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Preservation Techniques to Increase the Shelf Life of Seafood Products: An Overview

Alireza Rabiepour*, Fatemeh Zahmatkesh, Aria Babakhani

Fisheries Department, Faculty of Natural Resources, University of Guilan, Sowmeh Sara, Guilan, Iran
E-mail: rabiepooralireza@gmail.com (Corresponding author)

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Abstract: Currently, humanity is facing many types of diseases with various origins and the high costs of chemical drugs for treatment. Therefore, the consumption of healthy and nourishing foods such as seafood products to treat these diseases should be considered in the human diet. However, seafood products are subject to high spoilage owing to their high-water content, rich composition of unsaturated fatty acids, susceptibility to oxidation, near-neutral pH, presence of non-protein nitrogenous compounds, and microorganism activity. Therefore, appropriate storage methods are required to prevent spoilage. This review was done with the aim of providing preservation methods and increasing the shelf life of seafood products. In general, the results of this research stated that common and traditional techniques of seafood products preservation including salting, canning, chilling, freezing, fermentation, super chilling, drying, smoking, frying, pickling/marinating and pasteurization and also modern techniques for seafood products preservation such as microwave processing, ultrasound, pulsed electric field (PEF), irradiation, high hydrostatic pressure (HHP), micro fluidization, usage of natural preservatives (plants and algae extracts, biodegradable polymers, bioactive polysaccharides and biopeptides extracted from marine resources/ seafood by-products), packaging ((MAP), (AP), (IP), (VP), (RP)), nanotechnology and other new methods can preserve the product for a period of time efficiently, also significantly increase the desired sensory and organoleptic characteristics of the product and as a result, they increase quality, safety and shelf life. However, improving the weaknesses of traditional methods by using modern techniques can improve and maintain the nutritional value of the product.
Keywords: Seafood products; Preservation techniques; Food safety; Aquatics; Shelf life.

1. Introduction

Currently, the fisheries and aquaculture industries play a very special role in the economy (in creating jobs), providing sustainable healthy dietaries, and the development of new drugs to establish human health in different countries [1-2]. So that, the global fish consumption also increased from 9.0 kg per capita in 1961 to 20.5 kg in 2018. Aquaculture production accounted for 46% of the total production and 62% of the total sales value. Owing to the increasing demand for high-quality protein, reduction of the wild fish catch, and advancement in fish farming technologies, global aquaculture production is expected to double by 2050 [3]. Aquatics are a rich source of proteins, essential amino acids, fatty acids (saturated fatty acids, monounsaturated fatty acids, and polyunsaturated fatty acids (omega-3 and omega-6)), carbohydrates, vitamins, and minerals [2]. In addition, in recent years, consumers have preferred foods that have the ability to improve health and reduce or deal with the risk of contracting diseases [4]. Therefore, fish and seafood products are among the food commodities with high commercial value, high-quality protein content, vitamins, minerals, and unsaturated fatty acids. These are essential and beneficial dietary components for human and nutritional health and are highly appreciated and consumed worldwide [5-6]. Polyunsaturated fatty acids (PUFAs), particularly omega-3 and omega-6 fatty acids, can prevent atherosclerosis and thrombosis. These fatty acids have preventive effects on coronary heart disease, autoimmune disorders, and arrhythmias, lowering plasma triglyceride levels and blood pressure. Almost all minerals present in fish require the body. The minerals present in fish iron (Fe), Calcium (Ca), Zinc (Zn), Phosphorus (P), Selenium (Se), Fluorine (F), Iodine (I). These minerals have high bioavailability and are easily absorbed by the body [7]. Figure 1 shows seafood products from the fish processing industry.

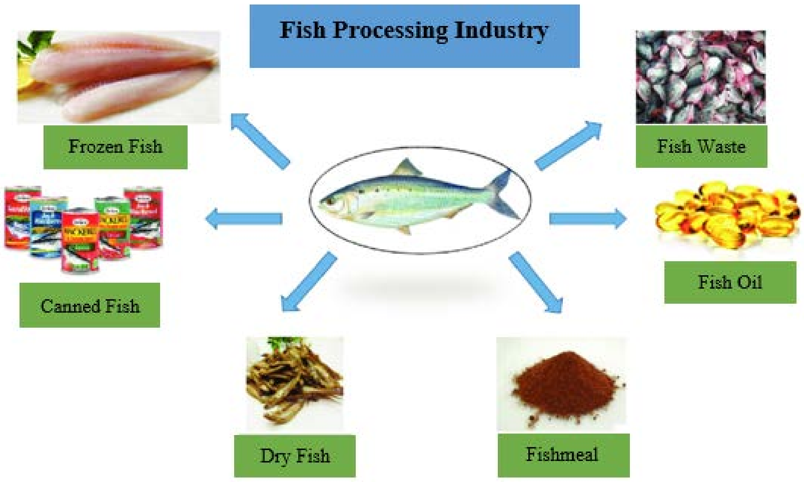

Fig 1. Seafood products from fish processing industry [8].

In fact, marine aquatics have found a suitable place in the food basket of families due to their high nutritional value [9]; however, despite all the advantages, seafood products, especially fish, have more free amino acids, non-saturated fatty acids, less connective tissues, and higher enzyme activities compared to other muscle products [10-12]. As a result, quality deterioration, such as protein degradation [13], lipid oxidation [14], and changes in fish odor, flavor, and texture [15], readily occur during the decay of aquatic products. These phenomena contribute to the short shelf life of aquatic food products, resulting in lower consumer acceptance [16]. Therefore, fishery products are extremely perishable owing to their biological composition, and thus require proper processing and preservation techniques to maintain their quality and safety [17]. Rancidity, fat oxidation, and bacterial reproduction and enzymatic and microbiological spoilage cannot be inhibited sufficiently by traditional preserve techniques (packaging, freezing, chemical treatments etc.) [18]. Consequently, Food preservation has always been and will continue to be an important aspect of daily life for ordinary people. This prevents a large amount of food from being wasted worldwide. Adequate food preservation is critical for foodborne infections caused by consuming damaged food [19]. Modern consumers seek fresh-like, minimally processed foods due to concerns regarding the use of preservatives in foods, as is the case with fresh fish. Hence, the demand of consumers for aquatic products with a long shelf life and high quality has urged the food industry to pursue highly effective and emergent preservation methods to assure food safety and extend shelf life without compromising food safety and aquatic products for shelf-life extension of aquatic products [20-21].

So, with these explanations, this research has discussed the preservation methods of seafood products, including common, traditional, and modern preservation methods that increase the quality, safety, sensory characteristics and shelf life of these seafood products.

2. Materials and Methods (Literature review)

The literature we reviewed to clarify the issue and writing this article was conducted using the Google Scholar search engine. Moreover, we applied the Semantic Scholar research tool, which is used to find various scientific publications and manuscripts and makes it easy to understand their goals quickly. Scopus and ScienceDirect were the next most valid databases for completing the literature review of the current paper. We also used PubMed, a well-known search engine that focuses particularly on the life sciences. Finally, the Research Gate network was our last database to look up the papers and extract the required data, and it is said to be the largest academic social network for all researchers. The time that we spent reviewing the scientific sources and researching our subject was three months, and the papers that we explored were written between 1982 and 2024. In addition, the following key terms helped us to perform an appropriate search for the papers: Fish and seafood products, Preservation techniques, Food Safety, Aquatics, and Shelf life

3. Common and traditional techniques of Seafood products preservation

3.1 Salting

Salting is a cheap and natural method widely used in the food industry. Its functionalities include ensuring microbiological, improving the sensory attributes, mainly color, (salty) taste, and texture, as well as acting as a binding and emulsifier agent [22-24]. It is well-established that 1.5–2.0% NaCl ensures the sensory attractiveness of canned or cooked seafood products [25]. For example, Jiang *et al.* [26], Physicochemical and microstructural mechanisms for quality changes in lightly salted tilapia (*Oreochromis niloticus*) fillets during frozen storage were examined. The enhancement of tilapia fillet quality was observed through the application of a light salting process, and it was determined that the conditions could influence the storage stability of frozen fillets during preparation. Moreover, fermented and salted fish (FSF), such as freekeh, moha, and renga, are very popular in Egypt; in various social gatherings and celebrations, fish-based dishes hold a central role as main courses. Despite their widespread popularity, these dishes pose significant health risks, encompassing both biological and chemical hazards. These hazards arise from potential contaminants present in fish tissues, posing a risk of transmitting food-borne illnesses, such as botulism intoxication, to consumers. Implementing a Hazard Analysis Critical Control Point (HACCP) system serves as a proactive measure to ensure the safety of fish-based dishes and safeguard consumers [27].

Seafood naturally contains sodium (Na), but in raw products, its concentration seldom surpasses 0.1 g per 100 g. Nevertheless, the sodium content can significantly escalate, up to a hundredfold, during processing procedures like salting, a common practice employed to enhance both the safety and appeal of seafood. The safety and attractiveness of the seafood [28]. The World Health Organization (WHO) suggests that NaCl intake should not exceed 5 g (2 g of Na) per day. However, the current consumption is approximately twice as high, and therefore, reducing NaCl intake has been identified as one of the most cost-effective measures that can be taken to improve the health of the global population [29]. The approaches for salt reduction in food, which ensure the quality, safety, and attractiveness of seafood, can be divided into four main groups: i) the reduction of NaCl content, ii) the use of NaCl replacers such as KCl, $MgCl_2$, and $CaCl_2$, iii) the addition of flavor enhancers (e.g., amino acids), and iv) the combinations of different approaches [30].

3.2 Canning

Canning, when executed correctly, stands as a crucial and secure approach to preserving food. This method involves preparing food, sealing it within sanitized cans or jars, and subsequently subjecting the containers to boiling to eliminate or weaken any lingering bacteria. As foods possess varying degrees of inherent protection against spoilage, the concluding step might require the use of a pressure cooker [31]. Food is heated in jars or other containers to destroy bacteria that cause food to spoil. The air is driven out of the jar during the heating process, and as it cools, it forms a vacuum seal. This vacuum seal keeps air out of the product, which would otherwise contaminate it with microorganisms. Food can be safely processed using either a boiling water bath or a pressure canner. Cooking the food, then sealing it in sterilized jars or cans, and boiling the containers for sterilization are all part of the procedure. Any residual microbe is killed or weakens under these conditions. Once a can or bottle has been opened, food conserved by canning or bottling is immediately at risk of deterioration. Water or microorganisms may enter the canning process due to a lack of quality control. The majority of these failures are quickly discovered because disintegration within the can produce gas, causing the can to bulge or burst [32-33]. However, there have been cases where poor manufacturing and cleanliness have allowed the obligate "anaerobe" Clostridium botulinum to contaminate canned food, producing an acute toxin that causes serious disease or death. Canned foods can be a substantial basis for sodium in the food. Excess salt raises the likelihood of health issues, such as high blood pressure [34]. A research inquiry explored the preservation of Undulate Venus shellfish (*Paphia undulate*) through canning, utilizing three distinct treatments: canning in its raw state, canning with a smoking process, and canning after cooking. The objective was to create a nutritious and health-promoting product through these preservation methods. Results reported that there was a significant ($p < 0.05$) higher in moisture content of canned raw compared with the other two treatments of canned smoked and canned cooked *P. undulate*, and there was a significant reduction of protein content ($p < 0.05$) in two treatments of canned smoked and canned cooked compared with the canned raw. A significant difference ($p < 0.05$) in fat content was canned raw < canned smoked < canned cooked. Lightness (L*) had a slight difference between all treatments of canned shellfish *P. u*ndulate. A simultaneous decrease in both lightness (L*) and redness (a*) was observed across all treatments of canned shellfish *P. undulate*. Among the treatments, canned raw exhibited the highest values for both lightness and redness. In terms of hardness, canned smoked demonstrated the highest value, followed by canned raw, then canned cooked, and then canned cooked. A slightly significant difference ($p < 0.05$) was noticed between the three treatments in sensory properties; data showed that all panelists preferred canned cooked to raw canned and canned smoked, and the degree of canned cooked was excellent [35].

3.3 Chilling

Chilling is the method of reducing the temperature of fish or fish products to a point near the freezing temperature of ice. This cooling process extends shelf life by decelerating physical and chemical reactions, as well as inhibiting the activity of spoilage microorganisms and enzymes [36-38]. Chilled fish maintains excellent sensory qualities, making it highly appealing to consumers. Nonetheless, it faces potential microbial safety challenges within the temperature range in which it is stored, as psychotropic pathogens can thrive and multiply without causing immediate sensory changes [39]. Chilling is an effective way of reducing spoilage in fish if it is done quickly and if the fish are kept chilled and handled carefully and hygienically. Immediate chilling of fish ensures high-quality products [40-41]. The important chilling methods of fish and fish products at non-freezing temperatures are 1- Iced storage, 2- Chilled seawater (CSW) storage, 3- Chilled freshwater (CFW) storage, 4- Mechanically Refrigerated seawater (RSW) storage, and 5- Cold air storage [42]. Ice slurries, also known as flow ice [43-44]. Because of their greater heat exchange capacity, these water–ice systems may achieve temperatures below zero faster, protecting the fish from oxidation and dehydration. Furthermore, ice slurries have more spherical particles than flakes, resulting in less physical damage [45-46]. Different additions to the fish, as well as the ice slurry, have been utilized to improve the effectiveness of these ice slurries. Natural antioxidants, ozone, and organic acid combinations are examples of these substances [47].

3.4 Freezing

Considering the current value chain, freezing takes place on board vessels and after landing at the processing plant, either as freezing on board fresh fish or, more commonly, after thawing and processing (double freezing) before transport to market [48]. Alone, freezing accounts for 62% of processed foods, with India ranking as the fourth-largest exporter of seafood, predominantly in frozen form. Within the contemporary food industry, the practice of freezing has been firmly established as an effective preservation method for enhancing the shelf life of various food products [49]. Freezing slows the biological, chemical, and physical deterioration of food and the degradation of food quality (color, texture, lipid oxidation, enzymatic activity). Quality loss in frozen fish has been attributed to protein denaturation, which correlates strongly with loss of sensory quality [50]. Freezing may have a negative effect on the structural and chemical properties of muscle. The faster and more homogeneous freezing proceeds, the smaller ice crystals are made, and it causes less textural damage to muscle fiber [51]. Slow freezing can result in the formation of big ice crystals, which can destroy cell membranes and increase the risk of oxidation, texture damage, and loss of water-holding capacity. During frozen fish storage, it is very important to keep a stable temperature to prevent the growth of ice crystals [52-53]. Also, some researchers, Dawson *et al.* [54], Fatty acid (C16:1) was found to decrease in meat fat during frozen storage, while there was no decrease in polyunsaturated fatty acids (PUFA).

Pressure shift freezing or high-pressure freezing, liquid immersion freezing, cryogenic freezing, and the longer utilized air blast freezers and plate freezers are among the most recently discovered rapid freezing procedures for muscle foods. Plate freezers are ideal for common fish and goods because they guarantee optimum contact between the food and the surface. For items of diverse forms, air blast freezers are the most effective and economical technique. The items are either put in a room or transported through a tunnel with a variable-speed cold airflow [55-56]. The flow of air can be provided horizontally and vertically when the goods are moving on a belt. A mixture of belt speed, product load, and airflow parameters will determine the speed at which the product freezes. In immersion freezing, the packaged items are dipped or sprayed with a liquid freezing media such as brine, propylene glycol, or ethylene glycol [57]. This freezing technology can function at greater temperatures than plate and air blast freezers at temperatures between -6 and -20 $^{\circ}$C with the same speed but higher efficiency, thanks to direct contact with the whole product surface. The same process as immersion freezing is employed in cryogenic freezing, except the liquids are liquid nitrogen or carbon dioxide instead of water [58].

3.5 Fermentation

Fermentation is among the oldest ways of food preservation. Nowadays, this technology is used to create a wide range of food products in homes, small-scale food businesses, and major corporations. Additionally, fermentation is a cost-effective method of food preservation that is significant economically for underdeveloped nations [59]. This process uses natural microbes or antimicrobials for preservation to improve the shelf life of foods. In this process, beneficial bacterial or fermentation products are used to control and inactive the microorganism's growth [60]. In fact, carbohydrates are transformed into alcohol or organic acids utilizing yeasts or bacteria under anaerobic conditions. All of the other qualities, including flavor and texture, are created by the action of lactic acid bacteria. Products can be stored in this way all year round [61]. Fermented foods are incredibly popular all around the world as tasty, healthy, and nourishing parts of our diets. They use a wide range of components and production methods to create them on a massive scale [62].

Fish sauce is a special flavored condiment formed by the traditional fermentation of low-value fish in coastal areas. It is widely consumed and manufactured across various regions globally, with a notable prevalence in Southeast Asia. The fermentation of fish sauce involves a rich diversity of microbial flora and intricate metabolic reactions among microorganisms, including processes like lipid oxidation, carbohydrate fermentation, and protein degradation. These activities contribute to the development of flavorful compounds during the fermentation process [63]. Fermented fish and fish-derived products constitute a significant component of dietary habits globally. The widespread appeal of these items can be attributed not only to their distinctive flavor, unique texture, and high nutritional value but also to the straightforward production process, often rooted in traditional and empirically established methods, which are commonly based on empirical traditional methods [64]. Park *et* *al.* [65], physicochemical and microbiological properties changes and metabolites in Myeolchi-jet (MJ) (salted-fermented anchovy) were investigated following long-term fermentation at low(10 °C; LT-MJ) and high (30 °C; HT-MJ) temperatures and performed metabolic profiling to evaluate these alterations at the molecular level. Both fermentation temperatures showed continuous increases in amino nitrogen (AN) and total nitrogen (TN) from 15 to 480 days. As the fermentation time extended, higher levels of amino nitrogen (AN) and total nitrogen (TN) were observed in high-temperature fermented Myeolchi-jeot (HT-MJ) compared to low-temperature fermented Myeolchi-jeot (LT-MJ). This indicated increased activities of proteases or halophilic bacteria in the higher fermentation temperatures. The identified amino acids in Myeolchi-jeot included tryptophan, tyrosine, histidine, arginine, lysine, and ornithine, with their concentrations rising with prolonged fermentation. Notably, volatile basic nitrogen and histamine contents exhibited greater changes in HT-MJ compared to LT-MJ, and metabolomics analysis indicated a continuous rise in histamine levels during fermentation. The overall quality of HT-MJ was compromised in comparison to LT-MJ, suggesting that maintaining the quality and safety of fermented seafood products derived from anchovies may be achieved through low-temperature fermentation for a duration of up to one year.

3.6 Super chilling

Super chilling, alternatively referred to as partial freezing or deep chilling, is defined by the application of extremely low temperatures—falling between traditional chilling and freezing. This technique involves lowering the temperature by 1–2 °C below the initial freezing point of the food product [37,66,67]. The super chilling process converts a small amount of water (5-30%) to ice, which forms a thin layer (1-3 mm) on the food surface. And an internal ice reservoir [68-69]. Thus, the combined effect of low temperature and internal/ external ice on food production slows deteriorative processes (such as microbial activity), and for short periods, ice may not be necessary during transport or storage [37,66,68,70]. Ideally, in super chilling, a small amount of water content is transformed into ice. Therefore, there is less freeze protein and structural damage (detachments and breaks of myofibers) by ice crystals compared to frozen storage. The shelf-life of super chilled food can be one and a half to four times longer when compared to the chilling process due to the reduction of microbial and enzymatic activity [37,67,69,71].

3.7 Drying

Drying is one of the oldest, widely applied food preservation operations. It consists of the reduction in the water content, slowing down microbial or enzymatic degradation reactions and consequently extending the shelf life and preventing food spoilage [72-73]. Additionally, the food volume and weight are reduced over the drying process, leading to size reductions in food packaging, easier transportation, and storage at low cost [74-75]. On the other hand, the drying process profoundly impacts the final product's quality, which depends on the physical and biochemical changes over this process [76]. The changes in the food matrix strongly depend on factors such as drying time, temperature, and the product's water activity [76-77]. If the drying process is inappropriate or incomplete, the quality of dried food or agricultural products will not be high enough to be introduced to the market. In some cases, the loss of food taste, dark color of the final product, or moisture gradients in the dried food can occur due to the inefficient drying process [75].

So, the quality of the product obtained depends largely on the methodology used. Generally, processes that involve low temperatures (such as freeze-drying) require long drying times, so high-temperature drying techniques are more extensive, although this may compromise the quality. So, the food industry faces the challenge of achieving shorter drying times under moderate conditions and maximizing product quality [75]. Each popular drying process limits the quality and energy efficiency of the finished items. New ways have emerged to improve the drying process, such as electro-based drying methods. Electrohydrodynamic (EHD), pulsed electric field (PEF), ultrasound-assisted, and dielectric drying (microwave and radiofrequency) are all examples of drying processes that use electrical energy for pretreatment or drying [78]. Reports have shown that combined drying technologies have distinctive characteristics compared with single drying methods. Drying methods have been developed from traditional natural drying and hot air drying (HAD) to other drying methods, modern vacuum drying (VD), vacuum freeze-drying (VFD), and Vacuum microwave drying (VMD) [79]. Hot air drying (HAD) is the most common dehydration process because of its low cost and easy controllability [80]. However, HAD has limitations of long drying time and nutrient loss. Hot air drying (HAD) is an efficient drying process and convective dehydration method with high efficiency and energy-saving. Compared with other methods, HAD has the advantages of simple operation, low investment in equipment, controlled drying parameters, and fast drying rate [81], which grants uniform, stable, and repeatable properties to dried aquatic products. Microwave drying (MD) is characterized by unique dielectric heating with the advantages of rapid dehydration, energy savings, high efficiency, and penetrability. The MD endpoint is not easy to control, and the energy is distributed unevenly [82]. The VFD process involves removing water from a frozen matrix by sublimation so it can effectively preserve most of the phytochemical characteristics [83]. However, VFD is also a slow drying process, and its processing cost is typically much higher than that of VD [84]. Also, with high production costs and uneconomical energy consumption, there is a challenge to use VFD.

3.8 Frying

One of the popular and affordable methods of food preservation is frying [85]. Foods have a longer shelf life when they are fried, and the flavors are also enhanced. On the other hand, using the wrong frying oil could be harmful to the health of the consumers [86]. Standard fried foods typically have a bright color, a crisp texture, and a wonderful flavor. In reality, fried meals are unhealthy because they are high in oil, calories, and acrylamide. Innovative frying technologies must be created in order to limit oil absorption during the frying process and produce healthier fried foods with less oil [87]. This method is the simplest and fastest method of processing fish, such as Mackerel. As one of the oldest methods of food preparation, it offers advantages such as ease, speed, and affordability [88]. Fried meals are the main option in our diets today. Customers of all ages favor them because of their good nutritional content and distinctive organoleptic qualities, which include flavor, color, texture, and scent. A number of chemical and physical changes occur during the frying process, including the gelatinization of starches, denaturation of proteins, water evaporation, and the development of the crispy fried crust. It can eliminate bacteria, deactivate enzymes, and lessen food's capacity to retain water [89].

Negara *et al.* [90], the research focused on studying the impact of frying processes on the nutritional and sensory characteristics of different mackerel products. It was found that the nutritional, physicochemical, and sensory properties of fried Mackerel were influenced by the frying methods used. Deep frying resulted in the oxidation of lipids and degradation of proteins, whereas air frying increased the overall acceptance score. Frying also had positive effects, such as reducing per fluorinated compounds (PFCs), eliminating some toxins, lowering the trypsin inhibitor (TI), and improving the sensory parameters of Mackerel with batter, marinade, and spice treatment. The nutritional and sensory parameters of minced mackerel products were preserved after frying. Interestingly, vacuum frying resulted in lower oxidation and maintenance of nutritional and sensory parameters of fried Mackerel (with or without treatment) and minced mackerel products. In another study, the effect of frying conditions on the quality attributes and flavor characteristics of self-heating fried Spanish Mackerel was investigated. The highest quality of fish fillets was achieved by frying at 160°C with 65% moisture content. The results of the study could serve as a theoretical basis for improving the food quality of self-heated fish products. [91].

3.9 Smoking

Smoking is a widely embraced method of processing fish in Europe, Africa, and the Far East, where smoked fish and meat are savored as culinary delights. This ancient preservation technique incorporates the impacts of salting, drying, heating, and smoking to enhance the flavor and shelf life of the fish. The smoking process involves exposing the fish to fire [92]. Smoked seafood includes two groups separated based on the temperature of processing: cold-smoked or hot-smoked. Cold-smoked products are processed at temperatures below 33◦C, classifying them as mildly processed [93]. A traditional cold smoking process involves salting, drying, and finally, smoking. The primary purpose of salting is to lower the water activity (aw) to inhibit spoilage mechanisms [94], and it can be done either by dry, brine, or injection salting. An additional decrease in aw takes place during the drying and smoking steps [95]. Cold-smoked seafood is very sensitive to deterioration, and based on sensory evaluations, it has a limited shelf life of 3–5 weeks when stored at 4◦C [93,96,97]. The spoilage of cold smoked products is mainly ascribed to off-flavors resulting from microbial growth and metabolism [96,98].

Analyses have identified more than 200 different substances to be released during smoking [99], not all of which are beneficial. Especially polyaromatic hydrocarbon (PAH) compounds such as benzo (a) pyrene are of concern due to their link with cancer development. The concern in relation to PAHs resulting from pyrolysis is one reason for the development of PCS. Smoke condensates are usually obtained from wood smoke produced by smoldering wood chips or sawdust, followed by refining and rinsing steps to remove unwanted compounds [100-101]. Liquid smoke or purified condensed smoke (PCS) is one of the methods which is becoming popular nowadays. Liquid smoke is easy to apply and easy to control [102]. For the use of liquid smoke, simple equipment is required, and the concentration of smoke compounds is controlled. The best use is from 1% to 5%. Fish meat has very little connective tissue. It is a highly natural cathepsin enzyme, so it is very easy to be digested by that autolysis enzyme, which makes the meat and makes it a good source for the growth of microorganisms − pathogenic bacteria and histamine-forming bacteria. Liquid smoke has not only bactericidal but also bacteriostatic effects, and together, they act as a synergic preservative. It can inhibit all pathogenic bacteria (i.e., *Escherichia coli*, *Listeria monocytogenes*, *Staphylococcus aureus*). As sprats belong to the Clupeidae family of fish, there is naturally occurring histidine in fish flesh. The application of liquid smoke lowers pH (5.56−5.58), which is caused by organic acids of condensation in the smoking process [103]. Also, the use of liquid smoke produces high-quality smoked fish products with less moisture content, lower salt, and microbiological parameters that are better compared to traditionally smoked fish products. A study examined the effect of vacuum packaging on fish balls prepared from *Capoeta trutta* with different concentrations of liquid smoke. The study concluded that incorporating liquid smoke had a favorable impact on the sensory taste of the product. Nevertheless, the research revealed that this addition did not have a noteworthy influence on the microbiological and chemical quality of the product [104]. In a study, the optimization of the conditions for utilizing liquid smoke in the production and preservation of innovative fish products. The findings revealed that a solution containing lemon extract (0.75%), acetic acid (0.5%), NaCl (2%), and liquid smoke (0.002%) could be effectively sprayed on sea bream and sea bass fillets. These treated fillets, when vacuum-packed and stored at four °C for a minimum of two weeks, exhibited low cell loads of spoilage bacteria throughout the storage period. After 14 days, the smoked fillets demonstrated a total viable count and psychotropic count of approximately 5 log CFU/g, Pseudomonadaceae at about 6 logs CFU/g, and Enterobacteriaceae at cell loads ranging from 2 to 3 log CFU/g. Notably, other microbial groups were absent, and no pathogens were detected [105].

3.10 Pickling/Marinating

Pickling or marinating is another ancient TFPT where the preservation actions are owed by the combined effects of salt and vinegar/acetic acid [51,106-108]. The presence of vinegar/acetic acid lowers the pH of the products, thereby retarding the growth of spoilage-causing microorganisms [51]. Furthermore, these compounds have inhibitory effects on enzymes, and bacteria are higher at greater concentrations [106,108]. However, generally, pickled/marinated products have a short shelf life and are thereby considered semi-preserved unless stored in a chilled environment, which can last for several months [51,106]. In the Philippines, the most common pickled/marinated seafood products are pickled anchovies, marinated mussels, and marinated fried sardines or Mackerel. In Turkey, pickling/marinating is classified into cold, cooked, and deep-fried marinades. Despite the difference in terms of pickling types, it is noted based on the method that most pickling techniques are common and similar in both countries. Pickled anchovies and marinated mussels in the Philippines are similar to the finished products of cold marinades in Turkey. Additionally, both countries have in common preparing marinated fried fish or deep-fried marinades. Filipinos do not normally cook pickled products, whereas Turkish tend to have another way of preparing marinated fish, which is being cooked (deep-fried) to extend the shelf-life [109].

3.11 Pasteurization

Pasteurization is a common method used to disinfect food products with the intention of eliminating pathogenic bacteria and reducing enzymatic activity. "It also aids in extending the shelf life of products," albeit for a limited period. Traditional pasteurization methods utilize continuous heat-transfer mechanisms to eliminate microorganisms in liquid foods, such as milk and juices. However, the traditional deactivation of organisms is conducted with thermal processing that can alter the flavor, taste, color, and nutritional values of the product. Therefore, the food industry and consumers are interested in developing new methods that can maintain the taste and color properties of products, preserve their nutritional value during food processes, and be more energy-efficient than basic thermal processes [110]. Da Silva *et al.* [111], evaluated the oyster marinating (*Crassostrea gasar*) and pasteurization process in vacuum packaging during storage. Microbiological, physicochemical, and sensory analyses were carried out on the oysters and the optimized product. In the vacuum-packed product, under refrigeration, pH, water activity (aw), total volatile bases (N-TVB), and texture analyses were performed every seven days for 35 days. Oysters have high protein, mineral, and amino acid content and low lipid content. The plan involved 23 and 221 hours, 2.5% acetic acid, 1% NaCl, and pasteurization at 62°C/2 min. The sensory analysis indicated acceptability levels exceeding 80%. Marinated oysters retained their suitability for consumption for 21 days, representing a viable alternative to both extend the shelf life and enhance the value of the product. Table 1 shows the effect of some preservation methods on the shelf life of fish and seafood products.

4. Modern techniques for Seafood products preservation

Nowadays, there is ongoing research on new technologies and conservation methodologies that can minimize the impact on the nutritional value of food products [118]. In this regard, we will briefly discuss modern techniques for preserving seafood products.

4.1 Microwave processing

Microwaves are a form of electromagnetic radiation with wavelengths ranging from one millimeter to one meter, making them a valid alternative to conventional heating methods. In the literature on the subject, microwave heating is often referred to as dielectric heating because waves are absorbed by materials having dielectric properties [119-120]. Such materials, also called dielectrics, have a relatively high specific resistance and low electrical conductivity. Moreover, the molecules or atoms comprising the dielectric (such as agri-food products) exhibit dipole movement. Microwave technology is a widely used technology within the food industry. It is applied for cooking, drying, thawing, pasteurization, or sterilization of food products, and most households contain a small microwave [82,121-123].

Table 1. The effect of different preservation strategies on the shelf life of seafood products.

Preservation techniques	Procedure explanation	Results	Reference
Canning	Evaluated impact of frozen storage, canning process, and packing medium on fatty acid composition of canned Atlantic mackerel (*Scomber scombrus*).	Significant decrease ($p < 0.05$) in saturated fatty acid (STFA) levels post-canning. Increase ($p < 0.05$) in polyunsaturated fatty acid (PUFA) and total omega-3 fatty acid levels. Higher values of PUFA/STFA and omega-3/omega-6 ratio observed. Impact of packing medium: Sunflower oil had high C18:2 omega-6, resulting in elevated PUFA and PUFA/STFA values but lower omega-3/omega-6 ratios compared to other media.	[112]
Cold smoking	Investigated effectiveness of combining cold smoking with natural antioxidants (SA) on farmed Meagre (*Argyrosomus regius*) fillets.	Lower total volatile basic nitrogen (TVB-N) levels in smoked meagre fillets with SA treatment. Reduction in lipid peroxidation (malondialdehyde levels) observed in SA treatment group compared to control.	[113]
Ultrasound-assisted	Evaluated effects of Chito oligosaccharides (COS) and ultrasound-assisted COS coatings on quality and microbial composition of refrigerated grass carp fillets (*Ctenopharyngodon idellus*).	Both coatings reduced spoilage organisms, with ultrasound-assisted coating (COS-UA) outperforming standard COS coating, extending shelf life by 2 days.	[114]
High hydrostatic pressure (HHP)	Investigated optimal HHP conditions for extending freshness of dark and white muscle fish fillets under different packaging methods.	HHP treatments extended microbial and sensory shelf life of fillets, with minimal impact on lipid oxidation and color changes.	[115]
Modified atmosphere packaging (MAP)	Examined effect of MAP on quality and nutritional stability of frozen oyster meat during storage.	MAP with high nitrogen content-maintained freshness and quality of oyster meat, reducing lipid oxidation and preserving amino acid composition.	[116]
Nano-encapsulation	Assessed effects of nano chitosan coatings with encapsulated essential oil on properties of sardine fillet samples.	Coatings prevented microbial growth and chemical spoilage, with encapsulated essential oil displaying highest sensory properties and extended shelf life.	[117]

Microwave drying also is used to remove moisture from fish and fishery products. Microwave combined with other drying methods, such as air drying, vacuum drying, or freeze drying, gave better drying characteristics compared to their respective drying methods or microwave drying alone [82]. In contrast to traditional methods, microwave processing offers a more uniform, axial, cellular, and homogeneous structure in the produced parts. Its application extends beyond the food processing industry to various sectors within the manufacturing industry. While alternative processes such as electric furnaces and ohmic resistance heating exist, the unique properties of microwaves, such as penetration radiation, controllable electric field distribution, quality improvement in the final product, energy and time savings, rapid heating, selective heat application, self-limiting reactions, and a reduced environmental impact, have led to extensive use in industrial and material processing applications [124]. Nguyen *et al.* [125], heating surimi products using microwave combined with steam methods investigated. The gel strength experienced a noticeable enhancement through a synergistic approach involving microwave treatment at 35 kW and steam heating, leading to a denser network structure, as revealed by scanning electron microscopy. Furthermore, the novel heating method employing moderate microwave power received the highest score in the comprehensive sensory evaluation, particularly after the frying process.

4.2 Ultrasound

Ultrasound is a non-thermal food processing technique that can replace thermal food processing. It involves using sound waves of varying frequencies, which are too high for humans to hear (above 16 KHz), to increase quality and reduce processing time and costs [126]. It can be used for a variety of food processing procedures, such as preservation, texture tenderization, extraction, emulsification, freezing, thawing, and microbial inactivation [127-128]. The production of cavitation bubbles, shear disturbance, microstreaming and free radicals during ultrasound treatment can destroy the cell walls of microorganisms, leading to their decay [129-130]. It can be used alone or in combination with other techniques to increase the safety of microbiological and sensory qualities of fish products [131-133]. Additionally, ultrasound-assisted extraction can improve extraction time, yield, and efficiency by reducing particle size, making it a popular choice for the extraction of valuable bioactive compounds from seafood by-products [134].

4.3 Pulsed Electric Field (PEF)

Pulsed Electric Field (PEF) processing is a non-thermal food preservation technique primarily employed for the inactivation of microbes. It is also utilized in extraction, drying, and various mass transfer processes [135-136]. PEF processing can extend food shelf-life, maintain high nutritional value, and acceptable sensory properties [137]. It involves using short-duration pulses (1–100 s) in strong electric fields (0.3–4 kV/cm) and is becoming more popular in seafood treatments and preservation [138]. PEF (pulsed electric field) treatment offers many advantages over heat treatments. It is capable of removing pathogens from unprocessed food products without affecting their nutrient content and taste. PEF is commonly used for the treatment of liquid and semi-solid food mixtures, as well as for the extraction of food constituents [139]. This treatment can also inactivate parasites and reduce the moisture content of tissue, which minimizes the formation of ice crystals and freeze damage in frozen products. PEF can enhance the extraction of nutritional food components from fish processing by-products [140] while preserving the physicochemical properties and achieving desirable organoleptic parameters and nutrient and vitamin contents of the final product [141-142]. PEF treatment has the added benefits of rendering fish flesh more porous and enhancing water-holding capacity. Moreover, it can serve as a valuable pretreatment for fish drying, as demonstrated by Klonowski *et al.* [135], in 2006. In addition to these advantages, PEF proves to be a rapid and efficient method for extracting chondroitin sulfate (ChS) from fish bones. This not only minimizes waste but also reduces the potential for pollution associated with chondroitin extraction processes [143].

4.4 Irradiation

Irradiation is a cold pasteurization process, and foods remain in the same physical state after irradiation as before [144]. It has proven to be a successful preservation technology because of its effectiveness in the inactivation of bacteria and pathogens with little effect on food nutrition and quality [145]. In addition to its primary purpose, it can also eliminate pests from spices, lengthen the lifespan of fresh produce, and regulate the growth of tubers and bulbs, such as potatoes and onions. Therefore, it can be employed as a preservation technique for food. This method is entirely safe and has received approval from the U.S. Food and Drug Administration (FDA) as well as more than 60 other national food control organizations for various types of foods [146]. Radiation sources used for food preservation include gamma rays, x-rays, ultraviolet, and accelerated E-beams, and doses of 0.1–10 kGy are acceptable for most categories of food [147-148]. In fact, irradiation has become a useful alternative for maintaining the quality and shelf-life extension of fishery products. As reviewed by Arvanitoyannis *et al.* [149], a large number of early studies regarding the impacts of irradiation on fish and seafood shelf life have shown that the optimum doses for fishery products were between 1 and 5 kGy. The microbial shelf life of irradiated products was 1–2 times that of the control samples. Mahmoud *et al.* [150], indicated that a low dose of X-ray irradiation (0.6 KGy) significantly reduced microbial growth in raw tuna fillets stored at 5, 10, and 25 _C, with a maximum reduction of TVC >7 log CFU/g. Krizek *et al.* [145], investigated the effect of radiation on biogenic amines of refrigerated trout fillets. They found that the increased dose from 0 to 2 kGy reduced the accumulation of putrescine, cadaverine, and tyramine and maintained the organoleptic properties. However, irradiation treatments will induce lipid oxidation, as evidenced by higher TBARS values, which resulted in off-odors and flavors during storage [151-152].

4.5 High hydrostatic pressure (HHP)

High Hydrostatic Pressure (HHP) is a non-thermal pasteurization technology, well-suited for liquid foods and highly perishable food products. This method involves subjecting foods to very high pressures (vessel pressure ranging from 300 to 800 MPa) for a brief duration, effectively eliminating microorganisms. This technology is particularly applicable in modern food processing industries where reliance on high-temperature processing is unnecessary for food preservation [153]. HPP-treated food must be packed and contain water, then closed in a chamber where the pressure is gradually increased. It is closed in a chamber where the pressure is increased. Depending on the type of food, the process lasts from several seconds to 20 minutes [154-155]. A study was conducted to review the impact of HPP treatments on major vegetative bacteria in specific foods. The results showed that HPP is a safe pasteurization technology that is capable of reducing major food bacterial pathogens by at least 5 logs. (*E. coli, S. enteritidis, L. monocytogenes, Vibrio, and Staphylococcus aureus*), without the application of heat [156]. A study was conducted to investigate the effects of high hydrostatic pressure (HHP) treatment on the shell-loosening properties of crayfish (*Procambarus clarkii*). The study also examined the changes in crayfish peel ability, quality, microstructure, and protein fluorescent features. The researchers established new methods to measure the peeling performance of crayfish. These methods included peel ability and meat yield rate (MYR). The normalization of peel ability and MYR was verified using different weights of crayfish tails and different treatments. The results showed that all HHP treatments reduced crayfish peeling work and increased MYR. The HHP treatment improved the texture and color of crayfish and increased the shell-loosening gap. The 200 MPa treatment exhibited the best results, with lower peeling work, higher MYR, and an expansion of the shell-loosening gap up to 573.8 μm. At the same time, the 200 MPa treatment maintained crayfish quality [157].

4.6 Micro fluidization

Microfluidizer is a non-thermal technology that produces stable emulsions by transforming two immiscible liquids with high pressure of up to 200 MPa. It has diverse applications in industries like cosmetics, pharmaceuticals, food processing, and agriculture, as it can solve emulsion instability problems such as sedimentation, creaming, or turbidity in beverages [158-159]. Microfluidizers can also modify protein, starch, and fiber structures, as well as deactivate enzymes and potential pathogens [160-161]. Despite these advantages, its industrial application is rare, and research on micro fluidization technology still needs to be expanded to the laboratory stage, even in the food industry [162]. Huang *et al.* [163]. conducted a comprehensive study comparing two emulsification techniques, high-pressure homogenization (HPH) and micro fluidization (MF), on krill oil emulsification. The study covered various aspects, including particle size characterization, structural evaluation, oxidative stability during storage, bio accessibility measurement, and in vitro simulated digestion analysis. Emulsions produced through micro fluidization displayed several notable advantages compared to those generated by high-pressure homogenization. Notably, micro fluidization resulted in smaller and more uniformly distributed particles, in contrast to the less uniform particles produced by high-pressure homogenization. Additionally, emulsions prepared through micro fluidization exhibited significantly enhanced oxidative stability during storage, with astaxanthin degradation occurring at a substantially lower rate (38.11% for HPH compared to 89.44% for MF).

4.7 Usage of natural preservatives

A variety of factors contribute to the onset of oxidative stress, marked by an imbalance between free radicals and the antioxidant defense system within the human body. Individuals can significantly mitigate the effects of free radicals by avoiding exposure to these contributing factors [164]. New approaches to reducing synthetic preservatives in the preservation of foods draw the attention of plant-derived bioactive compounds, especially for application in foods highly susceptible to spoilage, such as fish products [165]. For example, the natural antioxidant compounds extracted from marine sources can absorb free radicals and help the body's defense system in this matter [166]. In a research, it has been determined that aqueous and ethanolic extracts of *Dorema aucheri*, *Zataria multiflora Boiss*, and *Ferulago angulate* can be used as a potential source of antibacterial compounds for food and pharmaceutical industries [167]. On the other hand, the oxidative stability of oils, fats, and fatty food products can be affected by many factors, such as oxygen, light, heat, metal ions, and enzymes used. Finally, it brings about oxidative corruption. According to this, it would be expected that *D. aucheri* extracts, as an antioxidant, can be used in the food industry in the maintenance of fish oil [168]. In another study, the extract obtained from the leaf of the water hyacinth (*Eichhornia crassipes*) aquatic plant had higher antioxidant properties than the stem and root. So, water hyacinth can serve as a valuable source of natural antioxidants, which plays a crucial role in neutralizing free radicals. Consequently, it proves beneficial for human health and finds application in the production of nutraceutical compounds. As a result, it is suggested that instead of destroying the water hyacinth from the wetland ecosystem with different methods, it should be turned into value-added products with different processing methods [169]. Hodhodi *et al.* [170], The efficacy of Sargassum angustifolium brown algae extract, particularly rich in antioxidant compounds like phlorotannin, was demonstrated as an excellent choice for extraction purposes, catering to both dietary and medicinal applications.

In a study conducted by Babakhani *et al.* [171] in 2016, the antioxidative effects of seaweed extracts were explored in the chilled storage of minced Atlantic mackerel (*Scomber scombrus*). The antioxidant activity of absolute ethanol, 50% ethanol, and water extracts from two seaweed species, namely *Fucus serratus* and *Polysiphonia fucoides*, was assessed for their ability to mitigate lipid and protein oxidation in minced mackerel. The findings highlighted that the 50% ethanolic extracts of *P. fucoides* could serve as a promising natural source of antioxidants. These extracts demonstrated significant efficacy in retarding lipid and protein oxidation, leading to lower levels of peroxide value, volatiles, and carbonyl compounds. Moreover, they offered protection against the loss of α-tocopherol and tryptophan residues in the minced mackerel. In another study, the common kilka (*Clupeonella cultriventiris*) was dipped with solutions containing 1.5% thyme essential oil (*Zataria multiflora*) and ascorbic acid separately. The amount of pH, TVB-N, PV, TBA, and FFA in the treatments containing thyme essential oil and ascorbic acid was significantly lower than those of the control (P<0/05). The results showed that the use of natural antioxidants, thyme essential oil, and ascorbic acid could prevent the oxidation of frozen kilka (P<0/05) and also Increase the shelf-life of frozen Kilka. Of the treatments investigated in this study, the treatment containing 1.5% ascorbic acid showed the best result [172].

Brown seaweeds play an important role in food industries. Seaweed's cell wall and other components in the cellular matrix are made up of mostly structural polysaccharides, which include the hydrocolloids (alginates from brown seaweeds and carrageenan and agar from red seaweeds) that are in high demand in the food industry [173]. The data obtained by a study suggested that alginate coating with *Carum copticum* essential oil (CEO) in the form of nanoparticles can enhance rainbow trout burgers' shelf life stored at four °C [174]. Minced shrimp products have gradually become popular among consumers due to their convenient consumption. The changes in physiochemical properties occurred because of low-temperature storage. To investigate the cryoprotective effects of carrageenan on the pre-prepared gel of minced shrimp (*Litopenaeus vannamei*) gel during frozen storage, the variation trends in texture properties of shrimp heated gel (made by chopping, pre-preparing, freezing, and heating) and rheological properties of pre-prepared shrimp gel (made by chopping, pre-preparing, freezing, and thawing) with different carrageenan additions compared to commercial cryoprotectant were analyzed. Results showed that carrageenan could significantly improve braking force, gel strength of heated gels, and storage modulus and loss modulus of pre-prepared gels [175]. A study was conducted where fish gelatin and chitosan-based films were created and loaded with nano emulsified α-tocopherol (α-TP) and thyme essential oil (TEO), individually and in combination. The objective was to evaluate the effectiveness of these films in inhibiting fish quality deterioration. The researchers found that the combination of nano emulsified α-TP and TEO was effective in extending the quality of golden pomfret fish (*Trachinotus blochii*). The utilization of biodegradable active films extended the shelf life of the fish to 15 days, ensuring that the Total Volatile Basic Nitrogen (TVB-N) values remained below the rejection limit. This reaffirmed the effectiveness of these environmentally friendly films in significantly slowing down the deterioration of fish quality [176]. Hwang *et al.* [177], investigated the antioxidant, antimicrobial, and anti-atopic dermatitis (AD) effects of a novel peptide (CP) derived from a *Chromis notata* by-product hydrolysate. The findings highlighted the potential of CP as a therapeutic agent for Atopic Dermatitis and suggested a novel application of this *C. notata* by-product in the fish processing industry.

4.8 Packaging

Packaging conserves food products against physical, chemical, and microbiological damage. Non-biodegradable packaging derived from synthetic polymers can pose adverse effects on human and ecosystem health, contributing to a global environmental challenge that is of increasing concern in today's context. Hence, the usage of biodegradable biopolymers as a proper alternative for non-biodegradable packages has been widely addressed in recent years. Several compounds of aquatic proteins and polysaccharides, including collagen, gelatin, chitin, chitosan, alginate, agar, and carrageenan, are economical, available, and biodegradable biopolymers have abundant applications to be utilized as food product packages [178].

Chitosan and gelatine are recognized for their diverse bioactive properties, making them well-suited for both independent and collaborative applications in preservation. The utilization of chitosan and gelatine films involves incorporating additional materials, such as antimicrobial and antioxidant agents, to create active packaging with enhanced characteristics. The resultant active film, derived from the combination of chitosan and gelatine, demonstrates the ability to deactivate microorganisms and inhibit oxidative activity [179]. The results of a study showed that the use of polyphosphate as an additive, along with vacuum packaging and storage at -18°C for six months, was effective in maintaining the quality of rainbow trout fillets [180]. A film made of chitosan (CS) was created by adding nanosized TiO_2 and red apple pomace extract (APE) to it. The inclusion of TiO_2 nanoparticles in CS-APE films resulted in sensitive color changes, which were successfully used as an indicator to monitor the freshness of salmon fillets. Therefore, the development of CS-APE-TiO_2 film offers a new solution to transform red apple pomace into an active and multifunctional food packaging material that possesses considerable mechanical, antibacterial, antioxidant, and pH-responsive color-changing properties [181]. Figure 2 shows these changes.

4.8.1 Modified atmosphere packaging (MAP)

Modified Atmosphere Packaging (MAP) stands as a widely adopted technique for the preservation of seafood products [182]. This method employs high-barrier packaging materials to encase food items, with a controlled mixture of O_2, CO_2, and N_2 gases injected into the packaging material. The primary objectives of this process include inhibiting microbial growth [183], reducing enzymatic reactions, and slowing down the rate of lipid oxidation [184].

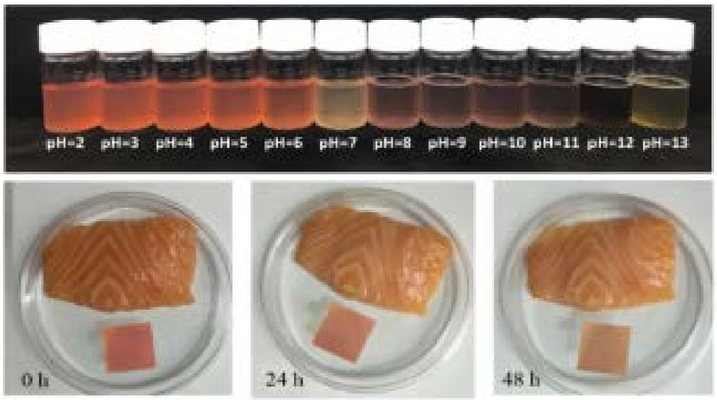

Fig 2. Color variation in pH buffer solution and color changes of film during storage of salmon [181].

MAP has demonstrated significant effectiveness in decreasing the growth rate of pH, Total Volatile Base Nitrogen (TVB-N), and Thiobarbituric Acid Reactive Substances (TBAR) values, thereby extending the shelf life of seafood products such as bream blocks [182]. Similar positive outcomes were reported in a study focused on rainbow trout fillets [185]. Storage temperature can directly affect the deterioration rate of aquatic products, and the combination of MAP and super chilling can significantly improve product quality [186]. Some researchers have studied the preservation effect of MAP (60% CO_2/40% N_2) on fresh Atlantic salmon fillets at −2 °C and 4 °C. The quality of MAP salmon fillets deteriorated slowly during super-chilling storage, but the combination of the two methods could effectively maintain the quality of salmon fillets for 24 days [187]. It was also claimed that APC and thermophilic bacteria were lower during storage at −0.7 °C than at four °C in catfish, while TVB-N and TMA proved that the quality of MAP catfish could be better maintained at −0.7 °C [188]. Pre-cooling conditions, sales environment, and packaging materials mainly determine the packaging cost of MAP products. The first two are one-time factory investments, and the cost is determined according to scale. Packaging materials mainly have gas and packaging bags, etc. According to a rough calculation, the product packaging cost price is approximately 0.071–0.092 EURO, more than ordinary air packaging, and the vacuum packaging cost price is slightly higher. However, gas-packaged products' shelf life and fresh quality are better, so the sales price is higher than ordinary packaging but greatly enhances the market competitiveness of the product [189]. Jiang *et al.* [190], the influence of hydrogen-based modified atmosphere packaging (MAP) on the preservation of dried shrimp was assessed during accelerated storage. Dried shrimp was stored at 45 °C and 85% relative humidity for eight days and simultaneously treated with H2 (0.03%, 0.1%, and 1%) compared to air control. H_2 MAP maintained the initial sensory qualities of dried shrimp, including color and odor. The rising trends in lipid oxidation and total volatile base nitrogen (TVB-N) content were mitigated by the presence of hydrogen (H_2). Non-targeted metabolomics results indicated a significant downregulation in purine metabolism, observed in both positive and negative ion modes, under 0.1% H_2 modified atmosphere packaging (MAP) on the eighth day. This downregulation was positively correlated with reduced levels of hypoxanthine, guanosine, and inosine. Therefore, H_2 MAP has the potential to delay the deterioration of dried shrimp during accelerated storage.

4.8.2 Active Packaging (AP)

Nowadays, the strong increase in product consumption, the purchase of products on online platforms, and the requirements for greater safety and food protection are concerns for the food and packaging industries. Active packaging brings about huge advances in the extension of product shelf life, food degradation, and loss reduction [191]. The principle of Active Packaging (AP) involves incorporating active compounds into the packaging material or container to perform specific functions such as antioxidant, antimicrobial, oxygen absorption, and carbon dioxide absorption. This results in an increased product quality and shelf life [192-193]. The development and characterization of active packaging nanofiber mats based on gelatin-sodium alginate containing probiotic microorganisms (*Lactobacillus acidophilus, Limosilactobacillus reuteri*, *Lacticaseibacillus case* and *Lacticaseibacillus rhamnosus*) to improve the shelf life and safety quality of silver carp fillets, In an effort to enhance the shelf life and safety quality of silver carp fillets, a treatment method was employed, resulting in improved bacterial, chemical, and sensory properties of the treated samples when compared to the unpackaged samples over the entire study period In addition, gelatin-sodium alginate nanofibers were found to be a suitable platform for the protection of living probiotics. They presented an alternative procedure for retarding the growth of food-borne pathogens and extending the shelf life of fresh carp fillets under refrigerated storage conditions [194].

4.8.3 Intelligent Packaging (IP)

Smart packaging (SP), also known as intelligent packaging (IP), is responsive to external stimuli such as moisture, light, oxygen, heat, pH, and bacterial growth [195]. Smart packaging (SP) introduces packaging technologies that incorporate a sensing system employed to package foods, medications, and a variety of other items. Active packaging is utilized to enhance product and consumer safety by extending shelf life, monitoring freshness, and providing quality information. The incorporation of an active component within a package with the aim of preserving or extending the product's quality and shelf life is referred to as active packaging. This innovative packaging approach not only helps maintain product quality but also enables the monitoring of the packed food's state during transportation and storage, providing valuable information on the product's overall quality [196]. Starch and agar-based color-indicator films integrated with shikonin extracted from *Lithospermum erythrorhizon*, when used in smart packaging of shrimp, the film shows a distinctive color change from reddish-pink to blue-violet, indicating the onset of shrimp spoilage [197]. Rostamzad *et al.'s* [198] study focused on the production and assessment of a smart biodegradable film based on carrageenan for packaging fish fillets. The biodegradable films, made from carrageenan and red cabbage extract (*Brassica oleraceae*), were examined for their effectiveness. Test results revealed that the carrageenan film containing red cabbage extract initially appeared colorless, but over time, it sustained and enhanced the detection of spoilage in packed fish. The film exhibited changes in Total Volatile Base Nitrogen (TVB-N) and pH values beyond permissible limits, and the color of the film turned dark, serving as an indicator to consumers about the quality and freshness of the packed fish. This study suggests the potential use of carrageenan film containing cabbage extract as an indicator for detecting spoilage in fish and other high-value meat products.

4.8.4 Vacuum packaging (VP)

VP is the first commercially developed form of MAP and consists of packing a product in a film with low O_2 permeability and sealing it after air evacuation [199]. VP improves the shelf life of food products by placing them in an airtight package, sucking the air, and sealing the package. The level of O_2 in the package decreases by removing air from the package, which prevents the growth of aerobic microorganisms and their deteriorative effects. The lack of O_2 also reduces the amount of spoilage due to oxidation. Removing the air that surrounds food inhibits the growth of bacteria, mold, and yeast because these and other spoilage microorganisms require O_2 to grow. Reducing the amount of O_2 to less than 0.1% is an indication of good vacuuming [200]. However, there is the risk of anaerobic microorganisms in vacuum packaging. This risk can be eliminated if vacuum packaging is combined with cooling or freezing [201].

In a previous study, the effect of vacuum packaging on oxidative spoilage indices in fish (*Lethrinus atkinsoni*) fillets frozen at −18°C for 0, 20, and 40 days was scrutinized. The fillets were divided into two groups: the first group was packed in polyethylene bags under vacuum, and the other group was considered as a treatment control and kept in a freezer at −18°C. The results showed that progress spoilage indices in samples packed in vacuum for 0, 20, and 40 days were significantly lower than those in the control treatment ($p < 0.05$). The peroxide, thiobarbituric acid, and free fatty acid contents decreased in frozen samples at 20 and 40 days in vacuum, but the pH value increased. The results showed that packed samples in freezing and vacuum conditions were a suitable method for low lipid oxidation in *L. Atkinson* fillets, which led to the extended shelf life of the samples. It is concluded that packaging in a vacuum combined with freezing treatment prevails over freezing in individuals by an acceptable long-term fish shelf preservation [202]. Anselm *et al.* [203] investigated the effects of vacuum packaging and chilling storage on the microbiological changes of the superheated steam-dried sardines in a study. Sardines collected from Mafia Island were air-dried and stored at room temperature (AR), air-dried, stored at chilling temperature (AC), vacuum-packed, stored at room temperature (VR), vacuum-packed, and stored at chilling temperature (VC) for 49 days. After drying, the total viable bacterial counts (TVBC) and total yeast and mold counts (TYMC) both decreased from the initial values of 9.14 (TVBC) and 2 (TYMC) log CFU/g in the fresh samples to 0.00 log CFU/g. The AR samples had the highest microbial growth during storage, whereas the VC samples had the lowest growth. The AR treatment was rejected within 21 days, whereas the AC, VR, and VC treatments prolonged the shelf life of the sardines throughout the storage period. Rezaeifar *et al.* [204] investigated the antioxidant and antibacterial characteristics of chitosan (CH) coated with lemon verbena essential oil (LVEO) and extract (LVE) on the quality of rainbow trout (*Oncorhynchus mykiss*) packed by vacuum packaging at 4°C. The following samples were evaluated: Control, VP, CH, CH-LVE 2%, CH-LVEO 1%, and CH-LVE 1%-LVEO 0.5% for 16 days at 3-day intervals. All of the samples significantly reduced psychrotrophic bacteria, total viable counts, Enterobacteriaceae, and H2S-producing bacteria as compared with the control group during keeping time. Thiobarbituric acid-reactive substance, peroxide value, total volatile basic nitrogen, and pH values were lower in all samples than in the control. CH combined with LVE and LVEO had an agreeable effect on sensory characteristics. Samples containing CH-LVE 1%–sensory assessors often prioritized LVEO 0.5%.

4.8.5 Retort pouches (RP)

Thermal retort processing is a widely used and cost-effective method of food preservation to address the challenge posed by Clostridium botulinum for the commercial sterility of a food product to obtain microbiologically safe and stable products by heating. Additionally, it will delve into the adaptability of retort equipment, including its ability to operate in stationary and various agitation states, as well as its flexibility in processing speed for both single batch and continuous operations [205]. The advantages of the RP over the tin can/glass bottle include reportable flexible containers, pouch form, less expensive flexible pouch, excellent mechanical and heat transfer properties, a high gas and moisture barrier, retention of product nutrients and sensory attributes, reduced preparation time for serving the product, easy opening of the pouch, less energy required to manufacture pouches, reduction in storage space for empty RP for processors, and minimum product–container interaction, without the risk of external corrosion [206]. A study was conducted to develop ready-to-eat, thermally processed GIFT fish in the masala (genetically improved farmed tilapia) packed in flexible retortable pouches. The GIFT fish were thermally processed at different F0 values (6.39, 7.57, and 8.19 min) in an over-pressure retort using the Eval Flex thermal validation and sterilization monitoring system to record the time–temperature, F0 value, and cooking value. The prepared GIFT in Masala underwent various quality tests, such as physical, textural, biochemical, microbial, and sensory assessments, in comparison with different F0 values. Based on the evaluation of commercial sterility, sensory characteristics, color, and texture profile, it was found that an F0 value of 8.19 min at 121.1°C with a cook value of 64.74 min and a total process time of 35.16 minutes was satisfactory for the development of GIFT fish masala packed in retort pouches [207].

4.9 The use of nanotechnology in Seafood product preservation

Nanotechnology is widely used in various technical processes, such as the development of new materials and the improvement of food safety and security. Nanomaterials are utilized to enhance the protective effects of food and to detect microbial contamination, hazardous chemicals, and pesticides. Nanosensors are used to identify pathogens and allergens present in food. Nanoencapsulation, on the other hand, is used to deliver bioactive compounds, increase food bioavailability, and extend the shelf life of food [208]. A study conducted by Zhao *et al.* [209] showed that the shelf life of red sea bream (*Pagrus major*) fillets wrapped in edible composite films based on chitosan nanoparticles was extended to 6-8 days. The plant essential oil compound anthocyanidin edible film had the most effective preservation effect for fillets, while the anthocyanidin compound chitosan nanoparticle edible film provided the best protection.

Another study was conducted to investigate the effects of nano emulsions, prepared with varying concentrations of olive oil, on the sensory, chemical, and microbiological quality of rainbow trout fillets. The study showed that the shelf life of rainbow trout fillets was extended to 10, 12, 14, and 16 days for the control, Tween 80 group, 15% olive oil nano emulsion group (O15), and 30% (O30) and 45% olive oil nano emulsion groups (O45), respectively. The use of olive oil suppressed fish smell, improved organoleptic quality, extended shelf life, had a positive effect on biochemical parameters, and inhibited bacterial growth compared to the control group [210]. In a previous study, electro spun gelatin nanofibers containing black elderberry (BE) extract, Au nanoparticles (AuNPs), and SnO2 were fabricated as intelligent packaging layers to monitor the freshness of fish fillets. The addition of AuNPs contributed to the thermal stabilization of the gelatin chain. The L, a, and b values of the nanofibers were measured, and a rapid color change occurred after exposure to volatiles. The highest difference in L (52.29%) was observed in the sample containing gelatin, BE, SnO_2, and AuNPs ($p < 0.05$). The study showed that the absorption of volatiles on nanofibers could be detected from the color changes of the nanofibers. These results can be applied to intelligent packaging layers in seafood products [211].

4.10 Other methods of seafood products preservation

Apart from the mentioned preservation methods, there are additional techniques, such as non-thermal plasma, that can effectively inhibit the growth and activity of microorganisms, prevent fat oxidation, enhance sensory acceptability for consumers, and ultimately elevate the quality and safety of fish and seafood products. Another noteworthy method is electrolyzed water technology, which has been shown to extend the shelf life of fish fillets during refrigerated storage [212-214].

5. Conclusion

The escalating global population growth has precipitated an amplified demand for food, resulting in the heightened consumption of industrially processed foods, including fast foods and inadequately processed items, which ostensibly fulfill human nutritional requirements. However, consumption of such foods has been associated with the onset of various diseases, such as obesity, diabetes, cancer, and gastrointestinal disorders. Consequently, a paradigm shift towards adopting a balanced and healthful dietary regimen is imperative, necessitating the exploration of alternative sources of naturally derived foods to address nutritional needs. Seafood products have garnered significant attention worldwide owing to their inherent nutritional and health-promoting attributes. Fish and seafood products are renowned for their richness in proteins, micronutrients, beneficial unsaturated fatty acids, vitamins, minerals, and assorted bioactive compounds, which secure a pivotal position in the global food supply chain while conferring protective benefits against a spectrum of diseases. Evidently, their functional properties transcend mere sustenance and extend to encompass therapeutic and medicinal advantages. Therefore, the consumption of seafood products should be considered in the human diet as a way to improve the function of human survival and the immune system. Furthermore, the utilization of byproducts stemming from aquatic processing endeavors paves the way for the development of seafood products with heightened intrinsic value, thereby fostering a trajectory aligned with the principles of sustainable development. However, heightened awareness of the nutritional and therapeutic properties of seafood products has resulted in a surge in their consumption rates, placing undue strain on marine ecosystems and fishery reserves to sustain unabated harvesting and utilization. Consequently, the evolution of aquaculture and its attendant systems has emerged as a viable resource to meet escalating global demands. Despite their functional and therapeutic advantages, seafood products remain inherently perishable owing to their elevated water content, rich composition of unsaturated fatty acids, susceptibility to oxidation, near-neutral pH, presence of non-protein nitrogenous compounds, and microbial activity. Thus, it is imperative to devise storage methodologies geared towards augmenting product quality, and prolonging shelf life becomes paramount. Traditional and time-honored techniques for seafood product preservation, including salting, canning, chilling, freezing, fermentation, super chilling, drying, smoking, frying, pickling/marinating, and pasteurization offer avenues for enhancing shelf life, while concurrently enhancing palatability. Salting, characterized by its simplicity and cost-effectiveness, enhances sensory attributes and imparts flavor nuances to terminal products. Similarly, canning, a widely embraced preservation technique, ensures product safety and popularity. Chilling, although efficacious in retarding physical and chemical reactions and microbial proliferation, requires expedited cooling post-harvest to preclude microbial spoilage. Freezing, heralded as a cornerstone preservation method, requires meticulous attention to quick-freezing protocols in order to mitigate tissue damage and preserve product integrity. Fermentation, a venerable tradition, yields products that are replete with health attributes and distinctive sensory profiles. Emerging modalities, including microwave processing, ultrasound, pulsed electric field (PEF), irradiation, high hydrostatic pressure (HHP), micro fluidization, and nanotechnology, represent frontiers in seafood preservation, augmenting product quality and safety. Encapsulating natural preservatives within packaging materials or containers augments product quality and safety. Modified atmosphere packaging (MAP), active packaging (AP), intelligent packaging, vacuum packaging (VP), and retort pouches (RP) provide versatile alternatives for preserving product freshness and quality. Nanotechnology, a burgeoning field, holds promise for enhancing the efficacy and efficiency of seafood preservation, offering avenues for detecting pathogens, controlling product quality, and prolonging shelf life. Embracing novel, innovative, and environmentally sustainable preservation techniques in alignment with established regulatory frameworks and standards holds promise for fostering the production of wholesome and untainted seafood products, thereby promoting consumer health and well-being. In summary, concerted efforts should be directed towards the continued refinement and advancement of seafood preservation methodologies, with an emphasis on fostering innovation, sustainability, and regulatory compliance. By doing so, we can endeavor to ensure the provision of safe, wholesome, and nutritionally robust seafood products, thereby fortifying public health and welfare.

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