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Review

A review of Kenyan inland aquaculture with an eye to the status of animal welfare in the sector

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Abstract
Kenya's inland aquaculture sector is one of the most productive in Africa. Efforts are currently being made at the national level to expand and intensify the sector. Despite the drive to develop Kenyan inland aquaculture, the sector continues to encounter barriers to sustainability and economic profitability. Fish welfare is also highly neglected which has implications for fish health and overall sector productivity. This review documents the current state of inland aquaculture in Kenya, covering its considerable growth since 2009 to the current day and looking at both intensive and extensive forms of fish farming, paying special attention to the challenges faced in terms of animal welfare. Given that the inland aquaculture sector in Kenya has been earmarked for further rapid growth, with considerable economic and strategic support in place to foster this, some of the core issues of sustainability must be recognised and addressed. This review focuses on one of those, namely animal welfare.

Keywords Inland aquaculture · East Africa · Pond farming · Sustainability · Fish health

1 The rise in Kenyan inland aquaculture

Fisheries and aquaculture contribute around 2% of Kenya's GDP [1], with aquaculture providing almost 25% of the country's fish production. The majority of that production comes primarily from inland fish farming. Inland fish farming is widely practiced in many counties across the country; however, the number of households farming fish is less than 1% of the total number of households (*i.e.*, ~ 24, 000 households out of a total of ~ 6.3 million) [2].

Although this review focuses on inland freshwater aquaculture, it is worthwhile to discuss the state of marine aquaculture briefly since aquaculture in Kenya consists of both freshwater and marine farming. In terms of mariculture, the main finfish species farmed are milkfish (*Chanos chanos*) and the flathead grey mullet (*Mugil cephalus*), as well as shellfish such as the giant mud crab (*Scylla serrata*), the hooded oyster (*Saccosteria cucullata*), the giant tiger prawn (*Penaeus monodon*) and seaweeds such as the elkhorn sea moss (*Kappaphycus alvarezii*) [19]. While specific production data for each marine species is currently unavailable, total mariculture production exceeds 100 MT [19]. The funding emerging from the "Kenya Coastal Development Project" spearheaded by a consortium of Kenyan government bodies was the driving factor for the commercialisation of both marine finfish and algae production [3].

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The advancement of mariculture within Kenya remains at an incipient stage, characterised by limited development and substantial room for growth. The underdevelopment of mariculture primarily stems from challenges related to accessibility, disputes over land ownership, a deficiency in well-defined regulations and inadequate fry availability which also presents a seasonal availability issue [3, 19]. The establishment of the National Mariculture Resource and Training Center (NMRTC) aims to strengthen the sector by providing resources like a mariculture hatchery and both a dry and a wet lab [3]. Apart from the inauguration of NMRTC there is an urgent need for the relevant authorities to prioritise the creation of a suitability map for Kenyan mariculture and a legal framework that views mariculture as an important contributor to food security, poverty alleviation and unemployment of coastal communities [3].

However, this review will focus on inland freshwater aquaculture in Kenya given that it represents the vast majority of aquaculture activity in the country. Kenya possesses abundant freshwater resources, including lakes, rivers, dams, reservoirs, streams and wetlands, many of which are suitable for the development of various forms of inland aquaculture [3]. Consequently, inland aquaculture is being promoted as a solution to address undernutrition, malnutrition, food insecurity and poverty in Kenya [4]. Since its introduction by the Colonial Government in the 1920s, Kenya's inland aquaculture sector has grown from a small player to a key component of the country's food system and Kenya is now among the top 10 producers of farmed fish in Africa [5] (Fig. 1). 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*) [6, 7].

In 2009, inland aquaculture was identified by the Kenyan government as a key sector within the agricultural industry in Kenya [3]. As a result, 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) [3, 8]. Inland aquaculture was identified by the Kenyan government as a key sector within the agricultural industry in Kenya [3], and the FFEPP was focused on expanding and intensifying inland aquaculture in Kenya [8]. This led to an immediate demand for certified tilapia and catfish fingerlings, as well as formulated fish feeds [9]. Also, Kenya's Vision 2030 includes legal, policy and institutional frameworks and public investments that will increase aquaculture production and help the sector to be recognised as a potential solution to reduce poverty, enhance food security and battle unemployment [3].

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 [8]. 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 [8, 9]. In 2021, Kenyan aquaculture production was 21,825 tonnes, constituting 0.9% of

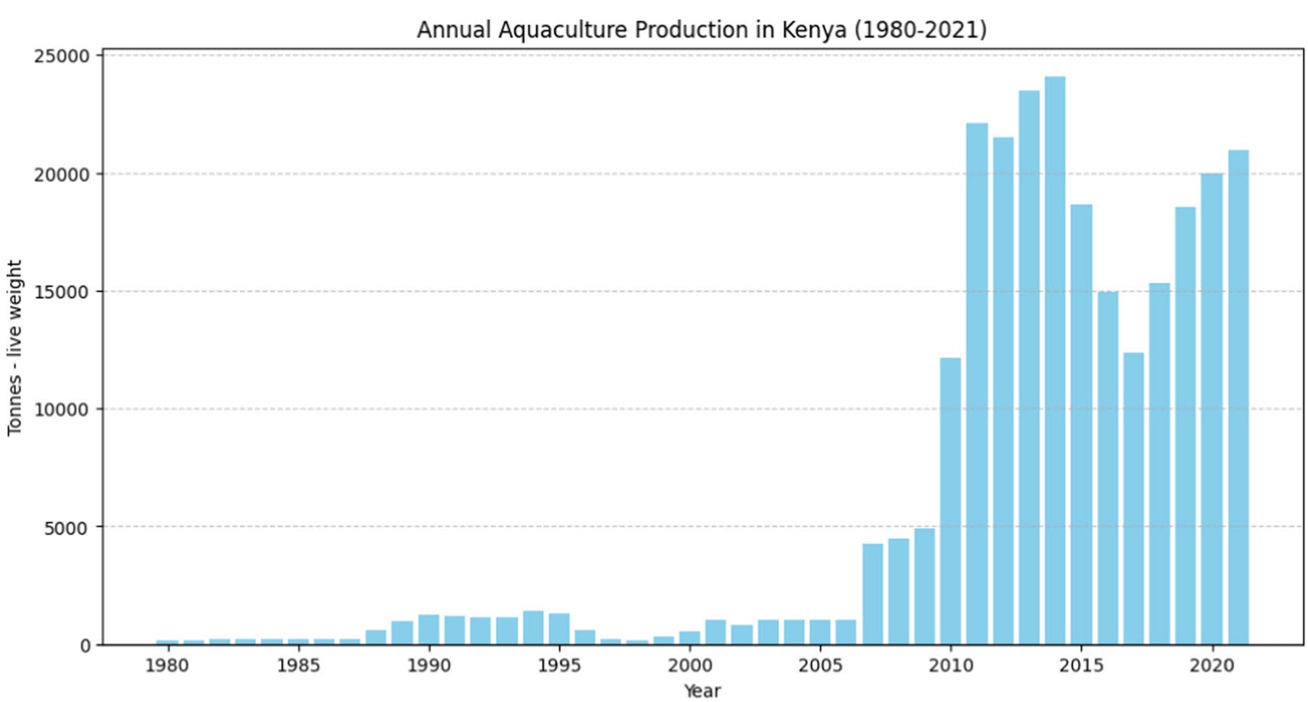

Fig. 1 Annual inland aquaculture production in Kenya (1980–2021). The data reveals significant fluctuations over the years, with notable increases in production in recent decades. This increase highlights the growing importance of aquaculture in Kenya since 2009 [15]

Africa's total fish production [9, 15]. Generally, the increase of the domestic production apart from minimising imports, will allow space for investments of private actors that will allow the introduction of new technologies and generally the advancement of the sector [3].

Kenya currently has 1.4 million hectares of aquaculture area, which has the potential to produce 14 million tons of fish and other aquatic animals or seaweed species like *Eucheuma spp.*, *Kappaphycus spp*. and *Hypnea spp* with a potential value of over 50 billion Kenyan Shillings (KSh) each year (approximately US$ 356 million) [10, 11]. Kenya's inland aquaculture sector is characterised mainly by pond systems that are small-scale and scattered (*e.g.*, fewer than five ponds per farm), which function primarily for sustenance [10, 12]. 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 metric tons (MT) [10]. The fish ponds primarily are typically earthen ponds that measure 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 [14]. This rapid growth comes as a result of the implementation of supportive policies, governmental stimuli and significant public investments [13]. Despite the expansion of the aquaculture sector, there are a few bureaucratic barriers to future growth. The requirement for multiple approvals, including licenses, environmental impact assessments, and public consultations, introduces considerable delays and procedural complexities[89]. These procedures are often warranted but could have the effect of deterring potential investors and slowing the initiation of complex projects.

2 Inland aquaculture species in Kenya

The Kenyan inland aquaculture sector primarily focuses on farming three main freshwater species: Nile tilapia (*Oreochromis niloticus*), African catfish (*Clarias gariepinus*) and rainbow trout (*Oncorhynus mykiss*) [13, 15]. Tilapia species are the most commonly farmed fish in Kenya, representing around 90% of production, and polyculture with the African catfish is commonly practised to reduce breeding in tilapines [15]. African catfish have a market both within Kenya, and within neighbouring countries (*e.g.*, Uganda and Tanzania), and catfish fingerlings are required for both stocking and baitfish [16].

Rainbow trout farming is primarily restricted to high-altitude areas such as the Mount Kenya region, where there are free-flowing rivers [17]. The common carp has also been introduced for aquaculture purposes, although they not favoured in markets [15]. The National Aquaculture Research Development and Training Centre in Sagana has been cultivating native species *Labeo victorianus* and *Labeo cylindricus* for aquaculture but no updates have been reported since 2014 [17].

3 Geographical spread of inland aquaculture in Kenya

Different counties in Kenya have varying levels of inland aquaculture-related activities. Most inland aquaculture production occurs in the Western and Central regions mainly due to reasons such as the geography, the climate and the sufficient water availability throughout the year [18]. In particular, counties like Kakamega, Bungoana, Kisii, Meru, Nyeri, Kisumu and Muranga have a higher number of ponds and inland aquaculture operations, and others, such as Kitui, Lamu and Elgeyo Marakwet, have very few [3, 19]. Most parts of Kenya are suited to some form of inland aquaculture. However, many areas are largely unused due to limited interventions and land and water scarcity [20]. 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, led to a decline in total inland aquaculture production between 2014 and 2017 [15, 19].

When it comes to land ownership, this challenge still remains to be solved, as the sector still lacks access to capitals and land. These issues constitute a serious barrier for women and youth, who still struggle to participate in the aquaculture sector. For instance, cage ownership and management still remains male dominated while women are mainly employed in the processing stage of the value chain [3].

4 Inland aquaculture systems in Kenya

Kenyan inland aquaculture features farming at three levels of intensity (detailed in the subsequent section) namely extensive production (between 500 and 1500 kg/ha/year), semi-intensive production (between 1,000 and 2,500 kg/ha/year) and intensive production (between 10,000 to 80,000 kg/ha/year). Semi-intensive systems contribute over 70% of Kenya's inland aquaculture production and typically consist of polyculture of Nile tilapia and African catfish [15]. Intensive aquaculture primarily involves rainbow trout in raceway systems, contributing 5% of aquaculture production in 2022

[15, 83]. Although the intensive culture of Nile tilapia in cages has grown in the last ten years, hyper-intensive tilapia culture is forecasted to contribute as much as 90% of all farmed fish in Kenya by both volume and value [15, 19]. Extensive production is poorly documented, but it is believed to contribute around 10% of the total production in Kenya [15].

The World Organisation for Animal Health defines animal welfare as 'the physical and mental state of an animal in relation to the conditions in which it lives and dies'. This concept is important because ensuring good welfare allows the animal under management to grow and thrive optimally, reducing losses to farmers and other stakeholders. Fish welfare *i.e.*, a fish's physical needs and its ability to cope with farm conditions, is closely related to the well-being of the reared organisms. Therefore, applying proper welfare management protocols is important for maintaining the sustainability and progress of the aquaculture sector [22]. Fish welfare has not traditionally been given extensive consideration in Kenya which has implications for fish health and overall productivity of inland aquaculture. Specifically, the country faces challenges such as emerging diseases and environmental pollution that are directly threatening the aquaculture industry [17]. Although aquaculture has become a governmental priority, which has led to policy efforts through measures like those for promoting sustainable management of sensitive fisheries like Lakes Victoria and Naivasha [15], there is still space for improving the welfare and sustainability of the sector. This review will adopt a welfare approach to assess Kenyan inland aquaculture, covering all dimensions where potential welfare issues may occur.

4.1 Semi-intensive systems and their relationship to animal welfare

Semi-intensive farming through pond aquaculture is the most common practice in Kenya, with many smallholder farmers owning multiple ponds [23]. Semi-intensive systems include supplementary commercial feed to support higher stocking rates, fertiliser is also commonly used [21].

Semi-intensive systems typically comprise earthen ponds, liner ponds or concrete ponds, holding species such as Nile tilapia and African catfish in monoculture or polyculture where aquaculture is integrated with either crop or livestock production [19]. 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 [19]. Cereal bran is also sometimes used as feed to enhance pond productivity [21]. Monoculture can be considered better for fish welfare as it avoids any potential issues of aggression or predation [56].

In Kenya, ponds often have a stocking rate of three fish/m [2] to achieve yields of 1 kg/m^2, [19]. The juvenile fry of tilapia and catfish that are commonly stocked at these densities typically weigh less than 5 g [68]. These systems are found throughout Kenya but are highest in number in the Rift Valley area, followed by Western and then Central Kenya [19].

Regarding fish welfare, to our knowledge, the research regarding Kenyan semi-intensive systems is still scarce. However, research on tilapia more generally, which is a key species for Kenyan inland aquaculture, reports no difference in the overall welfare of the tilapia raised in earthen ponds and cages in semi-intensive conditions [24]. Regarding stocking density, research from Tanzania showed that tilapia raised in stocking densities typical of semi-intensive systems in Kenya had higher survivability rates than those raised in higher stocking densities [81].

4.2 Extensive systems and their relationship to animal welfare

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 [15]. In particular, the species, stocking densities for the various aquaculture systems 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 estimates that extensive production in Kenya ranges from 500 to 1500 kg/ha/year which is a small proportion of total production [15].

In Kenya, most extensive systems are ponds found in the country's Central and Rift Valley regions, primarily in lakes, rivers, dams, and reservoirs. As mentioned previously, extensive systems rely solely on natural food sources produced within the system, such as plants and plankton [21]. In terms of welfare, extensive systems offer fish the opportunity to exhibit natural behaviours, find shelter, and avoid conflicts with other members of their species.

For instance, Nile tilapia reared in environments with low stocking densities tend to exhibit enhanced growth rates and better food conversion ratios. This is largely due to reduced competition for food, which allows both dominant and subordinate fish better access to nutrition [79]. Additionally, extensive systems provide a more natural habitat, promoting natural behaviours such as foraging and hiding, which can significantly reduce stress levels. The availability of adequate space and shelter helps to minimise aggressive interactions among the fish, contributing to a more stable and less stressful environment [22].

However, despite these benefits, extensive systems also present notable drawbacks. Nile tilapia raised in low-density environments experience increased expression of stress-related genes and a dampened immune response to and a resulting higher mortality from the oomycete Saprolegnia *parasitica* [80]. Managing water quality and disease in extensive systems can be more challenging due to their dependence on natural conditions, which are less controllable than in intensive systems [22].

4.3 Intensive systems and their relationship to fish welfare

Although, 70% of aquaculture in Kenya is currently semi-intensive, intensive systems are forecasted to contribute the vast majority of farmed fish in Kenya [15, 19]. Therefore, this review will focus on describing intensive aquaculture. Intensive systems are characterised by high initial investments, advanced technology and high production efficiency and are exclusively reliant on commercial feed [19, 21]. Raceways, recirculating aquaculture systems (RAS), cages, and aquaponics can all be seen in Kenya.

4.3.1 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/h/year [3, 19]. Raceways require the use of costly, high-quality feed, which only a small number of farmers can afford [19]. However, as rainbow trout are considered a luxury product in Kenya, their high market price makes them more profitable per kilogram compared to other farmed fish like tilapia, despite the higher production costs. This profitability is largely driven by demand from hotels catering to tourists [15, 19].

4.3.2 Recirculating aquaculture systems (RAS)

RAS in Kenya are primarily used for cultures of African catfish and Nile tilapia. This is done in tanks, either indoors or under greenhouses [19]. The fish are grown at high densities (ranging from five to 20 fish/m [2]) under controlled conditions [19, 25]. However, the adoption of intensive systems like RAS is limited due to the high initial capital investment and operating costs involved [14, 19]. 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 [25].

4.3.3 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 [26]. 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 [5, 27]. Fingerlings of tilapia that are typically stocked in Kenya are stocked at a weight of under 10 g. For catfish, this is less than 15 g. However, the further development of cage culture faces challenges related to site suitability, regulation and potential conflicts with other lake users [28].

4.3.4 Aquaponics

Aquaponics is still relatively new in Kenya, and consequently, there are many knowledge gaps regarding best practice and performance, which has hindered the adoption of the system [29]. Traditionally, aquaponics involves combining a recirculatory aquaculture system with plant production [30]. 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 [30].

Fish stocking densities in commercial aquaponic systems typically range from 60 to 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 and 19 kg/m [3, 31].

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 [31].

Knowledge on fish welfare in all types of intensive systems is very limited. However, there are many opinions in the media and amongst animal rights groups that intensive systems are inherently inferior as they are the aquatic equivalent of a 'factory farm'. Their poor perception of intensive farming is likely due in part to high stocking densities, which can lead to stress, aggression, and disease outbreaks in tilapia [79, 82]. A lack of natural shelters and hiding places in intensive systems can also lead to increased aggressive interactions [82].

5 Hatcheries in Kenya

Before the FFEPP was launched in 2009, 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 which are the parent fish used to breed juveniles [28]. Since the FFEPP launched, demand for fingerlings has grown to approximately 100 million per year [17]. In response, by 2016, Kenya had 125 approved hatcheries located strategically across the country to ensure easy access by farmers [32], most of which were privately owned (82%) [18, 19].

The Kenyan Ministry of Fisheries Development pushed for hatcheries to become authenticated to ensure that Best Aquaculture Management Practices (BAMPs) were being used to create high-quality fertilised eggs [28]. 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 [28].

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 [16, 18, 19]. Consequently, Kenya's hatcheries are thought to produce only 23 million tilapia fingerlings and 2 million catfish fingerlings per year [18].

Hatcheries are an important component of aquaculture which come with their own set of health and welfare challenges. For example, whilst breeding programmes provide high-quality genetic material that increases productivity and maximises profits while minimising producers' expenses, they are also associated with inadequate biosafety protocols and poor disease control, hybridisation and the accidental introduction of genetically modified species into the wild [13].

5.1 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 [18, 33]. 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 males and 100 females from various Sagana River and Lake Victoria strains. The offspring of these selected breeders have since been distributed across more than 12 breeding facilities nationwide to produce fingerlings for grow-out farms [13, 34].

5.1.1 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 180 to 400 g. At less than 203 g, females are typically smaller than males (> 300 g) [18]. 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 [18]. Pairing typically occurs in ponds or breeding hapas, and females are stocked at a ratio of 2:1 with males [18, 35].

To produce 10,000 fry per month from one pond, 200 females are required to produce 40,000 eggs per spawn [35].. It is estimated that approximately 18.5% of Kenyan farmers use breeding and genetic techniques, while the sector is characterised by low technical capacity [36].

Some Kenyan hatcheries use preventative measures to reduce the risk of Nile tilapia disease [37]. For instance, routine disinfection of farm and culture equipment and sometimes also prophylactics [38]. Drugs, antibiotics and chemicals are often used to eliminate bacterial and fungal infections and increase survivability [18, 39]. The treatments are typically carried out during the egg incubation stage (if performed) or at the fry stages [38, 39].

5.1.2 African catfish

Successful farming of African catfish has only been possible since artificial-propagation protocols were developed in the 1980s, as fertilised egg collection in the wild is unreliable, time-consuming and uneconomical, and the species does not naturally reproduce in captivity [16, 40]. Furthermore, induced spawning techniques performed at hatcheries remove the pressure on wild populations [41]. Hormonal administration techniques have been developed that induce final oocyte maturation and spawning, enabling reproduction in captive, controlled conditions [42]. The males are killed to collect their milt [43] so farms typically have double the number of males to females [44]. Fry and fingerling survival rates are reportedly very low, so to produce 100,000 catfish a month, 3000 brooders (2000 males and 1000 females) are required [44].

Females that are used are typically around 500 g and can release around 30,000 eggs per spawn. Once the larvae hatch, successful larval rearing primarily depends on suitable dietary provisions [45]. The brine shrimp (Artemia salina), which is easy to transport and maintain, along with zooplankton, are used to feed catfish [46, 47]. Kenyan hatcheries could benefit from using novel techniques such as h biofloc technology (BFT) for feeding. BFT is an innovative production system that involves the cultivation of beneficial microbial communities that convert pond bio-waste into nutrients reducing feed costs by around 30% [48]. Catfish larvae spawned from broodstock reared in biofloc systems also had positive results on survivability while maintaining larvae in biofloc systems could potentially improve their survival rate and final body length [48]. However, Kenya has been slow in adopting innovative technological interventions such as these [49].

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 [16]. 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 [49, 50].

5.2 Fingerling production in Kenya

At every spawning cycle, fry are typically moved to nursery ponds [18]. These are commonly open ponds, but tanks and hapas in ponds are also used [51]. 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 [3, 18, 33]. 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 [52, 53].

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 [18, 51]. 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 [3]. Moreover, the use of 17a- methyl testosterone is not necessarily considered safe as it can negatively affect biodiversity and the dynamics of the aquatic environment [54].

Males and females are typically kept separately for several weeks before pairing to create a narrower spawning window [18]. 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 [3, 18, 51]. 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 [51]. This also comes with obvious welfare concerns associated with any handling procedure that inherently generates more fish stress. Hybridisation is also performed, where two subspecies of tilapia are crossed to produce a higher proportion of males [55].

In Kenya, three fingerling production technologies have been noted [36]:

- the application of selective breeding for Nile tilapia and African catfish to enhance their desirable traits;
- the use of hormonal sex reversal to generate all-male tilapia fingerlings for reproductive control and to enhance their marketability; and
- the mass production of catfish fingerlings through artificial propagation, achieved by the use of pituitary hormone injections.

However, concerns have been raised regarding the use of hormonal treatments, as they may impact consumer acceptance due to potential residues affecting water quality and biodiversity. Despite the widespread adoption of hormones in monosex aquaculture, their usage may alter various physiological aspects, potentially affecting fish susceptibility to diseases and opportunistic infections, as well as contributing to environmental pollution.

Cannibalism in catfish fingerlings is a fundamental issue in hatcheries It is estimated that cannibalism is responsible for more than 50% of juvenile African catfish mortality. Thus, it is advised that size grading is performed after three weeks to homogenise size classes and reduce cannibalism phenomena. However, Kenyan hatcheries have started to put effective measures in place in order to reduce its prevalence for example through the adoption of grading procedures [56]. Cannibalism in stocked African catfish can occur due to their varying growth rates (despite being the same age, also known as allometric growth) [56]. As well as grading fish, enhancing and optimising feed rations can help to minimise cannibalism [57]. However, there are welfare concerns associated with grading, as any handling procedure is known to cause stress and potential physical damage to fish [58].

When it comes to training, staff lacks certain skills, though the government has made efforts to address this deficiency. Specifically, in 2009, the National Aquaculture Research Development and training Centre initiated a training program for hatchery managers, while a certification and accreditation system related to seed production was also developed [18].

6 The effects of feed management and nutrition on farmed fish welfare

Fish feed equates to 40–70% of the total cost of aquaculture production [17, 31]. Most fish feed in Kenya is produced by the private sector, and many of the ingredients are imported, 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 [17, 19, 59]. The lack of high-quality, affordable feed is one of the most significant challenges for the aquaculture industry in Kenya [60]. The use of locally mixed feed ingredients creates a potential welfare concern as the ingredients selected are not always chosen based on the fish species in question's nutritional needs, but more so on the affordability of the farmer. For example, the use of cereal by-products is not conducive to optimal fish nutrition [61]. Similarly, the use of slaughter by-products as an ingredient poses potential biosecurity risks.

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 screen manufacturing practices [17]. These standards were developed via consultations with stakeholders in the aquaculture sector and the Kenya Bureau of Standards [62]. 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 [59, 62].

Small-scale commercial feeds typically consist of plant-based ingredients, such as rice bran or maize 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*) [59]. There are several other locally available feed materials and ingredients commonly used by fish farmers in Kenya.

On-farm feeds are typically deficient in essential macronutrients and micronutrients and lack important amino acids such as methionine and lysine, which has significant ramifications for optimal fish welfare [63]. 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 [17]. Farmers who make their own feeds tend to produce them in mash, crumbles, or create sinking pellets as they do not have the extruders needed for floating pellets [59]. This lack of equipment leads to issues, as the reduced quality of feeds produced on-farm and from cottage producers 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. Furthermore, due to poor capacity, the quantity of feed produced is often insufficient to meet the fishes' needs [59]. As a result, the welfare of the fish is likely to be impaired in the absence of high-quality commercial fish feed. In particular, the lack of floating pellets means it is hard for farmers to assess feeding rates and feed apprehension behaviours, i.e., the proportion of feed that is consumed by the stocked fishes in a given amount of time [73].

Conversely, large-scale commercial pellet feeds comprise a complete diet, although most animal feed manufacturers in Kenya produce feed for livestock, and only a small handful produce fish feed [59]. Due to the cost of commercial pellet feed, they are geared more towards intensive farms, which are fewer in number [21]. All of these factors have consequences for fish welfare, as undigested feed can lead to poor water quality and malnutrition [73]. To address issues regarding the cost and quality of aquafeeds in Kenya, it is suggested to identify and introduce alternative feed ingredients from plants that are rich in protein, to develop cost-effective diets that meet the nutritional needs of the reared species and reduce the use of traditional protein sources [36].

6.1 Feed delivery

In Kenyan semi-intensive inland aquaculture systems, fingerlings are typically fed at least three times a day at 3% of their body weight, with diets containing 30–40% crude protein (CP) [62]. 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) and sometimes only even once with feeds containing 26–30% CP [62]. Feeding is commonly scheduled around 10:00 AM and 4:00 PM, usually at the same location, to ensure optimum levels of dissolved oxygen [62].

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 [62]. The lack of natural food sources in cages can create an additional source of stress for fish thereby potentially worsening their welfare.

Improper feeding techniques can present an important welfare issue in Kenyan aquaculture. 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 [21]. This can result in undernutrition and variation in growth rates which presents both welfare issues to the animals and economic issues to the farmers. Access to good quality nutrition is a key pillar of animal welfare. Furthermore, unless good record-keeping is routinely performed, farmers struggle to adjust the daily feed quantities when required [62].

Knowledge and skills in monitoring, recording, and calculating feed requirements and efficiencies are vital in ensuring the health, welfare 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 [21]. 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, such as poor water quality and economic losses [21]. It is known [77, 78] that less feeding can reduce growth and cause economic loss while overfeeding might result not only in economic losses due to feed waste but also cause stress and obesity in fish [21].

However, some interesting innovations in Kenyan aquaculture could improve feeding techniques while maintaining the use of on-farm feeds [21]. For instance, as powdered feed is typically wasted when it disperses, the adoption of bag feeding, where the feed is placed in bags throughout the pond, could allow the fish to feed on demand whilst minimising waste, improving feed ingestion rates and achieving higher retention rates [17, 21].

7 Water sources

Kenya is a water-scarce country; therefore, water availability is a key concern and often a deterrent for prospective farmers [64]. This is one of the reasons why many inland fish farmers use lined ponds instead of earthen ponds so that the water does not infiltrate the soil as fast (*i.e.*, to improve water retention capacity) [19]. Droughts and floods are endemic and frequent in Kenya and are often the reason why farmers choose to cease aquaculture production [65]. Inland aquaculture systems need between 35,000 and 60,000 m^3/ha/year of water for a pond depth of 1.5 m during a 240-day growing cycle, which accounts for estimated losses of 1-2 cm/day [66]. There is a risk, therefore, that water use for aquaculture may conflict with other water users, especially during droughts [65]. 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 [65].

The main water sources for aquaculture activities in Kenya are groundwater, lakes, well water, and rivers [19, 64]. In some places, shallow wells and municipal tap water are also used [19]. 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 [19]. Water treatment is not commonly performed, which risks introducing parasites, polluted water, wild fish, and predators from the water source into the aquaculture facility [65, 67]. The source of water comes with its own welfare concerns in terms of suboptimal water quality which might impair fish welfare.

Finally, Kenyan aquaculture needs to adapt to climate change. The increasing water scarcity requires the implementation of efficient management plans so that the sector can maintain its growth to meet the country's demand on aquatic products [3].

8 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 stocked fishes, financial losses, and potentially wider health and environmental risks [14]. 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 [23]. For example, the addition of raw livestock manure to the ponds and the practice of stocking fish at high densities can lead to elevated levels of nitrates, nitrites and ammonia in water which can be detrimental to fish health and welfare [23]. Moreover, fish stressed from high stocking densities and poor water quality are more susceptible to infections than healthy fish that are more resilient and have good welfare [23].

Keeping fish in optimum environments and giving them nutritious diets appropriate to their life stage is vital to mitigating the increasing risk of aquatic diseases, as are biosecurity and quarantining measures. Optimal ranges of nutrition depend on the farmed species, their life stage and the farming system in question and are best obtained from the feed manufacturers directly. As such, this review will not outline specific ranges. Preventative measures are particularly important in Kenya, given that few specialists in fish diseases are reportedly available to farmers [37]. 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 [37].

8.1 Disease prevalence and mortalities

In Western Kenya, it has been reported that up to 76% of fish farmers experienced mortalities in their hatcheries and farms [14]. The average loss rate was around 10% of their total production per farm, although 2% of farms reported mortalities exceeding half of their stocked fish [14]. 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 [14].

Some farmers in Kenya have reported significant fish mortalities in cages and ponds, ranging from 40–100% of their stock [26, 27, 37]. 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 [37, 68].

As discussed earlier in this review, high mortality rates are a significant issue in Kenyan hatcheries, and many mortalities are due to bacterial and fungal infections [69]. In particular, small-scale hatcheries often have higher mortality rates due to inadequate biosecurity measures and poor management practices that fail to prevent infections [69]. The most frequently reported diseases in fish farms include fungal infections (primarily *Saprolegnia*) and bacterial infections (mainly haemorrhagic and popeye diseases) [18, 68]. 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 [69, 70].

The use of chemicals and prophylactic treatments in Kenya takes place mostly on large-scale farms, mainly because they also own their own hatchery [72]. In 2019, the average value of vaccines and medicine use in Kenyan aquaculture was around 60, 000 KSH [32]. 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 which presents its own concerns [61, 70].

Treatments in hatcheries are typically administered during the egg incubation stage or at the fry stages to enhance the survival of hatched fry [23]. 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 [71]. Antibiotics are reported to be used by a very small percentage of Kenyan farmers, while a very small percentage of intensive farms use the probiotic *Bacillus subtilis* which is administered through both feed and culture water. *B. subtilis* is reported to boost fish immunity and growth as well as improve the organoleptic characteristics [72].

There is also an important lack of knowledge on the consequences of the use of several chemicals on the environment and on human health [72]. National awareness campaigns have resulted in a partial comprehension of antimicrobial resistance and the more responsible use of antibiotics. However, it is still necessary to raise awareness among farmers on fish health management and the consequences of inappropriate use of antimicrobials in aquaculture [71].

According to the Kenya Marine and Fisheries Research Institute, health management requires investments not only on skilled personnel but also on therapeutants' research, equipped facilities such as laboratories and quarantine facilities, policy making, disease monitoring and plans to increase stakeholder engagement. The State Department for Fisheries and Blue Economy has already set up three laboratories but are still lacking commissioning [3].

9 Transport and slaughter

Transport and slaughter are two practices which are closely related to animal welfare. Generally, the massive capture and overcrowding during the transport pre-slaughter and slaughter can be associated with poor welfare due to injuries, excessive production of mucus, loss of scales, gill damage, muscle bruising, bone fractures and exposure to extreme environmental conditions such as low dissolved oxygen, luminosity and water quality shock [73].

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 market or slaughter size faster [37]. Wholesale traders often directly purchase fish from farmers [37]. 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 [37].

Exposure to stressors such exposure to extreme luminosity or poor air quality linked to transportation or the pre- and post-transport phase, can cause severe physiological stress which may lead to severe mortalities and financial losses [73]. Fish transported using ice-filled polytene bags can undergo physical damage and exposure to microorganisms, whilst transported 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 [74]. In general, aquaculture regulations in Kenya are still in the initial stages so fish transport legislation is still quite vague [15]. Moreover, the lack of appropriate reporting and knowledge among farmers can lead to a decrease in welfare during transportation due to overcrowding, mishandling and poor water quality leading to increase to increased stress and mortalities.

To mitigate the significant challenges associated with transporting fish, several best practices could be employed to improve fish welfare. Generally, minimising the physical stress associated with handling is beneficial. Efforts should be made to move fish without removing them from the water whenever possible, as this practice reduces air exposure and physical damage [84]. Additionally, maintaining appropriate hauling densities is vital to avoid stress caused by overcrowding and elevated temperatures. These densities should be tailored to the specific species and consider the duration of transport [75, 76].

The use of temperature-controlled tanks equipped with aerators to maintain optimal oxygen concentrations during transport can improve fish welfare [86]. Utilising thermally non-conductive materials like polyurethane for tank construction can help maintain the temperature of the tank, thereby reducing stress on the fish [75, 76, 86]. Osmoregulatory stress, which is common during transportation, can be alleviated by adding salt to the transport water. However, the specific concentrations of salt required must be determined for each species to avoid adverse effects [85]. If ice is used for cooling and it is made from a chlorinated water source, it is essential to add sodium thiosulphate or sodium sulphite to remove residual chlorine and prevent toxicity [86].

There are no slaughterhouses for fish in Kenya currently.

10 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 related to the farming practices themselves which are limited by poor water quality, welfare measures, biosecurity, and improperly formulated or costly feeds [10, 13]. However, these challenges extend beyond caring for the fish themselves and include:

- Insufficient supply of high-quality (and affordable) fry and fingerlings.
- Slow adoption rate of fish farming technologies, innovations, and management practices.
- Absence of technical support and uptake for training programmes specifically designed for Kenyan fish farmers.
- High initial start-up costs and high risks of loss with their consequences for welfare.

- Insufficient numbers of extension personnel, resulting in less monitoring of farms and a reduced ability to help fish farmers resolve issues (and its associated impacts on fish welfare).
- Inadequate regulatory and legal framework for certifying fish feed and fertilised eggs, and ensuring production, supply, and quality compliance which reduce incentives for achieving good fish welfare.
- Emerging fish diseases and their consequences for fish health and welfare

The consequences of these challenges are wide-ranging, from endangering food security in Kenya to limiting the livelihoods of the farmers within the industry and compromising the welfare of the fish. This review has explored some of the latest successes and challenges the Kenyan aquaculture has experienced and used an animal welfare approach to identify the practices where fish welfare is likely to be particularly low.

To address these challenges effectively, raising awareness and providing education on sustainable and high welfare practices should be key policy recommendations. Additionally, offering targeted support and practical skills training to women and youth could facilitate the adoption of sustainable aquaculture practices and improve overall sector performance. As efforts to intensify aquaculture production in Kenya continue, addressing these concerns through education and targeted support is crucial to mitigating further adverse impacts on both human and animal welfare.

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Declarations

Competing interests The authors declare no competing interests.

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References

1. KilimoSTAT. Agricultural Sector Transformation and Growth Strategy. Towards Sustainable Agricultural Transformation and Food Security in Kenya. 2019–2029. Ministry of Agriculture and Livestock Development; 2019:216.
2. KilimoSTAT. Agricultural Census, 2019. Distribution of Aquaculture Households by Sub-sector and County. Published 2019. https://statistics.kilimo.go.ke/en/2_3d/. Accessed 29 Apr 2024.
3. Munguti J, Obiero K, Orina P, et al. State of aquaculture in Kenya. WestLink Services Limited, Nairobi, Kenya. Published online 2017
4. Ogello E, Munguti J. Aquaculture: a promising solution for food insecurity, poverty and malnutrition in Kenya. Afr J Food Agric Nutr Dev. 2016;16(4):11331–50.
5. Hinrichsen E, Walakira JK, Langi S, et al. Prospects for Aquaculture Development in Africa: A review of past performance to assess future potential. Published online 2022.
6. Aloo P, Charo-Karisa H, Munguti J, Nyonje B. A review on the potential of aquaculture development in Kenya for poverty alleviation and food security. Afr J Food Agric Nutr Dev. 2017;17(1):11832–47.
7. OECD/FAO. Agriculture in Sub-Saharan Africa: Prospects and challenges for the next decade. Published online 2016:59–95.
8. Obiero K, Cai J, Abila R, Ajayi O. Kenya: High aquaculture growth needed to improve food security and nutrition. Rome, Italy http://www.fao.org/3/ca4693en/ca4693en.pdf. Published online 2019.
9. FAO. Aquaculture Growth Potential in Eastern Africa – WAPI Factsheet. Food and Agriculture Organistion of the United Nations; 2023:99.
10. Odende T, Ogello EO, Iteba JO, et al. Promoting sustainable smallholder aquaculture productivity through landscape and seascape aquapark models: A case study of Busia County. Kenya Front Sustain Food Syst. 2022. https://doi.org/10.3389/fsufs.2022.898044.
11. Msuya FE, Bolton J, Pascal F, Narrain K, Nyonje B, Cottier-Cook EJ. Seaweed farming in Africa: current status and future potential. J Appl Phycol. 2022;34(2):985–1005. https://doi.org/10.1007/s10811-021-02676-w.

12. Alando P. The pros and cons of pond vs cage aquaculture in Kenya. The Fish Site. Published May 25, 2022. https://thefishsite.com/articles/the-pros-and-cons-of-pond-vs-cage-aquaculture-in-kenya. Accessed 10 Nov 2023.
13. Munguti J, Obeiro K, Orina P, et al. State of aquaculture report 2021: towards nutrition sensitive fish food production systems. Nairobi: Techplus Media House. 2021;190.
14. Kyule-Muendo D, Otachi E, Awour F, et al. Status of fish health management and biosecurity measures in fish farms, cages and hatcheries in Western Kenya. CABI Agriculture and Bioscience. 2022;3(1):18.
15. FAO. National Aquaculture Sector Overview - Kenya. Published 2023. https://www.fao.org/fishery/en/countrysector/ke/en
16. Munguti J, Iteba JO, Munguti J, Iteba JO. Advances in African Catfish (*Clarias Gariepinus*) Seed-Production Techniques in Kenya. In: Catfish - Advances, Technology, Experiments. IntechOpen; 2022. https://doi.org/10.5772/intechopen.105665
17. Munguti J, Kim JD, Ogello EO. An overview of Kenyan aquaculture: Current status, challenges, and opportunities for future development. Published online 2014.
18. Nyonje B, Opiyo M, Orina P, Abwao J, Wainaina M, Charo-Karisa H. Current status of freshwater fish hatcheries, broodstock management and fingerling production in the Kenya aquaculture sector. Livest Res Rural Dev. 2018;30(1):1–15.
19. Opiyo MA, Marijani E, Muendo P, Odede R, Leschen W, Charo-Karisa H. A review of aquaculture production and health management practices of farmed fish in Kenya. International journal of veterinary science and medicine. 2018;6(2):141–8.
20. IFAD. Aquaculture Business Development Programme. IFAD: East and Southern Africa Division Programme Management Department; 2017:209.
21. Munguti J, Obiero K, Odame H, et al. Key limitations of fish feeds, feed management practices, and opportunities in Kenya's aquaculture enterprise. Afr J Food Agric Nutr Dev. 2021;21(2):17415–34.
22. Van De Vis H, Kolarevic J, Stien LH, et al. Welfare of Farmed Fish in Different Production Systems and Operations. In: Kristiansen TS, Fernö A, Pavlidis MA, Van De Vis H, eds. The Welfare of Fish, Vol 20. Animal Welfare. Springer International Publishing; 2020:323–361. https://doi.org/10.1007/978-3-030-41675-1_14
23. Wanja DW, Mbuthia PG, Waruiru RM, et al. Fish husbandry practices and water quality in central kenya: potential risk factors for fish mortality and infectious diseases. Vet Med Int. 2020;2020: e6839354. https://doi.org/10.1155/2020/6839354.
24. Lertwanakarn T, Purimayata T, Luengyosluechakul T, et al. Assessment of Tilapia (*Oreochromis* spp.) welfare in the semi-intensive and intensive culture systems in Thailand. Animals. 2023;13(15):2498. https://doi.org/10.3390/ani13152498.
25. Macharia S, Kimani A. Kenya fish farming enterprise productivity capacity assessment and gap analysis report. State Department of Fisheries and Blue Economy, Kenya. Published online 2016.
26. Aura CM, Musa S, Yongo E, et al. Integration of mapping and socio-economic status of cage culture: towards balancing lake-use and culture fisheries in Lake Victoria, Kenya. Aquac Res. 2018;49(1):532–45.
27. Njiru J, Aura C, Okechi J. Cage fish culture in Lake Victoria: a boon or a disaster in waiting? Fish Manage Ecol. 2019;26(5):426–34.
28. Orina P, Ogello E, Kembenya E, et al. The state of cage culture in Lake Victoria: a focus on sustainability, rural economic empowerment, and food security. Aquat Ecosyst Health Manage. 2021;24(1):56–63. https://doi.org/10.14321/aehm.024.01.09.
29. Sabwa JA, Manyala JO, Masese FO, Fitzsimmons K, Achieng AO, Munguti JM. Effects of stocking density on the performance of lettuce (Lactuca sativa) in small-scale lettuce-Nile tilapia (*Oreochromis niloticus* L.) aquaponic system. Aquac Fish Fisheries. 2022;2(6):458–69. https://doi.org/10.1002/aff2.71.
30. Palm HW, Knaus U, Appelbaum S, et al. Towards commercial aquaponics: a review of systems, designs, scales and nomenclature. Aquacult Int. 2018;26(3):813–42. https://doi.org/10.1007/s10499-018-0249-z.
31. Obirikorang KA, Sekey W, Gyampoh BA, Ashiagbor G, Asante W. Aquaponics for improved food security in Africa: a review. Front Sustai Food Syst. 2021. https://doi.org/10.3389/fsufs.2021.705549.
32. KNBS. Census of commercial and institutional farms and speciality crops. Ministry of Agriculture, Livestock, Fisheries and Cooperatives; 2022.
33. Orina PS, Maina JG, Wangia SM, et al. Situational analysis of Nile tilapia and African catfish hatcheries management: a case study of Kisii and Kirinyaga counties in Kenya. Livestock Res Rural Dev. 2014;26:8.
34. Abwao J, Jung'a J, Barasa JE, et al. Selective breeding of Nile tilapia, *Oreochromis niloticus*: A strategy for increased genetic diversity and sustainable development of aquaculture in Kenya. J Appl Aquac. Published online 2021:1–20.
35. MWEA. Nile tilapia Fingerling production, Quality Fingerlings in Kenya. About Us. Published 2023. https://mweafish.com/about-us/tilapia.html. Accessed 14 Nov 2023.
36. Obiero KO, Waidbacher H, Nyawanda BO, Munguti JM, Manyala JO, Kaunda-Arara B. Predicting uptake of aquaculture technologies among smallholder fish farmers in Kenya. Aquacult Int. 2019;27(6):1689–707. https://doi.org/10.1007/s10499-019-00423-0.
37. Munguti J, Nairuti R, Iteba JO, et al. Nile tilapia (*Oreochromis niloticus* Linnaeus, 1758) culture in Kenya: Emerging production technologies and socio-economic impacts on local livelihoods. Aquaculture, Fish and Fisheries. 2022;2(4):265–76.
38. Magondu EW, Rasowo J, Oyoo-Okoth E, Charo-Karisa H. Evaluation of sodium chloride (NaCl) for potential prophylactic treatment and its short-term toxicity to African catfish *Clarias gariepinus* (Burchell 1822) yolk-sac and swim-up fry. Aquaculture. 2011;319(1–2):307–10.
39. Rasowo J, Okoth OE, Ngugi CC. Effects of formaldehyde, sodium chloride, potassium permanganate and hydrogen peroxide on hatch rate of African catfish *Clarias gariepinus* eggs. Aquaculture. 2007;269(1–4):271–7.
40. Marimuthu K. A short review on induced spawning and seed production of African Catfish *Clarias gariepinus* in Malaysia. IOP Conf Ser: Earth Environ Sci. 2019;348(1): 012134. https://doi.org/10.1088/1755-1315/348/1/012134.
41. Barassa J. Enhancing Sustainability in African catfish Seed Supply for Improved Production in Kenya. Published online 2020. http://erepository.uonbi.ac.ke/handle/11295/154910. Accessed 16 nov 2023.
42. Marimuthu K, Haniffa MA. Induced spawning of native threatened spotted snakehead fish *Channa punctatus* with ovaprim. Asian Fish Sci. 2010;23(1):60–70.
43. Macharia SK, Ngugi CC, Rasowo J. Comparative study of hatching rates of African Catfish (*Clarias gariepinus* Burchell 1822) eggs on different substrates. NAGA WorldFish Center Q. 2005;28(3 & 4):23–6.
44. MWEA. Catfish Fingerling Production, Quality Fingerlings in Kenya. About Us. Published 2023. https://mweafish.com/about-us/catfish.html. Accessed 14 Nov 2023.

45. Giri SS, Sahoo SK, Sahu AK, Meher PK. Effect of dietary protein level on growth, survival, feed utilisation and body composition of hybrid Clarias catfish (*Clarias batrach*us\times *Clarias gariepinus*). Anim Feed Sci Technol. 2003;104(1–4):169–78.
46. Garcıa-Ortega A, Verreth JAJ, Coutteau P, Segner H, Huisman EA, Sorgeloos P. Biochemical and enzymatic characterization of decapsulated cysts and nauplii of the brine shrimp *Artemia* at different developmental stages. Aquaculture. 1998;161(1–4):501–14.
47. Kibria G, Nugegoda D, Fairclough R, Lam P, Bradly A. Zooplankton: Its biochemistry and significance in aquaculture. Published online 1997. https://aquadocs.org/handle/1834/25882. Accessed 16 Nov 2023.
48. Ekasari J, Suprayudi MA, Wiyoto W, et al. Biofloc technology application in African catfish fingerling production: the effects on the reproductive performance of broodstock and the quality of eggs and larvae. Aquaculture. 2016;464:349–56.
49. Munguti J, Musa S, Orina PS, et al. An overview of current status of Kenyan fish feed industry and feed management practices, challenges and opportunities. Published online 2014.
50. Nairuti RN, Musyoka SN, Yegon MJ, Opiyo MA. Utilization of black soldier fly (*Hermetia illucens* Linnaeus) larvae as a protein source for fish feed–a review. Aquac Stud. 2021. https://doi.org/10.4194/AQUAST697.
51. Towers L. Hatchery management and tilapia fingerling production. The Fish Site. Published January 19, 2015. https://thefishsite.com/articles/hatchery-management-and-tilapia-fingerling-production. Accessed 14 Nov 2023.
52. Dagne A, Degefu F, Lakew A. Comparative Growth Performance of Mono-sex and Mixed-sex Nile Tilapia (*Oreochromis niloticus* L.) in Pond Culture System at Sebeta, Ethiopian. Int J Aquac. 2013;3.
53. Mlalila N, Mahika C, Kalombo L, Swai H, Hilonga A. Human food safety and environmental hazards associated with the use of methyltestosterone and other steroids in production of all-male tilapia. Environ Sci Pollut Res. 2015;22(7):4922–31. https://doi.org/10.1007/s11356-015-4133-3.
54. Thanasupsin SP, Chheang L, Math C. Ecological risk of 17α-methyltestosterone contaminated water discharged from a full water recirculating earthen masculinization pond. Human and Ecological Risk Assessment: An International Journal. Published online June 7, 2021. https://doi.org/10.1080/10807039.2021.1871845
55. Felix E, Avwemoya FE, Abah A. Some methods of monosex tilapia production: a review. Int J Fish Aquat Res. 2019;4(2):42–9.
56. Baras E, Jobling M. Dynamics of intracohort cannibalism in cultured fish: Cannibalism in cultured fish. Aquac Res. 2002;33(7):461–79. https://doi.org/10.1046/j.1365-2109.2002.00732.x.
57. Batzina A, Drossos IP, Karakatsouli N. Effects of grading on individual growth and feeding behaviour of European seabass *Dicentrarchus labrax*. Aquac Res. 2018;49(12):3759–68. https://doi.org/10.1111/are.13843.
58. Dunlop RA, Laming PR, Smith TE. The Stress of four commercial farming practices, feeding, counting, grading and harvesting, in farmed rainbow trout, *Oncorhynchus mykiss*. Mar Freshw Behav Physiol. 2004;37(3):179–92. https://doi.org/10.1080/10236240400006133.
59. Munguti J, Kirimi JG, Obiero KO, et al. Critical aspects of aquafeed value chain in the Kenyan aquaculture sector—a review. SAR. 2021;10(2):87. https://doi.org/10.5539/sar.v10n2p87.
60. Munguti J, Charo-Karisa H, Opiyo M, et al. Nutritive value and availability of commonly used feed ingredients for farmed Nile tilapia (*Oreochromis niloticus* L) and African catfish (*Clarias gariepinus*, Burchell) in Kenya Rwanda and Tanzania. AJFAND. 2012;12(3):6135–55.
61. Emam W, El-Rewiny MN, Abou Zaid AA, El-Tras WF, Mohamed RA. Trends in the use of feed and water additives in Egyptian tilapia culture. Aquac Res. 2022;53(9):3331–6.
62. Munguti J, Odame H, Kirimi J, Obiero K, Ogello E, Liti D. Fish feeds and feed management practices in the Kenyan aquaculture sector: Challenges and opportunities. Aquat Ecosyst Health Manag. 2021;24(1):82–9.
63. Kirimi JG, Musalia LM, Magana A, Munguti JM. Protein quality of rations for Nile tilapia (*Oreochromis niloticus*) containing oilseed meals. Published online 2020.
64. Jacobi N. Examining the potential of fish farming to improve the livelihoods of farmers in the Lake Victoria Region. Kenya: Assessing Impacts of Governmental Support. University of Akureyri; 2013.
65. Obwanga B, Lewo M, Bolman B, van der Heijden P. From Aid to Responsible Trade: Driving Competitive Aquaculture Sector Development in Kenya: Quick Scan of Robustness, Reliability and Resilience of the Aquaculture Sector. Wageningen University & Research; 2017.
66. Larsson B. Three Overviews on Environment and Aquaculture in the Tropics and Sub-Tropics. FAO; 1994. Accessed November 16, 2023. https://www.fao.org/3/ad002e/AD002E00.htm#TOC. Accessed 16 Nov 2023.
67. Ngugi CC, Bowman JR, Omolo BO. A New Guide to Fish Farming in Kenya. Oregon State University, College of Agricultural Science , Aquaculture CRSP; 2007. http://hdl.handle.net/1834/7172. Accessed 15 Nov 2023.
68. Akoll P, Mwanja W. Fish health status, research and management in East Africa: past and present. Afr J Aquat Sci. 2012;37(2):117–29.
69. Njagi I. Overcoming challenges to export in kenyan. aquaculture. Published online 2016
70. Walakira J, Akoll P, Engole M, et al. Common fish diseases and parasites affecting wild and farmed Tilapia and catfish in Central and Western Uganda. Uganda J Agric Sci. 2014;15(2):113–25. https://doi.org/10.4314/ujas.v15i2.
71. Madara E, Benton L, Heffernan C, Gitahi N. Antimicrobial use and practice in aquaculture production systems in Nairobi, Kenya. Published online 2022
72. Nzeve J, Muendo P, Opiyo M, Odede R, Leschen W. Fish health knowledge, management practices and prophylactic health products usage in aquaculture systems in Kenya. J Appl Aquac. Published online 2022:1–13.
73. Pedrazzani AS, Quintiliano MH, Bolfe F, Sans ECDO, Molento CFM. Tilapia on-farm welfare assessment protocol for semi-intensive production systems. Front Vet Sci. 2020;7: 606388. https://doi.org/10.3389/fvets.2020.606388.
74. European Commission. Welfare of Farmed Fish: Common Practices during Transport and at Slaughter; 2017.
75. Fang, D., Mei, J., Xie, J., & Qiu, W. (2023). The effects of transport stress (temperature and vibration) on blood biochemical parameters, oxidative stress, and gill histomorphology of pearl gentian groupers. *Fishes, 8*(4), 218. https://doi.org/10.3390/fishes8040218
76. Sun M, Hassan SG, Li D. Models for estimating feed intake in aquaculture: A review. Comput Electron Agric. 2016;127:425. https://doi.org/10.1016/j.compag.2016.06.024.
77. Park J, Roh HJ, Park J, et al. Overfeeding-induced obesity in rainbow trout (*Oncorhynchus mykiss*) linked to higher susceptibility to infection. Aquaculture. 2024. https://doi.org/10.1016/j.aquaculture.2023.740296.
78. Garcia F, Romera DM, Gozi KS, et al. Stocking density of Nile tilapia in cages placed in a hydroelectric reservoir. Aquaculture. 2013;410–411:51–6. https://doi.org/10.1016/j.aquaculture.2013.06.010.

79. Ellison AR, Uren Webster TM, Rey O, Garcia de Leaniz C, Consuegra S, Orozco-terWengel P, Cable J. Transcriptomic response to parasite infection in Nile tilapia (Oreochromis niloticus) depends on rearing density. BMC Genomics. 2018;19:723. https://doi.org/10.1186/s12864-018-5085-7
80. Shoko AP, Limbu SM, Mrosso HD, Mgaya YD. Effect of stocking density on the growth performance, survival, yield, and profitability of African catfish (Clarias gariepinus) grow-out culture in earthen ponds. J Appl Aquac. 2016;28(1):9–22.
81. Barcellos LJG, Nicolaiewsky S, De Souza SMG, Lulhier F. The effects of stocking density and social interaction on acute stress response in Nile tilapia (*Oreochromis niloticus*) fingerlings. Aquac Res. 2009;40(4):345–52.
82. Ministry of Mining, Blue Economy and Maritime Affairs, 2022 Fisheries Statistical Bulletin, Published 2023. https://kefs.go.ke/sites/default/files/Fisheries%20Annual%20Statistic%202022_0.pdf
83. Maule AG, Schreck CB, Samual BC, Barton BA. Physiological effects of collecting and transporting emigrating juvenile chinook salmon past dams on the Columbia River. Trans Am Fish Soc. 1988;117:245–61.
84. Mazic PM, Simco BA, Parker NC. Influence of water hardness and salts on survival and physiological characteristics of striped bass during and after transport. Trans Am Fish Soc. 1991;120:121–6.
85. Todd S. Harmon. (2009). Methods for reducing stressors and maintaining water quality associated with live fish transport in tanks: a review of the basics. , 1(1), 58–66. https://doi.org/10.1111/j.1753-5131.2008.01003.x
86. Wedemeyer GA. Physiology of Intensive Culture Systems. New York: Chapman and Hall; 1996.

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