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REVIEW ARTICLE

Nile tilapia (*Oreochromis niloticus* Linnaeus, 1758) culture in Kenya: Emerging production technologies and socio-economic impacts on local livelihoods

Jonathan M. Munguti[1] | **Rita Nairuti**[1] | **Jacob O. Iteba**[2] | **Kevin O. Obiero**[3] | **Domitila Kyule**[1] | **Mary A. Opiyo**[1] | **Jacob Abwao**[1] | **James G. Kirimi**[4] | **Nicholas Outa**[6] | **Mavindu Muthoka**[6] | **Cecilia M Githukia**[5] | **Erick O. Ogello**[6]

[1]Kenya Marine and Fisheries Research Institute (KMFRI), National Aquaculture Research Development and Training Center (NARDTC), Sagana, Kenya

[2]Directorate of Fisheries, County Government of Busia, Kenya

[3]Kenya Marine and Fisheries Research Institute (KMFRI), Sangoro Aquaculture Research Center, Pap Onditi, Kenya

[4]Department of Animal Sciences, Chuka University, Chuka, Kenya

[5]Kenya Marine and Fisheries Research Institute (KMFRI), Kegati Aquaculture Research Center, Kisii, Kenya

[6]Department of Animal and Fisheries Sciences, Maseno University, Maseno, Kenya

Correspondence
Jonathan M. Munguti, National Aquaculture Research Development and Training Center (NARDTC), Kenya Marine and Fisheries Research Institute (KMFRI), P. O. Box 451, Sagana, Kenya.
Email: jmunguti2000@gmail.com

Abstract

Nile tilapia (*Oreochromis niloticus*) is one of the most farmed fish globally, with a significant contribution improving local livelihoods, especially in developing countries. Nile tilapia was first cultured in Kenya in 1924 and is the most cultured fish species. Annually, *O. niloticus* accounts for 62% (∼15,000 tonnes) of total aquaculture production. Although *O. niloticus* is the most preferred cultured fish, its culture faces challenges, for example, early maturation due to prolific breeding behaviour leading to stunted growth that limits its culture and profitability among smallholder farmers. With the surging demand for locally farmed fish, innovative technologies have emerged to boost aquaculture production. Donor and public research-funded projects, for instance, the Kenya Climate Smart Agriculture Project, are validating various aquaculture technologies, innovations and management practices (TIMPs) to achieve 'triple wins' of increased fish production, improved resilience and reduced greenhouse gas emissions. In addition, the International Fund for Agricultural Development (IFAD)-funded Aquaculture Business Development Programme aims at commercialising aquaculture to improve local livelihoods. In this study, we adopt a scoping review methodology to review and synthesise published literature on tilapia culture in Kenya to explore current and emerging tilapia production technologies and document their socio-economic impacts on farmers' livelihoods. These emerging innovative technologies range from culture systems, for example, biofloc, periphyton, fingerpond technology, integrated aquaculture, breeding and genetics (selective breeding), fish health and biosecurity measures, to post-harvest loss reduction, value addition and marketing. The study findings reveal that the technologies have great potential to increase tilapia production and profitability and positively impact the local livelihoods of smallholder fish farmers through employment creation, economic growth and better nutrition.

KEYWORDS
aquaculture, livelihoods, sustainability, technology innovation and management practices (TIMPS), tilapia culture

1 | INTRODUCTION

Tilapias are among the most important warm-water fishes used for aquaculture production (Kumar & Engle, 2016). Several illustrations from the Egyptian tombs reveal that the culture of tilapia dates back 3000 years ago (El-Sayed, 2013). Tilapia is native to Africa but was introduced into other tropical, sub-tropical and temperate regions of the world during the second half of the 20th century to boost capture fishery, due to their high elasticity and tolerance to environmental and ecological factors (El-Sayed, 2006). Currently, over 140 countries in the world are involved in the culture and commercial trading of tilapia (Fitzsimmons, 2016; Kaleem & Sabi, 2021). The global harvest of farmed tilapia has surpassed 6 million tonnes (MT), placing tilapia second to carps as the most widely farmed freshwater fish in the world (Abwao et al., 2021; FAO, 2020). By 2030, global tilapia production is expected to reach 7.3 MT (FAO, 2020). Currently, the top tilapia producers are China (1.78 MT), Indonesia (1.12 MT) and Egypt (0.88 MT; FAO, 2017; Jansen et al., 2019; Yue et al., 2016). Philippines, Thailand, Honduras, Ecuador, Costa Rica and Ghana are also significant producers of tilapia (Yue et al., 2016; FAO, 2020).

Approximately 70 species of tilapia have been identified globally. Among the wide variety of tilapia, Nile tilapia (*Oreochromis niloticus* L.) is the most cultured species, and the need for a systematic effort to secure and further improve the genetic quality of farmed stocks is widely recognised (Bentsen et al., 2012; Popma & Masser, 1999). The first culture of tilapia was recorded in 1924 in Kenya and thereafter spread throughout Africa (Adeleke et al., 2020; Shrestha et al., 2018). Nile tilapia possesses many attributes making it an excellent candidate for warm water aquaculture, including fast growth rates, high tolerance to a wide range of environmental conditions, resistance to stress and diseases, ability to reproduce in captivity, a short generation time, ability to feed at a low trophic level and acceptance of artificial feeds immediately after yolk-sac absorption (Ng & Romano, 2013). Some of the other tilapia species with aquaculture potential (though not discussed in detail in this review) include *O. mozambicus*, *O. sarotherodon*, *O. aureus* and *O. jipe*. Some of these species are under study in various research institutes at Kenya like Kenya Marine and Fisheries Research Institute (KMFRI). *Oreochromis jipe*, for example, has been shown to have great potential for domestication and incorporation into aquaculture by a research by Omweno et al., 2020).

Nile tilapia is the most cultured species in Kenya, accounting for 80% of production, followed by African catfish (*Clarias gariepinus;* 14%) and other species (~6%) of national aquaculture production (KMFRI, 2017; Obwanga et al., 2020; Opiyo et al., 2018) as presented in Figure 1. Following the implementation of the Kenya Government's Fish farming enterprise productivity program (FFEPP) from 2010 to 2013 under the Economic Stimulus Program (ESP), private hatcheries were established to produce and disseminate Nile tilapia fingerlings to farmers (Abwao et al., 2021). The current information on hatcheries is limited to the lists of about 80 authenticated and about 30 non-authenticated hatcheries. However, the information is inadequate for planning purposes and the development of efficient fish seed production and dissemination systems.

The global culture of tilapia faces several challenges, including pests and diseases, lack of access to quality feeds and seeds, climatic change and, most recently, the Coronavirus disease (COVID-19) pandemic. However, tilapia production has hit major milestones owing to the development and adoption of novel technologies that have allowed farmers to overcome major production barriers and constraints (Yue et al., 2016). Some of the technologies and innovations being developed and tested in Kenya include biofloc technology (BFT) and periphyton technology, selective breeding, the use of alternative protein sources such as the black soldier fly in feed formulation and so forth. Similarly, culturing tilapia has contributed to improved livelihoods of people in developing countries, increased household incomes, improved food security and higher nutritional value through increased protein consumption (Yue et al., 2016).

In this paper, we review and synthesise the current published literature to identify knowledge gaps and the current understanding of the status and potential of sustainable Nile tilapia production in Kenya. The goal is to provide a knowledge platform to inform current research, policy, and practices to support the role of aquaculture in food and nutrition security. The review is specifically relevant to the agriculture sector, where the vision seeks to enhance fisheries development and management. This will also be relevant to both the national and county governments, especially because the fisheries and aquaculture sector is a devolved function.

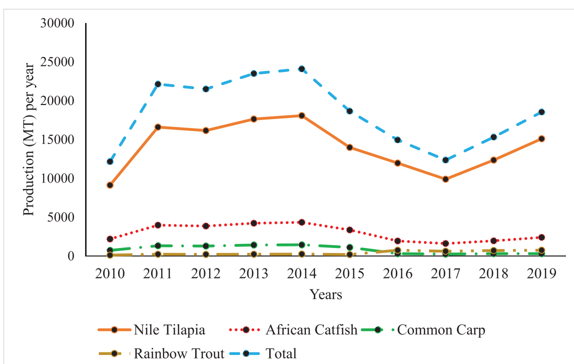

FIGURE 1 Cultured fish species production (in million tonnes) in Kenya from 2010 to 2019 (source: FAO, 2021)

2 | METHODOLOGY

The scoping review methodology and systematic review approach were adopted in the present study to generate a comprehensive literature review on the culture of Nile tilapia in Kenya (Arksey & O'Malley, 2005; Levac et al., 2010). The literature review is focused on the biology of the Nile tilapia, biotic and abiotic conditions that affect tilapia, culture systems, feed and feeding management, Nile tilapia breeding, production trends, diseases and management, environmental and social impacts of Nile tilapia culture, trade and marketing, challenges facing the production of Nile tilapia and existing opportunities in Nile tilapia culture. To meet the set objectives, a wide range of keywords (closely related to Nile tilapia and aquaculture) were searched in online database tools and scientific domains of Science Direct, Research Gate, Google Scholar and Web of Science, The Lens, Dimensions AI, Open Knowledge Maps and so forth. To further narrow and refine the search, Boolean operators ('OR', 'AND' and 'NOT') were appropriately used in the various databases and search engines. The collected literature database was organised into copies, excerpts and notes according to topics. The current paper is a result of research publications that met the inclusion criteria for the review paper.

3 | REQUIREMENTS FOR THE NILE TILAPIA CULTURE

3.1 | Feeding and nutrition

Early juveniles and young tilapia are mainly omnivorous feeders, feeding mainly on zooplankton and zoobenthos (Ngugi et al., 2007; Outa et al., 2014). They also exhibit ontogenetic feeding niche shifts and diel feeding patterns (FAO, 2018), whereby food is ingested during the day and digested at night (Trewavas, 1983). In their later stages, they ingest a wide variety of natural food organisms, including plankton, aquatic macrophytes, planktonic and benthic aquatic invertebrates, larval fish, detritus and decomposing organic matter (Elliott et al., 2007; Nairuti et al., 2000).

Previous studies done on the feeding and nutritional requirements of tilapia show that natural food organisms characteristically account for 30%–50% of tilapia growth, while supplemental feeding accounts for the remainder (Ngugi et al., 2007; Munguti et al., 2017). Although tilapia fishes are often considered filter feeders because they can efficiently harvest plankton from the water column, they do not physically filter the water through gill rakers as efficiently as true filter feeders such as gizzard shad and silver carp. Instead, the gills of tilapia secrete a mucous that traps plankton. To digest the ingested algae and succulent higher plants, tilapia physically grinds on the plant tissues between two pharyngeal plates of fine teeth, and the stomach pH (< 2) ruptures the cell walls of algae and bacteria (Mohamed et al., 2019; Munguti et al., 2014). Tilapia actively search for live microscopic invertebrates within the water column and do not disturb the pond bottom like the carp (Stickney, 2016).

TABLE 1 Requirements for tilapia feeds (g/kg). Specification adapted from Iluyemi et al. (2010)

S/No		Minimum requirement
i.	Crude protein	300.0
ii.	Phenyalanine/tyrosine	16.5
iii.	Valine	08.1
iv.	Threonine	6.9
v.	Isoleucine	8.2
vi.	Methionine/cystine	14.5
vii.	Histidine	6.9
viii.	Arginine	9.8
ix.	Leucine	11.1
x.	Lysine	12.3
xi.	Crude fibre	< 100
xii.	Phosphorus	10.0
xiii.	Lipids	≤ 100
xiv.	Digestible energy	11 kJ/g

In general, tilapia digest animal protein in feeds with an efficiency similar to that of channel catfish but are more efficient in the digestion of plant protein, especially more fibrous materials. Often, semi-intensive and intensive culture systems adopted for Nile tilapia culture focus on supplemental feeding using commercial feeds (Munguti et al., 2009). One of the reasons for the success of this species in captivity is its ability to accept formulated diets. The feed formulation should provide the required dietary requirements for growth and survival. It is therefore imperative that formulation is based on scientific data and considers both the macro- and micronutrients required by the fish. The nutritional and dietary requirements of tilapia are outlined in Table 1.

3.2 | Evolution of culture systems for Nile tilapia in Kenya

3.2.1 | Extensive systems

Traditionally, tilapia culture is conducted in extensive systems by most smallholder fish farmers in rural Kenya. However, with innovations and developments in the aquaculture industry, most farmers are moving towards semi-intensive and intensive culture systems. In these systems, tilapia fish are stocked in static ponds or pens with little or no inputs provided. The fish utilize natural food in the pond for their growth. Due to low input use, the productivity of these systems is low, ranging between 500 and 1500 kg/ha/year (SDF, 2016).

3.2.2 | Semi-intensive systems

The culture of tilapia in Kenya is mainly performed at the semi-intensive systems level. The fish are stocked in earthen ponds and cages, and the natural productivity mainly of plankton communities in the water column is used to sustain the stocked fish. Both organic and inorganic fertilisers are applied to the ponds to enhance the pond's primary productivity. Fish farmers also engage in exogenous feeding using cereals, bran and other locally available feeds to supplement pond productivity. The annual production contributed by these systems ranges between 1 and 3 Kg/m^2/year. The production of these systems is relatively low because the supplement feeds rarely provide all the nutritive requirements of the fish under culture. A report by SDF (2016) recorded that tilapia producers in Western Kenya had achieved production between 6 and 10 kg/m^2/year based on management levels employed by farmers.

3.2.3 | Intensive systems

Intensive systems are taking root in Kenya for the culture of Nile tilapia. In these systems, water flows in and out continuously, resulting in higher stocking densities. Good water quality and high protein feeds are a prerequisite for intensive culture systems. Less land and water are required to produce a much greater quantity of fish as compared to extensive and semi-intensive systems. The natural productivity in the culture units is supplemented by exogenous feeding using complete feeds, that is, the feeds are specifically manufactured for the species under culture and water aeration. Most fish farmers in the country are not able to use these systems due to the high initial capital investment and high operational costs. The yields from these systems are relatively high and range from 10 to 50 kg/m^2/year (SDF, 2016). A recirculating aquaculture system (RAS) is a new technology that is being embraced as a form of intensive aquaculture (Orina et al., 2018; Opiyo et al., 2018). RAS has tremendously increased the efficiency in aquaculture enterprises by reducing the grow-out period. The fish attains a harvest weight of 400 to 500 g within 4 to 5 months after the nursery period of 2 to 3 months, compared to 300 g in 9 months from farms not practising RAS (Obiero et al., 2019).

3.3 | Emerging technologies in Nile tilapia culture

3.3.1 | BFT and periphyton technology

Globally, as the debate on the overreliance on wild fisheries for fish meal and fish oil stocks continues, research efforts are geared toward identifying alternative sources of protein used in the formulation of fish diets. BFT is one of the novel technologies under development and validation in Kenya by Maseno University and Busia County under the Kenya Climate Smart Agriculture Project (KCSAP). The main principle of BFT is the recycling of nutrients by maintaining a high carbon/nitrogen (C:N) ratio in the water to stimulate the growth of heterotrophic bacteria, which in return converts ammonia into microbial biomass (Avnimelech, 1999, 2007; De Schryver et al., 2008; Kuhn et al., 2009). Properly maintained BFT can provide sufficient protein to maintain significant fish growth, although minimal supplementary feeding is required (Crab et al., 2012; De Schryver and Verstraete, 2009; Ekasari et al., 2010). Bioflocs contain more than 38% protein, 3% lipid, 6% fibre, 12% ash and 19 kJ g^{-1} energy on a dry matter basis, which are all vital for the production of tilapia (Azim & Little, 2008).

In a recent article, Ogello et al. (2021) concluded that the adoption of BFT in Kenya is likely to enhance the aquaculture production of smallholder fish farmers and thereby reduce food insecurity within households. BFT has been proven to increase protein utilisation efficiency, which improves the feed conversion ratio (FCR) and enhances the fish growth rate even with a lower dietary protein level (Zablon et al., 2022). The technology not only reduces the cost of production but is also environmentally friendly and easy to maintain and run. Depending on the level of investment available, BFT can either be pond- or tank-based. Under the KCSAP, for example, preliminary results have shown that ponds with BFT units have higher plankton diversity and abundance than those without. It has been reported that BFT ponds have higher fish growth and better FCR.

Periphyton technology, which utilises the attached biofilm communities on surfaces within the water, has also been proven to increase fish growth and reduce feed requirements. This is mainly due to the high protein content of the biofilms. Muthoka et al. (2021) demonstrated that periphyton technology can also increase fecundity and delay spawning in *O. niloticus* by up to 4 weeks. These technologies can revolutionise Nile tilapia culture in Kenya, especially by reducing the overreliance on chemicals for sex reversal in tilapia to curb early maturation and prolific breeding of tilapia under pond culture systems.

3.3.2 | Cages and RAS systems

Cage fish farming has been highly adopted by fishing communities living around Lake Victoria and several dams within the country. The annual production from cages is estimated to be 40,000 MT of fish per year. Although some aspects of this technology are still under study, especially in Kenya, the prospects are good. This is mainly due to the high stocking densities in these systems since the waste is constantly flushed out from the system by the waves. The main debate around the technology has been the potential negative environmental impacts it would have on water bodies, especially due to the accumulation of uneaten feeds. Although cage culture is a promising venture to increase productivity, offer employment opportunities and enhance economic wellbeing, site suitability for cage installations is poorly regulated, with over 45% of cages located within 200 m of shoreline acting as breeding grounds of fish and hence potentially conflicting with other lake users (Njiru et al., 2018). With an increasing number of cages in the lake, there is a need for policy and regulations to guide its investment to ensure environmental sustainability and economic performance (Aura et al., 2018; Njiru et al., 2018). Research is also geared towards the use of Freshwater Integrated Multitrophic Aquaculture (FIMTA) technologies. This is an extractive technology that involves the use of filter feeders and plants to take up the excess feeds and nutrients from the water around the cages.

Recirculating aquaculture systems (RAS) are also being embraced by farmers, especially in the arid and semi-arid areas of Kenya. One of the farms that has adopted and established an elaborate and efficient RAS system is the Kamuthanga fish farm in Machakos County. In this culture system, there is increased efficiency, reduced grow-out period and increased production, compared to systems not practising RAS systems. The efficiency is enhanced by the constant cleaning and aeration of water as well as waste filtration and elimination. The annual fish production from the farm is currently 40 tonnes per year, but there exists a potential to produce over 100 tonnes annually (Tschikof, 2018). Due to the high initial cost of investment coupled with the technical requirement for running these systems, very few RAS farms are currently operating in Kenya. To enhance food and nutrition security in Kenya, research and trials are being done to establish the potential of aquaponic and hydroponic systems in the production of tilapia. These systems are based on the premise of efficiency that relies on waste from the fish production system being used in the production of other food items like vegetables and fruits. Since tilapia is sensitive to water quality, the utilisation of wastes from the water by plants within these systems can enhance growth and performance.

Aggregated fish production systems (aquaparks) are also being implemented in some parts of the country. One such initiative is in Busia County for both ponds and cage-based production systems. Under this production model, several smallholder fish farmers are organised into groups and assisted in producing a pool of more than 100 fishponds in a centralised area. This reduces the losses and constraints associated with segmented small-scale tilapia production. This helps the farmers enjoy the benefits associated with economies of scale, especially regarding farm inputs, pooled management and efficient training and extension services. This system has been proven under the KCSAP to enhance the livelihoods of farmers and improve food and nutrition security in their households.

3.3.3 | Postproduction technologies

Fish are very perishable, and post-harvest technologies are crucial for the success of any aquaculture venture. Since tilapia is the most commonly cultured species in Kenya, post-harvest and marketing technologies need to take into consideration the requirement for this particular species. In Kenya, for example, there have been several traditional fish post-harvest technologies that have been used to extend the shelf life of fish and fish products. Some of these technologies include salting, smoking, frying and drying (Kyule-Muendo et al., 2017). Researchers from KMFRI have developed energy-efficient and healthy post-harvest technologies to help curb the problems associated with the traditional methods. One such invention is the smoking kiln, which uses less firewood and produces less smoke. This kiln can be used to smoke tilapia and can keep it fresh and edible for several months. Value addition has also been an area of research in recent times since it helps increase the income from fish and helps in extending the shelf life while making it more nutritionally superior. The KMFRI has developed several value-added fish products, including fish samosas, fish balls, fish paste and fish burgers, among others (Kyule-Muendo et al., 2017). Additional nutrient-rich products are being developed and validated under the KCSAP and will increase the profit margins for farmers. This can help improve fish farmers' and traders' livelihoods and enhance food and nutrition security at the household level. To enhance market linkages for tilapia production, some marketing platforms and tools have been developed in Kenya. Some of these include AquaRech. These apps help farmers access markets as well as extension services with ease.

3.3.4 | Genetic improvement of Nile tilapia in Kenya

Selective breeding is the process where the genetic variation present in desirable traits within a population is used to improve the production quality, efficiency and sustainability of the target species (Brummett & Ponzoni, 2009). The high production of aquaculture in Asian countries is a result of the adoption of selective breeding technology, which generated genetically improved farmed tilapia (GIFT). This programme was initiated and implemented by the International Center for Living Aquatic Resources Management, currently, WorldFish and Akvarforsk in Norway. The countries in Asia where the GIFT strain has had a great impact on aquaculture productivity include China, the Philippines, Malaysia, Bangladesh, Thailand, Vietnam and Sri Lanka. For example, in the Philippines, tilapia production increased by 186% between 1990 and 2007. The cost of production was also reduced by 32%–35% in the same period, signifying the impact of selective breeding on aquaculture productivity.

In Kenya, genetic improvement has been attempted in the culture of tilapia through selective breeding. Genetically improved tilapia have been proven to have faster growth rates, better survival rates and better disease resistance (Abwao et al., 2021). Researchers have over the years attempted to carry out selective breeding of *O. niloticus*. The first attempt in Kenya was through a project funded by the Kenya Productivity and Agribusiness Project, where the initial population comprised locally available *O. niloticus* strains from private and government hatcheries and the wild population from Lakes Victoria and Turkana. This trial was performed at the National Aquaculture Research Development and Training Center (NARDTC), Sagana, in 2010. The project aimed to develop a strain that would attain higher harvest weight in semi-intensive systems within a shorter time in comparison to the traditionally cultured fish. Suggestions were also made to earmark NARDTC as a breeding nucleus that would supply improved tilapia broodstock to other hatcheries. Although all the objectives of the program were not met due to limited budgetary allocation, there is ongoing research at the station, funded by the KCSAP and the AgriFI-Kenya Climate Smart Agricultural Productivity Project, which are focusing on improving traits in the Nile tilapia of economic importance for the distribution of improved broodstock and seeds to hatcheries and farms in the country. In an effort towards fish improvement, on-station trials have been carried out at Sagana with the promise of reducing the grow-out time and improving the survival rate as well as resistance to disease and climate change. The target strains of Nile tilapia improved and achieved an F8 generation

(F8-2017-01). The results achieved so far indicate that these interventions can bring accelerated development to the aquaculture sub-sector (Abwao et al., 2021). However, due to genotype-by-environment interactions, seeds may not perform optimally in all environments, further calling for ecological-based validation in farms across the different eco-regions and culture conditions in the country. The on-farm validation research initiated in Western Kenya demonstrated a 30% increase in growth, compared to the non-improved strains (Abwao et al., 2021).

3.3.5 | Nile tilapia diseases and management

In aquaculture, Nile tilapia may be subjected to stressful conditions, including nutritional deficiencies, for example, vitamin imbalances, poor water quality and physical, chemical and biological interferences, such as crowding, handling, transportation, pollution and organic enrichment (El-Sayed, 2006). These conditions make the fish vulnerable to diseases and may lead to severe mortality and economic losses (Opiyo et al., 2018). Very limited information exists on disease outbreaks in fish farms in Kenya. The lack of information on fish diseases could be linked to a lack of diagnostic infrastructure, lack of human resources with expertise in fish health, high cost of diagnosis, lack of well-equipped veterinary laboratories for identification of pathogens, absence of outbreak reports due to poor record-keeping by farmers and socio-economic status of the farmers (Akoll & Mwanja, 2012).

Some farmers have experienced mortality of fish on their farms between 40% and 100% of the stock in both cages and ponds (Aura et al., 2018; Njiru et al., 2018). While this is usually associated with water quality problems, this issue is health-related since no diagnosis is done at the farm level to rule out diseases. The bacterial infections reported in Kenya to be affecting the culture of Nile tilapia in farms are caused by *Aeromonas hydrophila*, *Pseudomonas fluorescens*, *P. aeruginosa*, *Edwardsiella tarda*, *Flavobacterium columnare*, *Mycobacterium fortuitum* and *Streptococcus iniae* (Akoll & Mwanja, 2012). In cages, symptoms like fin rot, cloudy eyes and skin lesions have been reported, indicating the possibility of bacterial and fungal infections (Aura et al., 2018). Disease occurrences on farms have been attributed to poor husbandry practices, including the use of on-farm formulated feed with a high bacterial load and the use of water directly from the source without prior treatment (Njagi, 2016; Walakira et al., 2014).

Some fish farms and hatcheries in Kenya use preventive measures to reduce the chances of Nile tilapia disease occurrence (AU-IBAR, 2016). Unlike in grow-out systems, disinfection of farm equipment and culture facilities are routinely included in fish health management schemes in hatcheries. The choice of management practices and application of prophylactics are based on the farmers' knowledge and experience (Magondu et al., 2011). Commonly used drugs and chemicals in Nile tilapia aquaculture systems in Kenya are potassium permanganate and sodium chloride to eliminate bacterial and fungal infections (Rasowo et al., 2007). Treatments in the hatchery are done at the egg incubation stage or at the fry stages to increase the survival of the hatched fry (Magondu et al., 2011; Rasowo et al., 2007). The only antibiotic that is used in Kenya by some private hatcheries is oxytetracycline to prevent bacterial infections (Nyonje et al., 2018).

Since quarantine facilities are few in Kenya and limited biosecurity measures have been put in place to monitor new introductions and occurrence of diseases in fish (Obwanga et al., 2017), the establishment of the Nile tilapia quarantine and diagnostic facilities should be prioritised with the increase in the importation of broodstock, especially the non-indigenous species of Nile tilapia, which may lead to the introduction of diseases and parasites (Njagi, 2016). With the intensification of the cage culture of Nile tilapia in Lake Victoria, more biosecurity measures need to be in place to avoid possible infections since cages are open systems that can allow an exchange of pathogens between cultured and wild fish in the lake (Njiru et al., 2018). Further, because specialists in fish disease are few in Kenya, farmers need to use preventative measures like maintaining a suitable environment for fish, stocking healthy fish, using quality feeds and limiting stress to prevent diseases in the intensive Nile tilapia farming systems (Farm Africa, 2016). Under the KCSAP project, farmers are being trained on biosecurity measures that will help reduce diseases in the aquaculture system and will also help reduce the effects of aquaculture on the environment.

4 | ENVIRONMENTAL AND SOCIAL-ECONOMIC IMPACTS OF THE NILE TILAPIA CULTURE

4.1 | Environmental impacts

In the past 5 years, there has been a gradual shift in Nile tilapia culture from semi-intensive, low-input systems to more intensive systems. The use of artificial culture inputs, such as hormones, drugs, processed feed, probiotics and fuel, is increasingly being adopted by farmers. The ecological footprint of more intensive systems on the landscape includes the conversion of large areas of valuable coastal and inland environments with subsequent destruction and loss of mangroves, lagoons, wetlands, use of wild-caught fish in feeds, high freshwater demand, coastal water pollution and soil degradation and effects of escape of farmed fish on wild fish (Naylor et al., 2000; Ottinger et al., 2016; Troell et al., 2014). On the other hand, high-intensity Nile tilapia farming in the cages may lead to enrichment and eutrophication of aquatic environments (El-Sayed, 2015). Therefore, the number of cages should be regulated with consideration of the lake carrying capacity to avoid depletion of dissolved oxygen, which may affect community diversity with negative implications on food chains and biodiversity. One of the possible technologies that can be adopted to help reduce the negative impacts of cage aquaculture in the lake is the Freshwater Multi-trophic Aquaculture (FIMTA; Outa, 2021). Most of the farmers also adopted the technique without any precautions or hygienic procedures. This practice could pose adverse ecological and human health threats. For example, Contreras-Sánchez et al. (2002) reported that feeding Nile tilapia with Methyl Testosterone (MT-treatedfish feeds) resulted in considerable 'leakage' of MT into pond water and sediments. MT has been detected in the water during MT treatment and can accumulate and remain in pond sediments for up to 8 weeks (El-Sayed, 2006).

Hormone traces may also pose a risk to hatchery workers and to non-target aquatic organisms in cases whereby hatchery workers do not put on protective gear while administering the hormone.

4.2 | Socio-economic impacts

4.2.1 | Food security and nutrition

Food security is a situation where people have economic and physical access to nutritious, safe and sufficient food to meet their dietary requirements and for an active and healthy life. Poverty is one of the major contributors to food insecurity; therefore, its eradication is key to improved food access. One of the major challenges in Kenya is chronic food insecurity and pervasive poverty. Nile tilapia culture, which dominates the aquaculture sector, plays a key role in food security, not only for subsistence and small-scale fishers who rely on it for food, services and generation of income but also for those who prefer it as a source of cheap high-quality animal protein (Obiero et al., 2014). Tilapia also plays a multifaceted role as a source of essential macro- and micronutrients that contribute to the reduced prevalence of malnutrition in Kenya. It constitutes high levels of bioavailable micronutrients, omega-3 fatty acids and minerals that are essential in neurodevelopment and visual functions in young children and aid in reducing the risk of cardiovascular diseases (Obiero et al., 2019). The high bioavailable micronutrients in tilapia make it a unique food commodity widely promoted in Kenya as 'nature's superfood' (Obiero et al., 2019).

A large percentage of people in Kenya obtain high-quality and inexpensive proteins from tilapia because it is the most easily accessible and affordable food fish. From the study of Ole-MoiYoi (2017) in Kenya, cultured tilapia constituted the largest portion of animal protein consumed by respondents from the 'poor' social-economic class. The findings by Ole-MoiYoi (2017) further indicated that as households became wealthier, terrestrial animal protein sources became more preferred. This meant that the poorer the household, the higher the fish protein intake. Tilapia, therefore, offers high-quality nutrition that is within the financial reach of households in the lower economic classes. Obiero et al. (2019) concluded that although formidable fish supply chain issues are still present, many households have attained meaningful food security benefits from aquaculture.

4.2.2 | Income generation

In Kenya, Nile tilapia is the most frequently purchased fish species (Obiero et al., 2014) and is of great commercial value as it forms the basis of commercial fisheries. It has contributed to offsetting irregularities in income when the fish is sold regularly as a source of income. It is reported that most fishermen have opted for tilapia because of high market returns and increased demand. The average cost per kilogram of Nile tilapia was Ksh. 147.52, which was higher than that of carp's Ksh. 122.93 between January and April 2016. This implies that Nile tilapia has a high economic value that provides economic wellbeing for the fish traders, recreation and employment opportunities. The income generated from the sale of tilapia is spent on school fees (37%) or reinvested back into fish farming (45%; Obiero et al., 2019). A few may choose to improve their state of household 'food security' by purchasing food (6%) or diversifying the food bought (1%; Munguti et al., 2021).

In most places in Kenya, fish ponds are owned by men who carry out tilapia farming primarily as a source of income and for consumption in their households. A portion of the produce is used for consumption, while the remaining is sold in local markets to generate additional income. Small-scale fish farming has also turned into a major supply of tilapia products to national markets. The farmers, therefore, generate profits and pay labour incomes, including salaries and wages. The generated profits have contributed to economic growth and provided savings from commercial tilapia farming employees, leading to poverty alleviation (FAO, 2017). Cage culture, which is dominated by tilapia culture around the Lake Victoria region, has also shown a huge potential to increase production and support economic growth around the area (Opiyo et al., 2018).

4.2.3 | Source of employment

The aquaculture sector, which is dominated by Nile tilapia culture (80%; Opiyo et al., 2018), provides direct employment to over 500,000 people and supports over 2 million people indirectly as merchants of fishing accessories, processors, traders, input suppliers or providers of related services. Further, the Kenyan government directed Kshs. 5.7 billion over 5 years from 2009 to implement the FFEPP/ESP, which provided full-time employment to over 150,000 fish farmers and short-term jobs to over 1.5 million youths and created more than 500,000 indirect employments at various levels of the value chain. A study by Orina et al. (2018) noted that tilapia cage culture in Lake Victoria directly provides jobs to over 500 people and indirect income opportunities to over 4000 people living in urban and rural areas. The creation of jobs aids in poverty alleviation because income is used to purchase food items that otherwise could not be afforded.

However, for Nile tilapia fish farming to be sustainable, the environmental and socio-economic sustainability of the operations should be put in place to create a win–win situation for the investors and the communities dependent on the shared resources. The jobs are created in the various nodes within the fish value chain. Each node is dominated by different genders and different age groups. These nodes include the production, mainly dominated by men, marketing and value addition, mainly dominated by women and the transport and distribution section of the value chain dominated mainly by the youth (Githukia et al., 2020). This demonstrates that the impact of tilapia aquaculture could contribute to achieving Sustainable Developmental Goals (SDGs) 1, 2, 3 and 5.

5 | NILE TILAPIA TRADE AND MARKETING

Wholesale fish markets of tilapia are distributed in major cities in Kenya, such as Nairobi, Mombasa and Kisumu, and towns, for example, Busia and Oyugis (Farm Africa, 2016). The majority of commercial Nile tilapia farmers sell their harvest to wholesalers, while small-scale farmers sell their fish to retailers and sometimes directly to consumers (Obiero et al., 2014). Farmers generally have agreements with wholesalers who purchase their harvest directly from the farm site. Street vendors and formal retailers are the main types of Nile tilapia fish marketers (Macfadyen et al., 2011). Informal street vendors purchase the fish from wholesale markets or traders and sell the fish in shops/cottages with shelter from the sun and rain, a table/fish box by the roadside or inside vegetable and fruit markets (El-Sayed, 2017; Githukia et al., 2020). In the case of formal retailers, fish sales take place at registered retail shops, which are generally equipped with facilities such as refrigerators/freezers for storing unsold fish. Many of these retailers provide fish cleaning and do value addition like frying services. The approach is widespread throughout the country and is especially popular in residential areas, where family members come home late from work and do not have time to clean and cook fish (El-Sayed, 2017). Some of the challenges in the marketing of tilapia are related to the importation of frozen tilapia from China into the country. This has interfered with the local fish sellers and vendors since the imports tend to be cheaper than locally produced tilapia. There have also been media reports indicating the possible impacts of imported frozen tilapia on human health (https://www.kenyans.co.ke/news/35478-fish-imports-china-found-contain-toxic-substances) and socio-economic issues affecting the local people. Local researchers and leaders have voiced their concerns about the potential impacts of frozen tilapia and whether the government should ban the imports (https://nation.africa/kenya/blogs-opinion/blogs/-there-s-a-need-to-reconsider-plan-to-ban-fish-from-china-3504328; https://www.standardmedia.co.ke/opinion/article/2001420098/of-chinese-tilapia-imports-and-our-huge-unexploited-potential).

Fish marketing and markets were adversely affected by the COVID-19 pandemic. The pandemic affected the supply systems, resulting in the closure of several businesses related to and dependent on tilapia production (OECD, 2020). Part of the solutions under consideration is the formation of strong web-based market linkages that will help link tilapia farmers to the markets and help them reduce such unfortunate happenings in the market.

6 | CHALLENGES AND OPPORTUNITIES IN THE NILE TILAPIA CULTURE

6.1 | Constraints

Constraints facing Nile tilapia culture can be summarised into four main domains: (i) issues external to the aquaculture value chain and affecting all stages of production; (ii) factors affecting the availability, cost or quality of inputs sourced for production; (iii) factors affecting production and (iv) factors affecting the post-harvest, value addition and marketing as summarised in Table 2.

6.2 | Opportunities

To achieve a rapid transformation of the Nile tilapia culture industry, there is a need to upscale modern technologies, innovations and management practices to realise the sustainable development envisaged in the SDGs. Some of the technologies and innovations include the development of model aquaculture parks (aquaparks), high-density intensive production cages in lakes and reservoirs, intensive RAS and tank-based systems, hydroponics and aquaponics (Munguti et al., 2021). Some of these technologies and opportunities are currently under study and trials by the KCSAP project. The Aquaculture Business Development Programme has also rolled out an interesting opportunity in field farmer schools for training local youth on aquaculture production technologies, management and entrepreneurship in aquaculture.

Since aquaculture is fast growing, there is a need for the development of new production technologies in aquaculture to maximise production and profits. For instance, RAS is mainly useful for dry land aquaculture, and BFT and periphyton technology use less feeds, hence can be adopted for better Nile tilapia production (Obiero et al., 2019b). With the increasing demand for Nile tilapia fingerlings and fish feeds, cottage industries managed by farmers and hatchery operators have an opportunity to engage in fish feed and fingerling production to supply the sector. Currently, the total annual demand for fish feeds and fingerlings is estimated at 35,000 tons and 50 million, respectively (KMFRI, 2018).

There is a need for competency-based training on special skills in Nile tilapia culture. The youth can be encouraged to join such training in various technical and vocational education and training institutions and universities. Weak extension services are a perennial challenge in the aquaculture sector. This is because the government does not employ staff regularly. The devolution of fisheries and aquaculture sectors to the county level presents the need for local people to educate the local fish farmers using the local dialect. This is a perfect opportunity for young people to be trained as extension officers so that they can offer demand-driven extension services on the culture of Nile tilapia. The proliferation of cage culture also presents an immense opportunity for young people to form business units, for example, aqua shops for selling cage accessories and offering consultancy services on cage construction technology and management (Munguti et al., 2021).

To maximise the available financial and market opportunities, women fish traders can be organised into groups to attract funding. With the opportunities created by changing eating habits where more people are now eating fish, the youth can also venture and explore opportunities in value-added product development and introduce the developed products into the markets. Examples of these products and commercial importance include Nile tilapia fish fillets, fish balls, fish fingers, sausages and fish gel from fish scales used in the pharmaceutical and cosmetics industries. There are opportunities for training youth in value addition techniques and the fabrication of value addition equipment. Opportunities also exist for investment in modern Nile tilapia processing technologies and marketing techniques and platforms (Munguti et al., 2021).

TABLE 2 Challenges and constraints facing the culture of Nile tilapia in Kenya. Adopted from KMFRI (2017)

Source and scope of impact	Critical issues/factors
Issues external to the aquaculture value chain and affecting all stages of production	Poor infrastructure (roads, power, water) Lack of information for farmers and would-be investors Capital inputs are expensive with high-interest rates and are often not suited or available to the aquaculture producers Inadequate investment to support research, capacity building and information dissemination Low levels of human capacity in county government for the provision of extension services
Factors affecting the availability, cost or quality of inputs sourced for production	Lack of quality fish feeds due to few large-scale feed mills potentially impacts negatively on the cost and reliability of the feeds The quality of hatchery fry may be poor due to broodstock used and poor management, inadequate certification of fry in the private hatcheries Lack of zoning of aquaculture areas; hence, land may not be readily available in the best areas for aquaculture production Water quality in ponds is not well maintained due to high pumping costs and competitive uses of water
Factors affecting the production	Lack of effective group organisation , which reduces the ability to negotiate on the cost of inputs and share experiences Best management practices not formally adopted or applied in culture systems Overreliance on donor funding from the government and development partners creates a 'donor syndrome' leading to unsustainable growth
Factors affecting the post-harvest, value addition and marketing	Current production volumes are small, restricting access to markets and the ability to engage in market promotion Domestic prices of farmed tilapia are high and cannot compete with wild-caught and imported tilapia Market infrastructure still lacking across the country Key opportunities of existing unused processing capacity are not well utilised in the newly developed mini-processing fish plants Limited value addition for farmed fish products hence high post-harvest losses and low prices of the product

7 | CONCLUSION

Kenya is among the developing countries benefiting from Nile tilapia culture. The culture has been expanding rapidly in response to the introduction of new strains, success in monosex tilapia production and improvement in both nursing and grow-out technologies. However, the culture of Nile tilapia faces many bottlenecks, including the high cost of fish feeds and quality seeds. Several interventions are still required in Nile tilapia culture to ensure that all the challenges are dealt with to make aquaculture more sustainable.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest that might arise as a result of the publication of this manuscript and the information therein.

AUTHOR CONTRIBUTIONS

Initiation, methodology, document review and formal analysis: Jonathan Munguti, Erick O. Ogello and Kevin Obiero. *Investigation, methodology, supervision and validation*: Mary Opiyo and Jacob Abwao. *Formal analysis*: Domitila Kyule and James Kirimi. *Investigations and visualisation*: Nicholas. O Outa, Mavindu Muthoka and Cecilia Githukia. *Writing original draft*: Jacob Iteba and Rita Nairuti. We certify that this is our original scientific research work, and it has not been submitted or published anywhere. The authors are responsible for all the content in the manuscript.

ETHICS STATEMENT

The current study was a review, and no animal or human subjects were used. Therefore, there were no ethical approvals needed.

DATA AVAILABILITY STATEMENT

We certify that the data used in this article were collected from the study and can only be availed through the request and permission of the third-party authors.

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ORCID

Nicholas Outa https://orcid.org/0000-0002-4085-0398
Erick O. Ogello https://orcid.org/0000-0001-9250-7869

REFERENCES

Abwao, J., Jung'a, J., Barasa, J.E., Kyule, D., Opiyo, M., Awuor, J.F. & Keya, G.A. (2021) Selective breeding of Nile tilapia, *Oreochromis niloticus*: a strategy for increased genetic diversity and sustainable development of aquaculture in Kenya. *Journal of Applied Aquaculture*, 1–20. https://doi.org/10.1080/10454438.2021.1958728

Adeleke, B., Robertson-Andersson, D., Moodley, G. & Taylor, S. (2020) Aquaculture in Africa: a comparative review of Egypt, Nigeria, and Uganda vis-a-vis South Africa. *Reviews in Fisheries Science & Aquaculture*, 29(2), 167–197.

Akoll, P. & Mwanja, W.W. (2012) Fish health status, research and management in East Africa: past and present. *African Journal of Aquatic Science*, 37(2), 117–129.

Arksey, H. & O'Malley, L. (2005) Scoping studies: towards a methodological framework. *International Journal of Social Research Methodology*, 8, 19–32.

AU-IBAR. (2016) *Mapping study of aquatic animal diseases in Africa–Eastern Africa*. Nairobi: Interafrican Bureau for Animal Resources.

Aura, C.M., Musa, S., Yongo, E., Okechi, J.K., Njiru, J.M., Ogari, Z., Wanyama, R., Mbugua, H., Kidera, S., Ombwa, V. & Abwao, J. (2018) Integration of mapping and socio-economic status of cage culture: towards balancing lake-use and culture fisheries in. *Aquaculture Research*, 49, 532–545. https://doi.org/10.1111/are.13484

Avnimelech Y. (1999) Carbon /nitrogen ratio as a control element in aquaculture systems. *Aquaculture*, 176, 227–235.

Avnimelech Y. (2007) Feeding with microbial flocs by tilapia in minimal discharge bioflocs technology ponds. *Aquaculture*, 264, 140–147.

Azim, M.E. & Little, D.C. (2008) The biofloc technology (BFT) in indoor tanks: water quality, biofloc composition, and growth and welfare of Nile tilapia (*Oreochromis niloticus*). *Aquaculture*, 283, 29–35.

Bentsen, H.B., Gjerde, B., Nguyen, N.H., Rye, M., Ponzoni, R.W., de Vera, M.S.P., Bolivar, H.L., Velasco, R.R., Danting, J.C., Dionisio, E.E., Longalong, F.M., Reyes, R.A., Abella, T.A., Tayamen, M.M. & Eknath, A. E. (2012) Genetic improvement of farmed tilapias: genetic parameters for body weight at harvest in Nile tilapia (*Oreochromis niloticus*) during five generations of testing in multiple environments. *Aquaculture*, 338, 56–65.

Brummett, R. E. & Ponzoni R. W. (2009) Concepts, alternatives, and environmental considerations in the development and use of improved strains of tilapia in African aquaculture. *Reviews in Fisheries Science*, 17(1), 70–77.

Contreras-Sánchez, W.M., Couturrier, G.M. & Schreck, C.B. (2002) Fate of methyltestosteronein the pond environment: use of MT in earthen ponds with no record of hormone usage. In: McElwee, K., Lewis, K., Nidiffer, M. & Buitrago, P. (Eds.) *Nineteenth annual technical report*. Corvallis, OR: Pond Dynamics/Aquaculture CRSP, Oregon State University, pp. 103–106.

Crab, R., Defoirdt, T., Bossier, P. & Verstraete, W. (2012) Biofloc technology in aquaculture: beneficial effects and future challenges. *Aquaculture*, 356, 351–356.

De Schryver P. & Verstraete W. (2009) Nitrogen removal from aquaculture pond water by heterotrophic nitrogen assimilation in lab-scale sequencing batch reactors. *Bioresource Technology*, 100, 1162–1167.

De Schryver P., Crab R., Defoirdt T., Boon, N. & Verstraete W. (2008) The basics of bio-flocs technology: the added value for aquaculture. *Aquaculture*, 277, 125–137.

Ekasari, J., Crab, R. & Verstraete, W. (2010) Primary nutritional content of bio-flocs cultured with different organic carbon sources and salinity. *HAYATI Journal of Biosciences*, 17(3), 125–130.

Elliott, M., Whitfield, A.K., Potter, I.C., Blaber, S.J., Cyrus, D.P., Nordlie, F.G. & Harrison, T.D. (2007) The guild approach to categorizing estuarine fish assemblages: a global review. *Fish and fisheries*, 8(3), 241–268.

El-Sayed, A. (2013) Tilapia feed management practices in sub-Saharan Africa. In: Hasan, M.R. & New, M.B. (Eds.) *On-farm feeding and feed management in aquaculture. FAO Fisheries and Aquaculture Technical Paper No. 583*. Rome: FAO Books, pp. 377–405.

El-Sayed, A.F.M. (2006) *Tilapia culture*. Wallingford, UK: CABI Publishing.

El-Sayed, A.F.M. (2015) *Social and economic performance of Nile tilapia (Oreochromis niloticus) farming in Egypt: a case study*. Rome: FAO Fisheries and Aquaculture Circular.

El-Sayed, A.F.M. (2017) Tilapia co-culture in Egypt. In: Perschbacher, P.W. & Stickney, R.R. (Eds.) *Tilapia in intensive co-culture*. Hoboken, NJ: John Wiley & Sons, pp. 211–236.

FARM AFRICA. (2016) *Report on market study of the aquaculture market in Kenya. KenyaMarket-Led Aquaculture Programme (KMAP)*. FARM AFRICA. (2016) Report on market study of the aquaculture market in Keny. https://www.farmafrica.org/downloads/study-of-the-kenyan-aquaculture-market.pdf. [Accessed 7 June 2022].

Fitzsimmons K.M. (2016) *Global tilapia market update 2015*. WAS 2016, Las Vegas. https://www.researchgate.net/publication/281241348_Global_Tilapia_Market_update_2015

Food and Agriculture Organization of the United Nations (FAO). (2017) *Global aquaculture production*. Rome: FAO.

Food and Agriculture Organization of the United Nations (FAO). (2018) *The state of world fisheries and aquaculture*. Rome: FAO.

Food and Agriculture Organization of the United Nations (FAO). (2020) *The state of world fisheries and aquaculture 2020: sustainability in action*. Rome: FAO.

Githukia, C.M., Drexler, S.S., Obiero, K O., Nyawanda, B.O., Achiengâ, J., Chesoli, J.W. & Manyala, J.O. (2020) Gender roles and constraints in the aquaculture value chain in Western Kenya. *African Journal of Agricultural Research*, 16(5), 732–745.

Iluyemi, F.B., Hanafi, M.M., Radziah, O. & Kamarudin, M.S. (2010) Nutritional evaluation of fermented palm kernel cake using red tilapia. *African Journal of Biotechnology*, 9(4), 502–507.

Jansen, M.D., Dong, H.T. & Mohan, C. (2019) Tilapia lake virus: a threat to the global tilapia industry? *Reviews in Aquaculture*, 11(3), 725–739. https://doi.org/10.1111/raq.12254

Kaleem, O. & Sabi, A.F. (2021) Overview of aquaculture systems in Egypt and Nigeria, prospects, potentials, and constraints. *Aquaculture and Fisheries*, 6(6), 535–547.

Kenya Marine and Fisheries Research Institute (KMFRI) (2018) *The status of Kenya fisheries: towards the sustainable exploitation of fisheries resources for food security and economic development*. Mombasa, Kenya: Kenya Marine and Fisheries Research Institute.

Kenya Marine and Fisheries Research Institute, KMFRI. (2017) *Kenya's aquaculture brief 2017: status, trends, challenges and future outlook*. Mombasa, Kenya: Kenya Marine and Fisheries Research Institute.

Kuhn D.D., Boardman G.D., Lawrence A.L., Marsh L. & Flick G.J. (2009) Microbial floc meals as a replacement ingredient for fish meal and soybean protein in shrimp feed. *Aquaculture*, 296, 51–57.

Kumar, G. & Engle, C.R. (2016) Technological advances that led to growth of shrimp, salmon, and tilapia farming. *Reviews in Fisheries Science & Aquaculture*, 24(2), 136–152. https://doi.org/10.1080/23308249.2015.1112357

Kyule-Muendo, D., Munguti, J.M., Opiyo, M.A., Obiero, K.O., Githukia, C.M., Orina, P.S., Njiru, J.M. & Charo-Karisa, H. (2017) *Fish recipe book*, volume 1. Nairobi, Kenya: Kenya Literature Bureau.

Levac, D., Colquhoun, H. & O'Brien, K.K. (2010) Scoping studies: advancing the methodology. *Implementation Science*, 5, 69. https://doi.org/10.1186/1748-5908-5-69

Macfadyen, G., Nasr-Allah, A.M. & Kenawy, D.A.R. (2011) *Value-chain analysis of Egyptian aquaculture*. Project Report 2011–54. The WorldFish Center, Penang,

Magondu, E.W., Rasowo, J., Oyoo-Okoth, E. & Charo-Karisa, H. (2011) 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*, 319, 307–10.

Mohamed, Z., Ahmed, Z. & Bakr, A. (2019) Assessment of phytoplankton species in gut and feces of cultured tilapia fish in Egyptian fishponds: implications for feeding and bloom control. *Acta Limnologica Brasiliensia*, 31, e27.

Munguti J.M., Obiero K.O., Orina P.S., Musa S., Mwaluma J., Mirera D.O., Ochiewo J., Kairo J. & Njiru J.M., (2017) *State of aquaculture in Kenya*. Nairobi, Kenya: Laxpress Services.

Munguti, J., Obiero, K., Orina, P., Mirera D., Kyule D., Mwaluma J., Opiyo M., Musa S., Ochiewo J., Njiru J., Ogello, E. & Hagiwara, A. (Eds.) (2021) *State of aquaculture report 2021: towards nutrition sensitive fish food production systems*. Nairobi, Kenya: Techplus Media House.

Munguti, J.M., Musa, S., Orina, P.S., Kyule, D.N., Opiyo, M.A., Charo-Karisa, H. & Ogello E.O. (2014) An overview of current status of Kenyan fish feed industry and feed management practices, challenges and opportunities. *International Journal of Fisheries and Aquatic Studies*, 1, 128–137.

Munguti, J.M., Waidbacher, H., Liti, D.M., Straif, M. & Zollitsch, W. (2009) Effects of substitution of freshwater shrimp meal (*Caridina nilotica* Roux) with hydrolysed feather meal on growth performance and apparent digestibility in Nile tilapia (*Oreochromis niloticus* L.) under different culture conditions. *Livestock Research for Rural Development*, 21, 1–13.

Muthoka, M., Ochieng Ogello, E., Ouma, H. & Obiero, K. (2021) Periphyton technology enhances growth performance and delays prolific breeding of Nile tilapia, *Oreochromis niloticus* (Linnaeus, 1758), juveniles. *Asian Fisheries Science*, 34, 290–300. https://doi.org/10.33997/j.afs.2021.34.4.002

Nairuti, R. N., Musyoka, S.N., Yegon, M.J. & Opiyo, M.A. (2000) Utilization of black soldier fly (*Hermetia illucens* Linnaeus) larvae as a protein source for fish feed–a review. *Aquaculture Studies*, 22(2), AQUAST697.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C., Clay, J., Folke, C., Lubchenco, J., Mooney, H. & Troell, M. (2000) Effect of aquaculture on world fish supplies. *Nature*, 405, 1017–1024. https://doi.org/10.1038/35016500

Ng, W.K. & Romano, N. (2013) A review of the nutrition and feeding management of farmed tilapia throughout the culture cycle. *Reviews in Aquaculture*, 5(4), 220–254.

Ngugi, C.C., Bowman, J.R. & Omolo, B. (2007) *A new guide to fish farming in Kenya*. Corvallis, OR: Pond Dynamics/Aquaculture CRSP, Oregon State University.

Njagi, I. (2016) *Overcoming challenges to export in Kenyan aquaculture*. https://thefishsite.com/articles/overcoming-challenges-to-export-in-kenyan-aquaculture. [Accessed 7 June 2022].

Njiru, J.M., Aura, C.M. & Okechi, J.K. (2018) Cage fish culture in Lake Victoria: a boon or a disaster in waiting? *Fisheries Management and Ecology*, 26(5), 426–434. https://doi.org/10.1111/fme.12283

Nyonje, B.M., Opiyo, M.A., Orina, P.S., Abwao, J., Wainaina, M. & Charo-Karisa, H. (2018) Current status of freshwater fish hatcheries, broodstock management and fingerling production in the Kenya aquaculture sector. *Livestock Research for Rural Development*, 30(1), 1–15.

Obiero, K., Meulenbroek, P., Drexler, S., Dagne, A., Akoll, P., Odong, R., Kaunda-Arara, B. & Waidbacher, H. (2019b) The contribution of fish to food and nutrition security in Eastern Africa: emerging trends and future outlooks. *Sustainability*, 11(6), 1636.

Obiero, K.O., Opiyo, M.A., Munguti, J.M., Orina, P. S., Kyule, D., Yongo, E., Githikia, C. & Karisa, H.C. (2014) Consumer preference and marketing of farmed Nile Tilapia (*Oreochromis niloticus*) and African Catfish (*Clarias gariepinus*) in Kenya: case study of Kirinyaga and Vihiga Counties. *International Journal of Fisheries and Aquatic Studies*, 1(5), 67–76.

Obwanga, B., Soma, K., Ingasia Ayuya, O., Rurangwa, E., Wonderen, D., van Beekman, G. & Kilelu, C. (2020) *Exploring enabling factors for commercializing the aquaculture sector in Kenya*. Research Report 011, Wageningen University & Research, Wageningen.

Obwanga, B., Lewo, M.R., Bolman, B.C. & van der Heijden, P.G.M. (2017) *From aid to responsible trade: driving competitive aquaculture sector development in Kenya; Quick scan of robustness, reliability and resilience of the aquaculture sector*. Report 2017-092, Wageningen University & Research, Wageningen.

OECD. (2020) *Fisheries, aquaculture and COVID-19: issues and policy responses*. http://www.oecd.org/coronavirus/en/?_ga=2.191535843.835145802.1649331282-1661942400.1649331281. [Accessed 4 June 2022].

Ogello, E.O., Outa, N.O., Obiero, K.O., Kyule, D.N. & Munguti, J.M. (2021) The prospects of biofloc technology (BFT) for sustainable aquaculture development. *Scientific African*, 14, e01053. https://doi.org/10.1016/J.SCIAF.2021.E01053

Ole-MoiYoi, L.K. (2017) Fishing for answers: can aquaculture transform food security in rural Kenya? PhD thesis, Stanford University. http://purl.stanford.edu/zf051hh9063

Omweno J.O, Orina P.S., Getabu Albert & Outa N.O. (2020) Growth and aquaculture potential of Tilapia jipe, *Oreochromis jipe* and Nile tilapia, *Oreochromis niloticus*. *International Journal of Fisheries and Aquatic Studies*, 8(3), 395–399.

Opiyo, M.A., Marijani, E., Muendo, P., Odede, R., Leschen, W. & Charo-Karisa, H. (2018) A review of aquaculture production and health management practices of farmed fish in Kenya. *International Journal of Veterinary Science and Medicine*, 6, 141–148.

Orina, S., Ogello, E.O., Kembenya, E.M. & Muthoni, C. (2018) *State of cage culture in Lake Victoria*, Kenya. https://repository.maseno.ac.ke/bitstream/handle/123456789/2258/STATEOFCAGECULTUREformail%20%281%29.pdf?sequence=1&isAllowed=y. [Accessed 5 June 2022].

Ottinger, M., Clauss, K. & Kuenzer, C. (2016) Aquaculture: relevance, distribution, impacts and spatial assessments–a review. *Ocean and Coastal Management*, 119, 244–266. https://doi.org/10.1016/j.ocecoaman.2015.10.015

Outa, N. (2021) Freshwater Integrated Multitrophic Aquaculture (FIMTA) technology in Lake Victoria. *AfricArXiv Preprint*, https://ucl.scienceopen.com/hosted-document?doi=10.14293/111.000/000016.v1. [Accessed 4 June 2022].

Outa, N.O., Kitaka, N. & Njiru, J.M. (2014) Some aspects of the feeding ecology of Nile tilapia, *Oreochromis niloticus* in Lake Naivasha, Kenya. *International Journal of Fisheries and Aquatic Studies*, 2(2), 1–8.

Popma, T. & Masser, M. (1999) *Tilapia life history and biology*. Stoneville, MS: Southern Regional Aquaculture Center.

Rasowo, J., Okoth, O.E. & Ngugi, C.C. (2007) Effects of formaldehyde, sodium chloride, potassium permanganate and hydrogen peroxide on hatch rate of African catfish *Clarias gariepinus* eggs. *Aquaculture*, 269, 271–7.

Shrestha, A., Chaudhary, C.K., Ghale, R. & Shrestha, A. (2018) Monosex male tilapia production. *International Journal of Animal Biotechnology and Applications*, 4(2), 18–23.

State Department of Fisheries (SDF). (2016) *Kenya fish farming enterprise productivity capacity assessment and gap analysis report*. Nairobi: State Department of Fisheries.

Stickney, R.R. (2016) *Aquaculture: an introductory text*. Wallington, UK: CABI

Trewavas, E. (1983) *Tilapiine fishes. Tilapiine, fishes of the genera Sarotherodon, Oreochromis and Danakila*. London: British Museum (Natural History).

Troell, M., Naylor, R.L., Metian, M., Beveridge, M., Tyedmers, P.H., Folke, C., Arrow, K.J., Barrett, S., Crépin, A.-S., Ehrlich, P.R., Gren, Å., Kautsky, N., Levin, S.A., Nyborg, K., Österblom, H., Polasky, S., Scheffer, M., Walker, B.H., Xepapadeas, T. & de Zeeuw, A. (2014) Does aquaculture add resilience to the global food system? *Proceedings of the National Academy of Sciences*, 111, 13257–13263. https://doi.org/10.1073/pnas.1404067111

Tschikof, M. (2018) A nitrogen-cycling model on an integrated aquaculture system in Machakos, Kenya. MSc thesis, BOKU University, Austria.

Walakira, J., Akoll, P., Engole, M., Sserwadda, M., Nkambo, M., Namulawa, V., Kityo, G., Musimbi, F., Abaho, I., Kasigwa, H., Mbabazi, D., Kahwa, D., Naigaga, I., Birungi, D., Ritaisire, J. & Majalija, S. (2014) Common fish diseases and parasites affecting wild and farmed Tilapia and catfish

in Central and Western Uganda. *Uganda Journal of Agricultural Sciences*, 15(2), 113–125.
Yue, G.H., Lin, H.R. & Li, J.L. (2016) Tilapia is the fish for next-generation aquaculture. *International journal of Marine Science Ocean Technology*, 3(1), 11–13.
Zablon, W.O., Ogello, E.O., Getabu, A. & Omondi, R. (2022) Biofloc system improves protein utilization efficiency and growth performance of Nile tilapia, *Oreochromis niloticus* fry: experimental evidence. *Aquaculture, Fish and Fisheries*, 1, 1–10.

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