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Research Article

Ecological Impacts of Cage Fish Farming in Lake Victoria, Kenya

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Abstract

The decline in capture fisheries globally as a result of growing population and increasing awareness on nutritional benefits of white meat has led to the development of aquaculture. This is anticipated to meet the increasing call for more food for the human population, which is likely to increase further by 2050. Statistics show that more than 50% of the global fish diet will come from aquaculture. This is attributed to technological advancement from traditional culture systems to modern culture systems, including cage farming.

Cage farming technology has been rapidly growing since its inception in Lake Victoria, Kenya. Since then, cage farming has witnessed remarkable growth due to technology adoption, swift monetary growth, urbanization, and infrastructural development, increasing demand for food for an ever-increasing population, increasing markets.

Cage farming in Lake Victoria, Kenya, offers an excellent opportunity towards recognition of the government's tactic to eliminate food insecurity, malnutrition, create employment, and promote the Blue Economy. However, being an open farming enterprise is likely to emit a large amount of fish waste into the ecosystem. Therefore, cage fish farming technology has been put into question due to increasing rates of environmental concerns. Hence, this paper review possible ecological impacts of cage fish farming towards sustainable utilization of aquatic resources in Lake Victoria, Kenya.

Introduction

Background information

The decline in capture fisheries globally as a result of growing population and increasing awareness on nutritional benefits of white meat [1-3] has led to the development of aquaculture. This is anticipated to meet the increasing call for more food [4] for the human population, which is likely to increase further by 2050. Statistics show that more than 50% of the global fish diet will come from aquaculture [5]. Aquaculture began commercializing some decades ago, resulting in the current contribution of 87.5 million tonnes worth USD 281.5 billion in 2020 [1]. This is attributed to technological advancement from traditional culture systems to modern culture systems, including cage farming [6,7].

Cage farming technology is rapidly growing since its inception in Lake Victoria, Kenya [8-10]. Lake Bain Development Authority (LBDA) conducted the first pilot trials in 1988 at Dunga Beach, Lake Victoria, but they bore no fruit [9]. In 2005, Dominion Farms Limited, Siaya County, fruitfully installed cages to bridge the rapid decline in fish landings from the lake. In 2007, the European Union (EU) also sponsored some trials in Small Water Bodies (SWB) within Lake Victoria Basin [11]. Success in cage farming through a participatory approach with Kenya Marine and Fisheries Research Institute (KMFRI) and Dunga Beach Management led to the installation of cages at Dunga Beach by Dunga Fishermen Co-operative in 2009 [9]. Since then, cage farming has witnessed remarkable growth due to technology adoption, swift monetary growth, urbanization, and infrastructural development, increasing

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demand for food for an ever-increasing population, increasing markets, government, and agrarian strategies [8,12].

Cage farming has attracted many investors in Kenya despite being a recent concept in aquaculture [10,13,14]. Currently, over 6,000 cages have been set up in Kenyan waters [15], signifying an increase compared to 3,696 cages in 2021 [8]. Among the five riparian counties embracing cage technology along Lake Victoria shores, Siaya County has the highest number of cages [8]. The average stocking density is 350 fish/m^3 with cage size ranging between 8 and 125 m^3 [16]. In L. Victoria, Kenya, Nile Tilapia (*Oreochromis niloticus*) is the most cultivated fish species, producing 12 million kg of fish per production cycle (approximately 8 months per annum) [8,9]. By 2018, over 3 million *O. niloticus* were stocked in cages [16]. The use of locally invented galvanized metal cages measuring 2 x 2 x 2 m is the most common cage design and material used by cage investors. Currently, cage farmers are embracing the use of more commercially oriented High-Density Polyethylene (HDPE), with the majority being spherical in shape [8].

Cage farming in Lake Victoria, Kenya, offers an excellent opportunity towards recognition of the government's tactic to eliminate food insecurity, malnutrition, create employment, and promote the Blue Economy [9]. However, being an open farming enterprise is likely to emit a large amount of fish waste and uneaten feed into the ecosystem. Further, the ecological changes in the lake are likely to cause conflict between cage investors and wild fisheries if no action is taken [17]. Studies indicated that total production, area under cage farming, depth of the lake, and water exchange rate primarily influence the extent of ecological health of the lake [18,19]. Despite Lake Victoria having huge potential to attract investors, cage farming is still illegal in some countries due to fear of environmental pollution, e.g., Lake Victoria, part of Tanzania [20]. Therefore, cage fish farming technology has been put into question due to increasing rates of environmental concerns. Hence, this paper review possible ecological impacts of cage fish farming for sustainable utilization of blue resources in Lake Victoria, Kenya.

Methodology

This study was a result of desktop data collection and in-depth analysis of information from secondary and tertiary sources. To accomplish the proposed objectives, a range of keywords related to "aquaculture", "cage farming", "ecological impacts of cage farming", Lake Victoria ecosystems, and "nutrients" were searched on Google Scholar. Significant information was obtained from peer-reviewed papers published from 2010 to 2025. The results were analyzed to provide a comprehensive overview to inform sustainable practices in Lake Victoria, Kenya.

Eutrophication

Eutrophication refer to as gradual increase in nutrient loads in the aquatic bionetworks. Although discharge of untreated waste, runoff and anthropogenic influence etc. alters ecosystem integrity, waste from cage farming also is likely to emit matter rich in nitrogen and phosphorous concentration [21-25]. However, its impacts depends on cage residence time, water depth, annual fish production and coverage area [18]. Although N and P are responsible for primary production, excess concentration affects the ecosystem integrity of the lake. Studies indicated that, cage farming increases nutrient load especially Total Nitrogen (TN) and Total Phosphorous (TP) into the ecosystem [26,27]. Approximately 80% and 87% of N and P, respectively, emanated from cage farming in Lake Malawi [28]. Aura et al., [9] and Kashindye, et al. [20] document increasing cases of TN and TP at the shores along the cages. Similar scenarios were also reported for marine cage farming [29]. Discharge of particulate and dissolved substances in the form of uneaten feeds, fecal waste and metabolites escalate the levels of TP and TN [4,21,26,30]. Feeds consumption in cages is not 100%, thus there is probability of feeds descending into the bottom water thus increases the eutrophication rate. Gichana, et al. [31,32] and Gichana, et al. [33] reported that less than 30% of the feeds are breakdown and absorbed by fish. The residual are evacuated as non-fecal or fecal losses into the ecosystem [31,34]. Non-fecal losses consist of digested food that are excreted as ammonia and urea whereas fecal losses are mainly solid wastes. They act as major source of nutrients in aquatic ecosystem through leaching and mineralization. Poor Feed Conversion Ratio (FCR) reported from caged fish also contributes significantly towards increasing TP and TN in ecosystem [13]. The amount of nutrients discharged from cages is determined by feeding proficiency of fish, type of feeds and the species reared. Further, the reduction of water velocity mainly due to the physical obstruction of water by fish in cages and any other organism attached is likely to increase nutrients load in water column [35]. This has raised alarm on need for eco-friendly technologies [20,36].

Both marine [29] and freshwater cage culture noticeably affect water quality parameters [20,37]. Dissolved oxygen (DO) is a critical aspect in fish farming as it affects growth rate, survival, and feeding efficiency [38,39]. The increasing decomposition rate of fecal waste and uneaten feeds in the water column considerably affects DO concentration [4,29]. This is as a result of NH_4^+ and NO_2^- accumulation in the water column [37,40], thus proliferates menace of algal blooms [9,41]. Algal decomposition by bacteria in the water column results in hypoxic and anoxic condition leading to massive fish kills. Further, high oxygen demand occurs in benthic sediments during late spring through summer, and stratification of the water column due to changes in water temperature. Recent fish kills in Lake Victoria, Kenya is attributed to lake mixing in addition to organic matter and nutrient load from cage farming and anthropogenic activities. However, some studies reported no significant effect of fish cage farming on DO [20,42]. Occasionally, high concentrations of nutrients from decomposing matter stimulate phytoplankton development, hence increasing DO as a result of photosynthesis. Further, cages located in deep waters with low production volume, high current speed, and low stocking density result in minimal variations in DO levels [37]. pH is critical in determining the levels of converting ammonia (NH_3) to ammonium (NH_4^+). It also influences the physiological functions of aquatic

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organisms, including fish [39]. Studies reported that cage farming significantly lowers the pH values of water [26]. These ecological changes may affect cage and wild fish production, as well as create conflicts between cage investors and wild fisheries [16].

Further, uneaten feeds, fecal waste, and dust from feeds significantly increase TSS in water [37]. Past research on Environmental Impact Assessment (EIA) indicated that cage farming releases approximately 27.50 kg to 92.23 kg of fresh sediments [43]. Further, Mente, et al. [40] reported fluctuations in TSS levels at the bottom of cages as a result of uneaten feed and fecal matter. High TSS level limits light permeation, thus hindering phytoplankton production [44] as well as the photosynthetic activity of benthic aquatic life. High flushing rate from water currents helps in reducing turbidity levels at the cage sites and vice versa [45,46]. Despite some researchers reporting no significant effect of cage farming on water quality parameters [47,48], it is highly recommended that the proper positioning of cage farming is ideal to encourage flushing and improve feeding efficiency to reduce feed waste, thus reducing turbidity problems in water bodies. Further, cage investors should consider ideal cage stocking density, feeds with fewer fines, feeding fish to satiation, and sticking to feeding charts to minimize feed surpluses as well as maintain the ecological integrity of water bodies.

Phytoplankton have the ability to accumulate and store heavy metals, thus used in bio-monitoring of aquatic ecosystems [49]. They are found at the base of the food pyramid and act as a source of food for invertebrates and fish, thus playing a key role in the production of organic matter. They display wide distribution with high sensitivity to fluctuations in ecological factors such as increased pollutants and nutrient loads [50]. Several scientists cited differences in phytoplankton richness, species, and bio-volume with respect to pollution levels, water mixing and nutrients variations. Eutrophication from cage farming largely affects phytoplankton abundance, composition, and diversity [13,51,52]. Increased eutrophication significantly promotes excessive growth of Harmful Algal Blooms (HABs), thus shifting phytoplankton structure from dominant diatom to cyanobacteria, resulting in the production of Microcystins (MC) that pose both aquatic and human health syndromes [53,54]. Past studies on eutrophic bays such as Nyanza Gulf, Kenya [55], Tanzania Bays [56], and Murchison Bay, Uganda [57] reported cyanobacteria to be the most dominant group. Further, the chlorophytes community declines in numbers after the stocking of cages [20]. However, some groups are tolerant to high eutrophication load, e.g., cyanophytes. Kashindye, et al. [20] reported no change in the abundance of cyanophytes before and after the stocking of fish cages. The tendency of fewer taxa growing faster and abundantly depends on the eutrophic status of aquatic ecosystems.

Plant cells have chlorophyll, a pigment in the chloroplast, which helps in oxygenic photosynthesis by trapping energy from sunlight. Cage farming significantly increases the concentration of chlorophyll a [26,58]. Same results were also cited by Tiburcio, et al. 2021 from Rosana Reservoir in Brazil; Baguma, et al. [37] in Lake Kivu and Sitoki, et al. [58] in Lake Victoria, Kenya. Further, excessive blooms of phytoplankton in Lake Kivu resulted in an increase in the concentration of chlorophyll a in water column [59]. Other studies on the discharge of socio-economic activities into the littoral zone of bays in the Bukavu basin reported a positive and strong relationship between chlorophyll a and nutrient concentration [60]. Therefore, chlorophyll a is directly proportional to nutrient enrichment in the ecosystem. Cage farming increases the concentration of chlorophyll a due to the discharge of high quantity nutrient rich fish feeds and fecal matter from the cages.

Zooplankton community

Plankton communities are bioindicators of aquatic ecosystems. Increased phytoplankton community favors the growth of zooplankton [61]. Musa, et al. [13] reported an increase in rotifers community during the production cycle in cages, while copepods and cladocera were reduced significantly. Increased nutrients leaching from cage activities promote phytoplankton blooms, thus a high abundance of rotifers. This is because increased eutrophication rate stimulates rapid growth of rotifers compared to other zooplanktons [61,62]. However, cladocera and copepods are very sensitive to deterioration in water quality [62,63]. Further, the growing fish biomass may also shift the composition of the zooplankton community. This is due to predation of rotifers as a result of their small sizes compare to other groups [64,65].

Bottom sediments

Accumulation of uneaten fish feeds and fecal matter from the cages results in deposition of high organic sediments at the cage sites, which favors the growth of some organisms [26,37,40]. As a result of decomposition processes, biological oxygen demand (BOD) increases, resulting in a reduction in DO levels [26,66]. Further, Musa, et al. [26] reported a gradual negative ORP in the sediments at cages site during the production cycle. This indicates anaerobic decomposition leading to the accumulation of hydrogen sulphide and methane in the sediments. Production of these gases, along with low DO levels, significantly contributes to mass fish kills in the cages [10]. This therefore raises an alarm on the need to install modern technologies in aquatic ecosystems to monitor and regulate the real time emission of harmful substances.

Benthic macroinvertebrates

Generally, macroinvertebrates are indicators of water quality in an aquatic ecosystem because they are usually abundant, able to withstand a wide range of pollution, and are sessile. However, deposition of large quantities of organic matter in the bottom of the lake is likely to cause a shift in the abundance and decomposition of benthic macroinvertebrates [67]. High deposition of silt acts as food for some macroinvertebrates [47]. Moreover, metallic cages used in fish farming release copper and zinc, which accumulate in the sediments, affecting benthos below fish cages over time [68].

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Benthic macroinvertebrates are known to have less biomass and diversity with a high proportion of deposit feeders with respect to an increase in organic matter [69]. This is because decreasing concentration of DO in the sediments leads to a shift in its composition and diversity [70].

As a result of organic enhancement at the cage site, a transition from arthropods to molluscs and annelids was reported [47,71,72]. Musa, et al. [26] also reported a high abundance of the aforementioned species at the beginning and vice versa at the end of the cage culture period. Chironomus sp. were reported to have high abundance at cage culture sites. This shows that they are tolerant to high pollution loads [73].

Other studies in Uganda, Napoleon Gulf reported changes in composition and diversity of benthic macroinvertebrates in the cage sites [74]. Some benthic organisms are known to be opportunistic, thus can withstand high pollution levels; e.g., Physella spp and Tubifex spp [75]. Oligochaetes and chaoborids thrive well in freshwater receiving organic waste [76,77]. Thus, high abundance indicate negative ecological effect on the Lake Ecosystem. However, some studies reported a lower abundance of oligochaetes and chaoborids at cage sites [78]. This is perhaps due to the influence of predation pressure, substrate type, natural or anthropogenic influence, and hydrological characteristics in an ecosystem.

Fish diseases

Cage farming is an intensive system with high stocking density and limited movement of fish. The overpopulation of fish increases host proximity and prevalence of infections [79]. Further, the adjacent nutrient-rich environment favors the development of diseases and infections if not well-maintained. Caged fish have a high probability of infections from the already infected fish [80]. Morton, et al. [79] alluded that infections can be transmitted from wild to caged fish and vice versa. Fishing gears, ocean currents, and escape accelerate the spread of infection within the ecosystem. However, little information exists on the transfer of infection between wild and farmed fish and vice versa. Past studies cited the spread of infectious salmon anemia virus from caged salmon to wild fish in Chile [81]. Further, cage structures act as substrate for algae; clogging of nets stimulates the evolution of other organisms, resulting in pathogenic infections in caged fish [82]. For instance, more than 50% of fish cage farmers in Lake Victoria reported outbreaks of fish diseases and parasitic infections. Fin rot was the most common due to poor water quality, high stocking density, and management practices [9,10,83]. Therefore, noble fish husbandry is essential in cage farming [84]. Disease is a major threat, and fish health management is an important aspect in planning [43].

Genetic pollution

In the late 1920s, L. Victoria fisheries involved bony and small species of haplochromine cichlids of no economic value in commercial fisheries [85]. Other native fish species include *Labeo victorianus*, *Bagrus docmac*, *Barbus* spp, *Protopterus aethiopicus*, *Synodontis* spp, *Alestes* spp, *Clarias*. However, due to low fisheries production, *Lates niloticus*, *Tilapia zillii*, *Cyprinus carpio*, *Oreochromis leucosticus*, and *O. niloticus* were introduced to convert small fish into bigger biomass [86]. Further, *O. melanopleura* was accidentally introduced from the fish ponds. Consequently, an ecological shift was reported due to hybridization between native and introduced species, and currently the lake is dominated by *O. niloticus*, *L. niloticus*, and *R. argentea* [10]. Further, expansion of fish cage farming has resulted in the introduction of fish species from unknown sources, leading to the disappearance of native fish species due to hybridization [87,88]. Inbreeding between farmed and wild fish has resulted in individuals with lower reproductive viability and survival rate. Escapees from cages can breed with wild fish stock, leading to pollution of genetic pools in the lake [89]. However, scarce information is documented on the effects of cage culture on genetic pollution in L. Victoria. Earlier studies in L. Victoria reported geometric, morphometric, and molecular variation in *O. niloticus* due to inbreeding of wild stock [90,91]. Loss of indigenous fish species in Lake Victoria, e.g., *O. esculentus*, has been documented as a result of hybridization [92]. Hence, cage farming may deteriorate the genetic purity and viability of the wild fish population. Therefore, there is a need for standard operating procedures to ensure authentic and qualified suppliers of fingerlings to cage investors in L. Victoria, as well as maintaining the genetic purity of the wild stock.

Wild fish biomass

Fish cage culture supplies resources to aquatic trophic food webs in matter and energy form, hence attracting many organisms [93]. Uneaten food and fecal matter are primary sources of nutrients contributing to the development of algae. However, the time of release, dispersal capacity, amount, and dilution rate dictate the degree of impact on the aquatic ecosystem [94]. Cage fish farming positively impact wild fish community by providing refugia and food [95]. High fish biomass at the cage sites was reported despite its eutrophic state [27,96]. This shows the positive effect of cage farming on the wild fish population. The abundance of squeaker catfish (*S. victoriae* and *S. afrofischeri*) was reported at the cage site. The supply of dissolved nutrients in the cages increases primary production. This is attributed to the formation of periphyton around submerged cage structures and net thus provide foraging grounds, shelter, and protection against predation.

Feeds from cages also boost the reproductive potential of wild fish populations by enhancing fecundity through increased energy reserves for growth and development. Further, a high energy reserve might reduce the sexual maturation age of fish [97]. Studies reported high relative gonad mass in farmed fish compared to wild fish [98]. However, farmed fish have diverse levels of fatty acids in the gonads, thus lowering reproduction viability compared to wild fish [99].

Also, dropping feeds from cage farming acts as food for wild stock. Benthic fish feeders reported high abundance as they scrap sub-merged materials and substrates on cage structures. However, haplochromines community is intolerant to poor water quality, thus recorded low biomass at the cage site [27].

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Currently, fishing pressure is very high at L. Victoria [100]. Cage investors restrict any kind of fishing activity around the cages. Therefore, cage sites act as refuge and foraging grounds for some fishes leading to high fish biomass and diversity in these areas [27]. Hence affects the population dynamics of wild fish stocks as well as the trophic ecology of ecosystems. Therefore, cage farming has the potential to restore and sustain some parts of wild fish biodiversity while supporting food security and nutrition.

Antibiotics and other drugs

Cage farming experience wide variety of bacterial and parasitic infections, which affect its production. Cage investors rely on chemicals, mainly antibiotics, for the prevention and treatment of infections [101]. However, scarce information exists on the amount of antibiotics used in the aquaculture industry globally [102]. Past studies on cage farming of Salmon reported that a large percentage of antimicrobials utilized through medicated feeds enter the ecosystem through fecal and urinary excreta and uneaten feeds [103]. In Asia, residual antibiotics were reported in the downstream of aquaculture production zones within the aquatic ecosystem [104]. This leads to deposition of persistent sediment rich-antibiotics favoring resistant microorganism hence affecting natural biogeochemical processes and microbial activity in the ecosystem. Further, these drugs can modify resistance by selecting Antibiotic Resistant Genes (ARGs) and accelerate transmission of horizontal genes, hence increase possibility of antibiotic resistance gene transfer from environs to human pathogenic bacteria [105,106]. However, scarce information is documented on the use of antibiotics and other drugs in fish cage farming in Lake Victoria.

Conclusions and recommendations

Currently, Lake Victoria is experiencing sequence of ecological transformation. Cage farming provides a significant opportunity towards the realization of Sustainable Development Goals of 2030, especially the achievement of food security and nutrition. However, studies have demonstrated that fish cage culture negatively impacts the aquatic ecosystem and aquatic life, which threatens the ecological balance of Lake Victoria.

Therefore, to fully harness the potential of fish cage farming as a sustainable strategy, there is need for installation of digital sensors in water bodies is vital to monitor the extent of damage from all the investors. Further, as a result of genetic pollution establishment of gene banks will aid in the determination of genetic purity for the L. Victoria fish species. Also, a multi-sectoral approach will help in achieving sustainable use as well as maintaining ecosystem integrity of Lake Victoria. This will not only contribute to economic growth but also a long term sustainability of Lake Victoria resources.

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