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REVIEW ARTICLE

A Review on Spoilage Microorganisms in Fresh and Processed Aquatic Food Products

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ABSTRACT

Aquatic food products are greatly perishable owing to their biological compositions. Spoilage is defined as any alteration in food products that lead to unacceptable attributes to the consumers, mainly through sensory perception. Microbial spoilage is a common type of spoilage among seafood products. In this paper, we reviewed and discussed the various spoilage microorganisms (molds, yeasts, and bacteria) in fresh and processed fish and fishery products. Many studies reported that processed fishery products, such as salted, dried, and hot-smoked fish, are commonly spoiled by molds, mainly under the genus of *Aspergillus* and *Penicillium*. Yeasts as spoilage agents have been associated with fish and fishery products stored at low temperatures, notably dominated by two genera, *Candida* and *Rhodotorula*, while other yeast species have also been linked to heavily-salted fish and fermented aquatic foods. The important genera of spoilage bacteria that have been documented in fresh and processed fish and fishery products were *Pseudomonas, Alcaligenes, Aeromonas, Enterobacter, Bacillus, Enterococcus, Psychrobacter, Escherichia coli, Listeria, Brochothrix,* and *Shewanella* species. Microorganisms play an important role in the spoilage of processed and fresh fish/fishery products. Further research should be undertaken to fully understand the microbial world, particularly associated with aquatic food products.

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Introduction

Aquatic food products are among the world's most nutritious and valuable foods. They are high in protein, which provides over 20% of the average per capita animal protein consumption for around 3.3 billion individuals (Tidwell & Allan, 2001; FAO, 2020). In 2017, roughly 17% of total animal protein and 7% of all proteins consumed worldwide were contributed by fish (FAO, 2020). All parts of fish are rich in proteins, which have three main types: structural proteins, connective tissue proteins, and sarcoplasmic proteins (Ghaly et al., 2013). Fish also contains other essential nutritional components, such as eicosapentaenoic acid (omega-3 (EPA), polyunsaturated fatty acids (PUFA), docosahexaenoic acid (DHA) as well as minerals and vitamins (Mohanty et al., 2017). However, due to the perishability nature of fish, it is highly sensitive to spoilage, making preservation extremely challenging (Ashie et al., 1996; Ayeloja, 2020). In healthy fish, all of the intricate metabolic reactions are balanced, and the meat is still sterile. However, when the fish is caught then, soon after it dies, it begins to spoil due to irreversible changes happening in its body. This effect resulted in fish decomposition and food waste (Adeyeye, 2016).

Spoilage is defined as any alteration in food products that lead to unacceptable attributes to the consumers, mainly perceived through sensory evaluation (Rawat, 2015). This includes chemical alterations (change in color or oxidation),

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physical damage, and the appearance of off-odors and off-flavors, which could result in the microorganism growth and metabolism in the food products (Gram et al., 2002). Microbial spoilage is undoubtedly the most widespread cause of spoilage and exhibits itself as conspicuous growth (colonies, slime), textural alterations (polymer degradation), or off-flavors and off-odors (Gram et al., 2002). The vulnerability of aquatic food products to microbial spoilage is due to the presence of high moisture content and nutrient availability (Singh et al., 2021). Generally, aquatic food products are highly susceptible to microbial spoilage compared with meat since meat has lower pH and moisture content. Spoilage types in aquatic food products are greatly dependent on the kind of microorganisms, product composition, muscle type, and storage environment. The utilization of non-protein nitrogen (NPN) compounds that lead to the formation of ammonia, fatty acids, and volatile compounds are the pre-mature stages of microbial spoilage among fish (Erkmen & Bozoglu, 2016). The spoilage of fish begins with the release of its body fluids. At the initial stage of spoilage, the development of a sickly-sweet odor can be observed, followed by stale-fish odor caused by trimethylamine, then by ammonia odor, and finally, putrid odors owing to hydrogen sulfide and indole (Erkmen & Bozoglu, 2016). Microbial spoilage is responsible for the 30% losses of landed fish worldwide (Ghaly et al., 2010; Kuley et al., 2017). Spoilage of fish can be measured apart from using sensory evaluation. This measurement involved the rapid determination of trimethylamine, where its increment parallels the elevation of bacterial growth (Beatty & Gibbons, 1937), the use of a volatile amine sensor (Pacquit et al., 2006) and colorimetric sensor array (Morsy et al., 2016).

In the natural aquatic environment, microorganisms are abundant on the surface and the gut of the aquatic food products (Romero et al., 2014; Rawat, 2015; Egerton et al., 2018). Fish and fishery products can contain bacterial pathogens initially contaminated from the soil and water, such as *Vibrio, Bacillus, Escherichia, Clostridium,* and *Serratia* (Erkmen & Bozoglu, 2016). Hence, fish can be a potential source of human pathogenic bacteria (Novotny et al., 2004). The primary microbial spoilage caused by bacterial flora is Gram-negative facultative anaerobic rods and aerobic rods, as well as coliforms, whereas molds are the major spoilage agents in smoked fish (Oranusi et al., 2014; Erkmen & Bozoglu, 2016). In addition, yeasts have also been associated with salted fish spoilage (Gram & Huss, 1996). In this paper, we reviewed and discussed the various spoilage microorganisms, i.e., molds, yeasts, and bacteria, in fresh and processed fish and fishery products by using scholarly papers published from 1937 to 2023. Various keywords, such as aquatic fishery products, bacteria, bacterial spoilage, fish freshness, fish spoilage, fish quality, fresh fish, microbial spoilage, molds, spoilage, spoilage microorganisms, and yeasts, related to the study, were searched from Sciencedirect, Google scholar, and Google search databases.

Quality of Fresh Aquatic Food Products

Aquatic food products play a vital role in international trade because of their ever-increasing consumption demand (Pal et al., 2016). They contain high levels of protein, omega-3 fatty acids as well as essential nutrients, making them a vital part of a healthy diet (Rhea, 2009; Pal, 2010). However, raw, inadequately cooked, and poorly processed fish and fishery products pose the greatest risk to human health (Pal et al., 2016). It is possible to contract infections or intoxications from eating fish or fishery products that have not been harvested fresh (Adebayo-Tayo et al., 2012a). In general, fish and other fishery products can be evaluated for their organoleptic characteristics (Tables 1 and 2). Aquatic products are generally evaluated with the human senses for freshness and spoilage after harvesting and before consumption (Lougovois & Kyrana, 2005). Fish and other fishery products that are fresh have a delicate flavor and aroma that is not as noticeable as less fresh foods (Lindsay, 1990, 1994). Espejo-Hermes (2004) stated that in order to prevent spoilage and subsequent losses from damage, aquatic products must be handled carefully right after harvest.

Table 1. General organoleptic characteristics of fresh and stale fish**.**

Organoleptic Change	Fresh fish	Stale fish	References
Odor	There are a variety of species with slightly different odors, but they are all generally pleasant smell	Fish that is stale may emit an unpleasant odor or emit a nauseating putrefactive one. However, generally, stale fish emits an offensive decomposition smell or distinct sour odor. The presence of such odors indicates staleness invariably.	Kawai and Sakaguchi (1996), Espejo-Hermes (2004), Varlet et al. (2006), Hasan et al. (2012)
Eyes	The appearance of the eye is full, bright, and perfectly fresh. There is a jet-black pupil with a convex shape. Transparent cornea.	Shrunken eyes or eyes that have completely collapsed. An often yellowish slime covers the surface. The staleness of the pupil causes it to sink and lose its blackness. A milky white pupil is generally a sign of severe staleness requiring immediate action.	Espejo-Hermes (2004), Truninger et al. (2020)

Table 1. (continued).

Organoleptic Change	Fresh fish	Stale fish	References
Flesh	The flesh is firm and elastic to the touch. Transparent white or bluish-white. The discoloration is not present. A strong bond is formed between the flesh and the bone. Tough and difficult to tear. There is a red color to blood under the tissue.	A soft and limp texture. Skin that is saggy and pitted when pressed. The backbone appears reddened. The bone can easily be torn away from it. A brownish or chocolate-colored blood is present under the tissue.	Espejo-Hermes (2004), Truninger et al. (2020)
General Appearance	Glistening, clean, smooth, and shiny appearance. The slime is transparent and moist. Neither discoloration nor fading.	The appearance is dull, lifeless, and stale. There is a gritty feel to staleness, especially if it is dry and rough to the touch. It is easy to rub off the scales and various levels of bleaching. Color discoloration of the abdominal walls, which may be brown, red, or blue.	Huss (1988), Alasalvar et al. (2002), Espejo-Hermes (2004)

Table 2. General organoleptic characteristics of fresh and stale fishery products.

Aquatic food products	Fresh products	Stale products	References
Fillets	Fillets have firm flesh and spring back when pressed, and the aroma is fresh and mild. Scales should be intact and shiny silver.	In stale fishery products, fillets lose their translucent whiteness as they age and develop a creamy color. A foul odor may be detected when cutting into or breaking the flesh because it is moist, flabby, and ragged.	Cheng et al. (2015)
Dried-Cured Product	Dried fishery products should have firm, shiny flesh, and their flesh should bounce back when touched. Ideally, the skin should be glowing and not dull. There may be a tight attachment between the skin and scales.	Cracked skin and loose scales are signs of rotting fishery products.	Leonard (2011), Doe and Olley (2020)
Smoked-Cured Product	The texture of the fishery product should be springy and firm when properly smoked, and the whole fish or fillets should feel fairly rigid when cooked.	Cured products lose their crisp dryness as it becomes stale, their surface becomes sticky, and their flesh becomes flabby and limp. It is also indicative of staleness if the belly flaps have a yellowish discoloration. In comparison with stale wet fish, smoke-cured fishery products rarely emit the objectionable odor typically associated with stale wet fishery products. Fishery products cured by this method are usually characterized by the unpleasant smell of smoke, which is strong enough to cover staleness odors.	Flick (2010)
Salted-Cured Product	Fishery products that have been salted should have a strong brine and aquatic organism smell, but it should not be a pleasant smell.	There is a possibility that the fish may be spoiled if it has a moldy, fermented, or vinegary smell.	Hafez et al. (2019)
Frozen-Cured Product	In terms of how frozen fishery products should be inspected, it should be remembered that a first-class product will retain its appealing appearance after thawing.	Stale fishery products usually have soft, wet, ragged flesh. A dull, creamy, or yellowish appearance replaces the clean, wholesome appearance of fresh fishery products.	Nielsen and Jessen (2007)
Fermented-Cured Product	Fishery product that has been fermented smells sour and vinegar-like.	Fermented fish looks pink or fuzzy when it is moldy. Not only is the smell sour, but it is putrid or rotten as well.	Beddows (1998)

Table 2. (continued).

Aquatic food products	Fresh products	Stale products	References
Pickled/Marinated Product	Pickled/marinated fishery product has a firm texture and opaque appearance, similar to cooked fishery product.	The flesh of pickled/marinated products is soft and has lost its firmness, with an overpowering fishy scent, slimy texture, and graying or bluish color.	Rasco and Hilderbrand (2009)
Minced Processed Product	Shiny and grainy flesh is an indication of a quality minced fishery product.	Sour or tangy odors indicate spoiled minced products, even if they look and feel fine. Rancidity is enough to indicate bacteria has started growing in minced fishery products on its own.	Kim and Park (2007)
Canned Product	A properly sealed container of canned goods without bulges, swells, or leaks, with a pleasant smell, is an indication of a fresh, canned product.	The container of canned product is leaking, bulging, or swollen; it is cracked, damaged, or abnormal; it leaks liquid or foam or has an unpleasant smell.	Warne (1988), Bratt (2010), Reblová et al. (2022)

Spoilage of Fresh Fish

Aquatic food products can be improved by preservation methods, pretreatment, and proper handling, which result in increasing their shelf life and preventing spoilage (Ghaly et al., 2010). In agriculture and fisheries, microbial spoilage and chemical deterioration account for 25% of gross primary production yearly (Baird-Parker, 2000). In addition, it is estimated that one-fourth and 30% of landed fish in the world's food supply are lost through microbial activity alone (in’t Veld, 1996; Amos et al., 2007). It has been reported by Ghaly et al. (2010) that fish spoilage is caused by three basic mechanisms, including enzyme autolysis, oxidation, and microbial growth (Table 3). The spoilage of fresh fish can occur very rapidly after it is caught. As Berkel et al. (2004) pointed out, the spoilage process (rigor mortis) of the fish will begin within 12 hours after catching in high temperatures of tropical regions. The term rigor mortis refers to the loss of flexibility of fish caused by the stiffening of fish mussels shortly after death (Adebowale et al., 2008). Many factors cause fish species to degrade, including lipases, digestive enzymes, oxidation, and bacteria on the surface (AMEC, 2003). As fish spoils, it breaks down into various components and forms new compounds. The new compounds cause fish flesh to change smell, taste, and different texture (Ghaly et al., 2010).

Table 3. Mechanism of fish spoilage (Ghaly et al., 2010).

Fish spoilage mechanism	Process
Autolysis enzymatic spoilage	As soon as fish are captured, major fish molecules undergo enzymatic breakdown, resulting in biochemical decay. Autolytic enzymes reduced early stages of deterioration however did not produce the typical off-taste off-smell of spoilage. This implies that autolytic degradation can limit product quality and shelf-life even when spoilage organisms are relatively low. A major impact of this process is on the quality of the textural surface and the production of formaldehyde and hypoxanthine. In addition, by causing extensive autolysis, the digestive enzymes cause the flesh to soften, the blood to drain out, and the belly wall to rupture.
Oxidative spoilage	Fish species with a high fat/oil content, such as herring and mackerel, are susceptible to lipid oxidation, which causes them to degrade and spoil. Oxidation occurs when fatty acids react with oxygen. As a result, fish lipids that contain polyunsaturated fatty acids are susceptible to oxidization.
Microbial spoilage	Newly caught fish have microorganisms that are determined by the microbial content of the water in which they live. *Micrococcus, Pseudomonas, Alcaligenes, Serratia*, and *Vibrio* are among the bacteria found in fish microorganisms. A major cause of fish spoilage is the growth of microorganisms that produce amines, including histamine, sulfides, cadaverine, putrescine, organic acids, aldehydes, alcohols, and ketones that have unacceptable and unpleasant flavors. Therefore, distinguishing between non-spoiled microorganisms and spoilage bacteria is vital since many of the bacteria present do not cause spoilage.

Molds as Agents of Spoilage

Molds are fungi that produce chains and branches and have cell sizes that range from 30 to 100 microns. Molds can be seen with the naked eye when they establish their branched structure and occur in a variety of forms, colors, and sizes (Singh & Anderson, 2004). They are adapted to growing on and through the solid substrate, producing spores either asexually or sexually, and using oxygen for metabolism. The key factors influencing mold growth during storage include temperature, relative humidity, moisture, water activity, nutrients, pH, and salt content (Sivaraman & Siva, 2015). The pH range for mold growth is typically 3 to 8, and some molds can thrive at very low levels of water activity, such as mold on dried food (Sahu & Bala, 2017). The spores are resistant to harsh environmental conditions; however, the highest sensitivity results from heat treatment. Some mold species can grow in refrigerators, while others can survive up to 90˚C for 12 minutes at higher temperatures. As part of nature's recycling process, mold attacks a variety of foods and other materials useful to humans (Rawat, 2015). Carcinogenic mycotoxins (molecular weight of B700 DA) and toxic are produced by them in a diverse secondary metabolism. Some spoilage molds are toxigenic such as some species of *Aspergillus*, which can produce aflatoxins, which can cause illness in humans (Pal et al., 2016; Sahu & Bala, 2017). Although molds are widespread, however food spoilage hazards are definite to a limited species. Many researchers stated that *Mucor* spp., *Fusarium* spp., *Aspergillus* spp., *Rhizopus* spp., and *Penicillium* spp. are among the most common molds that spoil beverages and food products (Singh & Anderson, 2004; Lianou et al., 2016).

In warm climates, Aspergilli and Penicilli molds tend to dominate spoilage due to their faster growth at higher temperatures (Petruzzi et al., 2017). Peanuts, tree nuts, grains, dried beans, and some spices are the most common food items that aspergilla spoil, producing mycotoxins. A predominant cause of spoilage in temperate regions is *Penicillium* spp., which occurs naturally in plant debris and soils from Antarctic and tropical environments. A number of *Penicillium* species produce potent mycotoxins, making them important spoilage organisms. Many species of *Penicillium* can attack and spoil fruits and vegetables; also, some of them are capable of attacking processed or refrigerated foods, such as jam and margarine. In addition to plant diseases, *Fusarium* species produce important mycotoxins, which can cause health problems for humans. The *Rhizopus* and *Mucor* are two of the more common molds found in bread, with both species typically requiring high levels of water to grow (Rawat, 2015). Both agronomic and public health perspectives point towards aflatoxins, patulin, ochratoxin A, tremorgenic, trichothecenes, and ergot alkaloids toxins as the most significant mycotoxins (Petruzzi et al., 2017).

The growth of molds on fishery products causes spoilage, discoloration, and rotting, changing the flavor, texture, odor, and nutrient quality of fish, making it unacceptable and unsafe for human consumption, which ends up in huge economic loss (Sivaraman & Siva, 2015; Pal et al., 2016). The genera of molds often found on fresh, spoiled fish and other seafood products are *Aspergillus* spp., *Aureobasidium* spp., *Penicillium* spp., and *Scopulariopsis* spp. (Susanto, 2011). Each year, about 25-30% of fish caught for human consumption were dried, salted, brined, and smoked as a technique for fish improvement (Pal et al., 2016). Salted, dried, and hot-smoked fish are commonly spoiled by molds (Lyhs et al., 2004). As dried and salted fish have very low water activity, bacteria cannot grow. However, the problem of mold growth arises when fish are drained of 15 % of their water content, which causes the fish to spoil (Chakrabarti & Varma, 2000; Pal et al., 2016). The growth of mold does not only ruin the product, but it may also produce mycotoxins that have health risks (Gram, 2009). Dutta et al. (2018) studied the species of isolated molds in smoked sardine (*Sardinella aurita*), and they discovered the presence of *Aspergillus fumigatus* and *Aspergillus flavus* which have mycotoxigenic potentials. According to Essien et al. (2005), these species produced aflatoxins that destroy the kidney and liver, resulting in human health problems. The presence of aflatoxin in smoked fish was detected by Jonsyn and Lahai (1992) when they studied smoked freshwater fish from Africa. Salt-cured fermented fish products usually have specific spoilage halophilic molds (*Sporendonema* and *Oospora* spp.), which have an undesirable appearance that depreciates the value of a product (Galaviz-Silva et al., 2008). In addition, *Aspergillus sydowii* and *Aspergillus niger* were detected during the later stages of fermentation (Biango-Daniels & Hodge, 2018). An obligate aerobe (*Wallemia sebi*) that may also be found in salt used in production causes spoilage depicted as "dun," which is visible brown colonies with diameters of 1-2 mm (Gram, 2009). The main spoilage agent of dried fish produced in temperate regions is *W. sebi*. *Eurotium repens*, *E. amstelodami*, and *E. rubrum* are also common isolates from dried fish, together with *Aspergillus* species consisting of *Aspergillus penicilloides*, *A. wentii*, *A. penicilloides*, and *A. sydowii*. *Penicillium thomii* and *P. citrinum* were also isolated from the species of *Penicillium* (Sivaraman & Siva, 2015).

Table 4. Mold species commonly isolated in fish and fishery products.

Fish and Fishery Products	Molds Species	References
Fresh Fish (*Tilapia nilotica*)	*Penicillium* spp.	Hassan et al. (2011)
Smoked Fish * sardine (*Sardinella aurita*)	*Aspergillus flavus, Aspergillus fumigatus*	Dutta et al. (2018)
*(*Tilapia nilotica*)	*Penicillium citrinum* and *P. expansum*	Hassan et al. (2011)
Salted Fish	*Sporendonema* spp., *Oospora* spp., and	Galaviz-Silva et al. (2008)
Fermented Fish	*Aspergillus flavus Aspergillus niger*, and *Aspergillus sydowii*	Hassan et al. (2011), Biango-Daniels and Hodge (2018)
Dried Fish	*Wallemia sebi, Eurotium repens, E. rubrum, E. amstelodami, Aspergillus wentii, Aspergillus penicilloides Aspergillus sydowii, Penicillium thomii,* and *P. citrinum*	Sivaraman and Siva (2015)
Canned *Tuna	*Penicillium* spp., *Aspergillus* spp., *Rhizopus* spp., and *Alternaria* spp.	Casalinuovo et al. (2015)
Crustaceans *Dry-salted shrimp (*Litopenaeus vannamei*)	*Aspergillus* spp., *Penicillium* spp., and *Furasium* spp.	Freitas et al. (2020)

Yeasts as Agents of Spoilage

Yeast is another type of microorganism that can spoil food products by reducing their sensory properties, which is harmful, but it also plays an important role in food preservation and production (Tofalo et al., 2020). It is widely known that yeasts contribute to the economy by fermenting food, alcoholic beverages, and bread (Fleet, 1992). Yeasts are unicellular fungi round or cylindrical in shape and are way smaller than molds, with 3 to 5 microns in size. The majority of them reproduce by budding or fission and grow in an oxygen-free or oxygen-depleted environment (Singh & Anderson, 2004; Tofalo et al., 2020). They adapted for life in unique, most notably liquid, environments and did not produce toxic secondary metabolites. They colonize foods with low water activity, low pH (fruits and juices), or high sugar and salt content where most bacteria do not survive (Sahu & Bala, 2017; Ianieva & Ogirchuk, 2018), and also can lead to food spoilage, including meats and dairy products (Lianou et al., 2016). Most food spoilage is caused by yeast species such as *Zygosaccharomyces*, *Saccharomyces* spp., *Candida* spp., and *Dekkera*/*Brettanomyces* (Rawat, 2015).

Zygosaccharomyces colonize high salt and sugar concentrations, so they are often spoilage organisms in fruit juices, alcoholic beverages, syrups, honey, dried fruit, jams, sauces, and confectionary products (Blackburn, 2006). The most important spoilage yeasts are *Zygosaccharomyces bisporus, Z. bailii,* and *Z. rouxii.* Food containers may burst and swell due to off-flavors and odors produced by their metabolism (Howell, 2015). The genus of *Saccharomyces* is best known for the role it plays in making bread and wine; however, it can also have negative effects, such as gassiness, turbidity, and off-flavors resulting from hydrogen sulfide and acetic acid that spoil the commodities they produce (Petruzzi et al., 2017). It is estimated that one-fourth of all yeasts in existence are *Candida* spp., a heterogeneous group of yeasts that can also cause human diseases, in which vegetables, fruits, and dairy products can be spoiled by them (Rawat, 2015). *Dekkera* spp. mainly spoil fermented products, such as alcoholic beverages and dairy products in which they produce off-taints arise from secondary metabolism, where phenolic and moldy flavors can detract from the aroma and appeal of wine (Howell, 2015).

According to Fleet (1992), the number of yeast cells per milliliter varies from 10^2 to 10^3 in aquatic environments. Microbial species' populations and diversity depend on their geographical location, seasons, and pollution levels, which reflect those of the surrounding waters (Rhea, 2009; Pal et al., 2016). Therefore, fresh-caught fish, mollusks, and crustaceans are expected to harbor yeast on their surfaces and inside their bodies. Seafood is an extremely perishable product due to its physicochemical characteristics, which are basic nutrients for microbial activity resulting in quality deterioration, therefore, limiting its shelf life (Adebayo-Tayo et al., 2012b; Comi, 2017). There is a wide range of microorganisms that can grow in this medium due to its pH, water activity, and high water content. The genera of yeast isolated on fresh, spoiled fish and other seafoods (shrimp, shellfish, and crabmeat) are *Trichosporon* spp., *Debaryomyces* spp., *Sporobolomyces* spp., *Candida* spp., *Rhodotorula* spp., *Cryptococcus* spp., *Pichia* spp., and *Hansenula* spp. (Susanto, 2011). The shelf life of iced and chilled foods is limited by the species, processing, and handling of the food, although refrigeration plays an important role in maintaining nutritional and sensory properties (Pal et al., 2016; Comi, 2017). In general, yeasts are unlikely to grow and spoil seafood when stored in the refrigerator, but there may be exceptions. According to Kobatake et al. (1988), yeasts play a greater role in spoiling fish meat, particularly when some yeast species, such as *Candida lipolytica*, produce volatile nitrogen bases and in frozen or refrigerated oyster meats, pigmented yeasts have been shown to grow, leading to pink or red meats. Ianieva and Ogirchuk (2018) studied the isolated yeasts in the processed food popular in Ukraine, the salted herring, and they identified the following yeast species as *Yarrowia lipolytica*, *Debaryomyces hansenii*, *Candida zeylanoides*, *C. sake*, and *C. zeylanoides*. As opportunistic pathogenic microorganisms, yeast strains cause the rotting of fermented fish by changing its color, smell, and flavor (Biango-Daniels & Hodge, 2018; Tofalo et al., 2020). A yeast that is in the final stages of fermentation, such as *Aureobasidium pullulans*, is a black yeast-like fungus that is capable of infecting humans (Mittal et al., 2018). In addition, heavily salted fish encourages yeast growth as well (Parajuli, 2018).

Table 5. Yeast species commonly isolated in fish and fishery products.

Fish and Fishery Products	Yeasts Species	References
Fish	*Debaryomyces* spp., *Candida* spp., *Rhodotorula* spp.	
Fresh Fish (*Tilapia nilotica*)	*Candida* spp.	Hassan et al. (2011)
Salted	*Candida zeylanoides, Rhodotorula* spp. *Candida zeylanoides, Yarrowia lipolytica, Candida sake,* and *Debaryomyces hansenii*	Ianieva and Ogirchuk (2018)
Fermented	*Hansenula anomala, Rhodotorula glutinis Candida tropicalis, Debaromyces hansenii, Candida zeylanoides, Pichia fermentans,* and *Hanseniaspora osmophilic*	Kouakou et al. (2012)
Smoked	*Candida* spp., *Rhodotorula* spp.,	Hassan et al. (2011)
Canned tuna	*Rhodotorula* spp.,	Casalinuovo et al. (2015)
Shellfish	*Rhodotorula* spp., *Candida* spp.	Fleet (1992)
Frozen Oyster meat	*Rhodotorula rubra*	
Crustaceans		
Crabmeat	*Rhodotorula* spp., *Candida* spp., *Cryptococcus* spp., *Trichosporon* spp.	Fleet (1992)
Shrimp (Dry-salted) (*Litopenaeus vannamei*)	*Candida* spp.	Freitas et al. (2020)

Bacteria as Agents of Spoilage

Bacteria are minute, one-celled organisms that live on almost all surfaces of the planet and are crucial to ecosystems (Russell & Gilmore, 2018). The bacteria only have one DNA loop, which serves as their command center and houses all of their genetic data, and instead of a nucleus, some bacteria contain an additional ring of genetic material called a plasmid (Dorman, 2020). This plasmid is where the genes of a certain bacterium have a competitive edge over other bacteria. For instance, it could have a gene making the bacteria immune to a specific antibiotic (Brito, 2021). Additionally, certain bacteria species may survive in environments with extreme temperatures and pressures (Sakthipriya et al., 2022).

Bacteria come in various shapes such as spheres "*cocci*", spiral "*spirilla*", rods "*bacilli*", comma "*vibriosis*" and/or corkscrew "*spirochaetes*" with size range from 1 to 5 μm (Pachaiappan et al., 2021). They may be found practically wherever on Earth, including in the soil, water, seas, rocks, and even in the snow (Azma & Zhang, 2021). Some can also be found in human, animal, and plant bodies (Sheppard et al., 2018). They are most prevalent in the gut and the lining of all living organisms' digestive systems (Johnson et al., 2022). There are both positive and negative perceptions about bacteria (Popkov et al., 2022). There are many bacteria in the human body, around ten times as many as human cells, and some of them are benign and helpful in assisting the body in functioning normally (Singh, 2023) and also beneficial in the recycling of the nutrients in the soil (Salwan & Sharma, 2022). In addition, bacteria are also important and useful in the food production of fermented products (Kumari et al., 2022). Despite these benefits of bacteria, some of them are also dangerous and are referred to as pathogenic bacteria because they cause diseases in people, animals, and plants. They also contribute to food spoilage, which in turn leads to diseases (Sohrabi et al., 2022). Currently, food-borne infections caused by bacterial contamination are one of the main issues affecting the health of humans and the quality and safety of food. Thirty-one pathogens may cause food-borne diseases, with *Salmonella* spp., *Campylobacter* spp., *L. monocytogenes*, *S. aureus*, and *E. coli* being the most common ones globally (Abebe et al., 2022).

The capacity of the bacteria to multiply is significantly affected by several factors, such as temperature, osmotic pressure, and pH (Khan et al., 2022). Bacteria are classified into three based on their temperature adaptability. These are psychrophiles, mesophiles, and thermophiles which bacteria grow at cold, moderate, and high temperatures, respectively (Zhang et al., 2022). In terms of pH, most bacteria prefer a neutral pH of 7.0; however, some are able to withstand high and low pH (Takano & Aoyagi, 2022). Additionally, bacteria are categorized according to how well they survive in various salinities as well as in their oxygen requirements. Bacteria can be categorized as aerobic, which needs oxygen, facultative that can grow with or without oxygen, anaerobic can grow without oxygen, capnophilic which the carbon dioxide accelerates its growth; and microaerophilic, depending on their oxygen requirements which requires slightly decreased oxygen tension (Mahon, 2023). The salinity that bacteria can withstand may also be used to classify them, including halophiles, which prefer NaCl concentrations of 3% or more; severe halophiles, which prefer NaCl concentrations of 15%-25%; and xerophiles, which prefer low NaCl concentrations (Roy et al., 2022). Understanding these various bacterial characteristics is crucial for figuring out how to prevent them from spoiling food, such as fish and other fisheries products.

Fish is a popular food, but only when it is fresh. A fish is a healthy animal that lives in the frigid ocean. Its meat is made up of several nutrients that are useful to humans, including proteins, carbohydrates, lipids, amino acids, trimethylamine oxide (TMAO), and others (Adrah & Tahergorabi, 2022). However, once it gets out of the water, it cannot last for very long in that state. Generally, it is considered that the fish's internal tissues are sterile (Erkmen & Bozoglu, 2016). However, after the fish dies, thousands of microscopic organisms that are invisible to the naked eye are present on the layer of its slimy skin and in its intestines (Diwan et al., 2022). Normally the surface of fish skin has a total count of 10^2-10^7 (CFU)/cm^2 of bacteria, whereas its intestine and the gills both contain 10^3-10^9 CFU/g of bacteria, and when it dies, these bacteria start to multiply (Rathod et al., 2022). These microorganisms are known as spoilage bacteria. Fish from temperate and tropical oceans as well as those from fresh and marine waters may have a range of spoilage bacteria, which are the most prevalent agents of spoilage and are mostly responsible for the deterioration of aquatic food products (Laorenza et al., 2022; Prasai et al., 2022). If these bacteria are not eradicated, they will continue to destroy the fish until it is completely spoiled, making them the adversary of everyone concerned in the production of fresh fish (Mir et al., 2022).

Fish normally have excessive water activity and low acidity (approximately pH>6); thus, bacteria develop quickly inside the fish, which has become the leading cause of fish spoilage (Françoise, 2010; Ghaly et al., 2010). As the bacteria grew, they produced a large number of metabolic waste products as well as additional chemical compounds, including amines and biogenic amines, alcohols, ketones, aldehydes, and organic acids. These chemicals are what give fish their unpleasant flavor and odor, which leads to organoleptic rejection (Boziaris & Parlapani, 2017; Ikape, 2017). Although spoiled fish may be made to seem normal in some cases, its taste will reveal what caused it to lose its flavor. One of the factors that promote the growth of spoilage bacteria in fish is the temperature which is regarded as the most important factor that encourages bacterial multiplication (Abraha et al., 2018). Bacteria multiply as the temperature rises, and it only takes a few hours under the sun's warmth to start showing signs of deterioration (Ali et al., 2022).

Foodborne bacteria such as *Escherichia*, *Bacillus*, *Clostridium*, *Micrococcus*, *Proteus*, and others grow mostly at room temperature and are mostly dominated in fish (Coimbra et al., 2022). Additionally, Gram-negative psychrotolerant bacteria like *Shewanella* spp. and *Pseudomonas* spp. may cause chilled fish to deteriorate, while raw fish may deteriorate due to fermentative gram-negative bacteria such as *Vibrionaceae* (Rathod et al., 2022). The presence of other psychrotrophic, aerobic and/or facultative anaerobic gram-negative are also some of the possible causes of fish spoilage (Inanoglu et al., 2022). Another cause of bacterial deterioration of fish is inappropriate fish handling.

The organoleptic conditions are the earliest and most obvious signs of spoiled fish (Syropoulou et al., 2022). In fish, bacterial proliferation results in a slimy coating of skin, discoloration of the eyes and, most noticeably, the gills, which is visible throughout the entire fish, and, finally, a loss of muscle texture as a result of proteolysis, which causes the muscles to softened (Torell et al., 2020). In regard to the foul and spoiled smell of fish, bacteria aid in the putrefaction of the proteins, caused by the unpleasant odor (Abdel-Aziz et al., 2016). The bacteria *Shewanella* spp., *Aeromonas* spp., *Enterobacteriaceae* spp., and *Vibrio* spp. create ammonia-like off tastes and fishy flavors (Kuley et al., 2017). If any of these signs were found on the fish, it is likely that the Fish has already spoiled and is therefore unsuitable for human consumption. Hence, in order to prevent risk and complications, it is crucial to know how to tell whether fish is fresh and when it has already spoiled.

Not only is raw seafood prone to deterioration, but microbial growth is also influenced by storage and processing conditions (Sheng & Wang, 2021). Since bacteria are found everywhere, and each one has a unique capacity for environmental adaptation, even products that have previously been treated might become contaminated by bacteria (Adedeji et al., 2012). *Photobacterium* and *Moraxella* and important microflora constituents on the fish's surface (Rawat, 2015). Even in canned food, which is often thought of as one of the well-preserved fishery products, bacteria such as spore-forming are found and are typically linked to the deterioration of heat-treated products because of their spores' ability to endure extreme processing temperatures (Elsayed et al., 2020). *Clostridium botulinum* is a spore-forming bacterium still present in canned fish; it cannot be killed by high temperatures, but its growth is only retarded, and even a little crack or hole might cause the product to become spoiled and unsuitable for consumption by humans (Aleksandra et al., 2022; Jarosz et al., 2022). Bacteria, including lactic acid-producing bacteria and *Photobacterium phosphoreum* can thrive better when fish are packed in carbon dioxide and added with small amounts of sodium chloride (Hauzoukim & Mohanty, 2020). Furthermore, the addition of organic acid in fish favors the growth of lactic acid-producing bacteria (Kuley et al., 2020). Although pasteurization kills vegetative bacteria, *Clostridium* and *Bacillus* spores can survive and reproduce, especially in unsalted fish (Chitrakar et al., 2019).

Table 6. Some bacterial spoilage in aquatic food products.

Aquatic Food Products	Bacterial Type	References
Silver carp (*Hypophthalmichthys molitrix*) surimi	*P. gessardii*, *A. media*, and *A. johnsonii*	Huang et al. (2022)
Refrigerated Atlantic Cod (*Gadus morhua*)	*Aeromonas* spp.	Hoel et al. (2022)
Fish burgers made with a mix of Sea Bass and Sea Bream meat	Lactic acid bacteria *Enterobacteriaceae* spp.	Iacumin et al. (2022)
Raw fish, sausages, fried fish, balls, cakes, and others	*E. coli, S. enterica, C. freundii, Bacillus* spp. and *A. faecalis.*	Kyule et al. (2022)
Smoked fish: *Clarias gariepinus*, *Oreochromis niloticus*, *Citharinus citharus*, and *Synodontis membranaceous*	Gram-positive bacteria *E. coli*	Omojowo and Iluahi (2021)
Shrimp surimi	*Psychrobacter* spp. and *Brochothrix* spp.	Wang et al. (2021)
Raw and Sun-dried fishes	*E. coli*, *Salmonella* spp., *Staphylococcus* spp., and *Pseudomonas* spp.	Nur et al. (2020)
Commercial fish balls	*Pseudomonas* spp., *Psychrobacter* spp., and *Brochothrix* spp.	Zhang et al. (2019)
Fresh and spoiled fish and fishery products	*Aeromonas, Escherichia coli, Bacillus, Alcaligenes, Enterobacter, Listeria, Pseudomonas, Enterococcus, Shewanella*	Pal et al. (2016)

Retarding or Delaying Spoilage

There are various methods of retarding or delaying spoilage in aquatic food products. These include the use of traditional techniques of processing aquatic food products, such as drying, brining, fermentation, salting, and smoking (Horner, 1997; Arason et al., 2014; Tahiluddin & Kadak, 2022), and non-traditional methods, such as chilling, freezing, and canning (Garthwaite, 1997; Espejo-Hermes, 2004; Jessen et al., 2014). More recently, the application of microwave energy processing has been highlighted to process aquatic foods (Viji et al., 2022). Moreover, the potential application of natural preservatives in the prevention of spoilage, thereby extending the shelf-life of aquatic food products, has been reported and well-documented (Mei et al., 2019). Traditional processing techniques retard or prevent fish and fishery products by lowering moisture content, reducing pH, applying heat, and fermenting. Non-traditional methods involve low temperatures and the use of extreme temperatures and anaerobic environments. Natural preservation chiefly uses the ability of natural products to have strong antimicrobial properties. All these methods are simply aimed at retarding or delaying spoilage in aquatic food products caused by a broad spectrum of microorganisms.

When the fish dies, its naturally occurring microorganisms (40 million microorganisms per drop slime) multiply quickly (Calmorin et al., 1990). All negligent fish handling contributes to the growth of spoilage bacteria (Rasul et al., 2022). For instance, when a fish's gut is full of bacteria, they are carelessly dumped over the fish, which will then contaminate the other fish. Also, when an unwashed fish swiftly spreads bacteria along the cutting line, the flesh becomes infected when it is carelessly dragged over the slimy cutting and skinning boards. All these careless fish handling aids the spoilage bacteria (Oladayo et al., 2022). Hence, better understanding and knowledge of proper handling of fish and fishery products is greatly important to lessen this spoilage caused by the bacteria.

The following ways may reduce or destroy microorganisms, thereby delaying spoilage (Calmorin et al., 1990):

1. Ripping out the gills and washing the belly cavity for large fish with chlorinated water;

2. Washing with refrigerated marine water if fish are sold in whole or round form in fresh condition;

3. Applying proper icing where every fish is covered with ice;

4. Eviscerating the fish when chilling and freezing and maintaining the temperature. In order for the shelf-life of fish to last up to one year, keep the fish freezing at an ideal temperature of -40 °C. However, when dealing with commercial cold storage, a 7.22 °C temperature would be sufficient, but shelf-life is usually short and may generally last for a few weeks.

5. If dealing with fish to be processed, all the equipment, materials, and utensils used in processing must be clean, and processors or workers must also be clean and neat,

6. If the fish are to be processed by pickling, distilled vinegar and refined sugar must be used; if salting, pure salt must be used; and if canning, containers such as glass jars and tin cans must be sterilized first; and

7. The sauce to be used must be boiled to eliminate microorganisms.

Conclusion

Microorganisms are the major spoilage agents of aquatic food products because aquatic foods are greatly perishable. Newly caught or dead fish and fishery products harbor a broad spectrum of natural microorganisms as well as carrying potential pathogens. The activities of microorganisms in fish and fishery products - with high biological components, favor fast multiplication under favorable conditions. Molds and yeasts were predominant spoilage agents in seafood products stored at low temperatures and in processed products, such as heavily-salted fish and fermented aquatic foods. Bacteria are ubiquitous spoilage agents and generally cause spoilage of any form of aquatic food products, either fresh or processed forms. Understanding the spoilage attributed to microorganisms is important in helping the avoidance of post-harvest losses. However, further research is necessary to fully understand the microbial world, particularly the fish and fishery products.

Conflict of Interest

The authors declare that there is no conflict of interest.

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