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A Scoping Review on Microbial Contamination of Fish from Lake Victoria, Kenya

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Abstract

Aquaculture in Kenya has significantly grown over time, contributing to economic growth and food security. Despite this, microbial contamination has led to losses that continue to face the industry along the fish supply chain. This review assesses microbial contamination hotspots and potential pathogens, using a scoping review approach using data from 2014 to 2024. This scoping review aimed to assesses microbial contamination hotspots and potential pathogens, using a scoping review approach using data from 2014 to 2024. Adhering with a pre-registered protocol, a scoping review methodology was employed. A search strategy was employed across multiple electronic databases such as PubMed, Scopus, Web of Science, Google Scholar, AJOL and grey literature. From an initial pool of 776 sources, 62 articles underwent data extraction. The reporting adhered to the PRISMA guidelines. The outcome of the review shows that current traditional practices during harvesting, handling and transporting are not in line with international food safety practices leading to numerous points of contamination. *Escherichia coli*, *Vibrio*, *Salmonella* and *Shigella* are the key pathogens identified. The improvement of infrastructure like refrigerated transportation, processing facilities and enhanced hygiene conditions among fish handlers would greatly improve the situation. This review recommends investment in efficient modern equipment, thorough screening of fish before market distribution and enhanced fish handler training. The implementation of these measures is crucial in ensuring the quality and safety of aquaculture products in Kenya.

Keywords: Microbial contamination, pathogens, aquaculture, food safety

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Introduction

Kenyan aquaculture plays a crucial role in economic development, enhancing food security, creating employment opportunities, and improving livelihoods (FAO, 2022; Madara et al., 2022). Lake Victoria serves as a significant source of freshwater fish, providing more than 90 per cent of the total fish production in Kenya, in the local market and the export markets. A number of commercially important fish species thrive in the lake, amongst them being the exotic Nile perch (*Lates niloticus*), the indigenous cyprinid (Rasbora argentea) and the introduced Nile tilapia (*Oreochromis niloticus*) (Madara et al., 2022) and African catfish (*Clarias gariepinus*) that gain popularity because of their rapid growth rates and flexibility to different agricultural conditions (Ayuya et al., 2021). The Nile tilapia stands out as the most commonly farmed fish in freshwater. It's known for its impressive productivity, commercial viability, and adaptability to smallholder farming systems (Munguti et al., 2021). We additionally provide the Lake Victoria sardine (*Rastrineobola argentea*), which the local communities manage. This fish has not only improved food security but also created livelihoods for local communities (Odhiambo et al., 2023).

The aquaculture sector in Kenya has also made considerable progress recently, and this has been facilitated thanks to the much-improved government support through various frameworks and initiatives. Government programs such as the Economic Stimulus Program along with Kenya's Vision 2030 and The Big Four Agenda, have made aquaculture a focal point. In time, increased attention to aquaculture has considerably expanded the aquaculture sector. The advances made in this sector will help to significantly provide food security through demand for products and increased avenues for economic development. However, the current losses being sustained by the industry as a result of microbial contamination have highlighted the need for the same attention to be paid to this aspect with expertise. In this review, the authors identify the hotspots of microbial contamination and potential pathogens in aquaculture using the scoping review method based on data from 2014 to 2024. The outcome of the review shows that current practices are not consistent with international food safety practices during harvesting, handling and transporting, and on many occasions, there will be multiple points of contamination. The improvement of infrastructure like refrigerated transportation, processing facilities and enhanced hygiene conditions among fish handlers would greatly improve the situation. This review recommends investment in efficient modern equipment, thorough screening of fish before market distribution and enhanced fish handler training. The implementation of these measures is crucial in ensuring the quality and safety of aquaculture products in Kenya.

Manufacturing, universal healthcare, affordable housing and food security. Other policy frameworks that recognize aquaculture as a significant contributor to rural poverty reduction, food security and employment creation, especially for large numbers of unemployed youth are in place (Aloo et al., 2017; KMFRI, 2017) and the demand for healthier sources of protein (Munguti et al., 2014).

The gradual increase in fish production in Kenya from 2015 to the present day followed a previous decline in wild capture between 2006-2015 that occurred largely due to overfishing (Aura et al., 2022), pollution (Chan et al., 2019), use of illegal equipment (Limuwa et al., 2018), climate change and ecosystem degradation (Njiru et al., 2019) and post-harvest losses. Kenya produces approximately 20,000 tonnes/year. This places it fourth in Africa in terms of fish produced by aquaculture (Munguti et al., 2021). This suggests that aquaculture projects have finally begun to be productive. Kenya has seen increased productivity as a result of appropriate management practices, the easy availability of high-quality feeds and fingerlings, and new technology (KMFRI, 2017; Opiyo et al., 2018). Fish farming in cages facilitates better outputs for Kenya's aquaculture industry contributing to food security, public safety and economic sustainability in the fish markets. However, the aquaculture industry is writing off significant losses due to fish spoilage and microbial contamination (Odoli et al., 2019; Orina et al., 2019). Post-harvest contamination adds an estimated 10% loss along the value chain. Fresh fish is a perishable commodity with a short shelf life since it begins to degrade after the harvesting stage; this process facilitates spoilage primarily due to high surrounding temperatures, poor infrastructure and long distances to markets (FAO, 2022; Lokuruka, 2016). Raw or minimally preserved fish is highly susceptible to habitation by microbes, toxins, parasites, and other contaminants. Microbial and parasitic contamination leads to foodborne diseases such as salmonellosis, cholera and listeriosis. All these diseases pose significant public health issues (Huss et al., 2004; Bruce et al., 2019). Fish spoilage is mainly characterised by the formation of slime or 'mucus', acidification, and changes in colour, texture, odor and flavour (Oramadike, 2017). Additionally, inept handling practices, such as bulk storage, heaping and inappropriate storage, can also result in fish losses of 100% and loss of quality in the harvested fish (Obiero et al., 2019). Here, we thoroughly assessed the current knowledge on pre- and post-harvest fish losses due to microbial contamination and spoilage in the Lake Victoria area of Kenya and identified some risk factors contributing to microbial contamination along the fish supply chain, with a view to proposing some innovative solutions for improving public health risks associated with fish quality and safety methods.

Methodology

Lake Victoria, the second-largest freshwater lake in the world, situated at an elevation of 1,134 meters and extending between 0°20′N to 3°00′S and 31°39′E to 34°53′E. Kenya shares Lake Victoria’s shoreline at approximately 6% with Tanzania and Uganda, with the countries holding 51% and 43%, respectively (Nyamweya et al., 2023; Ali & Abd Ellah, 2023). The lake basin sustains over 40 million people, with a high population density of 250 people per square kilometer, who are heavily reliant on its resources (Nyamweya et al., 2023). Ecologically, the basin includes a variety of ecosystems, including wetlands, forests, rivers, and the lake itself. These systems are critical for regional biodiversity and play a vital role in climate regulation and carbon sequestration (Ngodhe, 2021). However, they face pressures from deforestation, pollution, invasive species like *Eichhornia crassipes* (water hyacinth), and overfishing (Onganya, 2023). These issues have severely degraded water quality and contributed to declining fish stocks, threatening food security and public health. Economically, the Lake Victoria Basin functions as a key driver of East African development. Fishing alone employs hundreds of thousands, directly and indirectly, while agriculture and trade flourish due to the basin's fertile soils and strategic transport routes (Ngodhe, 2021). Yet, the basin remains vulnerable to socio-economic inequalities, poor urban planning, and climate-induced stresses such as flooding and droughts.

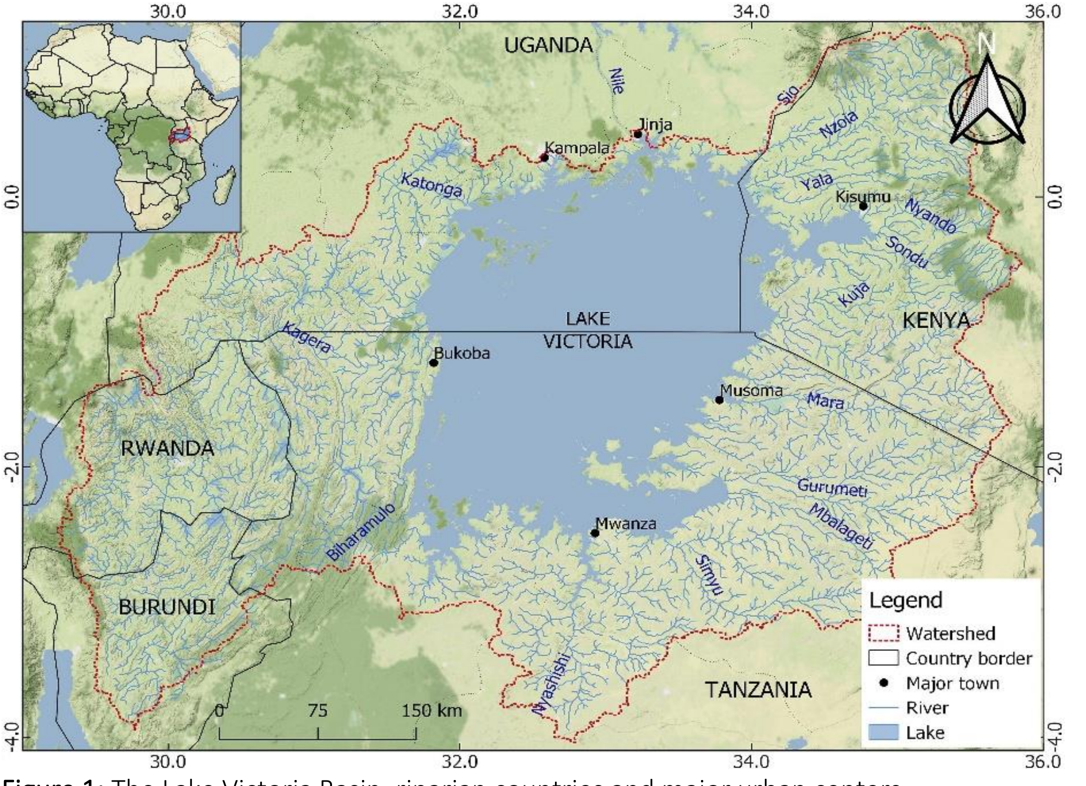

Figure 1: The Lake Victoria Basin, riparian countries and major urban centers
Source: *Nyamweya et al., 2023*

The study employed a scoping review to evaluate the existing literature on microbial contamination of fish from Lake Victoria, Kenya. This review adhered to the methodological framework for scoping reviews proposed by Arksey and O'Malley (2005) and further enhanced by Levac et al. (2010), while incorporating reporting guidelines from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) (Tricco et al., 2018).

The research question guiding this scoping review is: "What is the extent, range, and nature of evidence on microbial contamination of fish from Lake Victoria, Kenya?" What are the prevalent microbial contaminants found in fish from Lake Victoria, Kenya? What are the identified sources and pathways of microbial contamination in the fish value chain? How do various handling, processing, and preservation practices contribute to or mitigate microbial contamination? What is the impact of environmental factors, particularly water quality, on microbial contamination of fish in Lake Victoria?

The eligibility criteria for this review were guided by the Population, Concept, and Context (PCC) framework (Joanna Briggs Institute, 2020). For the Population (P), studies focusing on fish (any species, e.g., Nile perch, Nile Tilapia, Rastrineobola argentea) originating from Lake Victoria were included, encompassing wild-caught fish, farmed fish (e.g., cage farming), or fish products derived from these sources. The Concept (C) focused on microbial contamination, which included bacterial, viral, fungal, or parasitic contamination, and encompassed studies identifying specific pathogens, assessing microbial load, investigating antimicrobial resistance, or evaluating foodborne illness risks. The Context (C) was Lake Victoria, specifically within the Kenyan territorial waters and the associated fish value chains (landing sites, processing centers, markets, consumption points) in Kenya. Studies reporting on the broader Lake Victoria Basin were included if their findings were clearly relevant to the Kenyan context.

Inclusion criteria further specified peer-reviewed empirical studies (e.g., cross-sectional, descriptive, experimental), reviews, reports, and policy documents published in English. Studies had to focus on any stage of the fish value chain where microbial contamination was assessed or discussed, including identification of specific microbial species or indicators, discussion of contamination sources, or investigation of the impact of traditional or modern processing and preservation methods. Importantly, only studies published between 2014 and 2024 were included to ensure the temporal relevance of the findings. Exclusion criteria included studies not directly related to microbial contamination of fish (e.g., focusing solely on heavy metals), studies not conducted on fish from Lake Victoria or its immediate value chain in Kenya, opinion pieces or editorials without full-text availability unless they offered unique insights, and studies published in languages other than English.

A comprehensive three-step search strategy, adapted from the Joanna Briggs Institute (JBI) methodology for scoping reviews (Joanna Briggs Institute, 2020), was employed to identify relevant literature. Step 1 involved an initial limited search in two relevant databases (e.g., PubMed/MEDLINE and Scopus) using a few key terms related to the population and concept. This step helped in identifying relevant articles and informing the development of a more comprehensive search strategy by examining the keywords, subject headings (e.g., Medical Subject Headings [MeSH] in PubMed), and abstracts of highly relevant retrieved articles. In Step 2, a detailed search strategy was developed for all selected databases based on the initial limited search. This involved identifying all keywords and controlled vocabulary terms (e.g., MeSH terms, Embase subject headings) for each concept within the PCC framework. Boolean operators (AND, OR), truncation (*), and phrase searching ("") were utilized to maximize search sensitivity and specificity, with the strategy refined iteratively. For 'Fish Population', keywords like "fish," "aquaculture," "Nile perch," and MeSH terms such as "Fishes" were used. For 'Microbial Contamination', keywords included "microbial contamination," "pathogens," "food safety," specific pathogens like "Salmonella," and MeSH terms like "Food Contamination." For 'Context (Geographic)', keywords such as "Lake Victoria" and "Kenya," along with MeSH terms like "Kenya," were employed. An illustrative example search string for one database combined these concepts using Boolean operators, for instance: (Fish OR aquaculture OR "Nile perch") AND ("microbial contamination" OR pathogens) AND ("Lake Victoria" OR Kenya). Step 3 involved executing the refined search strategy across multiple electronic databases to ensure comprehensive coverage, including PubMed/MEDLINE, Scopus, Web of Science, CABI Abstracts (via Web of Science or specific platform), Google Scholar (for supplementary searching to identify grey literature), African Journals Online (AJOL), and institutional repositories of Kenyan universities (e.g., University of Nairobi, Maseno University, Moi University) for theses, dissertations, and technical reports. Additionally, reference lists of included studies and relevant reviews were hand-searched to identify any further pertinent articles not captured by the database searches. The search was restricted to studies published between January 1, 2014, and December 31, 2024.

The study selection process involved two stages. First, in Title and Abstract Screening, two independent reviewers screened all titles and abstracts against the predefined eligibility criteria. Any discrepancies were resolved through discussion and consensus, with a third reviewer arbitrating if necessary. Records deemed irrelevant were excluded, with reasons for exclusion recorded. Second, during Full-Text Screening, the full text of all potentially relevant articles was retrieved, and two independent reviewers then independently assessed each against the eligibility criteria. Reasons for exclusion at this stage were recorded according to PRISMA-ScR guidelines (Tricco et al., 2018), with discrepancies resolved through discussion or by consulting a third reviewer. A PRISMA-ScR flow diagram (Figure2) was used to transparently report the number of studies identified, screened, and included/excluded at each stage of the review (Tricco et al., 2018).

Data charting (often referred to as data extraction in systematic reviews) was performed by two independent reviewers using a pre-designed and pilot-tested data charting form. This iterative process allowed for modifications to the charting form as familiarity with the literature increased (Arksey & O'Malley, 2005; Peters et al., 2020). Information extracted from each included study encompassed general details (author, year of publication, study type/design, country of origin, publication status), study aims/objectives, specific study area/setting, population studied (fish species, sample size, type of sample), methodology/methods used (e.g., microbial analysis techniques, sampling methods, experimental design), and key findings related to microbial contamination. These key findings included identified microbial contaminants/pathogens (types and prevalence), microbial loads (e.g., Total Viable Counts [TVC], coliform counts), sources and pathways of contamination (e.g., water, ice, equipment, human handling), the impact of handling/processing/storage practices, and any reported antimicrobial resistance patterns. Additionally, any recommendations or implications for policy, practice, or future research suggested by the authors were extracted. Any discrepancies in data charting were resolved through discussion between the two reviewers or, if necessary, by consultation with a third reviewer. It is important to note that quality appraisal of individual studies was not formally conducted, as this is typically not a requirement for scoping reviews, which aim to map the literature rather than assess the certainty of evidence (Munn et al., 2018). Data was extracted on the relevant pathogens, source of contamination and relevant risk factors such as poor handling, unsanitary environment and poor storage. The extracted data were then sorted into topic categories, which allowed for synthesis and comparisons across studies. A narrative synthesis of the data was conducted, showing the levels of microbial contamination (the pathogen of most importance) and, ultimately, risk factors associated with pre and postharvest fish losses. The findings were reported in accordance with PRISMA (PRISMA, 2020).

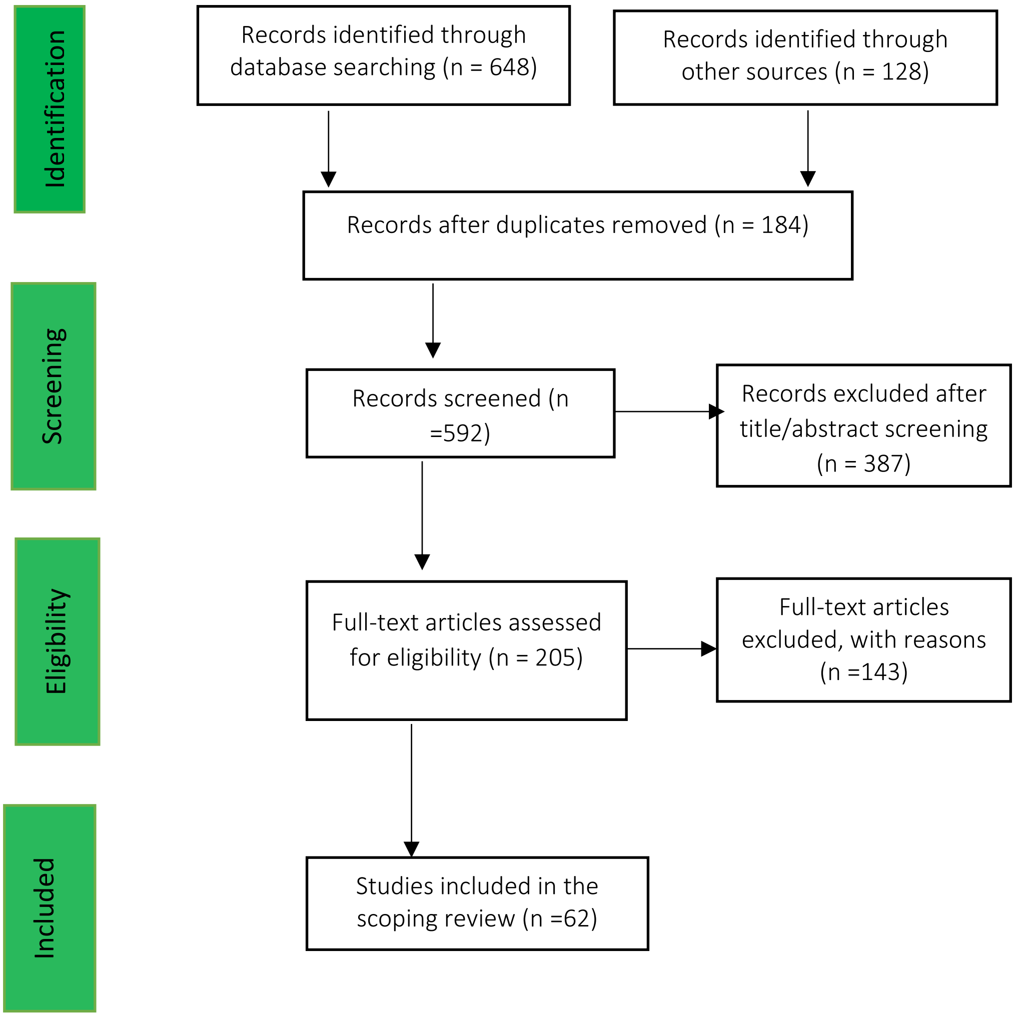

Figure 1. PRISMA flow diagram of included articles for scoping review

Results and Discussion

Postharvest losses due to contamination of fish and fish products

The fish and fish products post-harvest losses can be classified into nutritive, physical, quality, economic and losses due to processing procedures (Getu et al., 2015). Physical quality, nutrition and the total value losses largely occur during harvesting, landing, handling or processing. This tends to cause loss of nutrition and decrease of consumer desire towards fish products, which inevitably affects economic returns (Gramme & Dalgaard, 2002; Huss et al., 2004; Thant, 2019). Chemical reactions such as lipid oxidation, protein decomposition, and microbiological activity should be noted as some of the primary causes of fish deterioration (Lokuruka, 2016). Microbial Deterioration is especially significant as fish create an optimal habitat for bacterial proliferation owing to their elevated moisture content, neutral pH, and abundant nutritional composition (Lokuruka, 2016). This microbial activity causes degradation. Getu et al. (2015)

reported significant microbial contamination in areas around Lake Victoria as hotspots for postharvest losses. Common bacterial contaminants discovered in Lake Victoria linked to spoilage of fresh fish include Pseudomonas, Shewanella, and Vibrio (Mumbo et al., 2023), which generate and are responsible for off-odours, discolorations, and texture changes, so lowering the quality and safety of the fish products (Huss et al., 2004). Losses in nutritive, physical and quality values normally happen at harvesting, landing, handling or during processing. Losses of fish represent losses in nutritive value and potential for consumer acceptance, thus reducing economic return (Gramme & Dalgaard, 2002; Huss et al., 2004; Thant, 2019). It is widely reported that the factors that cause fish deterioration are chemical phenomena, such as lipid oxidation and protein denaturation, and modifications due to microbiological activity (Lokuruka, 2016). Microbial losses are proportionally significant as fish provide an ideal niche for bacterial growth, considering high moisture content, neutral pH, and suitable nutrition (Lokuruka, 2016). Microbial activity causes degradation of food. Getu et al. (2015) noted relationships between significant microbial contamination and post-harvest losses in areas around Lake Victoria. Common bacterial contaminants found around Lake Victoria identified as spoilage agents in fresh fish include Pseudomonas, Shewanella, and Vibrio (Mumbo et al., 2023), organisms that cause off-odours, discolouration, and textural changes, thus reducing the quality and safety of fishery value products (Huss et al., 2004). From the examination of studies on postharvest losses resulting from fish contamination, it would be necessary to ascertain exact numbers on unidentified risk areas.

Fish Pathogens from Lake Victoria

Studies conducted between 2014 to 2024 on fish contamination from Lake Victoria show that several pathogens mostly found in the natural aquatic habitat, often enter the final product through contamination of processing equipment, surfaces, food handlers and water used for fish processing (Onyango et al., 2017). Key pathogens identified across these studies include *Salmonella spp., Escherichia coli, Vibrio cholerae, Listeria monocytogenes, Shigella spp., and Aeromonas hydrophila* (Okemo et al., 2017; Odhiambo et al*.,* 2023). These pathogens are usually associated with poor handling practices, inadequate sanitation, and improper storage conditions during the postharvest phase as shown in Table 1.

To make matters worse, there are upwards of more than 150 bacterial isolates discovered in fish postharvest, encompassing many gram-negative bacteria also including Achromobacter, *Flavobacterium*, *Salmonella*, *Pseudomonas*, *Vibrio* and *Escherichia coli,* and gram-positive isolates including *Staphylococcus*, *Micrococcus*, *Bacillus*, and *Clostridium* (Wanja et al., 2020; Onjong et al., 2021; Kyule et al., 2022; Mumbo et al., 2023). To note, the gram-positive bacteria encompassed *Bacillus* species (e.g., *B. amyloliquefaciens*, *B. thuringiensis*, *B. pumilus and B. safensis*). Due to their endospores and toxins, Bacillus species can survive harsh conditions, and this might create a food poisoning risk (Kyule et al., 2022). The discovery of pathogens such as *Campylobacter jejuni* and *Yersinia enterocolitica* and enteric bacteria such as *Salmonella*, *Shigella* and *Escherichia coli* shows increased health risks associated with fish and fish products from this region, including typhoid, food poisoning and gastrointestinal infections (Kyule et al., 2022; Mumbo et al., 2023).

Table 1: Pathogens detected from fish from Lake Victoria, Kenya

Fish species	Pathogen	% Prevalence	Potential source of contamination	Reference
Nile perch	*Salmonella spp., Escherichia coli, Staphylococcus aureus*	20-40% 15-25%, 10-20%	Poor handling and hygiene practices during postharvest processing.	Mhongole et al.,2014 Onyango et al., 2017
Nile perch, Nile Tilapia	*Vibrio cholerae, Listeria monocytogenes*	10-15% 5-10%	Cross-contamination during transportation and storage	Onjong' et al., 2021 Mumbo et al., 2023
Nile perch	*Aeromonas hydrophila, Vibrio parahaemolyticus, Pseudomonas spp., Salmonella spp., Vibrio spp., E. coli*	30-50% 25-40% 10-30%	Contaminated water used during fish washing	Odongkara et al., 2022 Okemo et al., 2017 Wanja et al., 2020
Nile Tilapia	*Shigella spp., Clostridium botulinum; Bacillus spp., Staphylococcus spp.*	10-20% 5-15%	Poor processing conditions and storage associated with the proliferation of pathogens in fish products.	Kyule et al., 2022 Aura et al., 2024
Nile perch, Nile Tilapia	*Campylobacter jejuni, Yersinia enterocolitica*	15-25% 5-10%	Contaminated fish products during handling and processing at landing sites and markets.	Njiru et al., 2019
Nile perch	*Pseudomonas spp., Enterococcus faecalis*	20-30% 10-15%	Inadequate cleaning of processing equipment	Ouma et al., 2016
Nile Tilapia	*Salmonella spp., Escherichia coli, Shigella spp., Morganella spp., Providencia spp., Klebsiella spp., Legionella spp.*	20-35% 15-25% 10-20%	Improper sanitation practices and poor packaging in open-air fish markets	Okemo et al., 2017 Odhiambo et al., 2023
Nile perch	*Listeria monocytogenes, Vibrio vulnificus*	5-15% 10-20%.	Improper storage and transportation	Mhongole et al., 2014 Kowenje et al., 2020;
Nile perch	*Aeromonas hydrophila, Staphylococcus aureus*	30-50% 10-20%	Contaminated ice used during fish preservation	Oloo et al., 2022
Nile Tilapia	*Shigella spp., Campylobacter jejuni*	15-25% 10-20%	Poor handling practices at fish landing sites	Mumbo et al., 2023

Other researchers, including Mhongole et al. (2014) and Onyango et al. (2017), found high levels of contamination of Nile perch linked to unsatisfactory handling or hygiene during postharvest processing. Also reported were cross-contamination of Nile perch and tilapia during transport and storage, which facilitated the spread of pathogens like *Vibrio cholerae* and *Listeria monocytogenes* (Onjong' et al., 2018; and Mumbo et al., 2023). Other studies have pointed out the role of washing fish in contaminated water as a source of postharvest contamination in Nile perch, which could include pathogens such as *Aeromonas hydrophila*, *Vibrio parahaemolyticus*, *Pseudomonas*, and *Salmonella* species (Okemo et al., 2017, and Wanja et al., 2020; Odongkara et al., 2022) (see Table 2).

Table 2: Potential sources of post-harvest contamination of fish along the supply chain

Risk Factor	Description	% Loss	Reference
Personal Hygiene	Lack of proper hygiene practices among fish handlers	10-20%	Adebayo-Tayo et al., 2014
Water Quality	Use of polluted lake or river water for washing fish has potential for introducing pathogens.	15-25%	Oloo et al., 2015
Cross-contamination	Contact with contaminated surfaces, equipment, or other fish	10-30%	Mwang'onde et al., 2017
Storage Conditions	Improper storage conditions promote microbial growth and spoilage of fish.	20-40%	Munguía-Fragozo et al., 2018
Handling Practices	Improper handling practices contribute significantly to microbial contamination	15-35%	Onyuka et al., 2019
Transport Conditions	Lack of refrigeration lead to increased microbial contamination during transit.	10-30%	Obar et al., 2025
Temperature Control	Poor temperature control during transportation and storage leads to the proliferation of bacteria	25-50%	Odoli et al., 2020
Market Conditions	Open air market environments contribute to microbial contamination.	20-30%	Ogongo et al., 2021
Sanitation of Equipment	Use of poorly sanitized equipment, such as knives containers increase the risk of contamination	15-30%	Amoah et al., 2023
Delayed Processing	Delays in processing fish after harvest allow for bacterial proliferation.	20-40%	Amoah et al., 2023

Water as a Source of Microbial Contamination

Water quality is defined as the chemical, physical, biological, and radiological attributes of water. Due to this fact, it is significant to human safety and environmental well-being. Based on this, the presence of total coliforms and *E. coli* in Lake Victoria is often higher than the guidelines set by regulatory agencies (KS EAS 12, 2018; WHO, 2022). This poses a concerning threat to public health and impacts environmental safety. Studies looking at the microbiological quality of water in close proximity to Lake Victoria showed hectic levels of bacterial contamination mainly linked to anthropogenic activities involving washing, bathing, and launching boats disturbing sediments and increasing levels of coliforms (Okemo et al., 2017). Water microbiological quality standards come from the World Health Organization (WHO) and the Kenya Bureau of Standards (KEBS). Researchers have demonstrated that many factors contribute to the declining water quality for Lake Victoria. The large population density has created excess pressure on the resources, thus decreasing the efficiency of management actions (Juma et al., 2014; UNEP, 2004). Often, uncontrolled effluents from both sewage and industrial areas lead to increased pollution of the water (Njiri et al., 2005; Sifuna et al., 2018). Nantaba et al. (2025) determined that agricultural run-off has increased the amounts of fertilizers and pesticides that contaminate the waterways of Lake Victoria with nutrients and other potentially toxic chemicals. These agrochemical contaminants can influence aquatic systems with hazardous chemicals (Nyamweya et al., 2020). Also identified are pharmaceutical compounds that impact water quality and threaten aquatic organisms and people who rely on them (Opere et al., 2021). The extent of limitation of environmental regulations, and controlling and enforcing pollution controls, present continuing uncertainty for the quality of water in Lake Victoria (Aura et al., 2022).

Harvesting, Hygiene and Handling Practices

The quality and safety of fish relies on correct procedures for handling. Depending on the methods used for harvesting fish, for example, trawling, netting, and hooking techniques can affect the quality of fish and affect market acceptability. The physical damage and stress can affect fish integrity and makes them more susceptible to spoilage, and microbial contamination (Ouma et al., 2002). Poor decontamination cleaning, or cleaning equipment and surfaces, can mean high levels of bacterial representation and activity (Onyuka et al., 2019). Indigenous pathogens such as Vibrio species and non-indigenous pathogens such as Escherichia coli and Salmonella can multiply while handling fish if adequate hygiene and handling standards are not followed (Monteiro et al, 2015). We can contaminate the fish with the pathogens. Microorganisms present on our personal clothing, if adequate personal hygiene practices are not performed, such as not washing our hands well and using dirty aprons contaminate fish (Adebayo-Tayo et al, 2014). If we fail to clean and sanitize the tools we use to process fish, including knives, cutting boards, and containers, our processing practices can increase the risk of cross contamination and this can pose a serious threat to the quality of our fish (Amoah et al, 2023). It is our responsibility to regularly and thoroughly sanitize tools and equipment on future processing workflow, as appropriate cleaning practices can reduce the harm from harmful microorganisms and maintain the quality we strive for. Though improvements to sanitation can help with the prevention of harmful microorganisms; for example, in 2023, only 60% of Kenya had access to clean tap water (USAID, 2023).

Good hygiene practices, guidelines and training of fish handlers can also improve guidelines and standards (Adebayo-Tayo et al, 2014). Delays to processing fish after harvesting fish particularly if we are not able to keep fish refrigerated will allow for bacterial proliferation. Prompt processing and appropriate storage are essential to prevent spoilage and maintain fish quality (Amoah et al., 2023) but also require a stable electricity supply which is also not always available in Kenya; more than 20% of the population still lacks access to electricity and frequent power cuts are common in areas that are connected to the national grid (Njiraini et al., 2020).

Holding Temperatures

Temperature control is critical for maintaining fish quality after harvest and plays a key role in limiting the rate of bacterial reproduction. For optimal freshness, fish must be held and stored below 4°C (Onyango et al., 2021) to limit the growth of microbes. Lower temperature has been shown to slow down the rates of metabolism of bacteria and, consequently, spoilage and safety risk. The risk of pathogens and spoilage organisms introduced by high ambient temperature, typically in the 20-30°C range, will become more prevalent (Odoli et al., 2020). Traditional cooling options, including the use of aquatic weeds, resulted in limited success and higher levels of bacterial contamination because the effectiveness of the cooling measure is limited, and they can add more pathogens than they remove (Thant, 2019; Saklani et al., 2020; Caggiano et al., 2020). Modern cooling technologies have been proven to be very effective in slowing the metabolism of microbes and keeping fish quality and review temperature settings as prescribed along the whole supply chain, but this must be weighed against the carbon emissions cooling technologies contribute (Wu et al., 2022) along with the cost which will be seen by the end consumer. Chilling helps to extend the shelf life of fish by retaining their freshness and inhibiting microbial growth (Kowenje et al., 2020). Although modern storage facilities and effective temperature control during the distribution cold chain can help to ensure fish remain safe for consumption and retain any desirable quality attributes, it also opens the potential for pathogens, which can survive in ice, to be transported longer distances (Liao et al., 2023; Chatreman et al., 2020).

Processing Technologies

Fish preservation and the processing of value-added fish products are crucial for reducing post-harvest losses and ensuring food security. Modern technologies are essential to improve the quality and safety of fish products (Munguti et al., 2021). However, in Kenya, traditional methods such as smoking and drying remain common (Kyule et al., 2014; Munguti et al., 2021) but often fall short in addressing various quality and safety concerns associated with fish preservation. Sun-drying is a common practice in Lake Victoria, Kenya. This technique consists of placing fish on the ground, placing it on old fishing nets, drying it on racks, or placing it on mats made from papyrus reeds. Drying fish on racks usually gives fish less soil or dust contamination than drying fish on the ground, as fish laid directly on the ground often have soil contamination or are poorly dried and/or are discoloured, lower quality, and unconsumable (Onyango et al., 2017). Biological factors can also accelerate fish spoilage, and sun-drying for prolonged time frames may lead to insect and rat contamination (Ochieng, 2023). Furthermore, Onyango et al. (2015) found that sun-drying gives rise to conditions that may promote the development and resistance of bacteria rather than inhibiting the growth of bacteria.

Approximately 13.7% of all fish harvested in Kenya came from smoking, another ancient preservation method extensively used in Lake Victoria (Onyango et al., 2017). Fish subjected to high temperature by this process can decrease the nutrient value of fish, particularly lower lysine and availability of essential amino acids. Moreover, smoking can accelerate lipid rancidity and limit fat digestibility (Abila et al., 2000). The method traditionally involves the use of kilns that are uncontrolled with regard to temperature, leading to inconsistent smoking of fish that is likely reflected in fish quality (Kabahenda et al., 2009). The produced goods could have problems, including burning, a bad look from carbon soot, and more fragility. Often used and reasonably priced, salting causes dehydration to help stop microbial deterioration. On the other hand, too much salt intake increases health hazards including cardiovascular problems and hypertension (Yoo et al., 2020). Though it increases shelf life, the technique's health effects need careful control. Fish items are sterilized using chlorine solutions, such as sodium hypochlorite. But oxidation causes these solutions to lose their efficacy over time, so they are less useful for extended usage (Keyombe et al., 2018).

Hot oil treatment is regarded as a useful method when preparing Nile Tilapia fish (Onjong et al., 2018; Chelimo et al., 2021). However, inappropriate handling can lead to the introduction of heat-tolerant toxins generated by organisms such as *Bacillus cereus* and *Staphylococcus aureus* that compromise food safety. Reports of food illness brought on by *Salmonella* and *Staphylococus aureus* contamination have generated public health concerns (Onjong et al., 2018). Seasonal variations, especially in the wet season, have greatly affected fish preservation. High humidity leads to accelerated breakdown of processed, sun-dried, and smoked fish products (Onyango et al., 2017). Poor processing methods aggravate these problems even further, which lowers the nutritional content and quality of fish. Influenced by temperature and storage time, the storage conditions in street markets also significantly contribute to microbial activity (Onjong et al., 2021).

Packaging

The packaging material choices and practices can greatly affect the quality and safety of fish products. Among Kenyan fishermen, gunny bags (bags made of sisal ropes or papyrus baskets) are mostly used as packing material. Gunny bags are available for cheap, and they are the preferable option; however, they may not provide sufficient protection against environmental factors (e.g., air, light, and moisture) and bacterial contaminants, all of which can quickly spoil fish products (Onyango et al., 2017). Fish can be exposed to other substances that can support microbial growth in addition to undesirable changes when packaged with poor packaging materials. All of these factors contribute to decreasing shelf life and increasing risk of contamination. In addition, moisture can facilitate spoilage bacteria and cause the loss of fish texture that leads to disappearing taste (Nyamwaka et al., 2020). UV light exposure can also degrade fragile nutrients and produce off-flavours and discolouration (Nyamwaka et al., 2020). Reducing these risks entirely depends on good packaging and storage conditions. Modern packaging materials such as modified atmosphere packaging and vacuum-sealed bags offer better protection against spoilage factors (Sahoo et al., 2022). However, if these are made of non-biodegradable materials, such as plastic, their suitable disposal or recycling should be considered to help avoid environmental pollution. Appropriate storage conditions such as controlled temperatures and humidity levels, extend the shelf life of fish and fish products therefore ensuring their safety for consumption (Rana et al., 2019). By ensuring fish quality and ensuring sanitized fish minimizes public health outcomes, minimizing fisheries' economic losses depends on superior packaging options, sanitation management and appropriate storage practices (Nyamwaka et al., 2020; Sahoo et al., 2022).

Transport and Storage Conditions

Acceptable transport conditions determine fish product safety and quality (Sheng & Wang, 2021). In many cases, poor transport has had a notable impact on microbial contamination hazards while fish are in transit (Nyakundi et al., 2019). A lack of basic infrastructure is compounded by absent refrigerated truck transport and ice storages, which increase the odds of contaminating and quality-degrading fish (Nyakundi et al., 2019). An intolerable circumstance of fish from the Lake Victoria area remains, according to Okemo et al. (2017), that the preservation of fish is often done so in an unacceptable setting where the poor structural environment allows fish to be subjected to pest problems and the opportunity for microbial contamination, leading to fish spoilage and other quality issues. Fish products maintain the best quality when caught and COOLED rapidly to its long-term preservation temperature of 4 degrees (Munguia-Fragozo et al., 2018). Nevertheless, fish depend on refrigeration for assuring quality. A solution is solar-powered cold storage systems. For example, the Keep IT Cool (KIC) project provides solar-powered refrigeration and ice to small scale fish processors and traders. This method provides a sustainable and effective way to maintain fish quality and safety (UK AID Report, 2022) thereby improving fish handling methods. This eventually helps to offset the issues with inadequate refrigeration as well as minimizing the rising carbon footprints of energy generation from electric cooling systems.

Conclusions

Fish microbial contamination in Lake Victoria's aquaculture system is associated with the high prevalence of bacterial pathogens such as *Escherichia coli*, *S. aureus*, *Salmonella*, *Vibrio* and *Shigella* species which present significant threats to fish quality, fish safety and economic situation in the fish value chain. High levels of contamination mainly stem from a lack of proper sanitary practices at the time of harvesting, after harvesting, during transport and finally during the processing of the fish. This is compounded by obsolescence in infrastructure and limitations of all forms of current traditional preservation methods. Poor water quality, lack of refrigeration facilities, lack of hygiene practices and poor storage practices have been attributed to fish spoilage and loss of fish freshness diminishing marketability conditions and food safety. Traditional methods of preservation do not sufficiently prevent microbial growth and reduce the overall nutritional value and safety of fish and fish products in Kenya.

Recommendations

It is important to improve hygiene and handling practices along the fish supply chain in Kenyan aquaculture to reduce losses from sources emanating from microbial contamination. The key actions involve interventions regarding improving water and sanitation facilities and having modern processing with a low-carbon footprint, cold storage, and refrigeration on-site, during transport, and in markets to maintain storage temperature and greatly reduce the microorganisms and other contaminations that spoil fish. There are also avenues for training fish handlers and traders regarding better hygiene, handling, and storage practices (e.g., clean insulated containers and iceboxes) in order to safely store fish for temperature and food safety immediately after harvest. Investing in infrastructure and adopting innovative technologies such as solar-powered cold storage solutions, particularly in remote areas with limited electricity access, while using safer and more efficient processing methods, can significantly prolong fish shelf life and maintain nutritional quality, as well as limit the chances of contamination from external sources. Policymakers need to work closely with stakeholders to establish stringent regulations and enforce best practices that align with international food safety standards. The implementation of regular microbial screening and quality control checks along the fish value chain is necessary to ensure compliance with safety standards thereby protecting consumer health, reduce postharvest losses, improve fish quality, enhance food security, and bolster the economic resilience of communities dependent on aquaculture in Kenya.

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