Ethical Seafood Research

A Review of Kenyan Aquaculture: Challenges to Welfare and Sustainability in the Sector

Abstract

Kenya's aquaculture sector is one of the most productive in Africa, and there are considerable national efforts to grow and intensify this sector. Despite the drive to develop aquaculture in Kenya, the sector continues to encounter barriers to sustainability and fish welfare. This review documents the state of aquaculture in Kenya, from its considerable growth in recent years to the types of housing systems adopted and their challenges in regards to welfare and sustainability. Given that the aquaculture sector in Kenya has been hallmarked for growth, with considerable economic and strategic support in place to foster this, these issues must be recognised and addressed.

The rise in Kenyan aquaculture

Kenya possesses abundant freshwater resources, including lakes, rivers, dams, reservoirs, streams and wetlands, suitable for various aquaculture development forms (Munguti et al., 2017). Consequently, aquaculture is being promoted as a solution to address malnutrition, food insecurity and poverty in Kenya (Ogello and Munguti, 2016). Since its introduction by the Colonial Government in the 1920s, Kenya's aquaculture sector has grown from a small player to a key component of the country's food system and is now among the top 10 producers of farmed fish in Africa (Hinrichsen et al., 2022).

The practice began with static water pond culture of different species of tilapia and then grew to include other species, such as common carp (*Cyprinus carpio*) and African catfish (*Clarias gariepinus*) (Aloo et al., 2017; OECD/FAO, 2016). In the financial year 2009/2010, the Ministry of Fisheries Development launched the Fish Farming Enterprise Productivity Program (FFEPP) as an Economic Stimulus Programme (a large-scale subsidy programme aimed at revitalising the economy) (Munguti et al., 2017; Orina et al., 2014). Aquaculture was identified by the Kenyan government as a key sector within the agricultural industry in Kenya (Munguti et al., 2017), and the FFEPP was focused on expanding and intensifying aquaculture in Kenya (Orina et al., 2014). This led to an immediate demand for certified tilapia and catfish fingerlings, as well as formulated fish feeds (Farmers Review Africa, 2023).

Furthermore, Kenya's expanding population, rising incomes, lifestyle changes, and consumer preferences drive demand for fish products that can only be met through aquaculture or imports (Obiero et al., 2019). To meet the projected demand for fish in Kenya's growing population, domestic fish production in Kenya would have to reach 150,000 tonnes by 2030 to maintain the already low per capita fish consumption (Obiero et al., 2019).

Kenya currently has 1.4 million hectares of aquaculture area, which has the potential to produce 14 million tons of fish and other animals, valuing over Ksh 50 billion each year (approximately US$ 356 billion) (Odende et al., 2022). Kenya's aquaculture sector is characterised mainly by pond systems that are small-scale and scattered (e.g., fewer than five ponds), which function primarily for sustenance (Alando, 2022; Odende et al., 2022). In

2019, there were approximately 146,000 fish ponds and 6,000 cages in Kenya, and the ponds were thought to produce around 24,000 MT (Odende et al., 2022). The fish ponds primarily consist of earthen ponds measuring 300 m^2, while the cages are typically floating cages with dimensions of 4 m in length, 5 m in width and 4 m in height (Kyule-Muendo et al., 2022).

Aquaculture species in Kenya

The Kenyan aquaculture industry primarily focuses on farming three main inland species: Nile tilapia (*Oreochromis niloticus*), Rainbow trout (*Oncorhynus mykiss*), and North African catfish (*Clarias gariepinus*) (FAO, 2023). Tilapines are the most commonly farmed fish in Kenya, representing around 90% of production, and polyculture with the North African catfish is commonly practised to reduce breeding in tilapines (FAO, 2023). African catfish have a market both within Kenya, and from neighbouring countries (Uganda and Tanzania), and catfish fingerlings are required for both stocking and bait fish (Munguti et al., 2022a). Rainbow trout farming is primarily restricted to high-altitude areas such as the Mount Kenya region, where there are free-flowing rivers (Munguti et al., 2017). The largemouth bass (*Micropterus salmoides*) and the common carp *(Cyprinus carpio)* have also been introduced for aquaculture purposes, although carp are not favoured in markets (FAO, 2023). According to an article from 2014, the National Aquaculture Research Development and Training Centre in Sagana were cultivating native species *Labeo victorianus* and *Labeo cylindricus* for aquaculture (Munguti et al., 2014a), but nothing more recent has been reported.

Geographical spread of aquaculture in Kenya

Different counties in Kenya have varying levels of aquaculture-related activities. Most aquaculture production occurs in the Western and Central regions (Nyonje et al., 2018). In particular, counties like Kakamega, Bungoana, Kisii, Meru, Nyeri, Kisumu and Muranga have a higher concentration of ponds and aquaculture operations, and others, such as Kitui, Lamu and Elgeyo Marakwet, have very few (Munguti et al., 2017; Opiyo et al., 2018). According to the International Fund for Agricultural Development, most parts of Kenya are suited to aquaculture yet are largely unused due to limited interventions and land and water scarcity (IFAD, 2017). In particular, some regions, such as coastal regions, have difficulties with the water retention capacity of ponds, which, along with poor husbandry practices and infrastructure, has led to a decline in aquaculture production (Opiyo et al., 2018).

Aquaculture systems in Kenya

Kenyan aquaculture consists of extensive, semi-intensive and intensive systems. Semi-intensive systems contribute over 70% of Kenya's aquaculture production and are typically for polycultures composed of various species combinations (FAO, 2023). Intensive aquaculture primarily involves rainbow trout in raceway systems, contributing around 20% of production (FAO, 2023). Although the intensive culture of Nile tilapia in cages has grown in the last ten years, and hyper-intensive tilapia culture is forecasted to contribute as much as 90% of all farmed fish in Kenya by both volume and value (FAO, 2023; Opiyo et al., 2018). Extensive cage cultures tend to be used for rainbow trout, African catfish, and common carp (FAO, 2023; Opiyo et al., 2018). Extensive production is poorly documented, but it is believed to contribute around 10% of total production in Kenya (FAO, 2023).

Extensive systems

Although extensive systems have low initial costs and use low-level technology, farmers using these systems have limited control over the production process and relatively low production efficiency. In particular, the species, stocking densities and productivity levels are highly dependent on the environment's holding capacity and are typically characterised by low stocking densities and yields. For instance, the FAO suggests that extensive production in Kenya ranges from 500 – 1500 kg/ha/year (FAO, 2023).

In Kenya, most extensive systems are found in Kenya's Central and Rift Valley regions, primarily in lakes, rivers, dams, and reservoirs. Extensive systems rely solely on natural food sources produced within the system, such as plants and plankton. Fertiliser is sometimes used to enhance the production of natural food (Munguti et al., 2021c).

Semi-intensive systems

Semi-intensive farming through pond aquaculture is the most common practice in Kenya, with many smallholder farmers owning multiple ponds (Wanja et al., 2020). Semi-intensive systems are similar to extensive systems but include supplementary commercial feed to support higher stocking rates. As with extensive systems, fertiliser is also commonly used (Munguti et al., 2021c).

Semi-intensive systems typically comprise earthen ponds, liner ponds or concrete ponds, holding species such as Nile tilapia and African catfish in mono or polycultures (Opiyo et al., 2018). The ponds are usually fertilised with organic manure from cattle, sheep, poultry, or rabbits and supplementary feeds formulated on the farm or purchased from cottage fish feed production industries (Opiyo et al., 2018). Cereal brans are also sometimes used as feed to enhance pond productivity (Munguti et al., 2021c).

In Kenya, ponds often have a stocking rate of 3 fish/m^2 to achieve yields of 1 kg/m^2, although stocking densities of 6 juvenile/m^2 (producing 3kg/m^2) have also been seen in some circumstances (Opiyo et al., 2018). These systems are found throughout Kenya but are highest in number in the Rift Valley area, followed by Western and then Central Kenya (Opiyo et al., 2018).

Intensive systems

Intensive systems are characterised by high initial investments, advanced technology and high production efficiency and are exclusively reliant on commercial feed (Munguti et al., 2021c; Opiyo et al., 2018). Raceways, recirculating aquaculture systems (RAS), cages, and aquaponics are all seen in Kenya.

Raceway systems

Raceway systems are mainly used to cultivate rainbow trout in the Mount Kenya region, with production rates of between 10,000 to 80,000 kg ha^{-1} $year^{-1}$ (Opiyo et al., 2018). Raceways require the use of costly, high-quality feed, which only a small number of farmers can afford (Opiyo et al., 2018). Although as rainbow trout is considered a luxury, the production is higher in monetary value than weight, and is marketed to hotels to cater for tourists (FAO, 2023; Opiyo et al., 2018).

Recirculating aquaculture systems (RAS)

RAS in Kenya are primarily used for cultures of African catfish and Nile tilapia in tanks, either indoors or under greenhouses (Opiyo et al., 2018). The fish are grown at high densities (ranging from 5 to 20 fish/m^3) under controlled conditions (Macharia and Kimani, 2016; Opiyo et al., 2018). However, the adoption of intensive systems like RAS is limited due to the high initial capital investment and operating costs involved (Kyule-Muendo et al., 2022; Opiyo et al., 2018). Investments in RAS for Nile tilapia and intensive catfish production are primarily made in peri-urban areas near towns such as Nairobi, Kiambu, Nyeri, Meru, Kisumu, Machakos, Kilifi, Homa Bay, Kakamega and Busia (Macharia and Kimani, 2016).

Cages

Cage culture has gained significant popularity in Kenya, especially for producing Nile tilapia. Cage systems are found in the riparian counties around Lake Victoria, with the largest number of cages located in Siaya County (Aura et al., 2018). The cages are stocked at a rate of between 60 and 250 fingerlings/m^3, and the sizes of the cages range from 8 to 125/m^3 (Njiru et al., 2019). However, the development of cage culture faces challenges related to site suitability, regulation and potential conflicts with other lake users (Orina et al., 2021).

Aquaponics

Aquaponics is still relatively new in Kenya, and consequently, there are often knowledge gaps regarding best practice and performance, which has hindered the adoption of the system (Sabwa et al., 2022). Traditionally, aquaponics involves combining a recirculatory aquaculture system with plant production (Palm et al., 2018). The water, rich in nutrients from the fish production units, is then directed to plant beds for crop production before being cycled back to the fish-rearing units (Palm et al., 2018).

Fish stocking densities in commercial aquaponic systems typically range from 60-200 kg/m^3 in 5000m^3 tanks, although in Kenya, aquaponic systems tend to be small-scale or subsistence farms with lower stocking densities of between 15-19 kg/m^3 (Obirikorang et al., 2021).

As with many other intensive aquaculture systems, the cost of fish feed, which can account for up to 70% of costs, is a barrier to the uptake of aquaponics, as is the initial start-up costs, the need for electricity, and the lack of knowledge and expertise available (Obirikorang et al., 2021).

Hatcheries in Kenya

Before the FFEPP was launched, most hatcheries were owned and managed by the government and could not meet the demand for 28 million fingerlings due to inadequate infrastructure and poor quality broodstock (Orina et al., 2021). Since the FFEPP launched, demand for fingerlings has grown to approximately 100 million per year (Munguti et al., 2014a). In response, by 2016, Kenya had 125 authenticated hatcheries located strategically across the country to ensure easy access by farmers, most of which were privately owned (82%) (Nyonje et al., 2018; Opiyo et al., 2018). The Ministries of Fisheries Development pushed for hatcheries to become authenticated to ensure that Best Aquaculture Management Practices (BAMPs) were being used to create high-quality fertilized eggs (Orina et al., 2021). This meant that the authenticated hatcheries had to use high-quality broodstock, have reliable access to water, suitable sites, at least four breeding ponds and two nursery ponds, along with holding tanks, and all the required infrastructure for proper management and monitoring (Orina et al., 2021). However, despite these efforts, Kenya is still thought to lack sufficient knowledge and skills to enact the BAMPs, resulting in high fry and fingerling mortality rates of around 30% due to cannibalism and predation, as well as poor nutrition, genetics, quality standards and health management (Munguti et al., 2022a; Nyonje et al., 2018; Opiyo et al., 2018). Consequently, Kenya's hatcheries are thought to produce only 23 million tilapia fingerlings and 2 million catfish fingerlings per year, leaving a 77 million deficit compared with demand (Nyonje et al., 2018).

Broodstock

Although originally, most of Kenya's broodstock were obtained from the wild (mostly from Lakes Victoria and Kyoga), concerns over sustainability and the variable timing and scale of natural spawning meant that hatchery production was a more productive and reliable alternative (Nyonje et al., 2018; Orina et al., 2014). To facilitate this, the Kenya Marine and Fisheries Research Institute (KMFRI) conducts selective and mass breeding programmes for African catfish and Nile tilapia. In 2012, the KMFRI screened 200 sires and 100 dams from various Sagana River and Lake Victoria strains. The offspring of these selected breeders have since been distributed across more than 12 multiplication facilities nationwide to produce fingerlings for grow-out farms (Abwao et al., 2021; Munguti et al., 2021b).

Nile tilapia

In Kenya, Nile tilapia broodfish are typically kept at a density of 2-3 fish/m^2 in hatcheries and range in size between 180g to 400g. At less than 203g, females are typically smaller than males (>300g) (Nyonje et al., 2018). If the farm is large enough, the males and females are kept in separate ponds or hapas—square or rectangular net enclosures constructed using a fine mesh netting material to prevent the fry or fish inside from escaping—for 2-4 weeks to increase the chances of mating when paired (Nyonje et al., 2018). Pairing typically occurs in ponds or breeding hapas, and females are stocked at a ratio of 2:1 with males (MWEA, 2023a; Nyonje et al., 2018).

To produce 10,000 fry per month from one pond, 200 females are required to produce 40,000 eggs per spawn (MWEA, 2023a). Mortality is high, and so only 50% of the eggs are predicted to hatch, resulting in 20,000 fry, which are also plagued by high mortality rates, resulting in a likely outcome of 10,000 fingerlings in a month from one pond of 200 females (MWEA, 2023a). According to a survey of farmers, tilapia eggs are not typically incubated, even when farms have the facilities available (Orina et al., 2021).

Some Kenyan hatcheries use preventative measures to reduce the risk of Nile tilapia disease (Munguti et al., 2022b). For instance, routine disinfection of farm and culture equipment and sometimes also prophylactics (Magondu et al., 2011). Drugs, antibiotics and chemicals are often used to eliminate bacterial and fungal infections and increase survivability (Nyonje et al., 2018; Rasowo et al., 2007). The treatments are typically carried out during the egg incubation stage (if performed) or at the fry stages (Magondu et al., 2011; Rasowo et al., 2007).

North African Catfish

Successful farming of African catfish has only been possible since artificial-propagation protocols were developed in the 1980s, as fertilized egg collection in the wild is unreliable, time-consuming and uneconomical, and the species does not naturally reproduce in captivity (Marimuthu, 2019; Munguti et al., 2022a). Furthermore, induced spawning techniques performed at hatcheries remove the pressure on wild populations (Barassa, 2020). Hormonal administration techniques have been developed that induce final oocyte maturation and spawning, enabling reproduction in captive, controlled conditions (Marimuthu and Haniffa, 2010). The males are killed to collect their milt (Macharia et al., 2005), so farms typically have double the number of males to females (MWEA, 2023b). Survivability of broodstock and eggs is reportedly very low, so to produce 100,000 catfish a month, 3000 brooders (2000 males and 1000 females) will be required (MWEA, 2023b).

Females are around 500g and can release around 30,000 eggs per spawn. Once the larvae hatch, successful larval rearing primarily depends on suitable dietary provisions (Giri et al., 2003). The most widely used live food for catfish larvae culture is the brine shrimp (*Artemia salina*), which is easy to transport and keep (Garcıa-Ortega et al., 1998). Zooplanktons are also used in Kenya and elsewhere (Kibria et al., 1997). Kenyan hatcheries have recently begun to use biofloc technology for feeding, as it allows pond bio-wastes to be converted into nutrients and reduces feed costs by around 30% (Ogello et al., 2021). Growing catfish larvae in biofloc systems also has positive results on survivability and final body length (Ekasari et al., 2016).

Dry feeds are also used for catfish larvae, and fishmeal is a popular choice because it is high in good-quality proteins and has balanced amino acids (Munguti et al., 2022a). However, due to high demand and variable supply, fishmeal is an expensive feed, and so efforts are being made to explore the viability of other protein sources, such as black soldier fly larvae (*Hermatia illucens)*, blood meal, soybean, wheat bran, maise, and other commercial feeds (Munguti et al., 2014b; Nairuti et al., 2021).

Fingerling production in Kenya

At every spawning cycle, fry are typically moved to nursery ponds (Nyonje et al., 2018). These are commonly open ponds, but tanks and hapas in ponds are also used (Towers, 2015).

Nile tilapia hatcheries either produce both monosex and mixed-sex fingerlings, or solely mono or mixed-sex fingerlings, with over 50% of hatcheries in Kenya practising sex-reversal (Munguti et al., 2017; Nyonje et al., 2018; Orina et al., 2014). Male tilapia are preferred as they grow faster than females and keeping them in mono-sex groups prevents high energy losses through gonadal development and reproduction (Dagne et al., 2013; Mlalila et al., 2015). Monosex production technology is expensive, however, as it requires a sex reversal hormone (17α-methyl testosterone) as well as the required infrastructure, although other methods, such as manual sexing and hybridisation also exist (Nyonje et al., 2018; Towers, 2015). Success rates of sex reversal vary depending on the skills and experience of the farm staff, as the methods can require specialist skills and knowledge (Munguti et al., 2017).

Fingerlings must be a certain size for sex reversal, so breeding is typically managed to ensure the timings are correct. For example, males and females are typically kept separately for several weeks before pairing to create a narrower spawning window (Nyonje et al., 2018). Once hatched, the fry are collected, kept in ponds, tanks or hapas at high densities and fed feed that is treated with 17α-methyl testosterone for 28 days (Munguti et al., 2017; Nyonje et al., 2018). However, no single sex reversal technique is 100% effective, so producers may use more than one method (Towers, 2015).

Manual sexing involves the hand sexing of every individual to separate males and females for rearing. Reliability and efficiency vary according to the experience of the worker (Towers, 2015). Hybridisation is also performed, where two subspecies of tilapia are crossed to produce a higher proportion of males (Felix et al., 2019).

Cannibalism in catfish fingerlings is a fundamental issue in hatcheries, but Kenyan hatcheries have effectively reduced its prevalence by adopting grading procedures (Baras and Jobling, 2002). African catfish can have varying growth patterns despite being the same age (allometric growth patterns), and stocking fish of different sizes can result in aggression and cannibalism (Baras and Jobling, 2002). Grading fish can mitigate these issues, and can enhance feeding, as rations are optimised (Batzina et al., 2018). However, there are welfare concerns associated with grading, as the handling procedures can cause stress and physical damage to fish (Dunlop et al., 2004).

Feed management and nutrition

Fish feed equates to 40-70% of the total cost of aquaculture production (Munguti et al., 2014a; Obirikorang et al., 2021). Most fish feed in Kenya is produced by the private sector, and many of the ingredients are imported in, which further exacerbates the rising costs. As commercial fish feeds are too expensive for most Kenyan farmers, many source locally mixed feeds or produce fish feed themselves (Munguti et al., 2021a, 2014a; Opiyo et al., 2018). The lack of efficient and inexpensive feeds is one of the most significant challenges for the aquaculture industry in Kenya (Munguti et al., 2012).

Due to increasing demands following the FFEPP, there was a rise in the sale of poor-quality feed, which prompted the Kenyan government to establish national standards for fish feed, which have since been used to vet manufacturers (Munguti et al., 2014a). These standards were developed via consultations with stakeholders in the aquaculture sector and the Kenya Bureau of Standards (Munguti et al., 2021d). These fish feed standards aim to ensure that high-quality feed is available in the market and to address various challenges associated with aquafeeds, such as low levels of protein, short shelf life, high aflatoxins and other related issues (Munguti et al., 2021d, 2021a).

Farmers who make their own feeds tend to produce them in mash, crumbles, or sinking pellets as they do not have the extruders needed for floating pellets (Munguti et al., 2021a). There are issues associated with feeds produced on-farm and from cottage producers, as the reduced quality can compromise fish health, growth, and welfare, as well as water quality. This is particularly true if farmers are not aware of the differing needs of fish throughout development (Munguti et al., 2021a). Furthermore, due to poor capacity, the quantity of feed produced is often insufficient to meet the fishes' needs (Munguti et al., 2021a).

Small-scale commercial feeds typically consist of plant-based ingredients, such as rice bran or maise bran, which is then combined with dried freshwater shrimp, known in Kenya as Ochonga (*Caridina niloticus*), and fishmeal from a species of small silver cyprinid fish known as Omena (*Rastrineobola argentea*) (Munguti et al., 2021a). There are several other locally available feed materials and ingredients commonly used by fish farmers in Kenya (see table 1).

On-farm feeds are typically deficient in essential macronutrients and micronutrients and lack important amino acids such as methionine and lysine (Kirimi et al., 2020). Moreover, the plant-based ingredients contain a high amount of crude fibre, which adversely affects the digestibility and taste of the feed, leading to reduced fish productivity (Munguti et al., 2014a). Conversely, large-scale commercial pellet feeds comprise a complete diet, although most animal feed manufacturers in Kenya are livestock feed manufacturers, and only a few produce fish feed (Munguti et al., 2021a). Furthermore, due to the cost of commercial pellet feed, they are geared more towards intensive farms, which are fewer in number (Munguti et al., 2021c).

Table 1: Common fish feed materials and ingredients used in Kenya (Munguti et al., 2021a, 2012)**.**

Feed Category	Feed Materials/ Ingredients
Animal protein	Trash fish, bycatch fish, shrimp, fish meal, bonemeal, slaughterhouse wastes (e.g., offal, blood)
Aquatic plants	Water hyacinth, water lettuce, duckweed

Cereal by- and plant-based by-products	Rice (broken, bran, hulls), wheat (middling, germ, bran), maise (gluten feed, germ, gluten meal), coconut meal, molasses, soybean.
Fertilisers	Excrement from cattle, sheep, poultry, or rabbits
Other waste products	Brewer's waste,
Seed cakes	Mustard, coconut, groundnut, cotton, sunflower, soybean
Small terrestrial invertebrates	Earthworms, termites
Supplements	Low-protein manufactured feeds, amino acids, vitamin and mineral premixes
Terrestrial plants	Grasses, leaves (e.g., cassava), seeds of leguminous shrubs and trees

Feed delivery

In semi-intensive systems, fingerlings are fed at least three times a day at 3% of their body weight, with diets containing 30-40% CP (Munguti et al., 2021d). Like fingerlings, grow-out fish in semi-intensive systems are typically fed at 3% of their body weight. However, they are usually fed twice daily (morning and evening) with feeds containing 26-30% CP (Munguti et al., 2021d). Feeding is commonly scheduled around 10:00 AM and 4:00 PM, usually at the same location, to ensure optimum levels of dissolved oxygen (Munguti et al., 2021d). In semi-intensive systems, the feed supplements the natural food already within the water. However, increasing intensification and cage culture in Kenya, especially in Lake Victoria, has further exacerbated issues with the availability of high-quality feed: farmers are solely reliant on fish feeds because cages offer few natural food sources (Munguti et al., 2021d).

Improper feeding techniques can be an issue in Kenyan aquaculture, as farmers are often thought to neglect recommended rates for feeding and not consider factors such as ambient temperature, body mass and pond biomass when calculating feed rations (Munguti et al., 2021c). Furthermore, unless good record-keeping is routinely performed, farmers struggle to adjust the daily feed quantities when required. Knowledge and skills in monitoring, recording, and calculating feed requirements and efficiencies are vital in ensuring the health and productivity of farmed fish and is an area in which feed companies play a key role. However, due to the reliance on on-farm feed production, this support is widely lacking (Munguti et al., 2021c). As a result, practices such as over-feeding may be mistakenly adopted in the hope that it will achieve higher growth rates, whilst actually causing many issues, from poor water quality to economic losses (Munguti et al., 2021c).

However, some interesting innovations in Kenyan aquaculture have sought to improve feeding techniques while maintaining the use of on-farm feeds (Munguti et al., 2021c). For instance, as powdered feed is typically wasted when it disperses, some have adopted bag feeding, where the feed is placed in bags throughout the pond (Munguti et al., 2021c). This method allows the fish to feed on demand whilst minimising waste, improving feed ingestion rates and achieving higher retention rates (Munguti et al., 2021c, 2014a).

Water sources

Kenya is a water-scarce country; therefore, water availability is a key concern and often a deterrent for prospective farmers (Jacobi, 2013). Droughts and floods are endemic and frequent in Kenya and are often the reason why farmers choose to cease aquaculture production (Obwanga et al., 2017). Aquaculture systems need between 35,000 and 60,000 m^3/ha/year of water for a pond depth of 1.5m during a 240-day growing cycle, which accounts for estimated losses of 1-2cm/day (Larsson, 1994). There is a risk, therefore, that water use for aquaculture may conflict with other water users, especially during droughts (Obwanga et al., 2017). However, some farmers integrate their water use with agriculture, for example, by growing fish in irrigation water reservoirs or using the wastewater from ponds for irrigation (Obwanga et al., 2017).

The main water sources for aquaculture activities in Kenya are groundwater, lakes, well water, and rivers (Jacobi, 2013; Opiyo et al., 2018). Shallow wells and municipal tap water are also used (Opiyo et al., 2018). The water is either pumped or allowed to flow by gravity into a reservoir, where it is first left to settle before being channelled into the production units (Opiyo et al., 2018). Water treatment is not commonly performed, which risks introducing parasites, polluted water, wild fish, and predators from the water source into the aquaculture facility (Ngugi et al., 2007; Obwanga et al., 2017).

Fish health management

The drive in Kenya to intensify aquaculture systems brings with it an increased risk of fish diseases, which causes suffering in the fish, financial losses, and potentially wider health and environmental risks (Kyule-Muendo et al., 2022). Many of the fish diseases that occur in controlled environments are associated with or caused by inadequate husbandry practices and a lack of biosecurity measures (Wanja et al., 2020). For example, the use of raw livestock manure, high fish stocking densities, elevated levels of nitrates and nitrites and increased ammonia levels all pose considerable risks to fish health (Wanja et al., 2020). Moreover, fish stressed from high stocking densities and poor water quality are more susceptible to infections than healthy fish, who are more resilient (Wanja et al., 2020).

Keeping fish in optimum environments and giving them suitably nutritious diets for their life stage is vital to mitigating the increasing risk of aquatic diseases, as are biosecurity and quarantining measures. Preventative measures are particularly important in Kenya, given that few specialists in fish diseases are reportedly available to farmers (Munguti et al., 2022b). There are efforts underway, with some projects focussing on training farmers in biosecurity measures to help reduce the prevalence and spread of aquatic diseases and the wider environmental impacts (Munguti et al., 2022b).

Disease prevalence and mortalities

According to a survey conducted in Western Kenya, 76% of fish farmers experienced mortalities in their hatcheries and farms (Kyule-Muendo et al., 2022). The average loss was around 10%, although 2% of farms reported mortalities exceeding half of their stocked fish (Kyule-Muendo et al., 2022). Interestingly, the farmers in the survey did not necessarily attribute the mortalities to diseases and viewed them as inherently normal. Furthermore, most of the farmers surveyed were not implementing biosecurity measures to prevent fish diseases and infections, with less than 2% adopting such practices, potentially because of a lack of awareness regarding the importance of such measures (Kyule-Muendo et al., 2022).

Some farmers in Kenya have reported significant fish mortalities in cages and ponds, ranging from 40 - 100% of their stock (Aura et al., 2018; Munguti et al., 2022b; Njiru et al., 2019). Although these losses are often attributed to water quality issues, there is a possibility that diseases could also be contributing, especially as diagnosis and disease investigations are not commonly conducted at the farm level (Akoll and Mwanja, 2012; Munguti et al., 2022b).

As discussed earlier, high mortality rates are a significant issue in Kenyan hatcheries, and many mortalities are due to bacterial and fungal infections (Njagi, 2016). In particular, small-scale hatcheries often have higher mortality rates due to inadequate biosecurity measures and poor management practices that fail to prevent infections (Njagi, 2016). The most frequently reported diseases in fish farms include fungal infections (primarily saprolegniasis) and bacterial infections (mainly hemorrhagic and popeye diseases) (Akoll and Mwanja, 2012; Nyonje et al., 2018). Some Nile tilapia hatcheries have also been affected by *Streptococcus iniae*, a bacterium that causes affected fish, especially larvae, to exhibit a C-shape deformity (Njagi, 2016; Walakira et al., 2014).

To treat bacterial and fungal infections like *S. iniae*, Kenyan aquaculture systems often use drugs and other chemicals like potassium permanganate and sodium chloride, although often without veterinary input or guidance (Walakira et al., 2014). Treatments in hatcheries are typically administered during the egg incubation stage or at the fry stages to enhance the survival of hatched fry (Wanja et al., 2020). Private hatcheries in Kenya primarily use oxytetracycline as an antibiotic to prevent bacterial infections in African catfish broodstock, although concerns have been raised regarding antibiotic resistance in fish (Madara et al., 2022).

Transport and Slaughter

Slaughter occurs when fish reach the desired market size, which depends on the species and system used. Nile tilapia can reach slaughter size within six to nine months, with those reared in RAS reaching slaughter size faster (Munguti et al., 2022b). Wholesale traders often directly purchase fish from farmers (Munguti et al., 2022b). Due to limited storage facilities, farmers often have informal arrangements with traders and may be compelled to sell the fish at lower prices to prevent production cost overruns or spoilage (Munguti et al., 2022b).

Domestically marketed fish (both slaughtered and live) are typically packed in ice-filled polythene bags and transported in traditional baskets. Fish transported in this manner are vulnerable to physical damage and exposure to microorganisms, whilst live fish can suffer from severe stress and mortality if the water quality parameters (e.g., temperature, dissolved oxygen, and pH) are not managed properly (European Commission, 2017).

Conclusion

While Kenya's aquaculture sector has experienced significant growth, aided by support from local and international partners and frameworks, it faces several challenges that hinder its full potential. These include challenges to fish rearing itself, which is limited by poor water quality, welfare measures, biosecurity, and improperly formulated or costly feeds (Munguti et al., 2021b; Odende et al., 2022). However, these challenges extend beyond caring for the fish themselves and include:

- Insufficient access to affordable and high-quality fingerlings.
- Poor bookkeeping and record management, resulting in inaccurate data along the aquaculture value chain.
- Slow adoption rate of fish farming technologies, innovations, and management practices.
- Absence of expert support and uptake for schemes and training programmes specifically designed for fish farmers.
- High initial start up costs and high risks of loss.
- Inadequate staffing levels, particularly for extension personnel, as well as transportation challenges.
- Growing competition from inexpensive imported farmed fish products.
- Inadequate regulatory and legal framework for certifying fish feed and fertilized eggs, and ensuring production, supply, and quality compliance.
- Emerging fish illnesses, and conflicts over resource use.

The cost of these challenges is wide-ranging, from food security in Kenya to the livelihoods of the farmers within the industry and the welfare of the fish. This review has highlighted some of the successes and challenges the aquaculture sector faces in Kenya. Given that there is a considerable push to intensify aquaculture production in Kenya, it is vital that these concerns and challenges are addressed to prevent further negative impacts on the lives of humans and the fish being produced.

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