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Review Article

Revisiting Chemical and Microbiological Quality and Safety of Fish and Fish Products

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Abstract

Fish and fishery products constitute a primary global food source, providing essential protein and nutrients. Ensuring their safety and quality throughout the supply chain is paramount. The safety and quality of fish and fish products are paramount considerations in the global food industry but their quality and safety may be compromised at various stages of transport, handling, and processing. The major contaminants of fish and fish products are chemical and microbiological in nature. Chemical contaminants commonly found in fish, including heavy metals, pesticides, and persistent organic pollutants which pose significant risks to consumers. Microbiological contaminants are both pathogenic and spoilage microorganisms such as Salmonella, Listeria monocytogenes, and Vibrio spp which are often implicated in foodborne illnesses associated with seafood consumption. This review synthesizes current knowledge on the chemical and microbiological contaminants facing the fish industry while advocating for enhanced regulatory frameworks and sustainable practices to ensure consumer safety as well as modern methods for detecting these microorganisms, including molecular techniques like PCR (Polymerase Chain Reaction) and biosensors that enhance detection sensitivity.

Keywords

Fishery Products, Microbiological Safety, Chemical Quality Control, Preservation Technologies, Biogenic Amines

1. Introduction

Fish is considered a safe food in general, and the muscles of healthy fish are considered sterile, although debate on this continues [39]. While low in fat, fish constitutes a high-quality protein source rich in omega-3 fatty acids and vitamins such as D and B. Additionally, it serves as a critical dietary supply of essential minerals including calcium, phosphorus, iron, zinc, iodine, magnesium, and potassium. Consequently, global demand for fish and its derivatives has surged. Owing to insufficient aquaculture capabilities in many regions, a substantial portion of fish products is imported from coastal nations [40]. Beyond its nutritional value, fish constitutes a significant commodity in international trade, generating substantial foreign exchange. Global fish production has experienced dramatic growth over the past six decades to around 179 million tons in produced in 2018 with a valued at $401 billion. Correspondingly, Global fish consumption has risen from 9.0 kg per capita in 1961 to 20.5 kg in [31].

Fish and fish products play an important role in human diet as they are said to have health benefits such as protection from cardiovascular diseases as well as inflammation [100].

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However, fish and fish products have been involved in various foodborne outbreaks and recalls annually [107]. Microorganisms exert a profound influence on the safety of fish and fish products [108, 41]. The transmission and persistence of human pathogens within these products, coupled with the generation of chemical hazards arising from spoilage microbial proliferation, pose significant challenges. Fish have been established as reservoirs for a diverse array of bacterial pathogens associated with human illness including; Mycobacterium spp., Photobacterium damselae, Vibrio alginolyticus, Vibrio parahaemolyticus, Vibrio cholerae, Escherichia coli, Aeromonas spp., Salmonella spp., Staphylococcus aureus, Listeria monocytogenes, Clostridium botulinum, Clostridium perfringens, and Campylobacter jejuni [148].

The safety and quality of fish and fish products are paramount considerations in the global food industry but their quality and safety may be compromised at various stages of transport, handling, and processing [43]. This contamination maybe related to the raw materials, personnel, and processing tools such as forklifts through leakage, insect, and pest harborage [129]. Illegal fishing practices as well as the utilization of chemical preservatives compromise the quality and safety of fish as well as its products, especially in developing countries. Additionally, seafood can become contaminated during storage and processing. Contamination maybe caused by food borne pathogens which are naturally present in aquatic environments, such as Vibrio spp., or derived from sewage contaminated water such as Salmonella spp. Consumption of these contaminated fish may cause infection or intoxication to the [129].

The aim of this paper is to review the microbiological and chemical safety of fish and fish products.

2. Chemical Quality and Safety of Fish and Fish Products

2.1. Contaminants of Concern Heavy Metals in Fish Products

Heavy metals, notably mercury, cadmium, and lead, pose significant health risks when bio accumulated in fish and fishery products. Research conducted in Poland, South Africa, and Senegal has revealed widespread contamination of commercially available fish species with these toxic elements [22, 48, 93]. Farmed Atlantic salmon, mackerel, and Baltic cod exhibited elevated levels of metal pollutants [88]. Furthermore, organic contaminants, such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), exacerbate the threat to human health posed by fish consumption [70]. These contaminants stem from industrial effluents and agricultural runoff, and their bio magnification within aquatic food webs can result in chronic health effects [37].

Investigations around the world have consistently demonstrated the pervasive contamination of fish by heavy metals, underscoring the imperative for comprehensive legislative frameworks [23]. A study conducted in Poland on the content of HFAs in fish revealed the following: the content of mercury in the analyzed fish depended mostly on the species, as farmed Atlantic salmon and mackerel showed the highest levels of mercury content, and further research should be done to assess the contamination level of fish available in local markets [70].

2.2. Persistent Organic Pollutants in Fish

Persistent organic pollutants (POPs) are notorious contaminants with well-established deleterious implications on both ecosystems and human health [94]. Accumulated evidence unequivocally demonstrates that these contaminants bioaccumulate in fish tissues at levels posing significant risks to human health and ecological integrity. Baby POPs are chemical substances that do not undergo biodegradation and remain in the environment for their lifetime, with adverse impacts on life forms [17, 140]. In China, the varying concentration trends of different POPs in Taihu Lake have been analyzed, and the study showed the identifiable presence of various POPs in the fish samples [90]. Some POP concentrations appeared to rise over time, while others featured the reality of POP contamination in aquatic ecosystems as dynamic. Despite this, the consumption of fish exposed populations to relatively low risks of carcinogenicity, due mainly to PCBs and DDTs. Surveys conducted in Argentina sought to understand the histological and physiological impacts of POPs on fish; he observed high levels of contamination of fish tissues with OCPs, PCBs, and PBDEs [16]. Alterations in the histology and vitellogenin levels pointed to the fact that POP exposure impacted the organisms adversely. Further efforts, including the implementation of measures to reduce the impact of toxic chemicals on aquatic life forms, must be made.

2.3. Emerging Contaminants in Fish and Fish Products

New and complex recalcitrant compounds and pollutants of emerging concern that affect people and ecosystems include endocrine-disrupting chemicals, carcinogens, and mutagens, which have been detected in water, sediment, soil, and consumer goods [97]. Microplastics and pharmaceuticals are pervasive and widespread in aquatic ecosystems, making it critically important to study their behavior and impact [149]. The prospects for increased exposure to these newly generated pollutants in the Mediterranean Sea are threatening the environment and human health. For example, some aquatic species, such as the catshark Scyliorhinus canicula and the mussel Mytilus galloprovincialis, act as useful biomarkers to demonstrate the levels of pollution and pollutants' bioaccumulation [125] There is still a pressing need to reduce the impacts of these pollutants, given that they are on the rise, and a need to protect water bodies [66]. In addition, some studies have explored the combined influence between aged and virgin microplastics and pharmaceuticals in freshwater environments concerning red tilapia, with specific emphasis on sulfamethoxazole and propranolol pharmaceuticals [65].

2.4. Biogenic Amines and Histamine Formation in Fish

Histamine and other biogenic amines are produced through enzyme-catalyzed biogenic amine formation in fresh fish and fishery products, which increases the chances of food poisoning [152, 158]). Biogenic amines are nitrogen-containing organic compounds generated by enzymatic reactions that include decarboxylation, transamination, reductive amination, and degradation of parent amino compounds [146]. Histamine, cadaverine, putrescine, and tyramine are some of the most frequently identified biogenic amines in fish and fish products, as they accumulate because of bacterial actions that are caused by poor hygiene and temperature control during storage [64].

2.5. Lipid Oxidation and Quality Deterioration in Fish

One of the major factors contributing to quality deterioration in fishery products is lipid oxidation, a factor attributed to the high polyunsaturated fatty acid contents of fish lipids [26]. Fish lipids with high contents of polyunsaturated fatty acids are very prone to oxidation, which results in quality deterioration when stored and transported [154]. The oxidation of fish lipids has a negative impact on improving muscle quality throughout the chain, which is a challenge to the seafood value chain. Some studies have also investigated the use of antioxidant supplements under different steps in fish production and preservation and proven that compounds such as lycopene and α-tocopherol exhibit radical scavenging activity [124]. However, the process of lipid oxidation elimination is not simple and necessitates multi-faceted approaches with the right degree of bleeding methods, low temperature storage, and appropriate cooking procedures to protect the lipid fraction in the farm-to-fork. Under the informative content, there is at present a great interest aroused to develop effective and non-invasive techniques for the determination of lipid oxidation in fishery products. Moreover, specialized microscopy fluorescence microscopy, for that matter has been displayed to monitor lipid oxidation-related processes in fishery products to provide an understanding of changes in quality during storage and processing [34].

3. Mitigating Strategies for Chemical Quality Control in Fish

Consumers are understandably more concerned with the safety and quality of their food because Aquaculture Fishery is steadily growing into an important supplier of food in the world [164]. Based on the above considerations, a chemical and microbial risk assessment for different aquaculture subsectors, and the corresponding control measures are as follows: Since governments are putting more effort for increasing the production of aquaculture, risks that slow down the production line should be addressed. It is established that integrated policies in that regard that connect the national and international regulations of water quality are essential to guaranteeing consumers the necessary confidence in seafood safety [137, 153]. The threats facing the aquaculture sector include contamination, which poses the risks of safety concerns and reduced availability of seafood that consumers deserve, hence the need to improve on risk assessments and risk management across the aquaculture sector [138].

The framework for risk assessment of chemical and microbial risks in aquaculture aims to analyze the extent of risks in various subsectors of aquaculture and find out the best control options for those risks. Since consumers are becoming more conscious of their food consumption, particularly those that are perceived to be healthy, such as seafood, much emphasis must be placed on managing risks from farm to fork or from sea to table. Such concerted effort towards mitigating hazard risks will secure the sector’s sustainability for seafood and support the sector’s capacity to offer safe, nutritional, and sustainable foods in the global market [24].

3.1. Source Control and Sustainable Fishing Practices

Marine conservation areas are regularly set up to protect the environment; however, it is often a problem when it comes to the fishing industry. After the Second World War, ruined countries relied on marine fishery stocks to revive their economies, which in the long run created and encouraged the use of larger fishing gear and boats, which intensified the act of overfishing and the destruction of the aquatic base [35]. Modern fishing has also embraced innovation in gears and crafts, from rudimentary gadgets and tools to complex and modern equipment with electronic features of sonar and GPS devices, respectively [74].

3.2. Processing Techniques in Fish Products

The method of processing fish products has a central role to play in reducing post-harvest losses, especially in parts like Nigeria, where as much as half of the total produce is wasted by poor handling and processing [53, 143]. Currently, there is a high emphasis on the quality of fish being produced, which can only be achieved by the appropriate fishing techniques and handling of the fish during collection and transportation to processing companies. Bacteriological, chemical, and physical deterioration are some of the limitations that could be avoided by processing the products shortly after harvest and adopting worthy preservation methods [103]. The globalization of these challenges guarantees the production of healthy and safe fish to be sold in the market, and consumers are willing to pay higher prices due to availability of quality fish products.

3.3. Novel Preservation Technologies in Fish

Fish and fishery products (FFP) are short-lived, perishable items that are sensitive to spoilage due to microbial and lipid activities [119]. Natural antimicrobials and antioxidants have emerged as effective replacements for synthetic preservatives [24, 52]. To maintain FFP's quality and safety, post-harvest operations are needed to prevent spoilage. Preservative additives and technological incorporations are being used to prevent spoilage [52]. [78]. reported that, bioactive compounds found in plants, bacteria, fungi, animals, and algae can help preserve seafood quality and shelf life. Introducing new methods that supplement or replace traditional methods is crucial for addressing fish spoilage and safety concerns [140]. Due to the trend of consumers opting for minimal processing, natural preservation has been adopted as a preferred means of preserving foods compared to synthetic [136]. Isolates of natural antimicrobials and antioxidants have potential for controlling microbial growth and lipid oxidation in FFP and maintaining quality without compromising product qualities [115].

4. Microbiological Quality and Safety of Fish and Fish Products

Fish and seafood are highly perishable commodities that can harbor a variety of microorganisms, including bacteria, viruses, and parasites [150]. These microorganisms can be both pathogenic and spoilage in nature [55, 121]. These microorganisms can originate from various sources such as water, handling practices, processing environments, and storage conditions [116, 148]. The microbiological quality of fish is influenced by several factors, including environmental conditions where fish are harvested, methods used during capture and processing, and storage practices [102]. Common pathogens associated with fish include Salmonella, Vibrio spp., Listeria monocytogenes, and various parasites such as Anisakis species [151]. The World Health Organization (WHO) has reported that seafood-related illnesses account for a substantial proportion of foodborne diseases globally. For instance, outbreaks linked to Vibrio parahaemolyticus have been documented in several countries due to the consumption of raw or undercooked seafood [118].

There have been notable cases highlighting the importance of monitoring microbiological quality in fish products. For example, in 2019, an outbreak linked to imported frozen tuna resulted in numerous cases of scombroid poisoning due to improper handling during processing [127]. Similarly, a 2020 investigation traced an outbreak of Salmonella infections back to contaminated smoked salmon products sold across multiple states in the United States [163]. These incidents underscore the necessity for stringent regulatory frameworks governing seafood safety. To ensure consumer safety, regulatory agencies such as the U.S. Food and Drug Administration (FDA) and European Food Safety Agency (EFSA) have established guidelines for acceptable levels of microbial contaminants in fish products [73].

4.1. Pathogenic Microorganisms Found in Fish and Seafood

Fish and seafood are susceptible to contamination by various pathogenic microorganisms during capture, handling, processing, and storage. Among the most significant pathogens in these products are species from the genera Vibrio, Listeria, Clostridium botulinum, staphylococcus aureus, Yersenia spp, Aeromonas spp, and Salmonella.

4.1.1. Vibrio Species

Vibrio species are pathogenic to humans and can cause serious foodborne illnesses when contaminated fish and fish Vibrio species are a group of Gram-negative, rod-shaped bacteria that are naturally found in marine and estuarine environments [5]. They are halophilic, meaning they thrive in saline conditions, which makes them particularly prevalent in seafood. The most notable pathogenic species include Vibrio cholerae, Vibrio parahaemolyticus, and Vibrio vulnificus [21]. Vibrio cholerae is best known for causing cholera, a severe diarrheal disease. While not all strains of V. cholerae are pathogenic, those that produce cholera toxin (such as O1 and O139 serogroups) can lead to outbreaks [96]. Although primarily associated with contaminated water rather than fish, V. cholerae can be present in seafood harvested from contaminated waters. Vibrio parahaemolyticus is one of the leading causes of gastroenteritis linked to seafood consumption worldwide. It is commonly found in raw or undercooked shellfish such as oysters, clams, and mussels [101].

V. vulnificus is known for its high virulence and potential to cause severe illness or death, and it is often associated with wound infections following exposure to seawater or consumption of raw or undercooked shellfish [15, 59]. Vibrio species predominantly contaminate shellfish due to their filter-feeding nature, accumulating bacteria from surrounding waters. However, other types of seafood, such as finfish, can also harbor these pathogens if they come into contact with contaminated water during harvesting or processing. Vibrio species thrive in warm marine environments but have varying degrees of tolerance to cold temperatures [30]. [6]. reported that refrigeration slows bacterial growth significantly, it does not eliminate Vibrio species and freezing can reduce the number of viable bacteria but may not completely eradicate them.

4.1.2. Listeria Monocytogenes

Listeria monocytogenes is a species of Gram-positive bacteria that can be found in various types of contaminated fish and seafood, including raw or undercooked fish. [86]. reported that Listeria monocytogenes can survive in freezing temperature and even grow in fish at refrigerator temperatures, as indicated Table 1. The occurrence of L. monocytogenes in fish and fish products differed among countries and is also influenced by fish species, geographic locations, sampling stages, sampling parts, product types, and sample origins [13]. For instance, [86] reported that L. monocytogenes was able to multiply significantly in raw yellowfin tuna during refrigeration and frozen storage and concluded that tuna meat intended for raw consumption must be handled properly from farm to table to reduce the risks of foodborne illness caused by Salmonella and L. monocytogenes. There have been numerous documented cases of listeriosis linked to contaminated fish products worldwide. For instance, outbreaks associated with smoked salmon have been reported across Europe and North America. In one notable case documented by the Centers for Disease Control and Prevention (CDC), an outbreak linked to smoked trout resulted in several hospitalizations due to listeriosis [81].

Table 1. *Type of fish and fish products, associated potential pathogens and storage conditions.*

Type of fish and fish products	Potential Pathogens detected	Storage condition	Reference
Raw yellowfin tuna, Smoked salmon	Salmonella and Listeria monocytogenes	Refrigeration and frozen storage	[86, 132]
Shrimp, Shellfish, Dried fish, Squid, salmon, tuna	Salmonella	Refrigeration and frozen storage	[29, 68, 121]
Vacuum-packed fish or canned fish, salmon, trout, whitefish,	Clostridium botulinum	Refrigeration and frozen storage	[5, 11, 69, 95, 121]
Finish, Clam, Oyster, Shrimp, Raw oyster, Undercooked shrimp, and mussels	Vibrio parahaemolyticus and Vibrio vulnificus	Refrigeration and frozen storage	[10, 42, 101]
Catfish, tilapia, and carp, salmon and shellfish, smoked fish or sushi	Aeromonas spp	Refrigeration and frozen storage	[127]
Trout carp, oysters and mussels	Yersinia spp	Refrigeration and frozen storage	[83]
Smoked salmon, canned tuna, shrimp, and other shellfish	Staphylococcus aureus	Refrigeration and frozen storage	[127]

4.1.3. Salmonella Species

Salmonella is a genus of rod-shaped, Gram-negative bacteria that belongs to the family Enterobacteriaceae. It is one of the most significant pathogens associated with foodborne illnesses worldwide [81]. The genus comprises two species, Salmonella enterica and Salmonella bongori, with S. enterica being the most common in human infections. Salmonella contamination in fish and fish products can occur at various stages of the supply chain, from aquaculture environments to processing facilities. Fish such as salmon, tuna, and shellfish like shrimp and oysters have been reported to harbor Salmonella [29]. Processed fish products like smoked salmon or canned fish can also be susceptible if proper hygiene practices are not followed during processing. Salmonella is known for its resilience in diverse environmental conditions. [92]. reported that Salmonella can survive under refrigeration temperatures (4 ℃) for extended periods, although its growth is significantly slowed down at these temperatures (Table 1). [68] also reported that freezing does not kill Salmonella; instead, it may preserve the bacteria until thawing occurs and suggested that proper cooking and handling practices to be employed to ensure safety.

4.1.4. Clostridium Botulinum

Clostridium botulinum is a Gram-positive, rod-shaped bacterium that is anaerobic and spore-forming [20]. It is most notorious for producing the botulinum toxin, one of the most potent toxins known to science. This bacterium is classified into several types based on the antigenic properties of its neurotoxins: A, B, C, D, E, F, and G. Types A, B, E, and F are primarily associated with human botulism. Of these, type E is particularly relevant to fish and fish products due to its prevalence in aquatic environments. Clostridium botulinum type E is predominantly found in fish and marine environments. It has been isolated from various types of fish including salmon, trout, whitefish, and other freshwater species as well as marine fish such as cod and herring [11, 121]. The contamination can occur at any stage from capture to processing if proper hygienic practices are not followed. [2]. reported that smoked fish products are especially susceptible due to the anaerobic conditions created during smoking which favor the growth of C. botulinum.

C. botulinum spores are highly resistant to adverse environmental conditions including heat and desiccation [47]. They can survive in refrigerated conditions but do not grow or produce toxins at temperatures below 3 ℃. However, they can germinate and produce toxins at temperatures above this threshold if anaerobic conditions are present. Freezing does not kill the spores but can inhibit their growth temporarily until thawing occurs [51, 99]. reported that, the ability of C. botulinum to thrive in low-oxygen environments makes vacuum-packed or canned fish products particularly vulnerable if they are not processed correctly to destroy spores or prevent their germination. Botulism outbreaks linked to fish products have been documented worldwide. Notably, cases have occurred due to improperly processed smoked or fermented fish where type E toxin was implicated. For instance, an outbreak in Canada 2012 was traced back to home-canned salmon that had not been heated sufficiently to destroy C. botulinum spores [72]. In another case in Sweden, 2013, vacuum-packed smoked whitefish was identified as the source of a type E botulism outbreak [89].

4.1.5. Staphylococcus Aureus

Staphylococcus aureus is a gram-positive, facultative anaerobic bacterium that is commonly found in the environment, on the skin, and in the nasal passages of humans and animals [46]. S. aureus is known for its resilience and adaptability, which allows it to survive under various environmental conditions, making it a concern for safety in fish and fish products. S. aureus contamination in fish and fish products typically occurs through improper handling by humans during processing or packaging. This pathogen has been detected in various types of seafood, including both fresh and processed products such as smoked salmon, canned tuna, shrimp, and other shellfish [127]. The risk of contamination increases when hygiene practices are not strictly followed during processing. Staphylococcus aureus can thrive at temperatures ranging from 7 ℃ to 48 ℃, with an optimal growth temperature around 37 ℃ [1]). S. aureus can survive refrigeration temperatures (around 4 ℃ or 39 ℉) but cannot grow at freezing temperatures (-18 ℃). However, once thawed, if the conditions become favorable again (e.g., warm temperatures), the bacteria can resume growth [120].

4.1.6. Yersinia Spp

Yersinia spp. are a group of Gram-negative bacteria belonging to the family Enterobacteriaceae, which includes several pathogenic species known to cause disease in humans and animals [98]. Among these, Yersinia enterocolitica is the most significant concerning foodborne illnesses. This bacterium is a psychotropic organism, meaning it can grow at refrigeration temperatures, making it particularly concerning for fish and fish products stored under such conditions [32]. Yersinia enterocolitica has been isolated from various types of fish and seafood products. It is commonly found in freshwater fish such as trout and carp, as well as in shellfish like oysters and mussels [83]. The bacterium can also be present in processed fish products such as smoked salmon, sushi, and sashimi, where minimal cooking or preservation techniques might not eliminate the pathogen. Yersinia spp., particularly [121]. reported that Y. enterocolitica can survive and even proliferate at low temperatures typical of refrigeration (4 ℃) and concluded that, this characteristic makes them a persistent threat in chilled storage environments where other pathogens might be inhibited. However, they are generally sensitive to heat; thus, proper cooking can effectively eliminate them from contaminated products.

4.1.7. Aeromonas Spp

Aeromonas spp. are a group of Gram-negative, rod-shaped bacteria that are commonly found in aquatic environments. They belong to the family Aeromonadaceae and are known for their ability to cause diseases in both humans and animals. Aeromonas spp. have been identified as contaminants in a wide range of fish and fish products. They are particularly prevalent in freshwater fish such as catfish, tilapia, and carp, but can also be found in marine species like salmon and shellfish [127]. Ready-to-eat fish products, such as smoked fish or sushi are also susceptible to contamination due to minimal cooking processes that may not eliminate the bacteria. Aeromonas species can grow at temperatures ranging from 4 ℃ to 42 ℃ makes them particularly challenging to control in food supply chains where refrigeration is the primary method of preservation [82].

4.2. Spoilage Microorganisms and Their Impact on Quality and Safety of Fish and Fish Products

The spoilage of fish and fish products is predominantly caused by a variety of microorganisms, including bacteria, fungi, and yeasts. The most common microorganisms are Shewanella putrefaciens, Pseudomonas spp, as well as Photobacterium phosphoreum.

Table 2. List of specific spoilage microorganisms involved in different seafood products spoilage.

Product	Spoilage Activity	Specific spoilage microorganisms
Fresh fish	High	Vibrionacaeae, Aeromonas

Product	Spoilage Activity	Specific spoilage microorganisms
Fresh chilled fish products	High	Shewanella putrifaciens, Pseudomonas putrifaciens, Pseudomonas fluorescens, Fluorescent pseudomonads
Fresh chilled fish	Moderate	Photobacterium phosphoreum, Moraxella, Acinetobacter, Alcaligene
Chill vacuum-packaged cold-smoked	Low	Lactobacillus, Aerobacter, Flavobacterium, Micrococcus, Bacillus, Staphylococcus, Mesophilic

Source: Adopted and modified from [38].

4.2.1. Pseudomonas Spp

Pseudomonas spp. are Gram-negative, rod-shaped bacteria known for their metabolic versatility and ability to thrive in diverse environments [18]. Pseudomonas spp. are notorious for their rapid growth at refrigeration temperatures, which is a common storage condition for fresh fish products [122]. They produce extracellular enzymes such as proteases and lipases, which contribute significantly to the degradation of proteins and fats in fish tissue, leading to off-flavors, odors, and textural changes that characterize spoiled fish [156]. These bacteria are most commonly associated with the spoilage of fresh marine fish such as cod, haddock, mackerel, sardines and salmon. They have also been identified in processed fish products like smoked or salted fish, where they can survive despite reduced water activity levels [121]. Unlike many other bacteria that require warmer conditions for proliferation, Pseudomonas spp. can multiply even at temperatures close to 0 ℃, making them formidable spoilers in cold-stored seafood products [144].

4.2.2. Shewanella Putrefaciens

Shewanella putrefaciens is a typical spoilage organism in fish from temperate waters. They produce trimethylamine (TMA), hydrogen sulfide (H_2S), and other volatile Sulfide metabolites that give rise to the sulfurous off-odor and off-flavor associated with spoilage [166]. The types of fish most commonly contaminated by S. putrefaciens include those with high water activity and neutral pH levels, such as cod, haddock, mackerel, and herring [58]. Shewanella putrefaciens can survive under refrigeration temperatures typically used for storing fresh fish products; however, it does not grow well at freezing temperatures [162]. Its optimal growth temperature ranges from 0 ℃ to 30 ℃, with peak activity around 20 ℃ [48].

4.2.3. Photobacterium Phosphoreum

Photobacterium phosphoreum is a Gram-negative, rod-shaped bacterium that belongs to the family Vibrionaceae. It is bioluminescent, which means it can produce light through biochemical reactions involving luciferase enzymes. This bacterium thrives in marine environments and is commonly associated with cold-water fish species. It has been identified as a major spoilage organism in fish such as cod, haddock, and other demersal species that are stored under chilled conditions [45]. The ability of P. phosphoreum to grow at low temperatures makes it particularly problematic for refrigerated seafood products. The spoilage potential of P. phosphoreum is attributed to its metabolic activities that lead to the production of volatile compounds such as trimethylamine (TMA), which imparts a characteristic "fishy" odor associated with spoiled seafood [78]. This bacterium can proliferate even at temperatures as low as 0 ℃, and studies have shown that this bacterium can reach high population densities within days when fish are stored at temperatures just above freezing point [113].

4.2.4. Fungi and Yeasts

Fungi and yeasts also play a role in the spoilage of fish products, particularly those that have been processed or stored under suboptimal conditions as shown in Table 3. Molds such as Aspergillus spp., Penicillium spp., and Cladosporium spp. can grow on dried or smoked fish products where moisture levels allow fungal growth despite low water activity environments [36]. Yeasts like Candida spp. can be found on salted or brined fish products; they contribute to spoilage by fermenting sugars present in marinades or sauces used during processing [57, 142]. Both fungi and yeasts require specific environmental conditions for growth, typically warmer temperatures with sufficient humidity, and thus their presence is more common in inadequately stored or processed products [111].

Table 3. *Yeast species commonly isolated in fish and fishery products.*

Fish & fish products	Fungi species	Yeast species
Fresh fish	Aspergillus spp., Penicillium spp.	Candida spp

Fish & fish products	Fungi species	Yeast species
Salted fish	Aspergillus spp., Cladosporium spp.	Candida zeylanoildes, Rhodotorula spp, Canida sake and Debaryomyces hansenii
Fermented	Penicillium spp., Aspergillus spp.	Hansenula anomala, Rhodotorula glutinis, Candida tropicalis, Debaromyces hansenii, Candida zeylanoildes, Pichia fermentans and Hanseniaspora osmophilic
Smoked	Aspergillus flavus, Penicillium spp.	Candida spp, Rhodotorula spp
Canned tauna	Penicillium spp., Aspergillus niger	Rhodotorula spp
Shellfish	Cladosporium spp., Aspergillus spp.	Candida spp, Rhodotorula spp
Shrimp (Dry salted)	Aspergillus oryzae, Penicillium chrysogenum	Candida spp

Source: Thiluddin, Maribao, Amlani and Sarri (2022). Food Bulletin, 1 (1), 21-36.

5. Modern Methods for Detection of Microbiological Contaminants in Fish and Fish Products

Modern detection methods have been developed to accurately identify and quantify various types of microorganisms that may be present in fish and fish products. These methods utilize advanced technologies to improve sensitivity, specificity, and efficiency in detecting microbial contaminants [44,78]. These include methods such as biosensors, immunoassays, polymerase chain reaction and metabolomics.

5.1. Polymerase Chain Reaction (PCR) Techniques

Polymerase Chain Reaction (PCR) techniques have revolutionized the field of microbiological detection by allowing for the rapid amplification of DNA sequences specific to spoilage bacteria [147]. This method is highly sensitive and can detect even low levels of bacterial contamination in fish products. Real-time PCR (qPCR) further enhances this capability by quantifying the amount of bacterial DNA present, providing both qualitative and quantitative data on microbial load [63]. The specificity of PCR is achieved through the use of primers that target unique genetic markers associated with spoilage organisms such as Pseudomonas spp., Shewanella putrefaciens, and Vibrio spp. This method's speed and accuracy make it an invaluable tool in modern food safety laboratories. The results of the study conducted by [84]. which focused on the detection of foodborne pathogenic bacteria in seafood using a multiplex polymerase chain reaction (PCR) system indicated that the multiplex PCR method was effective in detecting multiple pathogens simultaneously in seafood samples and he concluded that PCR not only reduced the time required for pathogen detection compared to traditional culture methods but also increased the accuracy of identifying specific bacterial strains present in seafood.

5.2. Immunoassays

Immunoassays utilize antibodies to detect specific antigens associated with spoilage bacteria. These assays are highly specific due to the antigen-antibody interaction and can be designed to target a wide range of bacterial species found in fish products [131]. The most common immunoassays are enzyme-linked immunosorbent assay and lateral flow assays. Enzyme-linked immunosorbent assay (ELISA) is one common format used for detecting bacterial toxins or cell surface proteins indicative of contamination. This assay involves the immobilization of an antigen on a solid surface, typically a microplate, followed by binding with a specific antibody linked to an enzyme [126]. The enzyme acts as a marker that produces a detectable signal, usually a color change, upon reaction with an appropriate substrate. ELISA can be performed in several formats, including direct, indirect, sandwich, and competitive assays, each tailored to different analytical needs. In the context of fish and seafood pathogen detection, ELISA is particularly advantageous because it allows for the quantitative measurement of pathogen levels [110]. The assay's ability to process multiple samples simultaneously makes it suitable for large-scale screening operations in aquaculture industries.

Lateral flow assays (LFAs) operate on the principle of capillary action where a liquid sample migrates along a porous strip containing antibodies specific to the target pathogen [14]). As the sample moves through the strip, it encounters labeled antibodies that bind to any present antigens forming complexes that are captured at designated test lines on the strip. LFAs are particularly advantageous for field applications due to their simplicity and portability. They do not require sophisticated laboratory equipment or extensive training to interpret results, making them ideal for on-site testing at fish farms or processing facilities. The results of the study conducted by [131]. indicated that lateral flow assays (LFAs) demonstrated a high sensitivity and specificity for detecting

Vibrio spp., Aeromonas spp, and White Spot Syndrome Virus (WSSV) in both fish and shrimp samples.

5.3. Biosensors

Biosensors represent an innovative approach to detecting microbiological contaminants through the use of biological recognition elements coupled with a transducer system [49, 136, 27]. as shown in Figure 1. These devices offer real-time monitoring capabilities and can be deployed directly at points of sale or processing facilities [123, 19]. Biosensors designed for fish product analysis often employ enzymes or antibodies as recognition elements to detect spoilage indicators such as biogenic amines or volatile compounds produced by bacteria like Shewanella spp [79]. The integration of biosensors into food safety protocols enhances early detection efforts, reducing economic losses due to spoilage [135]. [110] reported that several types of biosensors, including electrochemical, optical, and piezoelectric sensors, have been successfully employed to identify pathogens such as Salmonella, Listeria monocytogenes, and Vibrio spp. in seafood products.

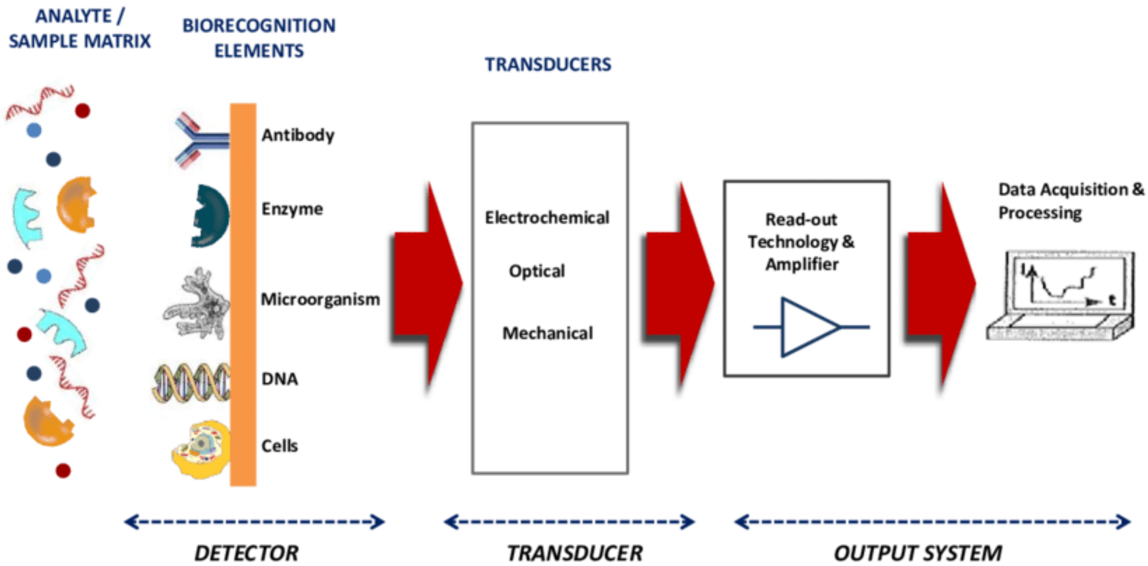

Figure 1. *Showing schematic diagram of a biosensor. Adopted from Bhatnagar et al. (2024).*

6. Modern Microbial Methods of Microbiological Contaminants in fish and Fish Products

Traditional methods such as refrigeration and freezing have been widely used to control microbial growth, but emerging technologies offer innovative solutions that enhance the safety and extend the shelf life of fish products [75, 159]. These include technologies like high-pressure processing, electrolyzed water, cold plasma and pulsed electric field [77, 157].

6.1. Electrolyzed Water

A novel disinfection technique has emerged in the food sector, utilizing Electrolyzed Water (EW) also known as Acidic Electrolyzed Water (AEW) as an alternative method of sanitation, noted for its environmental safety and user well-being [61, 7, 160]. AEW consists of two distinct variants: Strong Acidic Electrolyzed Water (StAEW), characterized by a pH of 2-3 and an ORP exceeding 1000mV, and Slightly Acidic Electrolyzed Water (SAEW) [28, 87, 165]. SAEW exhibits a pH range of 5.0-6.5, a lower available chlorine concentration (ACC) of 10-30, and an ORP exceeding 800 mV [67]. SAEW is produced through the electrolysis of a diluted hydrochloric acid (HCl) solution, typically between 2% and 6%, in an electrolytic cell without a diaphragm, in contrast to StAEW, which is generated from the electrolysis of a 2% sodium chloride aqueous solution [133, 134, 155, 167].

Electrolyzed water is extensively utilized in the seafood sectors of various nations, including the USA, China, and Japan, and has demonstrated efficacy in enhancing the quality of aquatic products by eradicating pathogenic or spoilage bacteria in seafood [112, 114]. A study by [104]. examined three fish species: fresh oil sardine (Sardinella longiceps), Pacific mackerel (Scomber japonicus), and horse mackerel (Trachurus trachurus). The findings indicated that electrolyzed water effectively diminishes bacterial deterioration on fish surfaces during distribution. Seafood processing depends on maintaining the cold chain to guarantee product quality and freshness [38]. Electrolyzed water ice (EW ice) has recently emerged as a novel approach in food sanitization, involving the freezing of electrolyzed water, which is beneficial for preserving seafood during production, transportation, and storage [161]. EW ice is widely used in seafood processing for maintaining the cold chain. Its unique properties not only help in preserving the freshness of aquatic products but also play a crucial role in inhibiting microbial proliferation. Research demonstrates that EW ice exhibits both preservation and sterilizing properties, maintaining the advantages of traditional low-temperature preservation techniques while improving food safety. [62] previously established that EW ice significantly inhibits the proliferation of aerobic and psychrotrophic bacteria, which are prominent agents of seafood spoilage. Moreover, it reduces the production of total volatile basic nitrogen (TVB-N) and thiobarbituric acid (TBA), which both serve as indicators of fish quality degradation [86].

6.2. High-Pressure Processing (HPP)

High-pressure processing (HPP) is an advanced non-thermal food preservation technique that utilizes extremely high pressures, ranging from 100 to 800 MPa, to inactivate pathogenic microorganisms and spoilage bacteria without significantly affecting the nutritional and sensory qualities of food [3]. HPP works by disrupting cellular functions in microorganisms through the application of uniform pressure throughout the product. This pressure causes irreversible damage to cell membranes, denatures proteins, and disrupts enzyme activities essential for microbial survival [76]. HPP effectively reduces or eliminates spoilage bacteria such as Pseudomonas, Shewanella, Vibrio, and Listeria species commonly found in fish products as reported by [12, 117]. also reported that HPP (400 to 600 MPa) is highly effective in reducing or eliminating pathogenic microorganisms commonly found in fish and shellfish, such as Listeria monocytogenes, Vibrio spp., and Salmonella spp, and it can achieve significant microbial reductions while maintaining the sensory and nutritional quality of seafood products and he concluded that HPP helps seafood manufacturers to maintain a balance between safety, quality, processing efficiency, and regulatory compliance.

6.3. Pulsed Electric Fields (PEF)

PEF involves applying short bursts of high voltage electric fields to food products placed between electrodes [71]. This process induces electroporation in microbial cell membranes, leading to increased permeability or rupture of cells, thereby causing microbial death. PEF is particularly effective against vegetative cells but may require combination with other methods to target spores or more resistant microorganisms [141]. PEF preserves sensory attributes while achieving significant reductions in spoilage organisms like Aeromonas spp as reported by [105].

6.4. Cold Plasma Technology

Cold plasma technology involves the generation of plasma, a partially ionized gas composed of ions, electrons, and neutral particles, at atmospheric or low pressures and ambient temperatures [33]. The reactive species generated by cold plasma, such as free radicals, UV photons, and charged particles, interact with microbial cells on the surface of fish products to induce oxidative stress and damage cellular components like DNA, proteins, and lipids [139]. This results in the inactivation of a wide range of microorganisms including bacteria, viruses, and fungi. Studies have demonstrated that cold plasma can effectively reduce populations of common seafood pathogens such as Listeria monocytogenes, Salmonella spp., and Vibrio parahaemolyticus without significantly affecting the sensory attributes or nutritional quality of the fish. The results of the study conducted by [56] showed that cold plasma using argon at each time point (4, 6, and 10 min) had a significantly inhibitory effect on the growth of L. innocua on ready to eat fish products.

Table 3. *Microbial control methods with their respective controlled microorganisms and fish products.*

Microbial control methods	Fish & fish product	Controlled microorganisms	Reference
High Pressure Processing (HPP)	Smoked salmon, Oysters Mussels, Dublin bay prawns, Scallops, Oysters and Frozen cooked pink shrimps	L. innocua, V. parahaemolyticus, Pseudomonas spp, L. monocytogenes	[12, 80, 85, 106, 109, 117]
Pulsed electric field	Shrimps, Salmon, Yellow tuna fish, fish bones	Aeromonas spp	[54, 60, 105, 130]
Cold Plasma Technology	Fresh mackerel, dried squish	Pseudomonas spp, Listeria monocytogenes, L. innocua, and Vibrio parahaemolyticus	[9, 56]
Electrolyzed water	fresh oil sardine, Pacific mackerel, horse mackerel, mussel, live clam,	Listeria monocytogenes, Escherichia coli, E. coli O104: H4, A. hydrophila, V. parahaemolyticus, Campylobacter jejuni and Vibrio parahaemolyticus	[4, 8, 104]

Source: Adopted and modified from Ekonomou and Boziaris (2021).

7. Sustainable Practices for Maintaining Fish Health and Reducing Contaminants

Sustainable practices for maintaining fish health and reducing contaminants involve a combination of preventative measures, monitoring techniques, and responsible management strategies [74]. These practices aim to ensure the well-being of fish populations while minimizing the presence of harmful contaminants in aquatic environments. One key sustainable practice is the implementation of proper aquaculture management techniques. This includes maintaining optimal water quality parameters, such as temperature, pH levels, and oxygen levels, to support fish health and growth [91]. Another important aspect of sustainable fish health management is the use of environmentally friendly feed options. Sustainable aqua feeds are formulated using ingredients that are sourced responsibly and do not contribute to overfishing or habitat destruction. By choosing feeds that are nutritionally balanced and free from contaminants, aquaculture operations can promote the overall health of their fish stocks while reducing environmental impacts. In addition to these practices, promoting biodiversity within aquaculture systems can help maintain ecological balance and reduce the risk of contamination. Introducing native species or utilizing polyculture techniques can enhance natural ecosystem functions and reduce reliance on chemical inputs for pest control or disease prevention [128].

8. Consumer Awareness and Education on Safe Fish Consumption

Health benefits, there seems to be a need to familiarize consumers with the health value of fish so that they can shift towards the right meal type. Seafood, particularly fish, constitutes a robust reservoir of omega-3 fatty acids, indispensable for cardiovascular health and cognitive function. Moreover, fish is a rich source of water-soluble vitamins such as D and B2, as well as essential minerals including calcium, phosphorus, iron, zinc, iodine, magnesium, and potassium. By accentuating these nutritional attributes, public health campaigns can effectively promote fish consumption and mitigate the prevalence of diet-related diseases [50]. While fish consumption offers numerous nutritional advantages, it is imperative to acknowledge that not all fish species confer these benefits equally; conversely, certain fish may harbor significant health risks due to environmental contamination. Specifically, fish inhabiting polluted waters can bioaccumulate harmful chemicals, such as mercury and polychlorinated biphenyls (PCBs).

Consumer decision-making process research has revealed that there is a potential for those making an informed decision in their food purchasing habits to consider the health and sustainability aspect of their ultimate consumption choices. Effective supply chain management raises consumer awareness and makes them more selective in their consumption of fish, which can necessarily affect the responsible production of fish and fishing [25]. It also helps in changing the nature of the population and sustainable use of sea-space and contributes to preservation of marine resources and permanent availability of the fish-stock to human population [145].

9. Future Research Direction

New research should focus on methods that can concentrate target organisms from food, eliminate inhibitory substances, detect PCR products, simplify procedures, and reduce cost. Future research could explore innovative processing technologies and interventions to control microbial contamination and chemical hazards in fish and seafood. This includes investigating novel preservation methods, packaging techniques, sanitation practices, and quality control measures to enhance the safety and shelf-life of fish products while preserving their nutritional value. Research should also focus on educating consumers about microbiological and chemical risks associated with fish consumption. Studies could assess consumer knowledge, attitudes, and behaviors regarding seafood safety issues, as well as evaluate the impact of public health campaigns, labeling requirements, and communication strategies on consumer choices and food safety practices.

10. Conclusion

Although fish is still a key element of a balanced diet with many health advantages, consumers must stay aware of the possible microbiological and chemical risks related to its use. Improving the quality and safety of fish products will depend much on continuous studies on safe fishing practices, better aquaculture techniques, government control over contaminants, and public awareness initiatives. Stakeholders can guarantee that the nutritional benefits of fish are not compromised by health concerns by giving both microbiological safety via strict hygiene standards and chemical safety via environmental monitoring top priority. Preservation methods are also required to stop fish spoilage and extend shelf life. Interdisciplinary cooperation among chemists, microbiologists, food technologists, and legislators will be absolutely vital in protecting public health as regulatory authorities hone standards depending on developing scientific knowledge even as they assist sustainable fisheries management.

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Conflicts of Interest

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