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Dry-aged and dry-cured fish: a critical review of the literature and food safety aspects

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Abstract
Fish curing is a preservation method that has evolved into a culinary practice, combining traditional techniques with modern food science. Its main aims are to reduce water activity to extend shelf life, inhibit foodborne pathogens, and enhance the flavor and texture of the products. Recently, controlled maturing techniques in dedicated cabinets, previously associated exclusively with meat, have begun to attract interest among chefs, restaurants, and food companies also in the field of preservation and flavor enhancement of fish. These methods involve exposing fish to controlled temperature, humidity, and airflow in dedicated cabinets for periods ranging from days to weeks, depending on species and desired outcomes. Despite the ongoing global spread of these methods, there is still a lack of specific guidelines for food business operators (FBOs) and regulatory references. This review offers a comprehensive assessment of the literature on fish maturation in dedicated cabinets, exploring food safety principles and identifying tools to support the economic and commercial potential of these technologies. A key distinction for FBOs and consumers is between dry-curing and dry-aging. Both encompass maturation in controlled environments, but dry-curing includes salting and the addition of spices and additives, resulting in ready-to-eat products. In contrast, for dry-aging, fish is simply degutted, scaled, and directly hung within cabinets. Although the literature remains limited, it is evident that monitoring of critical parameters (temperature, humidity, airflow) is essential to minimize spoilage, microbiological risk, and biogenic amine formation. FBOs must apply general good manufacturing practices (GMPs) and good hygiene practices (GHPs) for fish processing and some GMPs and GHPs specific to each dry-aging and dry-curing process, which must be individually validated. Further research is needed to optimize and validate processes for various species and to better understand biochemical and microbial changes. Moreover, specific guidelines for the food industry/operators to properly carry out these processes and ensure that the resulting products are safe for consumers should be drafted.

Introduction
It is well known that fish and fish-based products are, on one hand, source of important nutrients for the human diet, including essential amino acids, lipid-soluble vitamins, micronutrients, and highly unsaturated fatty acids, but on the other, they are highly perishable given their peculiar composition and structure characterized by the high content in non-protein nitrogen compounds, high moisture levels, and abundant resident microbiota (Nie *et al*., 2022). All these factors can promote the growth of microorganisms able to produce metabolites that negatively impact the sensory properties and safety of fish products (Speranza *et al*., 2021). Therefore, fish preservation encompasses a combination of techniques, aimed at extending the shelf-life of products by applying scientific and technological principles to enhance their desirable attributes. The traditional strategies employed to extend the durability of fish include fermentation, smoking, salting and marinating, or the use of thermal treatments such as chilling, refrigeration, freezing, drying, boiling, steaming, and many others. The products obtained through these techniques, although widely appreciated, often undergo undesirable modifications, ranging from decreased nutritional content to reduction in sensory qualities, which are in contrast to the growing consumer preference for minimally processed, high-quality foods. In recent years, several alternative methods have been introduced as innovative processing technologies designed to extend shelf-life while minimally impacting on the qualities of the product (Speranza *et al*., 2021), indeed improving the sensory characteristics and palatability of certain raw materials.

In this context, fish processing performed within dedicated cabinets at controlled environmental conditions of temperature, relative humidity (RH), and airflow is gaining popularity among restaurants and food companies (Savini *et al*., 2024), despite the absence of a clear definition, regulatory framework, national or international guidelines, and scarce scientific literature. The application of this method for fish initially appeared as something strictly limited to high-end restaurants, but to date it is a practice employed by many chefs across Europe (Panebianco *et al*., 2024). Specifically, the use of dedicated cabinets should be considered not only as a preservation method but rather a process leading to the production of an innovative fish product for all today's consumers demanding fresh or fresh-like, minimally processed fishery products that maintain natural quality attributes and safety.

Nevertheless, unlike in the case of meat, where Chapter VII of Regulation (EC) No 853/2004 (European Commission, 2004) defines "dry-aging", following an amendment by the Commission Delegated Regulation (EU) No 2024/1141 (European Commission, 2024), for fish no definition of such process has been proposed. Consequently, considerable confusion exists at the terminological, regulatory, and processing levels. As a consequence, the use of different terms to indicate raw fish that has been subjected to different processes/approaches selected according to the fish species, recipe, or consumer preference, makes it difficult to classify the derived products into specific food categories. It should be clarified that two main types of processes can be carried out in these dedicated cabinets, namely dry-aging and dry-curing, resulting in two primary products, respectively dry-aged and dry-cured fish, with additional subcategories for dry-cured fish. Dry-aged fish means a product similar to dry-aged meat (with the difference that almost all fish were salted before undergoing the ageing process), for which only cold temperatures, RH, and airflow are applied during the process. For dry-cured fish, the process includes salting (optionally with additives), seasoning with spices, and involves a shorter ageing period with the application of variable values of temperatures, airflow, and RH. Thus, based on the necessity to guarantee food safety, identify the potential critical control points (CCPs) and recommendations for the production of innovative products, this review analysed the literature concerning dry-aging and dry-curing of fish performed within dedicated cabinets, advancing a shared definition of this innovative process and some recommendations for future studies and analyses. Targeted literature research was carried out to identify recent scientific contributions related to dry-curing and dry-aging, with a particular focus on surface-level modifications in fish products. The databases explored included PubMed, Scopus, and Google Scholar. The search queries combined terms such as dry curing*,* dry ageing*,* fish processing*,* flavor*,* and food safety. Only peer-reviewed journal papers written in English were considered. Publications such as book chapters, editorials, and conference abstracts were excluded. To qualify for inclusion, studies had to meet the following criteria: i) be published between January 1, 2022, and the present date; ii) provide data on processes occurring exclusively during dry curing and dry ageing (studies focused only on other preservation or maturation methods were excluded).

Dry-curing and dry-aging of fish: definition, regulation, and process parameters

As mentioned above, to date, a clear distinction is missing between dry-aging and dry-curing, and terms are arbitrarily used. Dry-aging involves hanging fish in a controlled, chilled environment for a period to enhance flavor and texture by allowing natural enzymes to break down proteins. Dry-curing is a preservation process where fish is rubbed with salt (and sometimes sugar and spices and/or additives) and left to air-dry, drawing out moisture and extending shelf-life. For centuries, curing has been a common way to preserve fish, comprising all methods of preservation except refrigeration and canning, and including: i) the drying, smoking, salting, and pickling of fish; ii) various combinations of these methods; iii) miscellaneous methods such as the use of vinegar and fermentation processes or ripening. Specifically, drying could be considered, among physical methods of preservation, a moisture control measure achieved by lowering the water activity (a_w), which in turn arrests microbial activity and extends the shelf-life of fish and fishery products. However, the drying process should be carried out properly: in case of too rapid drying, it might result in layer hardening (hard texture) affecting the palatability of the product undesirably, whereas, in case of slow drying process undesirable microbes might survive and grow, or even, in case of very high temperature, lipid oxidation could be triggered resulting in off-flavored fish products (Mahmud *et al*., 2018). The term curing refers, among chemical methods of fish preservation, to the addition of salt, sugar, seasonings or spices, and additives to preserve food. Salt traditionally exerts its antimicrobial action by creating an environment with low a_w in food, forcing microorganisms to prolong the lag phase and eventually

enter the death phase. Although curing functions as a preservation method, it also affects the color and the flavor of the cured fish products (Mahmud *et al*., 2018).
Modernization of fish dry-curing encompasses the association of the chemical and physical transformation of the initial product within dedicated cabinets. Besides, only fish dry-aging can be defined similarly to what happens for dry-aging of meat. Indeed, simulating the definition of meat dry-aging laid down by the Commission Delegated Regulation (EU) No. 2024/1141 (European Commission, 2024), dry-aging of fish could be defined as the "hanging fish either in cuts or whole pieces, stored in a cool room or fridge in bags permeable to water vapor in and left to age for several days or weeks at controlled environmental conditions of temperature, relative humidity and airflow". Therefore, the management of the process should be based on proper selection and cleaning of the fish, and continuous monitoring of temperature, RH, and airflow parameters during all the ageing steps. In addition, proper fish preparation, general good manufacturing practices, and good hygiene practices for fish processing must be applied, as usually performed by the fish industry and the Ho.Re.Ca (hotel/restaurant/catering) sector. Usually, fresh or frozen and thawed fish are initially prepared, namely scaled and gutted, taking care not to damage the skin or to break the internal tissues (Panebianco *et al*., 2024), but alternatively, the skin is removed to promote drying, and then two operating sequences can be put in place:
1) *Dry-aging:* this process is often applied to whole medium- and large-sized fish previously scaled and gutted but not completely deboned or filleted: the fish is simply aged in the cabinet after the preliminary operations. The addition of salt or a brief brine wash before placing the fish in the cabinets is possible, but the use of a curing mixture containing spices or aromas is not normally expected. Usually, there is no distinction among production phases, but the same values of RH, ventilation, and temperature are maintained throughout the entire process. The dry-aged fish is typically cooked before being served, for example, in restaurants (Panebianco *et al*., 2024), but it might also not be subjected to further heat treatment.
2) *Dry-curing:* this process is usually preferred for fillets or fish parts that have been deboned, prepared, or minced beforehand. Similar to cured meat products, the prepared fish is initially cured using a mixture that usually contains salt, sucrose, dextrose, spices, and antioxidants. For these products, the process usually entails different steps, characterized by a specific combination of RH, ventilation, and temperature parameters during the different steps. The process in dedicated cabinets includes a dripping step that is performed with or without the mechanical salt removal, followed by different drying and ageing phases to transform fish into a ready-to-eat (RTE) product (Savini *et al*., 2024).
During both curing and ageing processes, the skin of the fish becomes progressively drier, superfluous fluids are released, and the texture of the flesh undergoes substantial modifications. Fish subjected to this gradual drying process develop distinct aromatic characteristics compared to fresh products, resulting in a concentrated and highly appreciated flavor profile. The dry-cured RTE fishery products include, for example, fish-based salami (both raw and cooked), tuna bresaola, aged swordfish loin, smoked salmon speck, tuna mortadella, and several other fish salumi. These could all be classified as *fish deli*, meaning all types of cured fish products made from different fish species produced by whole fish, cuts, fillets, or ground fish meat. Both curing and ageing processes facilitate the evaporation of moisture while allowing residual blood and slime to drain away, leaving the fish clean and odourless. Apart from the mix of ingredients that may be added during curing, the unique flavour profile of dry-aged or cured fish is strongly influenced by protein enzymes present in the flesh, which gradually break down over time, making the texture more tender.
During this drying process, a natural umami flavor is released as the broken-down proteins release amino acid chains, particularly glutamate. The concentration of this enzyme increases throughout the aging process, further intensifying the flavor of the fish (Ninomiya, 2015). In addition, during the dry-aging process conducted on whole fish, macroscopic changes occur on the skin and external parts. Panebianco *et al*. (2024) reported a marked dehydration of the skin and external parts of whole rainbow trout (*Onchorynchus mykiss*) subjected to dry-aging from day 3 to the end of the process

(day 14). An evident displacement of the ocular bulb at day 10 and especially at day 14 of dry-aging was also reported.
The process parameters, namely temperature, RH, and airflow, have no standard levels in the literature. However, their management significantly impacts the progression of the proteolytic cascade, influencing both the flavor and the microbiological safety of dry-cured and aged fish. A balance of the process parameters should be found: i) temperature and its stability could play a crucial role in achieving the desired characteristics, since their increase could be directly related to the speed of enzymatic process maturation, similarly to meat (Savini *et al*., 2024); ii) RH plays an important role in dehydration while intensifying the flavor, without spoiling the texture of fish - humidity control is related to the size (the larger the size, the higher the RH must be, otherwise drying does not take place homogeneously) in order to avoid excessive bacterial growth and dryness of the muscles and skin (Ticchi, 2021).
From the regulatory point of view, dry-cured and dry-aged fish can neither be classified as fresh nor prepared fishery products by the Regulation (EC) No 853/2004 (European Commission, 2004) but might be categorized as processed products, meaning "foodstuffs, resulting from the processing of unprocessed products, which may contain ingredients that are necessary for their manufacture or to give them specific characteristics". Indeed, processing means any action that substantially alters the initial product, including heating, smoking, curing, maturing, drying, marinating, extraction, extruding or a combination of those processes. Referring to dry-cured RTE fishes, like ham, salami, sausages, and other products derived from muscle, these are defined as food intended by the producer or the manufacturer for direct human consumption without the need for cooking or other processing effective to eliminate or reduce to an acceptable level microorganisms of concern (European Commission, 2004). However, in the Commission Regulation (EC) No 2073/2005 (European Commission, 2005) on microbiological criteria for foodstuffs, process hygiene criteria are not defined for the food categories dry-cured and dry-aged fish. On the contrary, the concentration of histamine, only for fishery products from fish species associated with a high amount of histidine, namely fish species belonging to *Scombridae, Clupeidae, Engraulidae, Coryfenidae, Pomatomidae, Scomberesocidae* families, might be applied as a food safety criterium, as well as the detection of *Listeria monocytogenes*, only for RTE fish products (European Commission, 2005).
In relation to the requirements concerning parasites, neither dry-curing nor dry-aging processes have been tested in order to evaluate their ability to devitalize parasites. Considering the parameters used and the duration of the process, no stage of either process qualifies as a CCPs capable of inactivating potential parasites. As a consequence, food business operators (FBOs) must follow Regulation (EC) No 853/2004 regarding requirements concerning parasites (European Commission, 2004). In more detail, FBOs placing on the market fishery products intended to be consumed raw or marinated, salted or any other treated fishery product, if the treatment is insufficient to kill the viable parasites must, ensure that the raw material or finished product undergo a freezing treatment in order to kill viable parasites that may be a risk to the health of the consumer. The freezing treatment must consist of lowering the temperature in all parts of the product to at least -20°C for not less than 24 hours or -35°C for not less than 15 hours for parasites other than trematodes. For some of the latter, in fact, lower temperatures and/or longer freezing times are necessary. As an example, EFSA reported that *Clonorchis* and *Opisthorchis* metacercariae can be inactivated by freezing at -10°C for 5 days (EFSA, 2024). In FAO technical paper No 444, it is reported that 3-4 days at -20°C are required to eliminate *C. sinensis*, while -28°C is sufficient to inactivate *O. felineus* larvae within 32 hours (Huss *et al*., 2003). In addition, particular cases where no freezing treatment is mandatory encompass: i) fishery products not intended as RTE, but rather submitted to a heat treatment that kills the viable parasite; ii) products that have been preserved as frozen fishery products for a sufficiently long period to devitalize the viable parasites; iii) the competent authority (CA) has evidenced the absence of parasites in the fishing grounds of origin for wild catches, or even for fish farming not presenting a health hazard given the environment is considered free from viable parasites; iv) the FBO verifies through procedures, approved by the CA, that the fishery products do not represent a health hazard

with regard to the presence of viable parasites (European Commission 2004). As clearly laid down by Regulation (EC) No 853/2004 (European Commission, 2004), for fish that have undergone or are intended to undergo before consumption a heat treatment that kills the viable parasite (with a core temperature of 60°C or more for at least one minute in the case of parasites other than trematodes) the freezing treatment is not carried out. In the specific case of dry-aged fish intended to be heated, a visual examination is performed for the purpose of detecting visible parasites. In any case, regardless of the ageing or curing processes, fishery products obviously contaminated with parasites cannot be sold or provided for human consumption.

Flavor development and food safety aspects

The dry-aging process enhances the flavor profile of raw fish, producing taste characteristics that are unattainable immediately after the catch. Microbial activity plays a pivotal role in the development of such flavors, leading to the activation of diverse metabolic reactions, particularly lipid oxidation and protein degradation, that significantly contribute to the formation of unique flavor formed by volatile precursors, primarily free fatty acids generated through lipolysis and free amino groups released by protein hydrolysis. In particular, this process produces characteristic compounds such as aldehydes, ketones, alcohols, esters, alkanes, aromatic compounds, and various other volatile substances. Aldehydes are primarily formed through lipid oxidation or amino acid degradation, while ketones arise from enzymatic breakdown (Liu *et al*., 2023).

Enzymes present in muscle fibers become activated *post-mortem* and within a day, start breaking down connective tissues, relaxing the muscle structure and softening the flesh. The enzymatic processes occurring during dry-aging generate a wide spectrum of new flavors, ranging from sweet to savoury, predominantly influenced by glutamate and other amino acids (Zhao *et al*., 2022).

The microbial community in dry-aged fish changes over the course of the process and affects flavor development (Zhao *et al*., 2022). The growth and the change of microbial communities have been linked to changes in substrate composition. In recent studies, changes in the microbial community composition of dry-aged fish were analyzed by means of high-throughput sequencing and metagenomics (Indio *et al*., 2024). Proteobacteria and Firmicutes were the two main microbial phyla within the microbiota of dry-aged fish, which suggests that they play an important role in the quality and shelf-life of dry-aged fish products (Zhang *et al*., 2021). Proteobacteria were reported with a relative abundance maintained above 50% throughout processing and contribute to the fermentation and proteolysis processes that break down proteins in the fish. This is important for microbial competition. Some Proteobacteria species can outcompete or inhibit the growth of harmful microorganisms, helping to control spoilage and extend shelf-life (Zhao *et al*., 2022). Firmicutes became the second dominant group in dry-aged fish and played an important role in dry-aged fish, particularly through their involvement in lactic acid fermentation and metabolism of carbohydrates and proteins (Zhao *et al*., 2022). In fact, the presence of Firmicutes is strictly linked to carbohydrate metabolism, while metabolism of amino acids and lipids are associated with bacteria of the genus *Proteus* (Liu *et al*., 2023). *Cobetia* and *Staphylococcus* were identified as the most abundant genera in dry-aged fish products, and they can significantly impact the ripening of dry-aged fish. For dried salted fish product, *Halomonas* and specifically *Staphylococcus* have been identified as the most abundant genera (Zhao *et al*., 2022). In particular, *Staphylococcus* are the predominant bacteria found in these fish products. These microorganisms may influence the flavor and quality of dried salted and dried fish. *Staphylococcus* can be employed as starters to accelerate flavor development while inhibiting the onset of fat oxidation (Zhao *et al*., 2022). Anyway, we must highlight that Staphylococcal food poisoning ranks among the most common causes of foodborne illness globally. It results from the consumption of food with preformed staphylococcal enterotoxins, thermostable proteins produced by coagulase-positive staphylococci, mainly *S. aureus,* for which the risk of toxin production depends largely on temperature and the storage conditions in a wide range of temperatures (from around 7°C to 48°C) (Bianchi *et al*., 2022).

Microbial metabolism can form flavor substances in food in two principal ways. Amino acid metabolism allows the development of flavors through transamination, whereby flavor precursors are formed from amino acids, such as aromatic amino acids. The second pathway is the elimination reaction, whereby methionine generates sulfur-containing compounds. Various microorganisms contribute to the biochemical reactions responsible for flavor development. For example, *Bacillus* produces amino acid transaminase, *Enterobacter* is associated with both branched-chain and aromatic amino acid transaminases, *Macrococcus* generates alpha-ketoacid decarboxylase, and *Lactococcus* produces phenylpyruvate decarboxylase. In dried fish, the primary source of flavor is also derived from the microorganisms involved in the fermentation and aging processes. The flavor formation process typically begins with lipase-mediated fat breakdown, leading to the release of free fatty acids (Liu *et al*., 2023).
Moreover, the complex microbial community and its growth are closely linked to food safety, being fish a perishable food due to bacteriological and enzymatic activities that take place after death, where microbial growth is one of the primary factors affecting fish preservation. Understanding the microbiological contamination of fish, alongside the changes in shelf-life and microbiological indicators during dry-curing and dry-aging, is essential to evaluate the end-food safety, in terms of both food safety and process hygiene criteria. In addition to bacteria existing on raw material, contamination occurring during the following stages has gained increasing attention, since microorganisms can be transferred to products not only during processing, but also during handling and by catering equipment (Sheng and Wang, 2021).
Panebianco *et al.* (2024) assessed the safety for consumption of whole rainbow trout subjected to dry-aging in a restaurant, analyzing dorsal, ventral muscles, and skin samples during the process. Given the absence of microbiological critical limits in Regulation (EC) No 2073/2005 (European Commission, 2005), the acceptability of the investigated fish products were assessed considering the benchmarks reported by the Interdepartmental Center for Research and Documentation on Food Safety of Piedmont region (CeIRSA) for the category ‘fish and fish preparation’ in relation to total mesophilic bacteria, *Enterobacteriaceae* and coagulase-positive staphylococci (CeIRSA, nd) as well as other limits reported in the literature, namely total psychrophilic bacteria (Mol *et al*., 2007), *Pseudomonas* spp. (Civera *et al*., 2011), lactic acid bacteria (Lyhs, 2002) and yeasts and molds (Nguyen *et al*., 2018). After slaughtering, manual removal of gills and scales, and brief (40-60 s) washing in a saline solution (15% NaCl) fish were suspended upside down in a dry-aging cabinet for 14 days. Two separate experiments were performed. The data loggers recorded 3.14°C as the mean temperature in the first experiment (E1), and 3.57°C in the second experiment (E2). The mean RH was of 77.65% E1 and 78.58% in E2. At the end of processing, dorsal muscle loads of total mesophilic bacteria, total psychrophilic bacteria, and *Pseudomonas* spp. were still acceptable, whereas *Enterobacteriaceae*, lactic acid bacteria, coagulase-positive staphylococci and yeasts and molds were below the limit of quantification. In ventral muscle samples, even though higher microbial loads were observed, all the microbiological indicators could be considered acceptable with the exception of yeasts and molds at day 14 in one out of two experiments. In skin samples, total mesophilic bacteria, *Enterobacteriaceae*, and coagulase-positive staphylococci were quantifiable from the first day of process and persisting until day 14, but only in two cases (*Enterobacteriaceae* at day 0, yeasts and moulds at day 3, both in E1), not satisfactory microbial loads were observed. Regarding pathogenic microorganisms, *L. monocytogenes* and *S. aureus* were absent in both muscle and skin samples. In conclusion, dry-aging could be considered a valid tool to keep acceptable microbial levels in rainbow trout during maturing, and 10 days was identified as the most appropriate ageing period setting 3°C and 78% of RH. The process parameters reported in the literature for fish are summarized in Table 1.
A different study considered TBC and *Enterobacteriaceae* as a proxy of process hygiene criteria, and the detection of *L. monocytogenes* as a food safety criterion for RTE dry-cured fish (Indio *et al*., 2024). Analyses, conducted by means of both culture methods and shotgun metagenomic were performed on fillets of *Salmo salar* (salmon), and cuts of *Xiphias gladius* (swordfish) and *Thunnus albacares* (yellowfin tuna), before, during, and at the end of a dry-curing process (Indio *et al*., 2024).

The process, performed in a dedicated cabinet, encompassed a 48-h salting step, followed by different combinations of controlled temperature, RH, and ventilation based on the fish species, as detailed in Table 1.
In the raw material and during the entire dry-curing process, the concentration of *Enterobacteriaceae* remained below 10 CFU/g, while TBC varied throughout the process, probably due to differences in the initial load of the different species and to the impact of contaminations originating from the operations prior to the fish purchase and transport to the laboratory. In relation to the taxonomic profile of salmon, swordfish and tuna before and during the dry-curing processes, the beta-diversity analysis revealed different profiles among the three species. In general, Pseudomonadota and Bacillota, formerly classified as Proteobacteria and Firmicutes, were the prevalent phyla, in agreement with findings in other salted and dried fish products (Wang *et al.*, 2018). The relative abundance of Bacillota was homogeneous among the three fish species, whereas the phylum Pseudomonadota was notably more abundant in swordfish, in which the prevalent genus was *Photobacterium* both in samples of raw material and increased during the curing process. *Photobacterium* is a psychrotrophic and halotolerant microorganism, ubiquitous in marine environments able to survive in fish and fish products, and it is identified as histamine producer bacteria (Reynisson *et al*., 2010; Kuuliala *et al*., 2018; Jääskeläinen *et al*., 2019). The microbial diversity observed between trout and swordfish, salmon and tuna seem to reflect the fact that they are respectively freshwater and marine fishes with different environments, as well as the different types of processing. It is well known that the adaptation of fish to the environment is strictly related to their capacity for feeding and that maintains a distinctive and close relationship with their surrounding habitat as well as with the microorganisms living within it. Further, intra and inter-species diversity found includes life stage, diet, season, habitat, captive state, sex and phylogeny (Wang *et al*., 2018). Among the several species, *Photobacterium damselae* and *Photobacterium piscicida* are classified as pathogenic for both fish and humans (Rivas *et al*., 2013). In tuna, the *Staphylococcus* genus started to increase during the drying step (after temperature from 19 to 11°C) and significantly increased at the end of the process. *L. monocytogenes* was not detected in the raw material by using the reference culture method and a minimal number of reads (relative abundance <0.007) were found in swordfish and tuna through shotgun metagenomic. Despite this finding, the hazard *L. monocytogenes* has to be taken into account considering its ubiquitous nature and its ability to grow at low temperatures and to persist in the food production environments (Fagerlund *et al*., 2022). In addition, within the RTE food category, the highest occurrence of *L. monocytogenes* (from 2.3% to 2.6%) is reported in fish and fishery products (RTE). Zakrzewski *et al.* (2024) reported a considerable pooled prevalence of *Listeria* spp. in raw fish (12.2%); the microorganism has been detected on the surface of fish, in the stomach lining, gills, and intestines, but the flesh typically remains uncontaminated unless there is cross-contamination from intestinal contents or through handling with contaminated equipment or improper transportation practices (Jami *et al*., 2014). While *L. monocytogenes* should always be considered in food safety practices, its role as a primary hazard in fish dry-aging and curing processing should be reassessed and potentially downplayed under controlled processing conditions, given its minimal presence in the raw material, its reduced ability to grow in drying conditions, and the fact that contamination is generally limited to non-edible parts of the fish.
The behavior of *L. monocytogenes* during dry-curing of fish conducted in a patented cabinet on salmon, yellowfin tuna and swordfish has been studied through two distinct challenge tests based on different contamination scenarios: one involving contamination of the raw material prior to the salting and dripping stages, and the other occurring during the mechanical removing of salt, just before the drying and aging phases (Savini *et al*., 2024). A notable reduction in *L. monocytogenes* levels was observed during salting for salmon, yellowfin tuna, and swordfish (0.72, 0.51, and 0.84 Log_{10} CFU/g) and during drying and ageing stages for tuna and swordfish (0.77 and 0.49 Log_{10} CFU/g). For salmon, among the three batches, a slight reduction in two and a slight increase in the third were reported. Probably, the elevated fat content of salmon may have provided a protective effect on inoculated *L. monocytogenes*. In fact, fat droplets within the food matrix are generally believed to inhibit microbial

growth when present in sufficiently high concentrations (Baka *et al*., 2017). The different behavior of the pathogen in salmon must be considered in light of the economic relevance of *Salmo salar*, which, due to being subjected to various processing methods, is the species most commonly contaminated by *L. monocytogenes* (Zakrzewski *et al*., 2024) and in the form of sushi salmon is also responsible for several outbreaks of listeriosis (Eicher *et al*., 2020). On the other hand, applying two predictive microbiology models, an increase of *L. monocytogenes* was expected. As already reported for dry-aged meat, the predictive models tend to overestimate bacterial growth since not all parameters can be included in the model itself, namely ventilation, RH and competitive microflora. Thus, these data obtained are precautionary and cannot be intended as a unique reference (Savini *et al*., 2024).

Fishery products may also pose potential chemical risks, including the development of harmful biogenic amines during storage (Visciano *et al*., 2020) whereas other chemical contaminants, such as lead, cadmium, mercury, dioxins and PCBs (polychlorinated biphenyls), PFOS (perfluorooctane sulfonic acid), PFOA (perfluorooctanoic acid), PFNA (perfluorononanoic acid), and PFHxS (perfluorohexane sulfonic acid), are less or not dependent on the fish processing. As dry-curing and dry-aging of fish are being implemented by an increasing percentage of restaurants and operators, it is clear the necessity of a comprehensive microbiological and chemical risk assessment to guarantee the safety of these increasingly consumed foods (Panebianco *et al*., 2024). However, to date, very few investigations are present in literature, considering that fermented and traditional fish-products are not the target of this review.

In relation to histamine and other biogenic amines, in the studies that considered the hazard, histamine was under the critical limits imposed by the Commission Regulation (EC) No 2073/2005 (European Commission, 2005) in risky fish families (Indio *et al*., 2024; Panebianco *et al*., 2024) and the other biogenic amines were under the limit of quantification, with the only exception of putrescine which was detectable with concentrations ≥ 0.5 mg/kg in rainbow trout ripened at restaurant level. Although it was detected, a relatively stable contamination of putrescine was observed until the end of dry-aging, suggesting that the investigated process (average temperatures of 3.14 and 3.57°C and mean RH of 77.65 and 78.58%, respectively, in experiments 1 and 2) did not increase biogenic amine levels in rainbow trout (Panebianco *et al.*, 2024).

However, although no biogenic amines were detected in salmon, tuna, and swordfish, the abundance of histamine-producing bacteria was identified. Swordfish cuts appeared the richest in terms of histamine-producing bacteria, namely *Photobacterium phosphoreum, Photobacterium kishithanii* and *Vibrio fluvialis*, followed by reads of *Klebsiella pneumoniae, Morganella psychrotolerans* and other species among *Photobacterium* and *Vibrio* genera (Indio *et al*., 2024). However, further studies are needed for the assessment of biogenic amines risk in dry-aged fish belonging to other species and processed under other process parameters.

Conclusions

This review provides relevant information to the FBOs, helping them improve the safety of their dry-cured and dry-aged fish products. In fact, despite the growing popularity and widespread presence of these products on the market and in restaurants, there are no specific regulations or guidelines. The few studies available in the literature indicate that dry-curing and dry-aging do not seem to have a negative impact on fish or the safety of these products, if they are carried out under continuous monitoring and strict control of process parameters. In line with the regulations currently in force for meat, parameters such as time, RH, temperature, and ventilation should be constantly monitored and adjusted according to the fish species being processed. Despite the need for regulatory frameworks and guidelines, the processes related to fish dry-aging and curing are still heterogeneous and lack standardization, making it difficult to identify or analyze good manufacturing practices (GMPs) and good hygiene practices (GHPs), and CCPs. The limited availability of data hinders the establishment of definitive and universally applicable guidelines, so each process and its corresponding product must be individually validated by FBOs. However, some potential GMPs specific to fish maturation may be suggested, including the control of environmental conditions during aging or curing, the characteristics and maintenance of equipment and facilities, as well as the control of raw fish quality. Possible GHPs may involve ensuring proper personnel hygiene, along with regular cleaning and sanitation of aging/curing cabinets and equipment, including the control of humidity levels and air circulation. Additional research is required to evaluate how these techniques affect other fish species. Moreover, further studies focusing on microbial safety, process optimization for different fish species and fish products, sensory attributes, and the impact of different processing conditions should be performed in order to validate specific dry-aging and curing fish processes and ensure consumer safety.

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Table 1. Parameters of dry-ageing and dry-curing processes available in the literature.

Phase	Process parameters				Fish species	Reference
	Duration	**Temperature (°C)**	**Relative humidity (%)**	**Ventilation (m/s)**		
Curing	40-60 s	Room temperature	n.a.	n.a.	Rainbow trout	Panebianco *et al.*, 2024
	48 h	2	85	3.4	Salmon, swordfish and tuna	Indio *et al.*, 2024
Dripping	4 h	24	80	3.4	Salmon	Indio *et al.*, 2024
	12 h	18	78		Swordfish and tuna	
Drying	6 h	19	51			Indio *et al.*, 2024
	6 h	14	54			
	6 h	11	57	3.4	Salmon	
	12 h	8	60			
	12 h	5	63			
	18 h	15	55		Swordfish and tuna	
	18 h	15	58			
	18 h	15	51	3.4		
	18 h	10	54			
	18 h	8	57			
	18 h	6	60			
Ageing	10 days	3.14 - 3.57	77.65- 78.58	n.a.	Rainbow trout	Panebianco *et al.*, 2024
	40 h	4	67	2.1	Salmon	Indio *et al.*, 2024
	32 h	4	60			
	72 h	4	50		Swordfish and tuna	

n.a., not applicable.