposes the industry to higher prices due to the scarcity of key ingredients. A recent review by [6] identified quality and costs of feed as one of the major factors limiting aquaculture development in Southern Africa. This affects the small-scale aquaculture sector the most because the majority of farmers are under-resourced and cannot afford commercial diets. Feed costs have been estimated to account for 75–85% of the total operational cost in aquaculture [7]. As a result, many small-scale catfish farmers in Southern Africa resort to using poor-quality feeds, which affects production and profitability.

In recent years, there have been investigations that tested the use of plant ingredients with high protein content in catfish diets in an effort to replace expensive ingredients, such as fishmeal in aquafeeds [8–10]. However, the use of plant-based protein sources in aquafeeds is hindered by the presence of high levels of anti-nutritional factors (ANFs). Anti-nutritional factors are known to reduce the digestibility and bio-availability of nutrients [11]. The other disadvantage associated with plant-based protein sources is their unbalanced amino acid profile. A high-quality diet must contain all essential amino acids needed to meet the nutritional requirement of a particular fish. Deficiency in some of the essential amino acids can lead to poor growth rates. Although some studies conducted in South Africa have shown that these limitations can be corrected by the inclusion of exogenous enzymes (to inactivate ANFs) or synthetic amino acids (to improve the amino acid profile) [12], these interventions have been found to be expensive for the small-scale farmers, due to lack of resources. Some studies have investigated the inclusion of insects in aquafeeds as an alternative protein source [13–15]. Much of this work is at an exploratory level. There is, therefore, a need for researchers to focus on identifying cheap, locally-available ingredients that can be used in aquafeeds. In the meantime, governments should consider temporary interventions, such as subsidized feeds, regulating pricing policies, and increasing access to credit facilities for catfish farmers.

2.2 Fingerling supply

The supply of high-quality fingerling is among the challenges affecting catfish production in Southern Africa. Most catfish farmers in the region do not have access to good-quality fingerlings. There are very few countries in Southern Africa with functional hatcheries that can supply the catfish industry with high-quality seeds. In South Africa, for instance, the government build several catfish hatcheries in the 1960s that were meant to supply fingerlings to catfish fish farmers, but most of these hatcheries have collapsed. The recently refurbished Aquaculture Technology Demonstration Center (ATDC) in Gariep Dam, Free State Province, South Africa, is one of those hatcheries. It is the only hatchery currently supplying fingerlings to local farmers. The long-term objective of this hatchery is to supply catfish fingerlings and train farmers within the South African Development Community (SADC), which covers most of the countries within Southern Africa. However, due to the location of the center in South Africa, it has so far been able to train only local farmers and produce fingerlings for farmers residing in South Africa. In Zambia, the government, in partnership with FAO, set up aquaculture research stations and hatcheries for research, breeding, and training [16]. These efforts are expected to enhance catfish production through training and production of fingerlings for local farmers.

Some universities and research stations offering aquaculture courses have supplied fish farmers with fingerlings in the past, but many are no longer actively involved in the production of catfish fingerlings. Therefore, in many countries, farmers still do not have access to quality fingerlings produced from genetically superior brood stock with known genetic composition. Most fish farmers in Southern Africa have to resort to using poor-quality fingerlings, mainly sourced from their own grow-out ponds or purchased from other farms. These fingerlings are usually of poor quality because of inbreeding and poor fish husbandry practices. Although farmers are also able to purchase fingerlings from private farms, these add to operational costs, as they are expensive to buy. Some farmers rely on fingerlings from the wild to stock their grow-out ponds. The challenge with fingerlings from the wild is that they may introduce diseases from the wild to capture fish, which could result in mortalities. The other challenge is that the collection of fingerlings from the wild is highly unreliable and unsustainable as it is not always feasible to collect sufficient numbers of fingerlings to stock grow-out ponds. Thus, there is urgency in Southern Africa for each country to establish new and modernized state-of-the-art hatcheries in order to produce high-quality fingerlings for the catfish industry.

2.3 Production systems

2.3.1 Earthen ponds

Catfish production in Southern Africa is mainly carried out in extensive and semi-intensive systems (95%), such as earthen ponds and aquadams. There are relatively few catfish farmers (5%) utilizing intensive culture systems (aquaponics, recirculating aquaculture systems - RAS) in the region. However, the majority of fish farmers in the region use ponds that have been constructed poorly, leading to low productivity. Many farmers do not seem to use the help of aquaculture experts when designing and constructing their ponds. This leads to poorly designed ponds with inappropriate volumes, which leads to poor maintenance, poor water quality, and inappropriate stocking densities. It has been suggested that the quality of earthen ponds used for catfish production in the small-scale sector in Southern Africa has a direct impact on the growth of the industry. Poor water quality maintenance usually leads to high total suspended solids and total dissolved solids, which leads to a reduction of primary production in earthen ponds [6]. A reduction of primary production in ponds has a direct impact on fish growth rates, and consequently, requires high feed input. This affects the profitability of farms in the long term.

Many catfish farmers in Southern Africa experience water quality problems quite often in earthen ponds. Farmers usually record low dissolved oxygen levels quite often, which is one of the factors responsible for high mortalities in earthen ponds. In earthen ponds, levels of dissolved oxygen and pH are managed by the balanced relationship between photosynthesis and respiration during the day and night, respectively. Excessive algal growth may reduce oxygen levels at night during respiration and cause fish to suffocate. On the other hand, during algal die-offs, oxygen levels decline drastically due to decomposing matter. Furthermore, excessive production of carbon dioxide (CO_2) at night during respiration may increase the pH of pond water, which, in turn, increases ammonia toxicity. High levels of ammonia and nitrite can be detrimental to the health of fish [17, 18]. The African sharptooth catfish can tolerate extreme water quality conditions, such as low dissolved oxygen and high ammonia levels. However, these conditions may create stress and reduce growth rates. It is, therefore, important for catfish farmers to learn to maintain these parameters at optimum levels for faster growth. Generally, farmers struggle to maintain good water quality in earthen ponds because there are no filters or heaters in the ponds. The problem of low dissolved oxygen levels in earthen ponds is exacerbated by the fact that the water is static unlike in RSAs where water circulates, passes through filters, and is aerated. In static ponds, the most common water quality problems are associated with the accumulation of organic by-products, such as uneaten feeds and feces.

Evidently, catfish farmers in Southern Africa have been using earthen ponds for over 60 years, but production has not improved. Although earthen ponds are cheaper to run compared to intensive systems, their profitability is quite low in Southern Africa. Nevertheless, since the majority of catfish farmers utilize earthen ponds, they should consider the installation of wind-powered aerators, especially in rural areas where electricity cost is unaffordable. Farmers in rural areas should also consider using cheap filters, such as Biofishency. The attraction about this filter is that it functions like a small RAS where water trickles from the top and passes through filters before being recycled. This technology is simple to assemble and requires little training to operate. It is known that this type of filtration could improve water quality and allow farmers to stock more fish in the ponds. Indeed, this technology may be suitable for smallholder farmers with medium-sized ponds.

2.3.2 Recirculating aquaculture system

Due to the drive for the commercialization of the catfish industry in Southern Africa, efforts must be made for farmers to use systems with high productivity, such as Recirculating Aquaculture Systems (RASs). For instance, semi-intensive production systems are the most widely used in countries, such as Egypt, where aquaculture production is higher [19–21]. The South African aquaculture industry has largely adopted RAS technology, but it is mainly used for tilapia production. A RAS is an advanced farming technology when compared to some of the widely used semi-intensive systems in catfish farming. In addition, a RAS is water-efficient technology that would be appropriate for use in water-scarce areas. It is a well-known fact that most countries in Southern Africa (i.e., Namibia, Botswana, and some parts of South Africa) are semi-arid and the availability of water is one of the factors affecting the growth of inland aquaculture. The benefit of using RAS is that fish are stocked at high densities under controlled conditions, which maximizes yield and profit. However, RAS technologies are expensive to purchase (high cost of initial capital investment in tanks, and greenhouses), maintain (high cost of electricity required to run the system), and require skilled personnel to operate (modern systems come with sophisticated components requiring training before use). Moreover, fish reared in RASs require a complete and high-quality diet, which results in high operational expenses. Consequently, there is slow adoption of RAS technologies in the small-scale catfish industry. Therefore, significant capital investment is still required from governments to assist farmers to adopt RASs in order to improve catfish production in Southern Africa.

2.3.3 Integrated aquaculture systems

There are few farmers using integrated aquaculture systems in the small-scale catfish aquaculture industry in Southern Africa. Integrated aquaculture systems refer to the utilization of the same water source to culture different types of species. For example, aquaponics is one type of integrated system in which fish and plants are grown together. The waste from the fish serves as fertilizer for the plants and this can help farmers to generate more revenue as they will be able to sell their plants (vegetables) throughout the year. Most aquaponics systems use RASs housed in a greenhouse tunnel, which ensures that farming can be done throughout the year. Since water availability is one of the most limiting constraints in catfish farming, aquaponics can be an ideal system in arid areas. The combination of fish and plants is a promising alternative for the small-scale catfish farming industry due to the economic benefits they can derive from this technology. In Egypt, for example, farming rice and fish together has been in existence since 1984 [22]. In Kenya, most farms use integrated systems with either a crop (vegetables and bananas) or livestock production (goats, cattle, and chicken) [23]. Furthermore, reports indicate that fish farmers in Kenya operating at subsistence level are shifting to commercial intensive culture systems [23, 24]. This should be a strong motivation for the adoption of integrated production systems in the catfish industry in Southern Africa.

2.3.4 Cage culture

Small-scale catfish farmers in Southern Africa can also consider cage culture, especially where resources do not allow for integrated fish farming or the use of RASs. Most countries in Southern Africa have several man-made dams that can be utilized for cage culture. The South African government, through DFFE, has identified several dams located in the Limpopo Province as suitable for cage culture. Although cage culture might be more expensive than pond culture, it is easy to manage water quality in cages because they allow for the maintenance of the desired water quality (dissolved oxygen, temperature, and ammonia removal) through the exchange of waste with the surrounding water. Reports show that cage culture is growing rapidly in Zimbabwe, Malawi, and Zambia, although it is mainly tilapia cultured in the cages in these countries [6, 25, 26]. This is an indication that cage culture has a huge potential to increase production in the catfish industry if it were to be adopted by the majority of catfish fish farmers.

2.4 Diseases

Disease outbreaks are also among the major constraints affecting catfish production in Southern Africa. Although *C. gariepinus* is considered a hardy and resilient species, some of the culture conditions make it susceptible to infections caused by parasites, bacteria, fungi, and viruses [27]. The oomycete fungus *Saprolegnia parasitica* is one of the most common opportunistic pathogens affecting a number of freshwater fish species [28]. This fungus is considered an opportunistic pathogen because it affects fish with a compromised immune system due to stressful conditions. As stated earlier, the majority of *C. gariepinus* farmers in Southern Africa use earthen ponds, which are exposed to low temperatures during the winter months. This stresses fish and increases their susceptibility to fungal infections as low water temperatures suppress their immune capacity to resist infections. *Saprolegnia* infections are also prevalent in fish hatcheries where they target incubated eggs [29]. They are also associated with injuries caused by ectoparasites as their attachment organs open wounds for secondary infections [27]. In addition, the recent outbreak of epizootic ulcerative syndrome (EUS) in Southern Africa has been a major concern for catfish farmers. Epizootic ulcerative syndrome is caused by the invasive oomycete fungus *Aphanomyces invadans* and it is an OIE-listed disease [30]. Studies indicate that this disease has become endemic in many river systems in Southern African, including Botswana, Namibia, South Africa, Zambia, and Zimbabwe [30]. In 2011, significant numbers of the wild population of *C. gariepinus* died in South Africa due to a EUS outbreak [30]. The rate at which this disease has been spreading poses a serious threat to the catfish farming industry in the region because some use rivers and dams as sources of water for their ponds or systems, which might facilitate the transmissibility of the pathogen to captive fish.

C. gariepinus has also been shown to be affected by freshwater white spot disease caused by *Ichthyophthirius multifiliis* ("ich") and trichodinosis caused by ectoparasites of the genus, *Trichodina* sp. [27]. These pathogens are highly problematic in RASs and can spread rapidly due to their direct life cycle. In South Africa, a few catfish farmers using RAS have encountered ich and trichodinosis. Fish in production ponds are also susceptible to a wide spectrum of bacteria, such as *Aeromonas* species, *Pseudomonas* species, *Edwardsiella ictaluri*, *Edwardsiella tarda*, *Streptococcus spp*., *Pseudomonas spp*., and *Flexibacter columnaris* [27]. These are well-known opportunistic pathogens of freshwater fish species. These pathogens can be difficult to treat once they infect a pond population because of challenges with pond sterilization. Of all these pathogens, the gram-negative motile bacterium, *Aeromonas hydrophila*, is one of the most prevalent opportunistic pathogens affecting a number of freshwater fish species in Southern Africa. In South Africa, strains of *A. hydrophila* have been isolated from diseased *C. gariepinus*. There are no reports about viral infections in Southern Africa, perhaps due to the lack of disease experts and surveillance programs for monitoring and detecting viral infections in freshwater aquaculture.

Fish cultured in outdoor ponds are also susceptible to infections by metazoan parasites with indirect life cycles because of the presence of intermediate hosts (snails or copepods) and definitive (birds), which allows for the life cycle of the parasites to be completed. These parasites include digeneans, myxozoa, nematodes, and cestodes and they are mainly found in internal organs in fish [27]. Internal parasites are difficult to treat because they live inside the fish. Infections caused by these parasites can be easily managed by spreading nets over the ponds to prevent aquatic birds from preying on fish carrying the developmental stage of the parasites. However, several farmers disregard this simple technique, probably because of a lack of resources and lack of training on disease management in pond culture. On the other hand, parasites with direct life cycles (e.g., egg-laying monogeneans) are more common in RASs, where they spread rapidly because fish in RASs are kept in high densities, which results in closer fish-to-fish contact.

2.4.1 Management of diseases

The prevention and management of diseases in aquaculture is an important aspect that determines the economic viability of an enterprise. However, data on the prevalence of diseases in the small-scale sector is not well documented. The majority of fish farmers in the small-scale sector do not keep fish health records of disease outbreaks or mortalities and this makes it difficult for investigators to establish the cause of fish deaths and make proper recommendations. Generally, there are few specialized fish veterinary laboratories in Southern Africa. In South Africa and other few countries (e.g., Zimbabwe) diagnoses of fish diseases are mainly done at those universities, government departments, and stations that conduct research on aquaculture and fisheries. It is important to establish more centers with the capacity for fish disease diagnosis in Southern Africa.

In the small-scale sector, the majority of fish farmers struggle to prevent and control diseases on farms mainly due to poor adherence to biosecurity measures or quarantine protocols, and this is a significant contributor to disease outbreaks on fish farms. Therefore, farmers in the catfish industry must develop and implement farm-level biosecurity measures. This can be achieved through the application of a combination of protocols, such as quarantine measures, disinfection of equipment, water treatments, use of uncontaminated feed, removal of sick fish, and appropriate disposal of dead fish. In South Africa, DFFE has developed an aquatic health plan or policy for the marine aquaculture industry, which allows the department to conduct surveillance regularly in order to reduce the risk of spreading pathogens. Regular surveillance is a useful protocol for the early detection of emerging and problematic diseases. Such programs should also be an integral part of disease monitoring programs in the freshwater aquaculture sector and other countries can develop similar surveillance programs. Scientists working on freshwater aquaculture projects must conduct regular farm visits to collect samples from farmers.

The other challenge associated with diseases in fish farming is that antibiotics and synthetic chemicals are no longer effective in treating some of the most persistent pathogens. It has been reported that most of the disease-causing agents in cultured fish have developed resistance to the commonly used antibiotics or synthetic chemicals [31, 32]. Therefore, farmers in the small-scale sector can benefit from the use of plant-based products to control diseases. The application of plant products to control diseases in aquaculture has been shown to be one of the most promising alternatives to antimicrobials. They have been reported to stimulate the immune system of fish and their active compounds act as antibacterial, antifungal, and antiparasitic agents [33]. Medicinal plants can easily be administered on fish farms through oral administration, injection, and immersion or baths. All that is required is to train farmers to prepare diets containing plant material, injections, and baths. Studies undertaken in South Africa have shown that commonly used medicinal plants, namely, *Artemisia afra* and *Moringa oleifera*, improved immunity and disease resistance in *Oreochromis mossambicus* and *C. gariepinus* [34, 35]. These studies showed that dietary supplementation with these plants improved immunity in *C. gariepinus* and increased resistance against *A. hydrophila*, which is one of the most problematic pathogens in catfish culture. It is, therefore, important to advise catfish farmers on the use of medicinal plants to control diseases in catfish farming in Southern Africa. These two medicinal plants are common in Southern Africa and farmers can readily access them. This will be the cheapest way to reduce mortalities on fish farms, as most antimicrobials are expensive for the majority of fish farmers on the small scale.

2.5 Water quality

The source and quantity of water are the most important factors to consider when a farmer chooses a site for an aquaculture facility. Very few farmers send their water samples to laboratories for analyses prior to commencing with farming. This should be one of the most important considerations for establishing a fish farm. For example, in many towns and rural areas in Southern Africa, the quality of water from dams and rivers has been declining due to increasing anthropogenic activities (mining, agriculture, and industries) and the discharge of water contaminated with sewage. Even water sources (rural rivers and streams) that were once considered pristine are now contaminated with some form of pollution. Such water sources might contain high levels of pathogenic bacteria, which can affect fish health, especially that of younger fish. Therefore, the practice of using water directly from streams as is the case on some catfish farms is an indication of a lack of training on water quality, which should be addressed immediately. It is, therefore, preferable for farmers to use protected water sources, such as boreholes, deep wells, and aged municipal water, as these are free from contaminants and pathogens.

2.6 Education and training

The majority of the small-scale catfish farmers do not have the requisite skills to operate a fish farm, even at a low level. These are among the major weaknesses that are hindering the success of the catfish industry in Southern Africa. Aquaculture is a highly specialized and evolving field where new developments are discovered often. In many countries, there are no programs designed to educate fish farmers on the latest developments in the field. There is thus a need for countries to design programs that could assist in the transfer of knowledge to farmers. This can be easily done through the establishment of demonstration centers at the country level that focus on skills training for catfish farmers. In South Africa, for example, ATDC has been tasked with the responsibility of training fish farmers and disseminate technology developments to farmers. In addition, some countries, such as South Africa, have well-established universities and research institutions undertaking research and offering degrees in aquaculture. These institutions must be encouraged to develop tailor-made training courses and manuals for the catfish industry. They should also offer training workshops regularly to promote technology transfer and attach their students to some of the local fish farms. In this way, the industry will produce hands-on aquaculturists that are familiar with the most pressing challenges facing catfish farmers in the region. It is also important for countries to initiate exchange programs in order to share skills, research, and technological advances. The Aquaculture Association of Southern Africa (AASA) is responsible for organizing annual conferences on aquaculture for farmers, academics, and researchers. This association should play a key role in the transfer of information, knowledge exchange, and facilitation of aquaculture workshops in Southern Africa.

2.7 Extension services

As stated previously, aquaculture is a highly specialized and evolving field and a competent fish farmer needs to possess a set of key technical skills required to successfully operate a fish farm. This requires that a fish farmer be adequately trained in all aspects of fish farming, such as basic fish husbandry practices: feeding, water quality testing and monitoring, identification, and management of diseases. Extension services have been identified as one of the most critical supporting structures needed by small-scale farmers to succeed in fish farming. In the small-scale aquaculture industry, extension services are generally inadequate and there are no sufficient communication channels between researchers or extension services and fish farmers. This leads to poor usage of knowledge needed to improve aquaculture in the sector. There is, therefore, an urgent need to develop and maintain links between researchers or extension services and fish farmers in the catfish industry. New research should look at developing online technologies, such as apps, that can bring different stakeholders together, that is, researchers, extension services, and farmers. This can be particularly useful because most catfish farms are located in remote areas where it may take time to reach farmers in person. Furthermore, the establishment of cluster groups of fish farmers can contribute immensely toward sharing of knowledge between them and extension officers or among themselves.

2.8 Research and development

Based on some of the limitations identified in this chapter, there is a pressing need for more research to be conducted in the catfish farming industry. This research should focus on the development of low-cost intensive production systems and improvement of the quality of broodstock and fingerlings. Scientists attached to the Aquaculture Research and Development component of DFFE in South Africa are currently undertaking research on the viability cryopreservation of sperm cells from *C. gariepinus*. These scientists are also conducting research on the development of polyploidy broodstock that can be used to produce sterile offspring. Sterile fish cannot reproduce, but use their energy for growth. The successful completion of the cryopreservation project will ensure that fingerlings can be produced in large numbers throughout the year. Meanwhile, the successful development of polyploidy brood stock will help farmers to produce fish that grow faster, thus increasing the profitability of fish farms. This project will also allow the farming of catfish where legislation does not permit it because of the invasiveness of the species. Some conservation laws prohibit catfish farming in places where it does not occur naturally. These are critical steps required for the catfish industry to eventually reach commercial production and ensure that fingerlings are available year-round. There is also a need to intensify research efforts on selective breeding and the development of cheaper and high-quality diets. Recent research conducted in South Africa has shown that the replacement of fishmeal with acid-fermented chicken silage can improve growth performance in Mozambique tilapia (*O. mossambicus*) [36]. Unpublished findings from these studies also show that the same diets improved growth performance in *C. gariepinus*. It is therefore highly recommended for catfish farmers in the small-scale sector to use these diets because they are cheaper and readily available. Furthermore, these diets are suitable alternatives because, unlike plant-based and insect diets that have been investigated in the past, they have increased digestibility due to the absence of inhibitory factors (antinutrients).

2.9 Legislation and policies

In most Southern African countries, a farmer needs a permit and must comply with all relevant laws (environment, water, and nature conservation) before setting up a fish farm. In this regard, governments play a critical role in the development of the catfish industry by rendering institutional support through the development of legislation and policies that create a conducive environment for the sector to thrive. Almost all governments in Southern Africa have developed policies and strategic frameworks aligned with the objectives of enhancing aquaculture production. This is intended to stimulate and boost the production of aquaculture products.

2.10 Funding and investment

Lack of funding is among the most limiting factors affecting the growth and development of the catfish industry in Southern Africa. As stated at the outset of this chapter, a number of governments and donors have invested substantially in aquaculture in Southern Africa. However, this is mainly for government-run projects, such as hatcheries and feed processing plants. Farmers still struggle to access funding from financial institutions. Generally, there is very little private sector investment in the catfish industry. The lack of adequate funding in this sector might be the reason it has remained largely small-scale. Some researchers have noted that the numerous challenges facing the sector led to low private investor confidence. In addition, very few governments provide soft credits and incentives to fish farmers in the small-scale sector. In South Africa, for instance, the Department of Trade and Industry has a reimbursable grant infrastructure program where fish farmers must spend between R1 million and R20 million in machinery, systems, and equipment, and then claim for reimbursement. The challenge with this program is that most farmers cannot afford to spend that money in order to qualify for this incentive. Furthermore, DFFE has introduced an Aquaculture Development Fund through a program called Operation Phakisa, a South African version of the blue economy initiative. This program was launched to provide financial support to struggling marine aquaculture farmers. It is critically important for a similar initiative to be put in place to provide financial assistance to freshwater aquaculture farmers. It is thus necessary for governments and the private sector to explore feasible ways in which the industry can be assisted with funding.

2.11 Marketing and trade

Generally, the marketing of fish remains a challenge in the small-scale sector. Most of what is harvested is for household consumption and the rest is sold to neighbors or informal markets. In most cases, the fish is sold fresh, which means it cannot be kept for long, as it will start spoiling. There is a need for farmers to consider using some of the processing methods, such as smoking, drying, and freezing, to increase the shelf life of their catfish products. These are simple and widely used processing methods, which help to inhibit microbial spoilage [22]. On the other hand, commercial catfish producers in South Africa are now starting to develop new methods of processing catfish meat to improve its marketability. These producers are now able to produce a variety of catfish products, such as mince, wors, sausages, burger meat, and fish cakes. Karoo Catch in South Africa is one of the catfish companies that has successfully developed various products from catfish meat. In fact, it is one of the most successful community-based empowerment enterprises in South Africa.

3. Conclusions and recommendations

It is clear from this chapter that there is a huge potential for catfish farming to grow rapidly in Southern Africa, but it has been facing many multifaceted constraints, which require radical and urgent interventions at research, farm, and government level. For instance, there is a need to focus on the adoption of advanced production systems in order to improve the growth of the sector. There is also a need to focus on the development of advanced breeding technologies to develop improved strains and high-quality fingerlings. More breeding centers are required in the region to address the shortage of fingerlings. It is therefore recommended that research projects such as the cryopreservation of sperm cells and the development of polyploidy broodstock be expedited. Governments should look at ways of increasing funding in the sector to enable farmers to adopt the latest farming technologies needed to enhance production. Efforts must be made to arrange regular training workshops on basic animal husbandry (i.e., feeding, disease management, and water quality monitoring) to help farmers successfully run their farms.

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Section 2

Catfish Feeding

Chapter 2

Insects Such as Termites Hold a Promising Future for the African Catfish (*Clarias gariepinus*)

Honor Ifon and Philomena Asuquo

Abstract

Due to the high cost of fishmeal, it has been desirous to search for alternative sources of protein which are cheap and can replace fishmeal without compromising the growth and well-being of cultured fish. The use of insects such as termites to totally or partially replace fish meal is indeed innovative since most insect-based diets are known to inhibit the growth of cultured fish species due to some underlying factors. However, termite meal has been applauded for its good nutritional quality (crude protein and lipids, mineral composition, fatty, and amino acids) comparable to fishmeal. The concentration of phytate and tannin which could otherwise inhibit nutrient digestibility and growth of fish can be eliminated through proper processing techniques. Interestingly, concentrations of other anti-nutrients such as oxalate, trypsin inhibitor, lectin, and hydrocyanic acid in termites are known to be negligible and as such may not affect the digestibility and absorbance of essential nutrients.

Keywords: aquafeed, catfish, fish nutrition, insect meal, termite quality

1. Introduction

Fish is a staple food in many nations around the world, and in many Asian and African nations, consumption patterns for fish and rice are similar [1]. A stronger contribution from aquaculture is expected to increase the annual consumption rate of fish from 20 kg per person in 2016 to 37.8 kg per person in 2030 [2]. The increased demand for high-value protein, which is anticipated to nearly double by 2050 as a result of the rapidly expanding population in developing nations, is one of the major nutritional problems around the world [3].

Recent research has focused on ensuring sustainable aquaculture in order to supply this constantly growing need for protein while staying within environmental constraints. Farmers now run the risk of being blackmailed and may give up aquaculture in favor of more lucrative endeavors due to the unsustainable rise in the price of beef meal, fishmeal, and soybean meal. This is because expensive fish meal and other expensive protein sources account for 60–70% of the cost of aquaculture operations [4]. These trends amply demonstrate the need for increasing the production of alternative sources of protein, such as insects, which are less expensive, readily available, trustworthy, and sustainable. Aquaculture is still the sector of animal food production that is expanding at the fastest rate.

Despite being in its infancy, aquaculture has produced a large majority of insects, many of which were laboratory experiments. However, insects have a bright future, especially for fish nutrition and sustainable aquaculture. Because of the excellent quality and quantity of protein and fat they provide, humans and domestic animals, including fish, have recently developed an overwhelming appetite for insect-based diets [5]. Numerous catfish species and other fish species have shown outstanding growth responses to insect-based diets, according to recent studies [6, 7]. When it comes to the aquaculture production rate among other fish species raised in Africa, catfish and tilapia are competitors. Due to their rapid development rates, tolerance to a wide variety of water quality, good sensory quality of their meats, and high desire and acceptance by consumers, catfish of the *Clarias* and *Heterobranchus* genera are popular choices.

Many studies on the potential of insects in aquafeed use houseflies, mealworms, and soldier flies in their trials [8–10], but very few studies use termites [11]. The Isoptera order and family of termites are eusocial insects that live in colonies with reproductive castes as their leaders [12]. They are significant players in the early stages of plant litter decomposition in tropical habitats, especially in Africa's deserts and rain forests. Furthermore, termites have contributed significantly to the staple foods of the majority of African and Asian countries, where there are more than 2.5 billion insect eaters [2]. They are among the most nourishing insects and the second most consumed insect order after Orthoptera [13]. They have been thoroughly examined for great quality and quantity of lipids, crude protein, and fatty acids. Edible termites such as those in the genus *Macrotermes* are generally safe and good for feed, but some *Noditermes* and *Cubitermes* species have been known to be hazardous to farm animals.

Crude protein, lipids, and fatty acids are abundant in edible termites, as are well-balanced essential amino acids such as lysine, threonine, and histidine. In addition to being rich in minerals like magnesium, manganese, potassium, iron, zinc, and phosphorus, they are also high in vitamins [14]. As a result, it has been suggested that termite meals compete favorably with fish meal in encouraging the growth and welfare of farmed fish. Unfortunately, termites can only be found in nature during particular months or seasons. For instance, they can be found during the alate or swarmer nuptial flights or at the beginning of the rainy season. The apterous reproductive adults can be seen in huge numbers close to light sources during swarming since they are drawn to light by nature. They now land, drop their wings, move in pairs into a crack in the ground, seal it shut, and mate to start a new colony. Poor villagers in certain African nations collect termites for food using a broom and a pail of water as they are drawn to their lights.

In addition to humans, fish are known to eat live termites that fall into their ponds. This opportunistic feeding takes place when live food is in plentiful supply in fish farms. The mouths of fish and other vertebrates have been modified to prefer insect prey. For instance, the broad mouths of African sharptooth catfish (*Clarias gariepinus*) and African giant catfish (*Heterobranchus longifilis*) allow them to swallow complete insects [15].

Termite meal is a crucial component that has been employed frequently to compound feeds in animal farms in nations like Cambodia, Thailand (Southeast Asia), Nepal (South Asia), Kenya, and Zambia (East Africa), as well as Togo, Burkina Faso, and Ghana (West Africa) [16]. Termites can be simply and inexpensively harvested [17]. Rural fish farmers can reduce the high cost of fish meal and other animal and plant proteins used in aquafeed by employing termites instead of cottonseed cake and soybean meal. Numerous authors have already discussed the usage of termites in food and feed [14, 18–20]. Studies [11, 21] found that African giant catfish (*H. longifilis*) and African sharptooth catfish (*C. gariepinus*) fed termite-based diets with an ideal inclusion level of 50% crude protein experienced excellent growth performance and nutrient utilization.

2. Field harvesting, farming, and processing methods

2.1 Termite harvesting in the field

Various techniques are used for harvesting termites in the field. These techniques, however, are based on the termite genus. The two most efficient techniques for Macrotermes are fractional termite mound demolition and trapping [13]. The majority of farmers that collect termites for animal feed use a variety of environmentally friendly trapping techniques that protect termite mounds [22].

In general, termite collecting involves using old clay, iron, or plastic containers, occasionally calabashes, or baskets fashioned from nypa or other palm leaves. These containers hold termite baits made of organic materials including plant detritus, crop residues, and animal droppings [23]. The containers are typically put upside down and close to termite colonies. To consume the substrates and become stuck, the termites enter the container. In addition to using a trapping system, collecting termites is another option available in the wet season, particularly following a significant downpour when adult winged termites swarm in April and October. Locals notice them because they are drawn to light naturally.

Despite being classified as seasonal insects, termites can be sustainably induced to be present even during the dry season, potentially ensuring a supply throughout the year [24]. Termite mounds in western Kenya are owned by farmers and passed down through inheritance. This has made the termite industry quite profitable in certain places [25].

Farmers use live termites in Southeast Asia to feed their farmed fish. They either collect the termites directly from the field or purchase them for 0.27 USD per kg from local markets [4]. By suspending a fluorescent lamb above fish ponds, mainly during the months of March and April and August and September, termites can be fed directly to the fish. Insects are taken as prey in fish ponds by the fish because they are drawn to light and its reflection in the water. Field-caught termites such as *Trinervitermes* species are frequently used as fish bait in Zambia [4]. Although termite rearing has historically been considered to be a very challenging task and frequently not advised due to high methane gas emissions, reports show that termite rearing contributes the least to global methane emissions when compared to rice cultivation, cattle production, mining, use of fossil fuels, and burning of biomass [26, 27].

2.2 Termite farming

Seasonal insects like termites can be grown in a controlled environment to produce them year-round [28, 29]. Typically, the production of eggs, larvae, and sustaining progenitors is the first risky step in insect farming [30]. Environmental management practices must be strictly followed during termite rearing in enclosures for the best possible growth and development. The importance of factors including ambient temperature, relative humidity, photoperiod, feed quality, and mitigating the spread of disease must not be understated [29, 31].

Such situations could be addressed by contacting a reliable technical advisory/supervision team for assistance with long-term intensive insect farming. Due to their destructive habits and reputation as pests among farmers, most research has focused on finding ways to remove termites rather than domesticating them for food. Due to this failure, termite farming is now only in the infantry or laboratory trial stage throughout the world. The termite laboratory rearing described in a 1991 publication is a unique one [32]. A subterranean termite's small-scale raising is described in the paper (*Reticulitermes speratus*). However, according to recent studies, termite farms are also present in Kenya and India. With a price of Sh 12 per 150 g dry weight on the local market, Kenya is a major producer of termites [25].

2.3 Processing methods

The termite meal is dried in the sun to prevent the nutrients from being destroyed by potential overheating during laboratory drying with an autoclave or other drying equipment [33, 34]. However, autoclave can still be cautiously employed especially during the wet season to ensure availability of raw materials for sustainable production of termite meals. Processing methods for the world's supplies of fish meal include drying and grinding, employing chemicals to extract some of the nutritious components, boiling, or fermentation. The quantity of protein available, the makeup of the resultant amino acids, and the digestibility are all determined by these processing methods [33].

3. Nutritional composition of termites

3.1 Proximate composition

Table 1 obtained from a 2013 study [24] depicts the relative composition of four species of edible termites consumed in western Kenya. The moisture content ranged from 6.5 to 8.8 g/100 g. However, an earlier study from the same region reported a lower content of 1.7 g/100 g [35]. The degree of moisture content of any dried food is greatly influenced by the drying environment, among other things. Due to the fact that some of the meals are dried on the ground, water may collect around them rather than drain away, making the drying process difficult [36]. The protein content of the termite species ranged from 33.5 to 39.3 g/100 g, which is comparable to the dried termite protein value of 35.70 g/100 g previously reported [35].

Termites have excellent protein quality that is advantageous for human and animal nutrition [5], even though these values are lower than those recorded in fish (70.6 g/100 g) and soybean (51.8 g/100 g) [37]. As can be seen in **Table 1**, the termites' lipid content varied from 44.8 to 47.3 g/100 g. Another study [38] found 19.70–24.10 g/100 g for various termite species in Nigeria, while a previous study [35], also recorded 53.4 g/100 g for sun-dried termites. Termites should be defatted prior to use as meal in order to bring the lipid content of termites to the levels reported in fish (9.9) and soybean (2.0) [37].

As reported, the ash content in termites ranges from 4.6 to 7.6 g/100 g [24]. However, a study found a value for dried termites as low as 4.8 g/100 g [35]. The presence of high levels of ash in termites may result from persistent ash contamination of

	Mendi termite	Sugarcane termite	War-like termite	Fungus-growing termite
Moisture	6.5	5.0	5.1	8.8
Protein	39.3	33.5	39.7	37.5
Lipid	44.8	46.6	47.0	47.3
Total ash	7.6	4.6	4.7	7.2
Dietary fibre	6.4	6.6	6.2	7.2
Carbohydrate	1.9	8.7	2.4	0.7

Except for moisture content, which is in wet weight basis, other compositions are as per dry weight basis of winged termites [24]. Mendi termite (Macrotermes subhyalinus). Sugarcane termite (Pseudacanthotermes militaris). War-like termite (Macrotermes bellicosus). Fungus-growing termite (Pseudacanthotermes spiniger).

Table 1.
Proximate composition of edible termites (g/100 g).

the soil during harvest and drying. Before such food samples are analyzed, sorting is a method to eliminate any visibly present soil, dust, and other physical pollutants. The average value of 15.8 g/100 g reported for fish [37] is lower than the ash content of termites, which is also lower. The carbohydrate content per 100 grams varies from 0.7 to 8.7 g. However, another study [39] recorded a value of up to 29.0 g/100 g. The range of dietary fiber per 100 grams is 6.2 to 7.2 g. Because chitin and cellulose have structural similarities, the fiber seen in insects is actually chitin [24]. Insects may therefore have high fiber content because of chitin.

3.2 Amino and fatty acids

From the reports on catfish nutrition and nutrient requirements, termites possess all the essential amino acids, such as histidine, methionine, and lysine, required for the sharp-tooth catfish to grow to their full potential [40, 41]. Because termite-based diets may not require the addition of methionine, lysine, or any other essential amino acid, they have an advantage over other insects in this regard. Ten amino acids are required for proper fish nutrition: arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine. According to the developmental stage (larva, pupa, prepupa, and imago), the type of diet, and the rearing conditions, the amount of protein in insect bodies varies. As a result of these variations, the amino acid content can also vary [15].

According to the data in **Table 2**, termite oil has a higher percentage of unsaturated fatty acids than polyunsaturated fatty acids (PUFA). The most common fatty acid in the lipid fraction of termite species was oleic acid [24].

3.3 Mineral composition

Termites are a great source of minerals like calcium, iron, and zinc, as indicated in **Table 3**. The contribution of micronutrients, which are well known to be lacking and generate serious public health concerns in poor people in developing nations, is particularly significant while focusing on the nutritional significance of edible insects [42]. Iron and zinc deficiency are major public health issues, particularly for mother and infant health [43]. In general, reports on the amounts of zinc and iron in different insects show that they are a valuable source of these minerals [44, 45].

	Mendi termite	Sugarcane termite	War-like termite	Fungus-growing termite
Capric acid	0.0	0.2	0.2	0.3
Caprylic acid	0.0	0.0	0.4	0.4
Lauric acid	0.0	0.0	0.2	0.2
Myristic acid	1.1	0.0	1.2	0.8
Palmitic acid	27.7	26.0	38.4	28.0
Palmitoleic acid	4.2	5.8	0.6	3.2
Stearic acid	6.3	5.9	9.5	6.1
Oleic acid	48.6	50.3	41.7	49.3
Linoleic acid	10.8	11.5	5.0	10.5
Linolenic acid	1.4	0.2	0.9	0.8

Compositions are as per dry weight basis of winged termites [24]. Mendi termite (M. subhyalinus). Sugarcane termite (P. militaris). War-like termite (M. bellicosus). Fungus-growing termite (P. spiniger).

Table 2.
Fatty acid composition of edible termites.

	Mendi termite	Sugarcane termite	War-like termite	Fungus-growing termite
Ca	58.7	48.3	63.6	42.9
Fe	53.3	60.3	116.0	64.8
Zn	8.1	12.9	10.8	7.1

Compositions are as per dry weight basis of winged termites [24]. Mendi termite (M. subhyalinus). Sugarcane termite (P. militaris). War-like termite (M. bellicosus). Fungus-growing termite (P. spiniger).

Table 3.
Mineral composition of edible termites (mg/100 g).

3.4 Anti-nutrient composition

The presence of antinutrients, which are typically linked with undigested cellulose in the intestines of insects, is one of the factors that restricts the use of insects as food for fish and other animals. Antinutrients can prevent nutrient digestion, which can have a negative impact on fish growth. Degutting, however, is a method for removing these anti-nutrients from insect guts. Additionally, it has been found that oven drying the termites before using them as animal feed successfully removes anti-nutrients such as phytic acid and antioxidant polyphenols without harming the vital nutrients [46]. Additionally, termites are said to have minimal or no concentrations of additional anti-nutrients such as calcium oxalate, trypsin inhibitor, lectin, and hydrocyanic acid [47].

4. Growth response and nutrient digestibility

4.1 Growth response

The catfish, *H. longifilis* has been observed to perform well in terms of growth when fed with diets containing termite meal [21]. In other studies, the growth of

African catfish was not adversely affected when termite meal was used to partially or entirely replace fish meal [11].

4.2 Nutrient digestibility

One of the main concerns of stakeholders who purchase insects in aquafeed is the nutritional digestibility of nutrients by fish fed insect meal. This worry is frequently brought on by the presence of chitin from the exoskeleton, which may decrease perceived digestibility and, as a result, the growth of farmed fish. However, the amount of chitin is dependent on the species and stage of the insect's growth [48]. It is questionable whether fish can digest chitin because some fish do so better than others.

It is interesting to note that catfish have a critical adaptive system for breaking down insect chitin. Many catfish have chitinase in their gastrointestinal tracts (GIT), which facilitates the ingestion of insects. Chitin from insects and crustaceans must be broken down by the enzyme chitinase, which is produced by the pancreas and the gastric glands. Termites and other arthropods have been a part of natural fish diets for a long time, as evidenced by the digestive enzyme chitinase, buccal organ alterations, and behavioral adaptations of fish like catfish [15].

In insects, the digestibility of proteins and amino acids (AAs) might vary depending on how much of the AAs are bonded to chitin or scleroderoprotein, which are mostly found in adult insect cuticles. The chitinolytic activity of enzymes like chitinase in the stomach and chitobiase in the intestine, which are present in the gastrointestinal tracts of many fish species that feed on insects and other macroinvertebrates like shrimp and crabs, allows these proteins or amino acids to be available for fish nutrition.

5. Conclusions

Due to their adaptability and capacity to adjust their amino acid and fatty acid profiles and transform cellulose into protein, termites are one of the best alternatives to fish meal when replacing it partially or entirely. Fishmeal is expensive, so it has been desirable to look for cheaper protein alternatives that can take its place without hindering the growth of farmed fish. Termite meal has received praise for having an excellent nutritional content that is comparable to fish and soybean meals (crude protein and lipids, mineral composition, fatty and amino acids). Chitin, a growth inhibitor for many farm animals, can be spontaneously broken down by catfish into useful components.

With the right processing methods, the concentration of phytate and tannin that could otherwise prevent fish from absorbing nutrients and growing can be reduced. It is interesting to note that other anti-nutrient quantities in termites, such as oxalate, trypsin inhibitor, lectin, and hydrocyanic acid, are known to be minimal and may not have an impact on the digestion and absorption of vital nutrients.

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Section 3

Advances in Catfish

Chapter 3

Perspective Chapter: Species Diversity and Distribution of Catfishes and Their Current Contribution to Global Food Security

Don Felix Ouma and James E. Barasa

Abstract

Ranking fifth in global aquaculture production of farmed fin fishes, with a total tonnage of 5, 518 878 metric tons worth US$ 10 569 972 Billion, Catfishes are exceptionally important as a seafood product. They are an especially important food resource in developing countries, more so since their farmed production does not require sophisticated technology. The diversity and natural distribution of catfishes are documented. Farmed production of *Pangasianodon hypophthalmus* in the Mekong delta and *Ictalurus punctatus* in China is reviewed as global success story in the culture of catfishes. Important lessons from these ventures are drawn for the culture of clariid catfishes, the dominant group farmed in Africa. Amongst this family, the African catfish, *Clarias gariepinus* (Burchell 1822) is the most widely cultured species, due to its hardy nature. However, its culture is constrained by insufficient seed supply, due to poor survival of fingerlings. These challenges are brought to the fore, so that future research efforts explore strategies of countenance, in order to increase food fish production, incomes, and livelihoods in Africa.

Keywords: catfishes, species diversity, clariids, survival, seed production, *Pangasius*

1. Introduction

1.1 Diversity of Catfishes

Catfishes are a diverse group of ray-finned fish named for their prominent barbells, which resemble cat whiskers. Catfishes belong to the Phylum Chordata, class Actinopterygii, and of Order siluriforms. The group has about 40 families distributed around the globe. Despite their name, not all catfishes have prominent barbells, some members of the order siluriforms are defined by features of the skull and the swim bladder. They are most diverse in tropical South America, Africa, and Asia, but more

Family	Common name	Region	Valid species
Loricaroidei			
Trichomycteridae	Pencil or parasitic catfishes	South America, Costa Rica, Panama	240
Callichthyidae	Armored catfishes	South America or Panama	199
Loricariidae	Suckermouth armored catfishes	South America	813
Astroblepidae	Naked suckermouth or climbing catfishes	South America or Panama	54
Diplomystidae	Velvet catfishes	Chile and Argentina	6
Scoloplacidae	Spiny dwarf catfishes	South America	5
Siluroidei			
Ictaluridae	Bullhead catfishes	North America (Canada to Guatemala)	51
Bagridae	naked or bagrid catfish	Africa and Asia: Lake Tanganyika	210
Cranoglanididae	Armorhead catfishes	China and Vietnam	5
Siluridae	Sheatfishes	Europe and Asia	97
Pangasiidae	Shark catfishes	Asia and South East Asia	28
Amblycipitidae	Torrent catfishes	South Asia	33
Amphiliidae	Loach catfishes	Africa	80
Akysidae	Stream catfishes	South East Asia	57
Sisoridae	Hill-stream catfishes	South Asia	218
Clariidae	Air-breathing or walking catfishes	Africa and South East Asia	111
Chacidae	Squarehead, frogmouth, or angler catfishes	South East Asia	3
Lacantuniidae	Chiapas catfish	Mexico	1
Malapteruridae	Electric catfishes	Africa	19
Mochokidae	Squeaker or upside-down catfishes	Africa (Lake Tanganyika)	204
Ariidae	Sea catfishes	Australia, Papua New Guinea, tropical and temperate continental shelves, including Africa.	15
Doradidae	Thorny or talking catfishes	South America	88
Auchenipteridae	Driftwood catfishes	South America and Panama	105
Aspredinidae	Banjo catfishes	South America	39
Plotosidae	Eel tail or tandan catfishes	Indo Pacific, Australia, New Guinea	40
Pimelodidae	Long-whiskered catfishes	South America, Panama	107
Cetopsidae	Whale catfishes	South America	42
Anchariidae	Madagascar catfishes	Madagascar	6

Two orders are recognized for catfishes globally: Loricaroidei and Siluroidei. Adopted from [1].

Table 1.
Families of Catfish with the number of valid species in each family.

than half of all catfish species are to be found in America. Catfishes are important biodiversity resources, playing important ecological roles in food chains in aquatic ecosystems. Similarly, they form important food fish for local communities and contribute to income generation and livelihoods (**Table 1**). According to [2] the most cultured among global catfish populations are the Amur catfish (*Silurus arsotus*), Channel catfish, *Ictalurus punctatus*), Stripped catfish, *Pangasianodon hypophthalmus,* and the African catfish (*Clarias gariepinus*). Africa has ten siluriform families [2–4], which include: Amphiliidae, Ariidae, Austroglanididae, Bagridae, Clariidae, Claroteidae, Malapteruridae, Mochokidae, Plotosidae, and Schilbeidae. Catfishes group into 32 families, distributed globally, with currently 3,407 valid species [5]. Like the spectacular haplochromine cichlids of the Great lakes of Africa, some groups form species flocks in the habitats where they occur. These include *Bathyclarias*, endemic in Lake Malawi [6], where they comprise up to 12 species [6].

According to [7], catfishes are distinguished by pairs of barbels, cylindrical body without scales, largemouth, pectoral, and dorsal fins that bear spines. For the clariid family, the key distinguishing feature is the suprabranchial organ formed by arborescent structures from the second and fourth-gill arches [8–10] and flat dorso-ventrally flattened skulls. Clariidae is naturally distributed in Asia, Syria, and Africa. In Africa, this family has 13 genera and 74 species. Amongst the species include the *Heterobranchus* species, *Dinotopterus*, *Bathyclarias*, *Clarias gariepinus, Clarias anguillaris,* and other nominal species of *Clarias* in Africa. The clariids are mostly found in the muddy bottoms where they graze on variety of food materials hence regarded as omnivores. Some clariids such as *Xenoclarias* and *Dinotopterus* are found in Lakes Tanganyika, Victoria, and Malawi, the upper Congo, the middle and the upper Zambezi, the Okavango, L. Ngami, the Chobe, the Cunene and the Quanza in South Africa, and other Great lakes of Africa. The Gymnallabes live in turbulent well-oxygenated rivers of the Congo, but they lack the respiratory accessory organs. The Bathyclarias species are also found in Lake Malawi [10, 11] (**Table 2**).

2. Diversity and distribution of catfishes

Family	Species	Distribution	References
Bagridae (Bagrid catfishes)	Black Nile catfish, *Bagrus bajad* (Forskkal 1775)	Lake Turkana	[12]
		Lakes Chad, Albert, Turkana	[13]
		Rivers Nile, Niger, and Senegal	[13]
	Sudan catfish, *Bagrus docmak* (Forskkal, 1775)	Lake Turkana	[12]
		Lake Victoria and mouths of major tributaries: Nyando, Sondu, Mara, Nzoia, and Yala	[14]
	Somalia catfish, *Bagrus urostigma* (Vinciguerra, 1895)	Northern Ewaso Nyiro, Lower reaches of Coastal Rivers (Sabaki, Tana), Athi river	[12, 14]
	Bagrus meridionalis	Lake Malawi	[15]

Family	Species	Distribution	References
Claroteidae (Clarotid catfishes)	Giraffe catfish, *Auchenoglanis occidentalis*	Lake Turkana	[12, 14]
		Congo River (DRC)	[16]
	Golden Nile catfish, *Chrysichthys auratus* (Geoffroy Saint Hilaire, 1809)	Lake Turkana	[12, 14]
	Bagrid catfish, *Chrysichthys nigrodigitatus* (Lacepede, 1803)	Tropical freshwaters of Mauritania, Senegal, Angola, and Lower Congo River (DRC)	[17]
		Lake Tanganyika	[18]
	Wideheaded Catfish, *Clarotes laticeps* (Rüppell, 1829)	Ewaso Nyiro North, Galana-Sabaki (Tsavo drainage), Lower Tana River, Dawa River (Juba)	[12, 14]
	Somalian giant catfish *Pardiglanis tarabinii* (Poll, Lanza & Sassi, 1972)	Lower Tana River	
		Juba system in Somalia	[19]
Schilbeidae (Butter or Glass catfishes)	Somalia glass catfish *Parailia somalensis* (Vinciguerra, 1897)	Lower Tana River at Hola	[12, 14, 20]
	Silver catfish, Butter Catfish, *Schilbe intermedius* (Rüppell, 1832)	Galana-Sabaki, Lower Tana, Northern Ewaso Nyiro, Dawa River (Juba system)	[12, 14]
		Lake Victoria and its major tributaries such as Sondu, Nyando, Yala, Mara, and	
		Lake Tanganyika	[21]
	Egyptian Butter catfish *Schilbe uranoscopus* (Rüppell, 1832)	Lake Turkana, Turkwell River at Katilo	[12, 14]
	Schilbe durinii (Gianferrari, 1932)	Lake Tanganyika	[21]
Amphiliidae (Mountain catfishes)	Marbled Mountain catfish, *Amphilius jacksonii* (Boulenger, 1912)	Lake Victoria drainage (affluent rivers: Nzoia, Yala, Nyando, Sondu, Mara, and their tributaries, Streams of Kakamega forest, Sio, etc)	[12, 14]
		Lake Tanganyika	[21]
	Stargazer Mountain catfish, *Amphilius uranoscopus* (Pfeffer, 1889)	Southern Ewaso Nyiro drainage, Pangani drainage, Athi and Tana River systems, Nairobi stream, Lake Victoria basin (affluent rivers)	[12, 14]
		Headwater streams of Mt Kenya, Aberdares, and Taita Hills	[22]
		Widespread in headwater streams across East and Central Africa: Pongolo River in Natal, Okavango delta and the Zambezi drainage, east coast rivers of Northern Natal	
		Streams in Ethiopia and Tanzania	[23]

Family	Species	Distribution	References
		Lake Tanganyika	[21]
	Amphilius kivuensis (Pellegrin, 1933)	Lake Tanganyika	
	Amphilius pedunculus (Thomson & Page, 2015)	Lake Tanganyika	
	Amphilius ruziziensis (Thomson & Page, 2015)	Lake Tanganyika	
	Sand catlet, *Leptoglanis aff. rotundiceps* (Hilgendorf, 1905)	Lake Victoria drainage (affluent rivers), esp Nzoia, Kuja-Migori	[12, 14]
Clariidae (Air breathing catfishes or African catfishes)	Victoria snake catfish, *Clariallabes petricola* (Greenwood, 1956)	Lake Victoria drainage: the lake itself and lower reaches of affluent rivers	
	Alluaud's catfish, *Clarias alluaudi* (Boulenger, 1906)	Lake Victoria drainage	
	African catfish, *Clarias gariepinus* (Burchell, 1822)	Lake Victoria drainage, Lake Kanyaboli, Pan African distribution	
		Lake Turkana system	
		Suguta River	
		Lake Bogoria drainage, Lake Baringo system,	
		eastward flowing river basins (Tana, Athi, …)	
		Northern and Southern Ewaso Nyiro Rivers,	
		Dawa River (Juba system)	
	Smoothhead catfish, *Clarias liocephalus* (Boulenger, 1898)	Lake Victoria basin, including the lake itself and all affluent rivers	
		Lake Kanyaboli	
		Nairobi dam (Upper Athi River) where it was probably introduced	
	Werner's catfish, *Clarias werneri* (Boulenger, 1906)	Lake Victoria basin	
	Vundu, *Heterobranchus longifilis* (Valenciennes in Cuvier and Valenciennes, 1840)	Lake Turkana, middle Omo River	
	Lake Victoria deep water catfish, *Xenoclarias eupogon* (Norman, 1928)	Endemic to Lake Victoria drainage	
	Bathyclarias euryodon (Jackson, 1959)	Lake Malawi	[6]
	Bathyclarias gigas	Lake Malawi	
	Bathyclarias ilesi		
	Bathclarias longibarbis		

Family	Species	Distribution	References
	Bathyclarias nyaensis		
	Bathyclarias rotundifrons		
	Bathyclarias Worthington		
	Dinotopterus cunningtoni	Lake Tanganyika	[21]
	Tanganikallabes mortiauxi (Poll, 1943)	Lake Tanganyika	[21] [24]
	Tanganikallabes alboperca (Wright & Bailey, 2012)	Lake Tanganyika	
	Tanganikallabes stewarti (Wright & Bailey, 2012)	Lake Tanganyika	
	Pseudotanganikallabes prognatha (Wright, 2017)	Lake Tanganyika	[21]
Malapteridae (Electric catfishes)	Electric catfish *Malapterurus electricus* (Gmelin, 1789)	Lake Turkana, Turkwell River; Omo system, and Malagarasi River in western Tanzania	[12, 14]
Ariidae (Sea catfishes)	African Sea catfish, *Arius africanus* (Playfair & Günther,1866)	Lower courses of Sabaki and Tana Rivers; coastal species	
Mochokidae (Squeakers and Suckermouths)	Short barbelled suckermouth, *Chiloglanis brevibarbis* (Boulenger, 1902)	Athi and Tana River systems	
	Pangani Suckermouth, *Chiloglanis deckenii* Peters, 1868	Pangani drainage, including Lumi River	
	Kerio suckermouth *Chiloglanis* spec. “Kerio” or *Chiloglanis niloticus* (Boulenger, 1900)	Kerio River system (Lake Turkana drainage)	
	Chanler Falls suckermouth, *Chiloglanis* spec. “Northern Ewaso Nyiro”	Northern Ewaso Nyiro (below Chanler Falls)	
	Someren’s Whitehead, *Chiloglanis somereni* (Whitehead, 1958)	Lake Victoria drainage (affluent rivers), esp. tributaries Waroya of Nzoia, Nyerere and Indigo of Yala, and Migori of Kuja, as well as the Mara River system. Mainly riverine species.	
	Dwarf Nile catfish, *Mochokus niloticus* (De Joannis, 1835)	Lake Turkana system	
	Marbled Victoria Squeaker, *Synodontis afrofischeri* Hilgendorf, 1888	Lake Victoria drainage: Lakes Sare and Victoria, Affluent rivers	
	Sudan Squeaker, *Synodontis frontosus* (Vaillant, 1895)	Lake Turkana system	
	Geledi squeaker, *Synodontis geledensis* (Günther, 1896)	Northern Ewaso Nyiro system, near Lorian swamp	
	Feather-barbelled squeaker, *Synodontis manni* (De Vos, 2001)	Lower Tana River	

Family	Species	Distribution	References
	Nile squeaker, *Synodontis schall* (Schneider in Bloch & Schneider, 1801)	Lake Turkana	
	Tana squeaker, *Synodontis serpentis* (Whitehead, 1962)	Galana-Sabaki and lower Tana River systems	
	Lake Victoria squeaker, *Synodontis victoriae* (Boulenger, 1906)	Lake Victoria drainage	
	East coast squeaker, *Synodontis zanzibaricus* (Peters, 1868)	Pangani drainage, Galana-Sabaki, Lower Tana River, Northern Ewaso Nyiro system	
	Ocellated Tana squeaker, *Synodontis* spec. "Lower Tana"	Lower Tana drainage	
	Synodontis njassae	Lake Malawi	[15]
	Synodontis greshoffi (Schilthuis, 1891)	Congo River Basin	[25]
	Clown Squeaker, *Synodontis decorus* (Boulenger, 1899)	Lake Tanganyika	[21] [26]
	Synodontis dhonti (Boulenger, 1917)		
	Synodontis grandiops (Wright & Page, 2006)		
	Synodontis granulosus (Boulenger, 1900)		
	Synodontis ilebrevis (Wright & Page, 2006)		
	Synodontis irsacae (Matthes, 1959)		
	Synodontis lucipinnis (Wright & Page, 2006)		
	Synodontis multipunctatus (Boulenger, 1898)		
	Blackspotted squeaker, *Synodontis nigromaculatus* (Boulenger, 1905)		
	Cuckoo catfish, *Synodontis petricola* (Matthes, 1959)		
	Synodontis polli (Gosse, 1982)		
	Synodontis tanganyicae (Borodin, 1936)		
Pangasiidae (Migratory catfishes)	*Pangasius djambal* (Bleeker, 1846)	Jambi, Batang Hari, Sumatra, Indonesia Barito, Central Borneo, Indonesia	[27]
	Pangasius rheophilus (Pouyaud & Teugels, 2000)	Tanjung Selor, Kayan, Bulungan, East Borneo, Indonesia	
		Tanjung Redep, Berau, Bulungan, East Borneo, Indonesia	

Family	Species	Distribution	References
	Basa catfish, *Pangasius bocourti* (Sauvage, 1880)	Mekong River, Vietnam	
	Pangasius nasutus (Bleeker, 1863)	Musi, Sumatra, Indonesia	
		Palangkaraya, Kahayan, Central Borneo, Indonesia	
		Kapuas, West Borneo, Indonesia	
	Pangasius conchophilus (Roberts & Vidthayanon, 1991)	Mekong River, Vietnam	
	Black ear catfish, *Pangasius larnaudii* (Bocourt, 1866)	Chau Doc, Mekong basin, Vietnam	
	Pangasius sanitwongsei (Smith, 1931)	Chau Doc, Mekong basin, Vietnam	
	Pangasius pangasius (Hamilton, 1822)	Chandpur, Ganges, Bangladesh	
	Pangasius krempfi (Fang & Chaux, 1949)	Mekong River, Vietnam	
	Pangasius kunyit (Pouyaud et al., 1999)	Sanga-sanga, Mahakam, East Borneo, Indonesia	
		Pontianak, Kapuas, West Borneo, Indonesia	
		Barito, Central Borneo, Indonesia	
		Kinabatangan, Sabah, North Borneo, Malaysia	
		Mekong River, Vietnam	
	Pangasius polyuranodon (Bleeker, 1852)	Jambi, Batang Hari, Sumatra, Indonesia	
		Barito, Central Borneo, Indonesia	
		Kapuas, West Borneo, Indonesia	
		Batang Rajang, Sarawak, North Borneo, Malaysia	
		Sarawak, North Borneo, Malaysia	
		Mahakam, East Borneo, Indonesia	
		Mekong River, Vietnam	
	Pangasius macronema (Bleeker, 1851)	Mekong River, Vietnam	
	Pangasius humeralis (Roberts, 1989)	Sintang, Kapuas, West Borneo, Indonesia	
	Pangasius lithostoma (Roberts, 1989)	Sintang, Kapuas, West Borneo, Indonesia	
	Pangasius kinabatanganensis (Roberts & Vidthayanon, 1991)	Sukau, Kinabatangan, Sabah, North Borneo, Malaysia	
	Pangasius nieuwenhuisii (Popta, 1904)	Mahakam, East Borneo, Indonesia	

Family	Species	Distribution	References
	Striped (Tra/Sutchi) catfish, *Pangasianodon hypophthalmus* (Sauvage 1878)	Mekong River, Vietnam	
	Mekong giant catfish, *Pangasianodon gigas* (Chevey, 1930)	Mekong River, Thailand	
	Pteropangasius micronemus (Bleeker, 1847)	Batang Hari, Sumatra, Indonesia	
		Indragiri, Sumatra, Indonesia	
		Jombang, East Java, Indonesia	
		Sibu, Batang Rajang, Sarawak, Malaysia	
	Pteropangasius pleurotaenia (Sauvage, 1878)	Chao Phraya, Thailand	
	Helicophagus typus (Bleeker, 1858)	Jambi, Batang Hari, Sumatra, Indonesia	
	Helicophagus leptorhynchus (Ng & Kottelat, 2000)	Mekong River, Laos	
Ictaluridae (Bullhead catfishes)	Blue catfish, *Ictalurus furcatus*	North America, widely translocated outside its native range	[28]
	Channel catfish, *Ictalurus punctatus* (Jordan, 1905)	Western North America, New Zealand,	
	Brown catfish, *Ictalurus nebulosus* (Gill, 1906)		

Table 2.
Families of catfishes, common species per family and their distribution. Although not complete, this table captures the diversity of catfishes, and where each species is distributed globally.

3. Contribution of catfishes to food security in Africa

According to [29], a total of 27 catfish species were farmed in 86 countries worldwide in 2017, with a total production of 5, 518 878 tonnes, worth US$10, 569 972 billion of farm gate value. A large percentage of this production is from Pangasiid and Clariid catfishes, which contributed 51% and 24%, respectively, to the total annual production [29], which represents diversity and resilience of these two groups. The Mekong river harbors up to 16 species of *Pangasius*, grouped into 4 genera of *Helicophagus*, *Pangasianodon*, *Pangasius,* and *Pteropangasius* [30]. However, only 2 species are farmed in the river-based capture aquaculture: the river catfish (or sutchi or tra catfish) (*Pangasianodon hypophthalmus*) and Bocourt's catfish (*Pangasius bocourti*) [31]. Of these species, *P. hypophthalmus* is the most commonly cultured species, due to its higher fecundity, which occurs mainly at the surface, therefore, its larvae are easily caught for seeds [32] and exploit diverse food resources [33]. The culture of *P. hypophthalmus* in the Mekong delta of Vietnam grew at an average annual rate of 37% between 1997 and 2008, reaching a total annual tonnage of 1.4 million tonnes in 2009 [34], with an export turnover worth US$1.85 billion in 2011. This rapid increase in production of Vietnamese farmed *Pangasius*, an iconic industry directly employing over 180,000 people, was fueled by high and expanding market demand in over 100 countries, especially in the USA and Europe [34]. Despite adverse media

Date	Transformation
1940–1950	Tra catfish cultured in small family ponds, using natural seeds collected from the Mekong and its tributaries. Farming is concentrated in An Giang and Dong Thap provinces, upstream of the Mekong River Delta in Vietnam
1981–1982	First trials of tra catfish intensive culture in small ponds in Can Tho city using wild-caught fingerlings
1996–1999	Intensive culture of tra catfish in ponds, and expanded gradually to other provinces. First trials of tra catfish culture in cages (replacement of basa catfish) and pens were also conducted. Both production systems used wild and hatchery-reared fingerlings
2000–2004	Tra catfish intensive culture in cages and ponds expanded rapidly. Hatchery-reared fingerlings met the demand for stocking. Productivity was significantly improved. Farmers gradually shifted from homemade feeds to commercial feeds
2005 to present	Collapse of tra catfish cage and pen culture occurred. Significant improvements to pond culture techniques and marked increases in productivity. Introduction of sustainable production standards such as SQF-1000, AquaGAP, GlobalGAP, and BMPs.

These measures significantly spurred production, raising the industry from artisanal to a commercial export-oriented one, supplying over 100 countries globally. Source: [36].

Table 3.
Historical transformation of the Vietnamese striped catfish farming in the Mekong.

reports of possible poison levels in *Pangasius* imports from Vietnam, demand for these fish products skyrocketed, buoyed by favorable reports of risk assessment and management, through toxicological risk surveys [35] (**Table 3**).

With current production of cultured *P. hypophthalmus* in Vietnam equivalent to 65% of European aquaculture production [37], the industry provides a microcosm of what production efforts for related species need to be put in place to spur production. Starting as a small-scale backyard activity, farmers grew the fish in ponds, with limited input and harvests [38]. This transitioned to the use of pens and cages in the Mekong, with use of poor-quality seeds caught from natural aquatic systems, especially from the Cambodian waters of the confluence of the Mekong, Bassac, and Tonle Sap Rivers [39]. However, with the ban on the collection of natural seed stocks for the species by Cambodian authorities in 1994 [40], production declined slightly, but this challenge in seed availability stimulated a focus on seed production technology. Similarly, challenges associated with water flow under cages led to a transition to pond culture along the lower reaches of the Mekong. This, infused with technological improvements in the artificial propagation of seeds, vertical integration of the pond farming systems, and processing of the final product, significantly transformed production between 1997 and 2007 (**Figure 1**).

Therefore, although a majority of the farmers were small-scale, with up to 81.9% of the 5,393 farms being less than 1 ha in size, high production was still achieved and maintained (**Figure 2**) [38].

3.1 Factors contributing to a rise in farmed Vietnamese striped catfish in the Mekong

The production units were vertically integrated, with seed production, fry production, fry to fingerling, and grow-out units being distinct, in different locations and

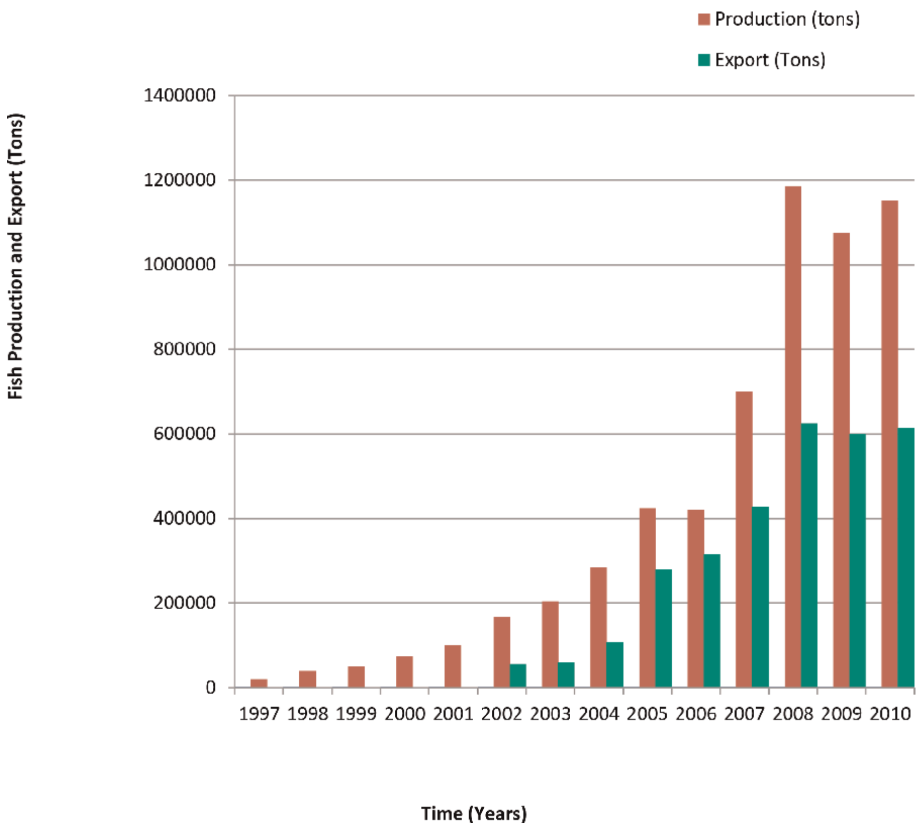

Figure 1.
Total tonnage of farmed Pangasianodon hypophthalmus *produced and exported in Vietnam, from 1997 to 2010. Source: [38].*

setups. This ensured specialized labor and effort (cluster of operations) increased efficiency of the sector and effective dissemination of technology to farmers [38]. Similarly, special attention was given to seed production and broodstock management at hatcheries. The major technique that revolutionized the sector was the development of artificial propagation of tra catfish seeds [42], and the dissemination of the technology to all hatcheries in the Mekong. This ensured the availability of adequate high-quality seeds for the enterprises, following the ban on collection of natural seed stocks in the Mekong. Apart from this, a large number of hatcheries were developed, ranging from small-scale or back yard to commercial scale or large establishments (0.2 to 15 ha) [43]. There were 93 hatcheries for tra catfish in the Mekong delta, producing up to 818.3 million hatchlings annually under optimal operations of 29 cycles of fry production annually [44]. Many hatcheries maintained a large number of broodstock (up to 29,200) so the frequency of reusing a brooder was very low [38]. This reduced the rate of inbreeding and genetic drift, two processes that often negatively impact quality of seeds or fry, and this consequently improved the quality of the seed. Many hatcheries also replace their brood stock frequently [43], with stocks from their own extensive farms, neighboring grow-out farms, or from natural sources [38, 43]. Continuous improvement of seed quality is undertaken, for instance through selective breeding program for the species that has been initiated [45]. Feeding regimes in nursery units are also quite improved, ranging from recommended practices of live feeds such as

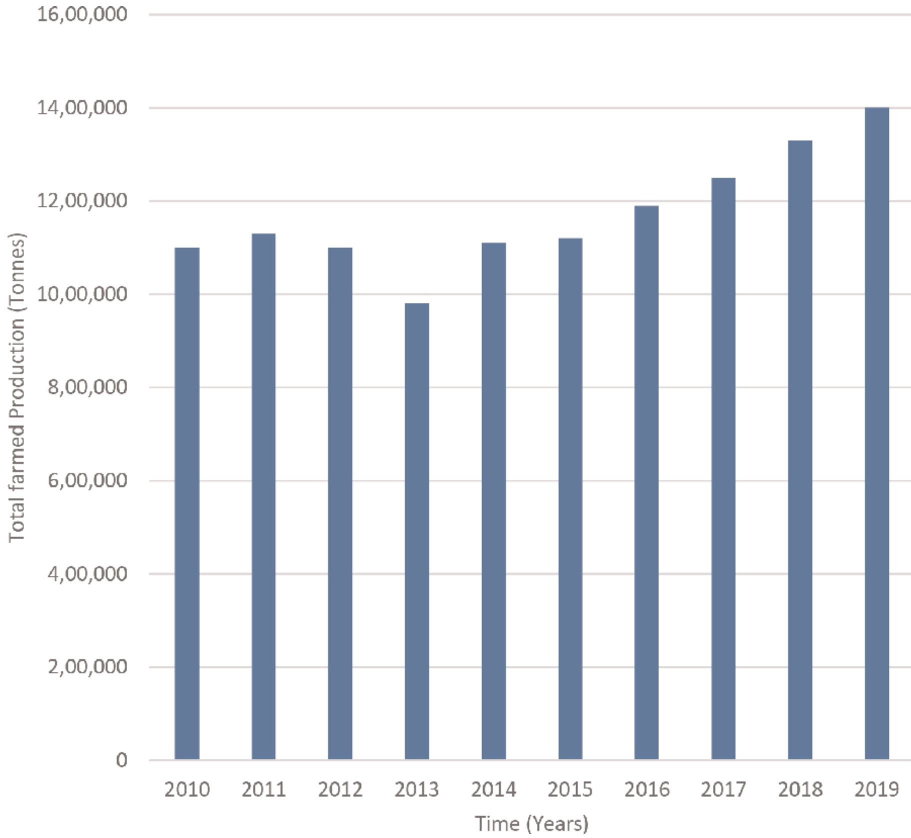

Figure 2.
Annual production of farmed striped catfish, Pangasianodon hypophthalmus *in Vietnam 2010 to 2019, the lead global producer of farmed Pangasiid catfishes. Annual production steadied from 2010 to 2019, mainly because of commitment of farmers and an expanded export market for the product. Source: [41].*

Moina, or other such natural feeds for larvae, to commercial diets for fingerlings. The feeding ration was 5 to 18% body weight at a frequency of 4 to 8 times daily [43]. Grow-out systems were mainly operated by small-scale farmers (72%) [46], comprising deep ponds averaging 2.0 to 6.0 m, with a water depth of 3.5–4.5 m, with a high stocking density of 18 to 125 fish m^{-2} depending on seed availability and financial ability of farmers. Average yields ranged from 70.0 to 850 t ha^{-1} $crop^{-1}$, although the pond area and productivity per unit area have been increasing since 2000 [46].

Growth in the production of *P. hypophthalmus* was also boosted by export-oriented markets, with the USA being the main market in the 1990s. Increasing imports of tra catfish to the USA were boosted by the admission of Vietnam to the Asia Pacific Economic Consortium (APEC) block, and the dropping of tariffs on raw seafood [47]. The increased imports of tra catfish affected markets of the local ictalurid catfish and occasioned trade restrictions via new laws against tra catfish and renegotiation of bilateral agreements against the species [48]. These restrictions were worsened by negative internet and media campaigns against striped catfish industry of Vietnam [49]. However, with the explosion in the production of striped catfish in the 2000s, export market diversified, to about 136 countries between 2002 to 2008 [38], with the European Union being the major market [38]. This phenomenal growth occurred despite trade restrictions by the USA due to negative publicity about *Pangasius*.

Expanding export markets was due to deliberate efforts by Vietnamese authorities to promote production while exploring alternative markets. Some of these efforts included: certification of groups of small-scale operators. Certification is a procedure by which a certification body gives written or equivalent assurance that a product, process, or service conforms to specified requirements and is carried out by competent and accredited body [38] (**Figure 3**).

Certification is important as it ensures that food quality and safety are achieved with respect to internationally traded food commodities and that the production systems comply to accepted norms and are socially responsible. Similarly, certification of a product ensures that farming systems have minimal environmental impact and that the production systems are sustainable. Certification also assures markets (buyers, retailers, and consumers) that the fisheries products are safe to consume and originate from aquaculture farms or capture fisheries adopting responsible management practices [38].

Certification of tra catfish farmers, therefore, assured the international market of the safety and quality of the product, and the confidence associated with this spurred

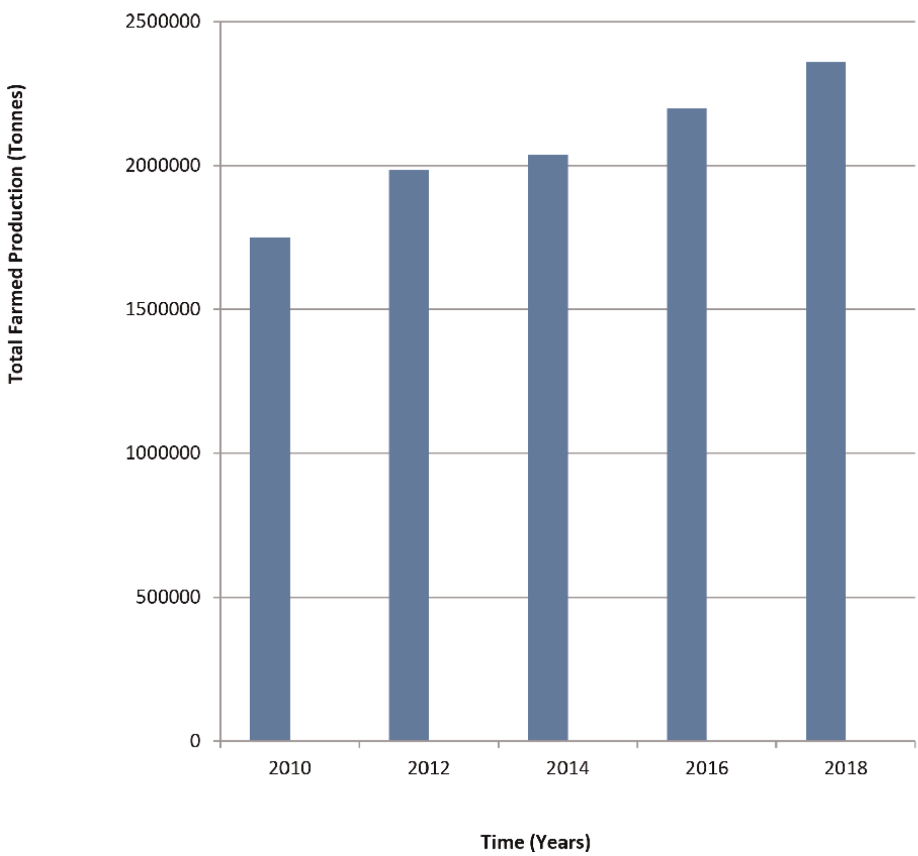

Figure 3.
Global Production of farmed striped catfish, Pangasianodon hypophthalmus *2010–2018. Intensification of production and use of technology, high-quality seeds produced from hatcheries' commercial diets, and processing of the product using global quality control systems commercialized the industry. Global production was averaging 2.4 million tons, 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. Source [41].*

demand for the product. Related to marketing of the product, the Vietnamese Government adopted negotiation with organizations such as the WWF, to address the biased negative publicity against tra catfish, and the WWF removed the species from its red list of endangered species. Similarly, Government encouraged farmers to adopt BMPs, cluster management approaches, and compliance to responsible farming practices to deter future problems. Due to the very marginal profits made across the tra catfish value chain, improved processing operations increased efficiency of processing, so that a relatively small amount of fish was required to produce 1 kg of processed fish. Production was also sustained by increased turnover or high production by farmers, exploiting the benefits of economy or scale of production [38]. This was further boosted by authorities implementing the guaranteed price scheme at each link of the value chain, to cushion operators against large fluctuations in prices [50]. Generally, there was deliberate action to maintain a suitable quality of the product, with desirable nutritional profile, as well as low content of pollutants, such as mercury, organochlorine pesticides, and polychlorinated biphenyls, consistent with the European rapid alert notification system [38]. Such actions included reduced use of veterinary drugs and other restricted or banned chemicals in the value chain of the fish by farmers and other operators, in compliance with food quality and food safety regulations.

Despite the rapid explosion of tra catfish culture in the Mekong, the industry has had very minimal environmental impacts on the Mekong ecosystem [38]. This is because only 2% of the waters of the Mekong pass through the ponds, and therefore the impact of aquaculture on the water quality of the river is minimal since sedimentation, mineralization, and infiltration occur in the ponds [51]. Further limitation of environmental impacts is achieved through the use of sludge from ponds as fertilizer for rice paddies, which helps to achieve environmental and economic sustainability for the farmers [52]. Similarly, hatchery-reared stocks of tra catfish have not impacted natural populations of the species and related fishes in the Mekong, through hybridization from escapees [53].

3.2 The Channel catfish, Ictalurus punctatus (Rafinesque, 1818)

The channel catfish (*Ictalurus punctatus*) is a member of the family Ictaluridae in the order Siluriformes. The native range of the Channel catfish or the North American Channel catfish, *Ictalurus punctatus*, is the southern Canadian Prairie Provinces south to the Gulf States, west to the Rocky Mountains, and east to the Appalachian Mountains [54]. Further, it extends to St. Lawrence River and its tributaries from southern Quebec through to Ontario including the Ottawa River and its tributaries, all the Great Lakes except Lake Superior, in southwestern Ontario and the southern part of Manitoba (**Figure 4**). This extends to Susquehanna River and the Florida Peninsular. However, the fish has been introduced in Georgia, North Carolina and South Carolina, and in most of the USA, including the Pacific and Atlantic drainages [54]. It is also widely introduced in Europe, Japan, and China (**Figure 4**). Its large size and excellent taste make it a popular target of anglers. Its high fecundity, tolerance to extreme environmental conditions, and resistance to diseases make it an excellent species for commercial cultivation.

The congener, Blue catfish, *I. furcatus*, and the hybrid between *I. punctatus* * *I. furcatus*, are also important in culture [56], and the three contribute to more than 60% of total aquaculture production in the USA, especially in the southern states of Mississippi, Louisiana, Arkansas, and Alabama [57]. The US catfish industry peaked in

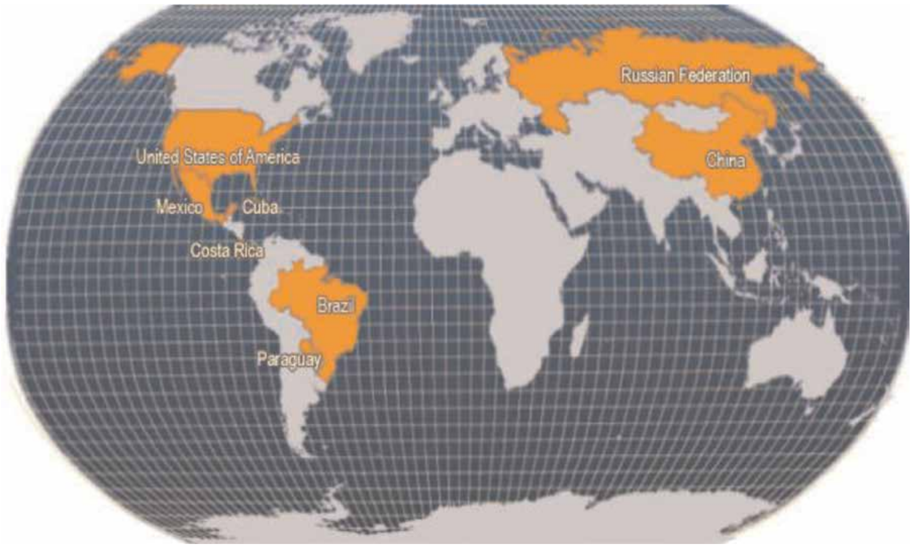

Figure 4.
Global distribution of the North American Channel catfish, Ictalurus punctatus*. Countries culturing* Ictalurus punctatus *are shown in orange color. Source: [55].*

2003, but declined later, in part due to competition from the Vietnamese catfish imports.

Sizeable fingerlings are stocked in fertilized ponds. During growth, fish of bigger size are intermittently harvested for market, and an equal number of fingerlings is added to ponds to replace the harvested fish. Therefore, multiple-batch production is often adopted, although fish grow faster in single-batch stocking [58]. So a pond often has fish of different sizes, and cropping for market is frequently carried out, to supply the market steadily, and also control flooding the market with fish and negatively affect fish prices [55]. This is maintained for several years, without draining ponds. Initial feeding ration is about 50% body weight, which is reduced gradually, to 3–4% body weight. However, water quality in ponds is monitored frequently, and aeration of water is carried out, to ensure the fish under high stocking density do not suffer stress, disease outbreaks, and mortality. Apart from ponds, fishes are also reared in cages, raceways, and tanks (**Figure 5**).

3.3 The Culture of Channel Catfish in China

The Channel catfish, *I. punctatus* was introduced to China from the USA in 1984, and successful artificial propagation was achieved in 1997, to support seed production for commercial culture. Rapid growth in the culture of the species in the country was recorded, due to several factors. Domestic consumption of the species reached 130,000 tons in 2013, of which 120,000 tones were fresh fish while 10,000 tones were processed [59]. The culture of the species has led to the growth of associate industries, strengthening synergies in the sector. For instance, due to the high demand for Channel catfish in many provinces of China, companies such as the Gaobazhou Aquatic Products processing company, promote value addition to the fish products, boosting sales, while simultaneously creating employment opportunities for locals [60] (**Figure 6** and **Table 4**).

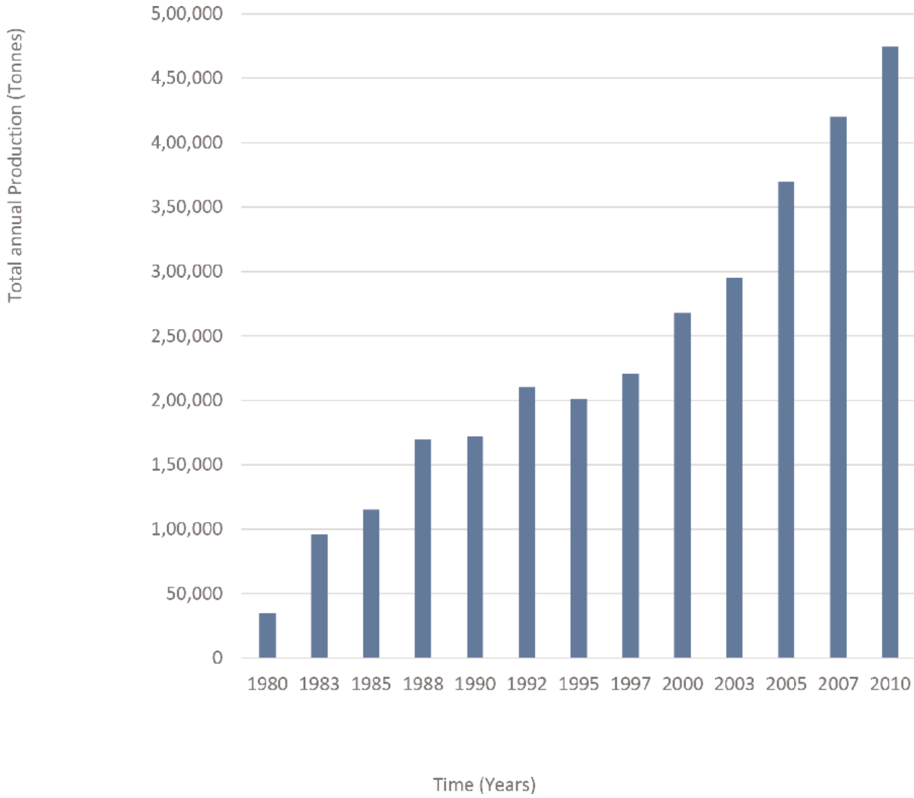

Figure 5.
Annual average global production of farmed Channel catfish, Ictalurus punctatus *from 1980 to 2010. Source: [29].*

3.4 Seed production to support the expansion of Channel catfish culture in China

Following the importation of *I. punctatus* to China in the 1980s, artificial production was successfully initiated and perfected, assuring the sector of sufficient seed production. However, production of adequate amounts of quality seed was affected by degradation of germplasm quality, inbreeding, variation of germplasm, reduced growth rates of fry, and increased incidence of diseases [60]. In order to address these challenges, Government authorities established the National Channel Catfish improved variety bases in Sichuan, Hubei, and Anhui, to undertake breeding schemes for improved varieties of *I. punctatus* for culture [60]. The result of these efforts was the development of improved strain of catfish named the Jiang Feng No. 1 [60], whose growth rate is 22.1 to 25.3% greater than that of any other strain [60]. Later, 2 improved lines were developed by screening different populations for economic gain and growth performance, using the Best Linear Unbiased Prediction (BLUP) method. This led to the development of two hybrid lines with high growth rates, resistance to diseases, and survival. Further research on this focuses on identifying populations of high genetic variation and quantitative trait locus (QTL) of economic interest, to develop superior strains for use by farmers [63]. In line with these, fish seed breeding centers, together with other hatcheries for farmers adopted best management practices, especially focusing on managing quality of broodstock. Most hatcheries maintain a large number of brood fish, ranging from 30,000 to 50,000. This is necessary

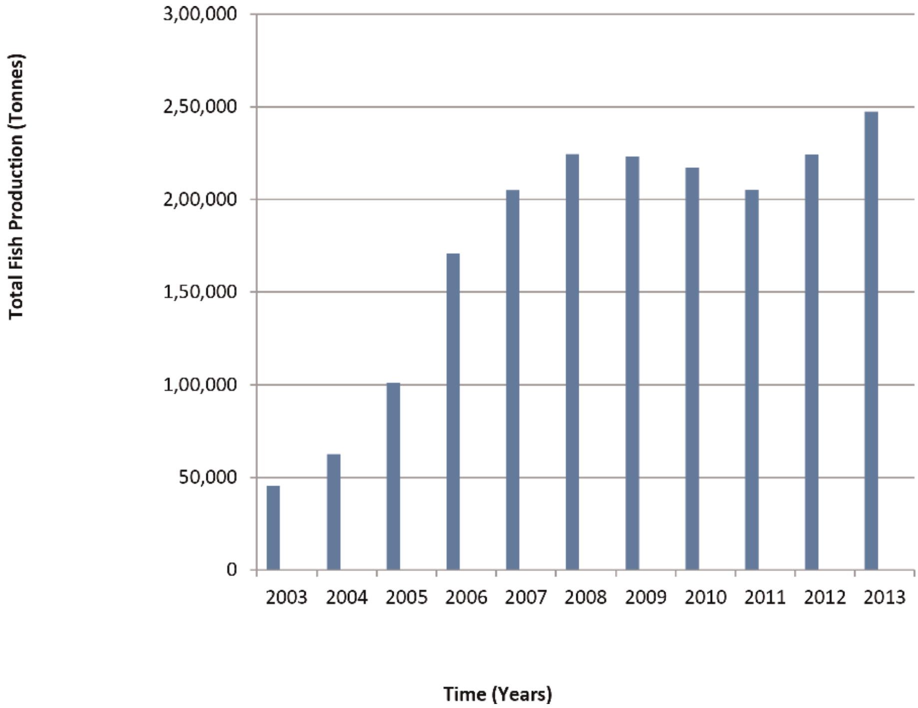

Figure 6.
Annual Farmed Channel catfish, Ictalurus punctatus *production in China, 2003 to 2010. Source: [61]. There was a rapid increase in production between 2005 to 2013, because of artificial propagation of seeds, and improvement in quality of seeds and strains used by farmers.*

because a large sample size from which breeding pairs of fish are drawn maintains high genetic variation that positively impacts seed quality. Due to these improvements, seed production for Channel catfish farmers reached 800,000,000 to 1 billion, and rose to 1.5 billion fry in 2013 [60], helping to spur a vibrant culture industry for the species.

3.5 The culture of African Catfish, *Clarias gariepinus* (Burchell, 1822)

While the different families of catfishes are widely distributed in natural aquatic ecosystems in Africa and are landed from fisheries by local fishermen, the African Catfish, *Clarias gariepinus* is the most commonly exploited species. There are 58 species of *Clarias*, of which 33 are in Africa, while 25 are distributed in Asia [21, 64]. In Africa, apart from *C. gariepinus*, *C. anguillaris* and *Heterobrachus longifilis* are also common in aquaculture, although these 2 are of restricted distribution [64], mainly in the Nile and West Africa. Other non-*Clarias* clariid catfish genera in Africa include *Bathyclarias* (in Lake Malawi) and *Gymnallabes typus* (in the lower Niger River and Cross River basin of Nigeria and Cameroon).

A systematic revision of 120 nominal species of *Clarias* by Teugels reduced these to only 32 valid species [65]. In a related study, Teugels [66] documented 74 species of African clariid catfishes within 12 genera. The description of two species of *Xenoclarias* as *Clarias eupogon* (Norman, 1928) and *Xenoclarias holobranchus* (Greenwood, 1958) was changed to *Xenoclarias eupogon* (Gee, 1975) using more samples, as a monotypic genus. Similarly, three clariid genera, *Clarias*, *Clariallabes,* and *Heterobranchus* occur

Phase	Time	Developments/Milestones
I	1984–1997	Artificial propagation techniques developed and successfully applied rapid spread of the culture of the species in China Use of ponds tried and perfected Optimization and production of quality feed for cultured fish Annual production of the species is less than 10,000 tones, mainly concentrated in Hubei and Guangdong Provinces Fish marketed live, with high prices due to low production
II	1998–2003	Onset of development of Channel catfish industry in China Use of cages to grow fish introduced Improved breeding techniques Developing nutritionally optimal feeds Adoption of best management practices Improved control of quality and marketing of the product Export of produce to the USA successfully accomplished: 326 tons in 2003 Annual production rose to 45,500 tones in 2003 Fish marketed mainly as fresh produce
III	2004–2009	Industrialization of Channel catfish production in China Wider spread of culture of Channel catfish in China Rapid expansion in annual yield of the species, reaching 224,500 t in 2008 Processing plants were built in many provinces: Hunan, Jiangsu, Shandong, Guangdong, Hubei, and Guangxi provinces among others. Increased export of frozen fish to the USA, reaching 17,000 tons in 2008.
IV	2010 to date	Stability in Chinese Channel catfish industry High cost of processing raw fish, with reduced yields and market demand A drop in exports, with only 6,568 tons of fish exported in 2011. A decline in annual total production, with 205,000 tons in 2011. Fluctuating prices of fish on domestic markets Increased market demand, pushing up prices for the product High demand has stimulated industrial recovery of the sector, with high annual yields of 247,399 tons in 2013.

Source: [62].

Table 4.
Historical milestones in the growth of the Channel catfish culture in China.

in Southern Africa [67], with *Clarias* having 6 species, while *Clariallabes* and *Heterobranchus* have a single species each [67]. In Southern Africa, a total of six *Clarias* species exist: *Clarias gariepinus*, C. *liocephalus*, *C. cavernicola*, *C. theodorae*, *C. stappersii*, and *C. ngamensis* [67]. On the other hand, six *Clarias* species inhabit Central Africa: *C. gariepinus*, *C. platycephalus*, *C. camerunensis*, *C. gabonensis*, *C. buthupogon*, and *C. angolensis* [68]. In lower Guinea, a total of 13 *Clarias* species are documented, including *C. gariepinus*, *C. anguillaris*, *C. agboyiensis*, *C. gabonensis*, *C. buthupogon*, *C. angolensis*, *C. pachynema*, *C. submarginatus*, *C. platycephalus*, *C. maclaroni*, *C. ajensis*, *C. longior,* and *C. camerunensis* [69]. Similarly, several *Clarias* species exist in Lake Victoria and its influent rivers in East Africa. Apart from *C. gariepinus*, several species including *C. liocephalus* (Boulenger 1898), *C. alluaudi* (Boulenger 1898), *C. theodorae* (Weber 1897), *C. werneri* (Boulenger 1906), and *Xenoclarias* also abound [70].

In Asia, 3 Asian clariid catfish species are used in aquaculture: *Clarias batrachus* (Linnaeus, 1758) in India [71], *C. macrocephalus* in South-East Asia [72], and *C. fuscus* (Lacep'de, 1803) in Taiwan and Hawaii [73]. *Clarias batrachus* also inhabits Southern Thailand in Malay Peninsula, Mekong, and Chaophraya River basins. *Clarias magur*

(Hamilton, 1822) is also present in the Malay Peninsula and India, while *C. nieuhofii* (Valenciennes, 1840) inhabits South East Asia, successfully tried as an aquaculture species [74].

While these descriptions may not be quite accurate and require urgent revisions, they illustrate the diversity of *Clarias*, which is often unrecognized and undescribed, yet extremely important as biodiversity for local economies, and food resources for local communities. Similarly, some of these clariid species could be useful aquaculture candidates, to help overcome some of the challenges of *C. gariepinus* as a farmed species. From the diversity of clariid catfishes, it is also clear that there are two groups: the large and small-sized *Clarias* species. The large *Clarias* is represented by *C. gariepinus*, while the small group includes most other species across different regions of Africa. *Clarias gariepinus* has been widely translocated, at least in 35 countries, mainly for culture [64]. These translocations often ignore existing laws that ban transfer of fish across drainage basins [75] and pose risk to existing native stocks or species, due to hybridization. Examples of hybridization between different *Clarias* species include *C. anguillaris*C. gariepinus* in Nigeria [76] and a hybrid of *C. macrocephalus* (better taste and culinary attributes) **C. gariepinus* (faster growth and higher resistance to diseases). This hybrid is the main fish stocked for culture, because of faster growth and higher resistance to diseases, with its product valued at over US $100 million in Thailand [77]. The introduction of *C. batrachus* and *C. macrocephalus* from Thailand to China, the Philippines, Taiwan, and Hong Kong led to the loss of endemic cyprinids from Lake Lanao, Mindanao due to predation and the displacement of native *C. macrocephalus* from Luzon [64]. Introgression of alleles from this hybrid into the genome of natural population of *C. macrocephalus* devalues the natural genetic resource of *C. macrocephalus* [78] and also causes decline in the natural stocks of *C. batrachus* (**Figure** 7) [79].

3.6 Challenges facing the culture of *Clarias gariepinus* in Africa

Although it is well recognized as a suitable fish species for aquaculture to meet food security, income generation, and livelihoods for local communities in Africa, annual cultured production of the species is low. FAO estimates that average production for farmed clariid catfishes was over.

300,000 tons, which was valued at nearly US$400 million in 2006 [77]. Total production of *C. gariepinus*, the main farmed clariid catfish species, averages 200,000 tons in 2014 [41] (**Figure 8**). Diverse efforts to increase average production in many countries of Africa have not yielded much fruit, despite ample supplies of water, land, labor, and technical know-how, as well as diverse populations of natural germplasm (**Figure** 7).

The main challenge stifling the culture of *C. gariepinus* is poor survival of fry or larvae [81]. This reduces the quantity of fry produced by farmers at hatcheries, negatively impacting seed availability and supply for commercial aquaculture ventures. In East Africa, *Clarias* fingerlings have taken on an even bigger role and importance, being used as live baits for catching Nile perch and *Lates niloticus* in the Lake Victoria long line fishery activities [82]. It is reported that a total of 3 million *Clarias* live baits are required daily by *L. niloticus* fishermen on Lake Victoria [83], a demand that creates enormous opportunities for *Clarias* farmers and hatchery operators to generate income and livelihoods. Despite this, the supply of fingerlings from hatcheries in East Africa is very low, forcing bait traders to exploit natural populations for fingerlings. Harvesting fingerlings from natural populations is not environmentally

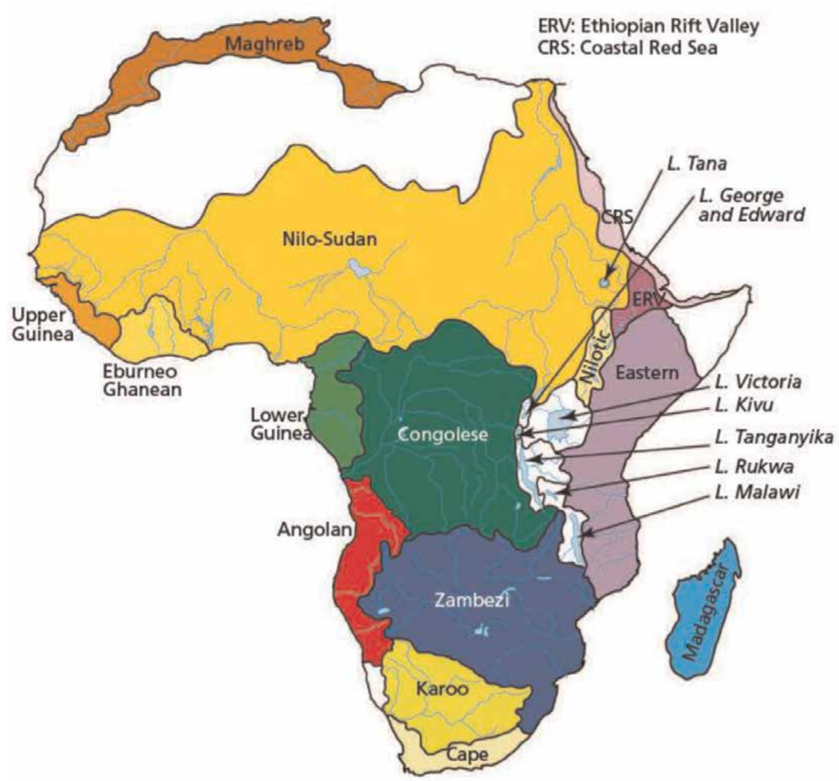

Figure 7.
The main ichthyological provinces of Africa (Adopted from [80]. Except the Maghreb, Karoo and Cape, Clarias gariepinus *is widely distributed in the rest of the Provinces on the continent.*

sustainable, with intermittent supply as availability is rain-dependent. This practice also exacerbates overexploitation of natural fish stocks, contrary to the need to conserve natural fisheries resources, especially for the Lake Victoria basin, whose endemic fish species already declined [84] due to many factors [82, 85]. Apart from endangering the health of fishermen who collect the fingerlings from the wild, this practice does not yield adequate numbers of fingerlings required quickly. It, therefore, involves a waste of time, and transport costs as fishermen have to venture into different parts of the lake, swamp, or river and spend many hours scouring different sites for catfish fingerlings. For sites within Lake Victoria, this task is especially complex and risky, due to dense mats of the water hyacinth, *Eichhornia crassipes* [86] that cover large areas of the lake.

In order to avoid these challenges and support the conservation of natural fisheries resources while simultaneously helping hatchery operators to generate income and livelihoods, artificial propagation of *Clarias* at hatcheries has been proposed and encouraged [85, 87–89]. However, despite the fact that artificial propagation of *Clarias* at hatcheries is well perfected, practiced, and documented, high mortality of *Clarias* fry at hatcheries still persists. In some hatcheries, mortality of more than 80% of hatchlings occurs, severely curtailing efforts of increasing seed availability for farmers. In some cases, the whole batch of incubated eggs fails to hatch, due to contamination with bacteria and fungi [90] in hatchery and egg incubation

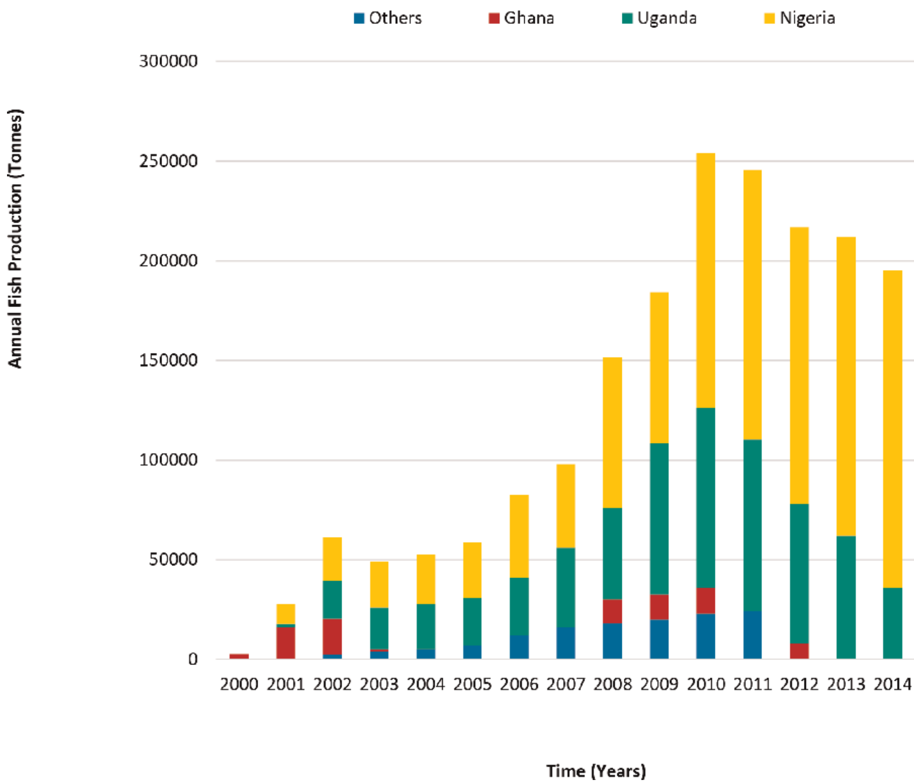

Figure 8.
Annual production of Farmed Clarias gariepinus *in Africa, 2000 to 2014. Most of the production is from 3 countries (Nigeria, Uganda, and Ghana), as the lead producers on the continent, with most countries producing insignificant amounts of catfish annually. Source: [41].*

facilities. Over the last several decades, research efforts have concentrated on addressing poor survival of *Clarias* fry or fingerlings at hatcheries. These research efforts included studies on improving quality of diets for larval catfish [81, 91–93], expanding the range of *Clarias* production systems [94], control of bacteria and fungi in egg incubation units [95], as well as fry nursery units [96], and improving the choice of source population of brood stock used at hatcheries for propagation [88, 89], as well as management of elite lines of brood stock for seed production [86]. In this regard, hatchery managers and farmers need to understand that the use of poor quality broodstock of mixed ancestry or suffering low genetic variability yields seeds of poor quality [89] because of outbreeding depression that compromises the fitness of offspring [97]. Despite this suite of studies aimed at addressing the challenge of poor survival of *Clarias* fry or fingerlings, the problem is far from being comprehensively addressed, in order to achieve sufficient seed availability and supply. There is need to understudy seed production and supply in the farmed catfish industry of Asia, especially the Vietnamese striped catfish, *P. hypophthalmus* and the Chinese Channel catfish, *I. punctatus*. We suggest that future efforts in addressing seed quality and quantity in *C. gariepinus* aquaculture will have to focus on using improved strains. Techniques of improvement, such as selective breeding and genomic selection will need to be employed, and research in these fields need to be strengthened.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 4

Advances in African Catfish (*Clarias Gariepinus*) Seed-Production Techniques in Kenya

Jonathan Munguti and Jacob Odeke Iteba

Abstract

African catfish is one of the aquaculture species in Kenya and a potential source of cheap protein for human nutrition. However, the major hindrance in the culture of catfish is seed production. The high-mortality rate of fry and fingerlings experienced by hatchery operators has limited the access and availability of catfish seeds. This had resulted in low-annual average production of farmed catfish. To address these challenges, different methods have been employed to enhance its seed production. One of such methods is induced spawning followed by larval rearing by the use of live feed like *Artemia*, thereafter, fry rearing with dry formulated feed, sorting by size, and stocking in nursery ponds. This chapter, therefore, will review the different mechanisms that had been adopted to enhance the seed production of catfish thus boosting its production in Kenya.

Keywords: African catfish, seed production, induced spawning, live feed, aquaculture

1. Introduction

The African catfish (*Clarias gariepinus*), also known as the mud catfish (**Figure 1**), is a good candidate species for culture to boost fish production for both domestic and global markets, which will improve human nutrition and food security in Africa [2]. The hardy nature of catfish in terms of its use of supplementary feeds, high tolerance to water stress, and high market acceptance makes it a suitable candidate for culture promotion in Africa as noted by [2].

In Kenya, the African catfish, from a biological perspective, is undoubtedly the most ideal aquaculture species [3]. It is widely distributed, hardy, and thrives in diverse environments, such as lakes, rivers, and fish farms [3]. Although, catfish is the most suitable species for aquaculture in Kenya; it contributes only 18% of total farmed fish production compared to Nile tilapia, which contributes 75% of total production [4] as illustrated in **Figure 2**. This shows that the high potential for catfish culture had not been fully exploited and indicates certain challenges that need to be addressed.

Figure 1.
*African catfish (*Clarias gariepinus*) (image source: [1]).*

Clarias gariepinus culture in Kenya is practiced as a small-scale rural activity [3]. The system is largely semi-intensive [5] and is done in polyculture with Nile tilapia to control its prolific breeding and increase production per unit pond area [6]. African catfish is mainly cultivated under mixed-sex semi-intensive systems in earthen and liner ponds. The ponds are fertilized with organic manure, and the fish are fed on supplemental feed [4].

As noted by [3], several opportunities are available in Kenya for the production of African catfish. These include high-nutritional value, availability of feeds, and ready market for the fingerlings among others. The demand for catfish fingerlings as

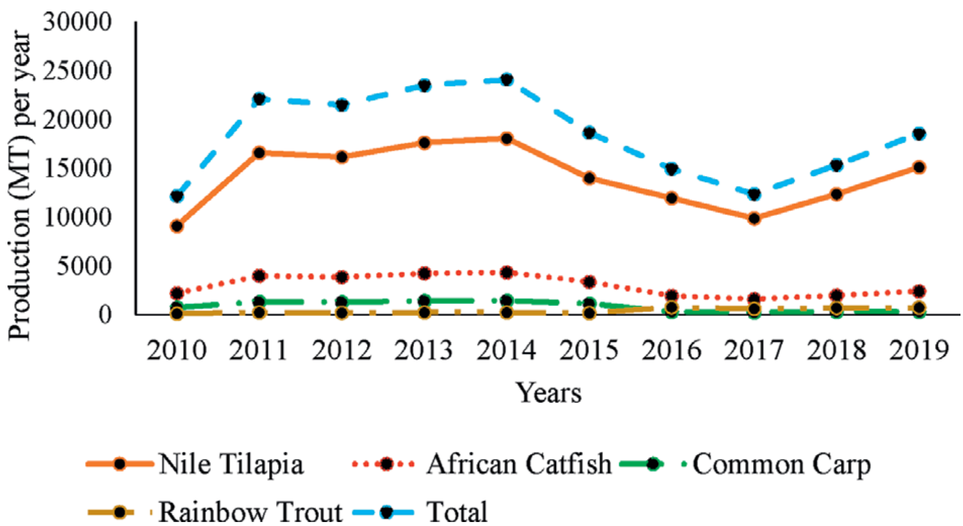

Figure 2.
Cultured fish species production (in MT) in Kenya from 2010 to 2019; source: [4].

bait fish for the Nile perch fishery in Lake Victoria has attracted a lot of interest from fish farmers [7]. In addition to the local demand, presently there is a huge demand for catfish fingerlings (both for stocking and bait fish) in the neighboring countries (Uganda and Tanzania) [8]. Therefore, farmers can also target the regional market in addition to producing for the local market,

Although catfish is suitable for aquaculture production in Kenya, there are several challenges to its quick adoption as an aquaculture candidate by farmers as noted by [3]. The scarcity of high-quality fingerlings in hatcheries remains a major impediment to the commercialization of catfish culture [2]. Fish farmers are often forced to resort to collecting fish seed from the wild or purchasing poor-quality seed from hatcheries [7]. Technologies for African Agricultural Transformation (TAAT) Aquaculture compact also noted that besides poor-quality fish seed, fish farmers are confronted with the following challenges in producing catfish. These include low skills of fish breeders in Best Management Practices (BMPs), high fry, and fingerling mortality associated with cannibalism, predation, poor feeding, and the lack of knowledge on fish-health management among hatcheries [2].

Therefore, this review explores the different techniques for breeding and seed production of African catfish that have been developed and can easily be adopted by fish farmers in Kenya to boost the culture and production of catfish in the country.

2. Review methodology

The scoping review methodology [9] and systematic reviews approach were adopted in the present study to generate a comprehensive literature review on the advances that have been made in seed production of African catfish in Kenya. The literature review is focused on artificial propagation, use of living, and formulated feeds for feeding and catfish grading measures in the hatchery. To meet the set objectives, a wide range of keywords (closely related to African catfish production) were searched in online database tools and scientific domains of Science Direct, Research Gate, Google Scholar, and Web of Science. To further narrow and refine search, Boolean operators ("OR," "AND," and "NOT") were appropriately used in the various databases and search engines. The collected literature database was organized in excepts, copies, and notes according to topics. The current paper is a result of research publications that met the inclusion criteria for the review paper.

3. Advances in African catfish (*Clarias gariepinus*) seed-production techniques

3.1 Artificial propagation

According to [10], domestication of *C. gariepinus* can be traced to 1950's and the success in African catfish farming can be linked to the successful development of artificial-propagation protocols in the 1980's. African catfish breeds naturally during the rainy season in flooded rivers, inundated paddy fields, and earthen ponds [11]. The seed collection of this species from the wild is unreliable, time-consuming, and uneconomical for large-scale culture of this fish [11]. To overcome these problems, artificial propagation of catfish through induced spawning techniques at hatcheries is thought to be the only alternative to reduce exploitation pressure on natural populations of these indigenous fish species of the Lake Victoria basin [7]. Furthermore, this practice generates income and livelihood opportunities for farmers [12] as well as guarantees quality and adequate numbers of seeds [13]. As noted by [7] identification and isolation of high-quality catfish brood stock for use at hatcheries in artificial propagation in combination with improved husbandry for resultant fry could be a good measure to increase the availability of catfish seed and enhance its commercialization in Kenya.

As noted by [11], the developments of catfish artificial-propagation techniques have allowed farmers to profitably breed and culture this species that does not naturally reproduce under captive conditions. Over the last few decades, hormonal administration techniques have been used to induce final oocyte maturation and spawning that has allowed reproduction in controlled conditions [14]. Moreover, as reported by [15] induced breeding techniques have significantly contributed a lot to the expansion and diversification of the aquaculture industry. The *gonadotropin-releasing hormone (*GnRHa) and domperidone are the most popular compounds for induction of ovulation and spermiation in various fish species [13]. The introduction of GnRH analogs has been proven to be efficient in inducing maturation and spawning in many fish species, including catfishes [16]. Successful induced spawning depends upon the dosage of hormone injection, the stage of maturity of the fishes, and environmental condition, such as temperature, water currents, and rain as reported by [13]. As reported by [17], various commercially available synthetic ovulating agents in a ready-made form that contained GnRHa and dopamine antagonists, such as ovatide and ovaprim, are becoming easily accessible nowadays and found to be efficient and successful spawning agents in different fish species as noted by [18]. Successful spawning through a synthetic analog of GnRH has been reported in several air-breathing fish species including African catfish [13].

3.2 Use of live feeds and formulated feed diets

One of the suitability of African catfish for aquaculture arises from its acceptance of both artificial and non-specialized feeds, and the larval period is considered critical in their life history as noted by [19]. Successful larval rearing depends mainly on the availability of suitable diets that are readily consumed, efficiently digested, and that provide the required nutrients to support good growth and health [20]. Fish larvae often depend on live food, and in general, fish species like catfish have been reared successfully in aquaculture at the larvae period with fully digestive system at starting time of feeding. As noted by [21], live foods, besides their nutritional value, are highly digestible, easily detectable, and easy to capture by the fish larvae due to their swimming movements in the water column.

As reported by [21], the most widely used live food in catfish larvae culture is the brine shrimp (*Artemia salina)*. It is popular for mass production because of its viability over longer period of time and its ease of transport, due to its ability to form cysts. *Artemia* is also very nutritious to the larvae (>56% crude protein, 17% lipid and 3% carbohydrate) as noted by [22]. Zooplanktons, such as *Daphnia*, *Moina,* and rotifers are the other live food currently being used in Africa and other parts of the world. Besides being known to improve the flavor, color, and texture of fish that feed on them, they are valuable sources of crude protein, amino acids, lipids, fatty acids, minerals, enzymes, and carotene [23].

In Kenya, hatcheries have recently adopted the use of biofloc technology (BFT) to enhance the provision of live feed to the fish larvae. The BFT uses the principle of nutrient cycling through complex bio-pathways to produce natural food for fish [24]. The working machines are the bacterial flocs that convert pond bio-wastes into edible nutrients for the cultured animals, thus it reduces feed cost by about 30% and ensures higher profitability as reported by [24]. BFT is useful for mass production of live food resources, which are indispensable for successful larviculture in hatcheries since they constitute organic particles, food debris, chemoautotrophic, and heterotrophic bacteria, which are nutritious and ultimately result in improved growth performances of fish [25]. As noted in a study by [26], the biofloc increased protein utilization efficiency, lowered the Food Conversion Ratio (FCR), and enhanced the fish-growth rate of Nile tilapia fish fry. These can also be applicable in the culture of catfish larvae in the hatcheries. For instance, [27] in their study reported that, though African catfish broodstocks maintained in the biofloc systems resulted in comparable fecundity and eggs quality to those broodstocks in the control systems, it significantly improved the larval quality and embryonic development rate. Moreover, culturing the larvae in biofloc systems improved their survival and final body length [27]. Nevertheless, absolute use of live foods as the diet for catfish larval rearing can be slightly alleviated by weaning with dry formulated fish feeds.

The use of dry feeds for catfish larval and fry rearing should satisfy the nutritional requirements of the species and should be readily accepted. As reported by [20], a fundamental aquaculture species considers dietary protein essential since adequate dietary protein significantly influences growth, fish survival, and feed cost. The main source of protein in aqua feeds remains to be fishmeal, as it contains a profile of high-quality protein with balanced amino acid, and the high demand for it, along with supply fluctuation made fishmeal expensive [28]. As a result, relentless efforts have been made to substitute a fish meal with other cheaper sources of protein, such as the use of Black Soldier Fly (BSF) [29]. In Kenya as reported by [30], several protein sources of both animal and plant origins (blood meal, soybean, wheat bran, maize, and other formulated feeds) are being tested as fishmeal replacements and are in use by different aquaculture farms in the culture of catfish.

3.3 Grading technique

As reported by [31], cannibalism is another fundamental issue affecting the culture of catfish that can be addressed by adopting grading techniques. The *C. gariepinus* exhibits allometric growth patterns where larger fish have higher growth potentials than small-sized individuals [32]. Heterogeneous size distributions often lead to social dominance, which in turn results in aggressive behavior and cannibalistic responses [31]. This in turn increases their susceptibility to diseases and weakens the fishes making them more liable to cannibalism or death [33]. Therefore, to enhance profitability from catfish aquaculture production, strategies that are designed to reduce cannibalism should be explored.

As reported by [34], size grading practices is a common procedure used during intensive fish rearing to reduce size variations and have resulted in differences in growth, production, feed conversion, and foodfish size distribution. Moreover, size grading practices have been advocated method to control large differences in the size of fish during the nursery period of many piscivorous fish species as noted by [31]. Furthermore, [35] notes that sorting enhances feeding since ration sizes and feed granulation can be customized to the fish size. In a study to determine the effects of size grading on the growth performance and cannibalism of *C. gariepinus* [36] noted that, the growth performance of *C. gariepinus* was affected by the frequency of fish grading whereby the growth rate was improved by 15% and 12% in the grading every two weeks and grading every four weeks over the control group. The study also established that mortality owing to cannibalism was affected by grading frequency where the highest cannibalism mortality occurred in *C. gariepinus* where there was no grading (42.4%) followed by grading every four weeks (18.9%) and intermediate at grading frequency every two weeks (7.5%). Therefore, hatcheries' operators in Kenya have adopted grading techniques to effectively reduce intracohort cannibalism rates in larviculture of *C. gariepinus* as noted by [31] to enhance its seed production.

3.4 Management strategies by the government

The government has established a system of hatchery authentication to ascertain the quality of broodstock, the seed produced, and the availability of necessary facilities and skills in order to maintain the quality of catfish seed [37]. The authentication of hatcheries is being undertaken by the State Department for Fisheries and the Blue Economy in collaboration with Kenya Marine and Fisheries Research Institute (KMFRI) [37]. Note that the steps followed by the system are not very far from the approach that has been followed by other major aquaculture-producing countries like China. Similarities are observed in how the government responded to seed-quality problems by encouraging investment in hatcheries by the private sector, whereby hatcheries in Kenya are mostly owned by private fish farmers (82%) and only a few (18%) are owned by the government institutions [37]; instituting seed-quality control policy measures to improve seed-quality management; including the establishment of fish-seed certification methods and standards, which were developed by KMFRI in collaboration with the Kenya Bureau of Standards (KEBS) and State Department for Fisheries and the Blue Economy; and encouraging and supporting the production and distribution of quality seed [38].

These management strategies were aimed at maintaining the quality of brood fish and seed because poor management had led to deterioration in the quality of broodstock and seed over time as noted by [37]. Therefore, a training program for hatchery managers was initiated at the National Aquaculture Research Development and Training Center (NARDTC), Sagana in 2009 where all hatchery managers were trained on the necessary skills in hatchery operations. Moreover, [37] reports that, to enable fish farmers purchasing catfish seed from government-endorsed hatcheries trust the product, a seed certification and accreditation system was developed [37]. Also notes that, in Kenya, one of the requirements for a hatchery is that the manager should possess a diploma or degree certificate in aquaculture. This is an effort by the government to make hatchery management more professionalized and able to adopt technologies, innovations, and management practices (TIMPS) leading to higher production of quality catfish seed.

4. Conclusion

The potential of *C. gariepinus* to make a significant contribution to Kenyan fish production is very real. The demand for seed has increased steadily and several farmers have engaged in the culture of catfish. The techniques, such as artificial propagation, the use of live and dry formulated feeds, and grading have been developed for

African catfish production and can be easily adopted by fish farmers to enhance the growth and survival of larvae and fingerlings. Certainly, in the next few years, catfish farming will make a significant contribution to food security, foreign exchange generation, and the creation of employment opportunities, which are key to economic growth and poverty alleviation in Kenya.

Conflict of interest

The author(s) declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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Section 4

New Ideas for Catfish

Chapter 5

Catfish as an Ecotoxicological Model for Assessment of Nanoparticle Toxicity Profiling

Muhammed Atamanalp, Arzu Ucar and Gonca Alak

Abstract

The developing technological infrastructure has accelerated the evolution of nanoscience and encouraged the use of nanomaterials in very large areas. However, environmental liberation of nanomaterials can pose potential risks. Although different toxicity screening methodologies have been successfully used to assess the potential risks of these substances, little is known about their environmental impact. Fish are the most visible members of the aquatic ecosystem, vulnerable to toxicants. Although the ecotoxicology of fish and nanoparticles are complex, this review evaluates approaches to using catfish as a bio-indicator for the effects of nanoparticles on fish.

Keywords: nanoparticle, toxicity, catfish, fish metabolism

1. Introduction

Nanotechnology is the branch of science that deals with the characterization, production, management, and manufacturing use of nanostructured materials (NM) for different sectors/applications. The NMs produced with this technology generally have an intermediate size between 1–100 nm and can be converted to desired lengths. This process (size reduction) increases the surface-to-volume ratio (thus surface energy), biological efficiency, and adsorption capacity of the obtained product. In addition, its chemical/physical (such as diffusion, strength, color, solubility, and quantum effects), optical, magnetic, and thermodynamic properties are significantly improved [1, 2]. Innovative nanostructured materials and nano-composites equipped with these superior properties have a wider application area (environment, agriculture, medicine, food, etc.) than their macro counterparts and are one of the fastest developing research areas, especially in the food industry. Due to nanotechnological advances, NMs are estimated to be components of more than 2,000 commercial products, and this number is expected to increase significantly in the coming years. However, during the production, carrying, use, and exterminating of these products, NMs are inevitably released into the environment, especially in the waters as the final destination [2]. Keller et al. [3] reported that 0.4–7% of these products eventually enter the aquatic environment, assuming that there is approximately 309,000 tons of NM production globally. Contaminations in aquatic environments, which are the final destination of all pollutants, can occur through industrial wastewater, domestic sewage, and coastal recreational activities (e.g. swimming and diving) [4–6]. Especially with the increasing environmental awareness in recent years, the NMs' risk to the aquatic ecosystem has become an increasing concern [7].

Although at present, the development of NM-related adverse outcome pathways has mainly focused on human toxicity, an additional nanosafety component to consider in risk assessment of this class of material is eco-toxicity [8]. The unique physicochemical properties of NMs enable them to interact with biomolecules and change essential biochemical pathways. However, the abundance of NMs in water bodies can affect water quality and threaten the survival of aquatic species also they can be accumulated through the food chains [9]. The reaching of nanoparticles to aquatic environments and possible action mechanisms had been figured out by Bundschuh et al. [10] and shown in **Figure 1**.

As in all vertebrates, fish's general physiological response to threatening situations is called "stress." A short time after the perception of a stressor, the stress response begins in the organism. The physiological response (Stress response) triggered by stressors is a set of adjustments that can maintain internal homeostasis to a certain level and sustain vitality [11]. Mildly stressful situations may have positive effects (eustress), while higher intensities may have negative consequences. The stress response is initiated and controlled by two hormonal systems that lead to the production of corticosteroids (mainly cortisol) and catecholamines (such as adrenaline and noradrenaline). Together, these regulate secondary stress response factors that alter the distribution of essential resources such as energy

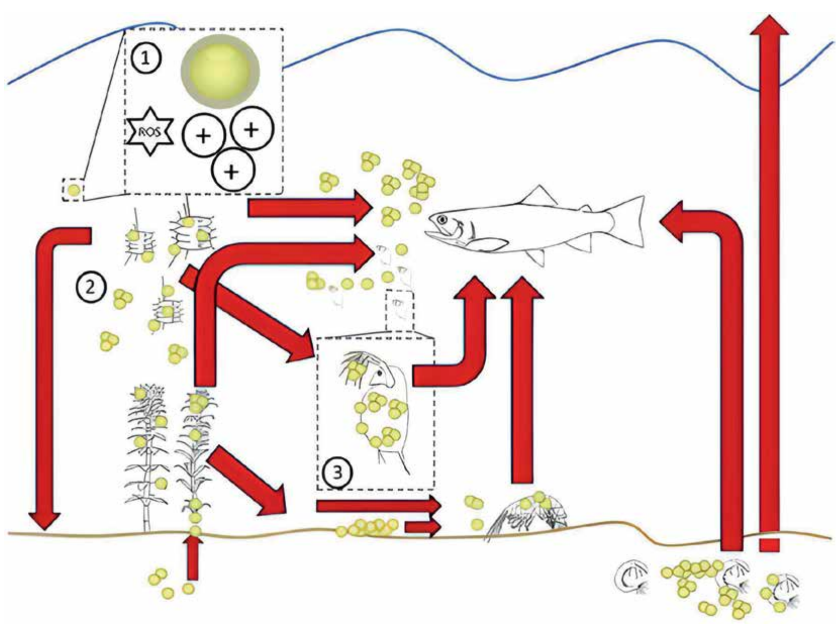

Figure 1.
Exposure and potential pathways to toxicity of nanoparticles in aquatic environments (red), (1) toxic properties, (2) biomagnification potential induced by adsorption leading to assimilation, and (3) aquatic absorption onto organisms and fish, aquatic plants, various invertebrates, and uptake by algae and other organisms. ROS, reactive oxygen types Bundschuh et al. [10].

and oxygen to tissues and organs and also compromise hydro-mineral imbalance and the immune system. It is known that long-term exposure to stress negatively affects basic life functions (growth, development, disease resistance, energy balance, behavior, and reproduction) [12].

Stress response of organisms sent to a stimulus (stressor) that is perceived as dangerous helps maintain homeostasis [13]. These reactions are grouped as primary, secondary, and tertiary phases (**Figure 2**) [14]. The primary phase represents a neuroendocrine response. Cortisol is released from interrenal cells and catecholamines are released from chromaffin. High levels of these hormones trigger a secondary response. The secondary phase presents as hyperglycemia, vasodilation of the arteries in the gill filaments, increased heart rate, and decreased immunity [15]. The first two stages are considered adaptive and maintain homeostasis by enabling the fish to adapt to stress factors. On the other hand, in the tertiary phase, it includes systemic changes in which organisms are not able to adapt to stress factors and this leads to negative effects on the situation. Its effects on behavior, health, growth, and reproduction, including swimming performances, emerge in this context [14].

Behavioral alterations are the other most widely used biomarkers at the individual level. Because changes in behavior are the integration of many cellular processes necessary for the viability of the organism, population, and community. Therefore, the observation of behavioral changes provides a unique toxicological perspective connecting both the ecological and biochemical consequences of environmental pollution [16]. Behavioral changes of living things in aquatic ecosystems are accepted as the most sensitive indicators of possible toxic effects. Social interactions such as changes in feeding activities, swimming behaviors, competition, hunting, reproduction, and aggression of fish exposed to different insecticides have been determined [17].

Since behavior acts as a link between physiological and ecological processes, it is an ideal parameter for studying environmental pollutant effects. Fish are the prominent aquatic indicators in this parameter due to the ease of monitoring their behavior. However, a very good knowledge of their physiology is an advantage for ecological monitoring of contamination [18]. Individual fish's behavioral performance follows certain physiological sequences triggered by external stimuli acting through neural networks [19].

The metabolism of fish is closely related to its behavioral state and is affected by many varied physiologic functions. Metabolic dysfunction caused by aquatic pollutants can result from disruption at many different physiological levels [20–24]. Metabolic degradation of the whole organism had been expressed in a number of different ways, most commonly indicated by varying resting metabolic rates (ventilation

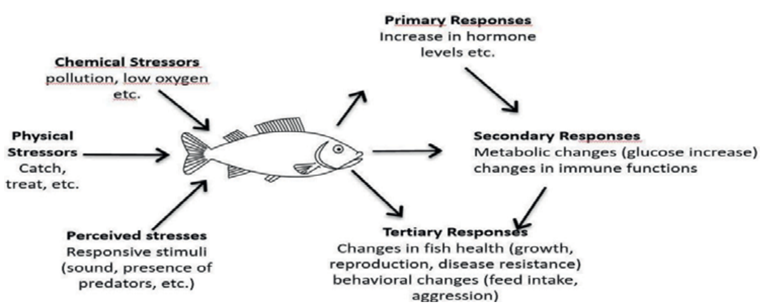

Figure 2.
Stress response phases [14].

rate or oxygen consumption) or reduced swimming performance (critical swimming rate, U_{crit}) [25–28].

Catfish are gaining increasing attention as bioindicators for monitoring NP-fish interaction. In this section, eco-toxicological concerns of the NMs/NPs and their effects on the ecosystem are presented, with special emphasis on catfish health. For this purpose, we wanted to prepare a data pool for future research by integrating the data and information found in scientific publications with catfish as a bio-indicator, emphasizing where targeted analyzes are needed among different potential pathways/mechanisms of toxic effect in ecotoxicological findings for NMs. It is aimed to gather NM effect studies on catfish, which has an important place in aquaculture. The results of different researchers on different catfish species are summarized in **Table 1**. In this way, the NMs' biological effects on this fish species, including negative effects, aim to provide a complete picture of the situation, which will provide a better understanding of the mechanisms of the biological effects of NMs and assist in the sustainable development of nanotechnology, which is increasingly used.

Although it has clarified the potential hazards of NPs on aquatic organisms and their environmental effects, the knowledge about the mechanisms of cellular toxicity caused by NP/NM due to overproduction of reactive oxygen species (ROS) is not very extensive. In order to overcome this lack of information, studies on different fish species are continuing intensively, thanks to these studies, the effects of NPs on bioaccumulation, oxidative stress, and subsequent activation of the antioxidant defense system have been revealed [44–46]. NPs are taken up by fish, the most important component of Aquatic ecosystems, and transported to various tissues – organs via blood [47]. In vitro and in vivo studies on NM in fish had shown that NPs can induce oxidative stress by triggering the ROS formation. Stimulation of oxidative stress causes extensive damage to biomolecules such as DNA, proteins, lipids and cellular membranes [48]. Oxidative stress in the cellular system is produced as a result of an imbalance between oxidative and reducing processes and is typically induced when the physiological antioxidant defense system is unable to counteract the increased level of ROS [35]. Like other vertebrates, teleosts attempt to convert ROS into harmless metabolites to maintain and restore normal cellular homeostasis and functions. For this, a wide variety of enzymatic and non-enzymatic antioxidant defense systems have been developed [49, 50]. These include low molecular weight antioxidants such as glutathione (GSH) and high molecular weight defenses with enzymes such as superoxide dismutase (SOD), catalase (CAT) as the first line of defense, and enzymes involved in glutathione metabolisms such as glutathione peroxidase (GPx), glutathione reductase (GR) and glutathione-S-transferase (GST), and glutathione reductase (GR) [51]. However, some fish species may be at the forefront due to their advantages in monitoring NP-induced oxidative stress processes in different cellular systems of teleost fish. One of these species, catfish (Siluriformes) is one of the important species worldwide in aquaculture, with an annual production of approximately 6 million tons in 2018 [52]. They live mainly in freshwater and are widely distributed in the tropics of Africa, South America, and Asia. Consisting of more than 3000 species and an estimated 1750 undescribed species, the Siluriformes is one of the largest orders of the Teleostei [53, 54]. Catfish are of paramount importance not only for commercial but also for recreational fishing. Their high domestication potential and adaptability to intensive breeding conditions, high fecundity, and nocturnal foraging habits characteristics are attractive. The ability to live in turbid waters, high resistance to diseases, successful tolerant to

Nanomaterial	Live material	Obtained alterations/Effects	References
Silica nanoparticles (SiNPs)	African catfish, *Clarias gariepinus*	8-OHdG and MDA elevation, reduction in AChE, effects on GPX, SOD	Rahman et al. [29]
Copper ferrite nanoparticles ($CuFe_2O_4$NPs)	Channel catfish ovary cells	Significant increase in LPO, GST, and GPX was observed in CCO cells exposed to $CuFe_2O_4$NPs after 24 h of treatment. However, the CAT and GSH levels in CCO cells exposed to $CuFe_2O_4$NPs decreased significantly after 24 h. The CCO cells exposed to 10 μg/mL concentration of $CuFe_2O_4$NPs for 24 h showed remarkable changes in their morphology.	Srikanth and Nutalapati [30]
Tucumã nanocapsules	Silver catfish, *Rhamdia quelen*	The most abundant carotenoid in tucumã oil was *all-trans*-beta-carotene. Nanocapsules are good carriers for tucumã oil. Tucumã oil nanocapsules do not have a toxicity effect in catfish.	Nascimento et al. [31]
Nano-sized zinc oxide (nano-ZnO)	Yellow catfish *Pelteobagrus fulvidraco*	Increased intestinal Zn contents. The *zip6* and *zip10* mRNA expression levels were higher in the H-Zn group than those in the control (0 mg/kg nano-ZnO). Epsl5, *dynamin1, dynamin2, caveolin1*, and *caveolin2* mRNA expression levels tended to reduce with dietary nano-ZnO addition. Dietary nano-ZnO increased TG content and G6PD activities.	Chen et al. [32]
Amme-functionalized single-carbon nanotube (NH_2 f-SWCNT)	Channel Catfish (*Ictalurus punctatus*)	Decrease of CAT and SOD activity, an increase in MDA and LDH. Real-time PCR assay showed inflammatory response with a dose-dependent increase of tumor necrosis factor alpha (TNFα) and transient increase of IL-1β in the liver.	Gao et al. [33]
Chitosan nanoparticles (CSNPs)	African catfish, *Clarias gariepinus*	FSH and 17-β estradiol (E2) were significantly decreased in female catfish. While testosterone and luteinizing hormone (LH) were increased after exposure to BPA. Significant reduction in CAT, GSH-px, TAC, GSH, and GST levels.	Hamed et al. [34]
ZnO NPs	Magur catfish *C. magur*	Resulted in oxidative stress as evidenced by an initial sharp rise of intracellular concentrations of H_2O_2 and malondialdehyde (MDA) but decreased gradually at later stages. GSH level increased gradually in all the tissues after a mitial decrease.	Koner et al. [35]
Gold nanoparticles AuNPs	African catfish *C. gariepinus*	The embryo's hatching rate and larvae's survival rate decreased. Embryonic malformations such as pericardial edema, yolk sac edema, neck, and head defects	Marimuthu et al. [36]
Nano-Zn	Intestinal epithelial cells of yellow catfish	Increased the contents of TG and free fatty acids (FFA), the activities of G6PD, 6GPD, ME, and FAS.	Ling et al. [37]

Nanomaterial	Live material	Obtained alterations/Effects	References
Single-walled carbon nanotube (COOH-SWCNT) chitosan (CS) hybrid (COOH-SWCNT-CS).	Magur catfish *C. magur*	DNA damage was observed in fish injected with nanotubes alone than chitosan hybrid groups. Histological observations revealed severe liver cell damage at higher concentrations of COOH-SWCNT whereas, in COOH-SWCNT-CS, no such damage was observed. However, kidney tissue remained unaffected in all groups.	Wisdom et al. [38]
Titanium dioxide nanoparticles (TiO_2 NPs)	African catfish, *C.gariepinus*	Neurotoxicity, changes of antioxidant enzymes, and retardation of food uptake.	Matouke and Mustapha [39]
Titanium dioxide nanoparticles ($FeTiO_2$ NPs)/ Nickel ferrite nanoparticle ($NiFe_2O_4$ NPs)	Catfish	Abnormal behaviors such as loss of equilibrium, pigmentation, and lying down at the bottom of the aquaria were observed.	Rao et al. [40]
Chitosan nanoparticles (BD+CHN)	African catfish (*C. gariepinus*)	Significantly improved water quality, daily weight gain, feed utilization, and survival as well as body composition	Udo et al. [41]
Copper (Cu) as nanoparticle (Cu-NPs)	Catfish, *C.batrachus*	Effects on expression levels of several steroidogenic enzymes (*3β-hsd, cyp11a1, 11β-hsd2, 11β-h*, and *star*) and transcription factor genes (*wt1, ad4bp/sf-1, dmrt1, sox9a*, and *gata4*)	Murugananthkumar et al. [42]
Nano-ZnO, TiO_2, CuO, and CO_3O_4	Primary culture of channel catfish hepatocytes	Significant toxicity in both HepG2 cells and catfish primary hepatocytes. The results demonstrate that HepG2 cells are more sensitive than catfish primary hepatocytes to the toxicity of metal oxide NPs.	Wang et al. [43]

8-OHdG: 8-hydroxy-2-deoxyguanosine, MDA: Malondialdehyde, AChE: Acetylcholine esterase, GPX: Glutathione peroxidase, SOD: Superoxide dismutase, CAT: Catalase, LDH: Lactin dehydrogenase, TNFα: Tumor necrosis factor alpha, H_2O_2: Hydrogen peroxide, FFA: Free fatty acids, TAC: Total antioxidant capacity, LH: Luteinizing hormone

Table 1.
Obtained alteration/effects of NM/MPs on catfish reported by different researchers.

low dissolved oxygen levels, efficient feed conversion, and ease of fillet processing, make them important in aquaculture [52, 55].

As in other aquatic organisms, the effects of NPs on catfish had attracted the attention of researchers and had been the subject of many studies. According to their origin, NPs caused different sizes of changes/negatives in catfish. As can be seen from **Table 1**, the neurotoxicity effect [39] is one of the effects that should be considered the most. In addition, the negative effects on hormonal balance [34] are undesirable in terms of breeding catfish with its economic importance. Similarly, behavioral changes [40] will be effective upon reproduction. Studies on enzymes that show general health and well-being in fish [33, 35] also show how effective NPs are for catfish.

2. Conclusion

Nanoparticles, which have an important place in developing technology, cause problems in aquatic ecosystems, as well as in other fish species. In this book chapter, which brings together studies by different researchers on different catfish in the Siluriformes group, it draws attention to taking the necessary precautions to prevent this economically important species from being exposed to NPs.

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Catfish, one of the largest groups of freshwater fishes, are not only important ornamentals and sport fishing and research animals but also an important source of protein. This book compiles current research on this species, providing information on its production methods and uses.

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