Review

Research Progress on Nutritional Value, Preservation and Processing of Fish—A Review

Ahtisham Ali 1, Shuai Wei 1,* 1, Adnan Ali 2, Imran Khan 3, Qinxiu Sun 1, Qiuyu Xia 1, Zefu Wang 1, Zongyuan Han 1, Yang Liu 1 and Shucheng Liu 1,4,*

1 College of Food Science and Technology, Guangdong Ocean University, Guangdong Provincial Key Laboratory of Aquatic Products Processing and Safety, Guangdong Province Engineering Laboratory for Marine Biological Products, Key Laboratory of Advanced Processing of Aquatic Product of Guangdong Higher Education Institute, Guangdong Provincial Engineering Technology Research Centre of Seafood, Zhanjiang 524088, China
2 Livestock & Dairy Development Department, Abbottabad 22080, Pakistan
3 Department of Food Science and Technology, The University of Haripur, Haripur 22620, Pakistan
4 Collaborative Innovation Centre of Seafood Deep Processing, Dalian Polytechnic University, Dalian 116034, China
* Correspondence: weis@gdou.edu.cn (S.W.); liusc@gdou.edu.cn (S.L.)

Abstract: The global population has rapidly expanded in the last few decades and is continuing to increase at a rapid pace. To meet this growing food demand fish is considered a balanced food source due to their high nutritious value and low cost. Fish are rich in well-balanced nutrients, a good source of polyunsaturated fatty acids and impose various health benefits. Furthermore, the most commonly used preservation technologies including cooling, freezing, super-chilling and chemical preservatives are discussed, which could prolong the shelf life. Non-thermal technologies such as pulsed electric field (PEF), fluorescence spectroscopy, hyperspectral imaging technique (HSI) and high-pressure processing (HPP) are used over thermal techniques in marine food industries for processing of most economical fish products in such a way as to meet consumer demands with minimal quality damage. Many by-products are produced as a result of processing techniques, which have caused serious environmental pollution. Therefore, highly advanced technologies to utilize these by-products for high-value-added product preparation for various applications are required. This review provides updated information on the nutritional value of fish, focusing on their preservation technologies to inhibit spoilage, improve shelf life, retard microbial and oxidative degradation while extending the new applications of non-thermal technologies, as well as reconsidering the values of by-products to obtain bioactive compounds that can be used as functional ingredients in pharmaceutical, cosmetics and food processing industries.

Keywords: fish; nutrition; preservation; processing; by-products

1. Introduction

Fish is a widely cultivated food product with highly economical trading in Southeast Asian countries such as Hong Kong, Singapore, Malaysia and Thailand [1]. Fish production has been predicted to reach 196 million tons in 2025 worldwide [2]. Fish is a very diversified food commodity mostly cultured in tropical and subtropical regions. The demand for fish is significantly increasing with the increase in the world population because of their favourable taste, efficient feed conversion and high commercial value [3].

Fish are considered highly nutritious products of the aquaculture system due to the presence of well-balanced macronutrients such as proteins, lipids and micronutrients such as vitamins and minerals [4]. These fish are a good source of human food that promotes growth and protection of the body from a variety of health diseases such as cardiovascular and coronary heart diseases and prevents rickets and mental diseases in children [5].
protein present in fish has high nutritional value because essential amino acids serve as antioxidant elements in various nutraceutical industries. These amino acids possess many properties such as gel formation, oil adsorption, water-holding capacity and health-related properties. Amino acids also have antihypertensive, blood quality maintenance, muscle tissue repairing and system-regulating properties in humans [6]. Lipids are important for health and are rich in polyunsaturated fatty acids (PUFAs), especially eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) which help to prevent cardiovascular diseases and coronary heart diseases and maintain mental health in children [7]. Similarly, fish contains a perfect balance of all essential vitamins, especially vitamins A and D, and are also a significant source of vitamin B. Vitamin B mostly prevents calcium-deficient diseases and rickets in children. Minerals are micronutrients that vary from species to species, including calcium, iron, zinc, selenium, iodine, phosphorus and potassium. These micronutrients have high bioavailability and antioxidant properties that are useful for curing various diseases [8].

Fish and their products can be spoiled easily if not preserved properly. Fish and fish product quality deteriorates because of digestive enzymes, lipid oxidation and microbes which actively contribute to fish spoilage [9]. Compositional changes in protein and lipids lead to the development of new products that cause physiological and chemical changes. Therefore, it is necessary to understand and minimize the factors that contribute to fish spoilage by using active preservation techniques to sustain the freshness of fish and fish-containing products [10]. Various preservation techniques are used to preserve and process fish at an industrial level such as pulsed electric field pulsed electric field (PEF), fluorescence spectroscopy, hyperspectral imaging technique (HSI) and high-pressure processing (HPP) while traditional techniques include cooling, freezing and super-chilling [11]. Excellent food preservation techniques effectively prevent microbial spoilage and prolong the product shelf life with limited adverse changes in the quality and nutritional values, texture and flavour. Many studies have focused on chemical and low-temperature storage methods for fish preservation. Fish is a part of a healthy diet and provides essential components such as proteins, vitamins, polyunsaturated fatty acids and minerals that are necessary for healthy growth. Fish is a highly perishable food and its quality is adversely affected during storage by several factors such as enzymatic autolysis, microbial growth and oxidation [12].

Extensive amounts of by-products are produced as a result of fish processing and are estimated to be up to 60% of the total fish weight [13]. Usually, fish processing by-products are dumped as waste in oceans and on land and contain highly valuable components that can cause serious environmental pollution. These by-products are also used as dietary components in fish meal, silage and fertilizer production. Fish processing by-products contain components such as the skin, scales, viscera, head, trimmings, roe and bones which are unfit for human consumption and are discarded as waste [14]. These by-products are a good source of nutritional components, especially lipids and proteins as well as functional components (Figure 1).

New processing technologies are being used to facilitate the production of highly valuable marketed products that can obtain high economic prices. In this way, discarded waste can be reduced and environmental pollution can also be reduced. Therefore, it is currently considered a necessary and challenging factor to develop new technologies to enable the recovery of valuable fish processing by-products for obtaining functional ingredients that can be used as high-value-added products for human consumption [15].

The objective of this current review is to revise the importance of the nutritional value of fish and focus on the potential applications of preservation technologies including low-temperature-based techniques and antimicrobial and antioxidant preservatives. This review article also summarizes the possible applications of thermal and non-thermal processing technologies as well as the production and utilization of various bioactive compounds at an industrial level.
2. Nutritional Value of Fish

Fish are among the most commercially valuable species in Asia. Moreover, fish are considered key species in coastal ecosystems, and their decline due to fishing pressure has a significant impact on the ecosystem. Therefore, overfishing to meet market demand is a concern [16]. Furthermore, the nutritional value of fish has shown some beneficial effects on human health with efficient protective measures against cardiovascular diseases, cancer and Alzheimer’s disease [17]. Fish has contained high nutritional value due to having rich contents of protein, water, amino acid composition and fatty acids [18].

2.1. Proteins

Fish protein has long been considered to have a high nutritional value due to its being rich in many bioactive peptides and essential amino acids. They are readily digested due to the presence of low connective tissues and can be used for various metabolic activities [19]. These proteins have various pharmaceutical and nutraceutical applications and are being efficiently used as functional ingredients in many food items. Even though they have some useful properties such as oil absorption, water-holding capacity, gel formation, emulsification and foaming properties [20]. In addition, fish protein has various significant bioactive properties such as antioxidative, antithrombic and antihypertensive properties (Table 1). Fish proteins are used to repair muscle tissues, and improve immunity and blood quality. Fish proteins can also be used to prevent protein–calorie malnutrition (PCM) in animals [21].

Table 1. Nutritional composition of fish muscle and their applications.

| Nutrients | Percentage | Applications | Reference |
|-----------|------------|--------------|-----------|
| Protein   | 15–24%     | Potential source of animal protein, antioxidants and metabolic activities; improve muscle tissues and immunity; application in biotechnology and pharmaceutical. Provide lipid-soluble vitamins (A and D) and essential omega-3s (PUFAs) absent in the body, lowering blood pressure and triglycerides in the blood; helps to reduce cardiovascular, childhood asthma, hypertension and Alzheimer’s disease. | [22] |
| Lipid     | 0.1–22%    |              | [23]      |
In addition to being a food source, protein also performs various dominant functions to prevent bacterial and viral infections and helps to maintain the water balance and regulatory system in the human body [29]. The amino acids of proteins have a variety of nutritional values, chemical actions and medicinal properties. For instance, amino acids are used in pharmaceuticals as an excipient for drug development and employed as a food additive in food and feed supplement sources. In the flavouring industry, amino acids such as alanine, aspartate, monosodium glutamate and arginine are the most commonly used flavour enhancer ingredients in a variety of foods. Amino acids have various applications in the pharmaceutical industry such as purifying proteins and are used in the formulation and production of many antibiotics [30].

### 2.2. Lipids

Lipids play an important role in the nutritional value of fish due to the presence of long-chain PUFAs which consist of omega-3 fatty acids, particularly EPA and DHA [26]. These fatty acids have great beneficial impacts on human health and nutrition and prevent various diseases [31]. PUFAs help to reduce blood pressure and high concentrations of triglycerides in blood vessels. The high intake of fatty acids proved to have a beneficial impact on preventing cardiovascular diseases. Omega-3 fatty acids are mostly recommended as an essential element in the growth of children and have some preventive effects against coronary heart diseases [32].

Among fatty acids, DHA is particularly good for optimizing brain growth and neurodevelopment in children while EPA is important for cardiovascular health [33]. Many other benefits include prevention against arrhythmias, therapeutics for asthma patients, protection against atherosclerosis and manic-depressive illness, reduced symptoms of cystic fibrosis and survival of cancer patients [34]. The American Heart Association has recommended at least two servings of fish per week to reduce the risk of cardiovascular diseases. In addition, these fatty acids are used in biodiesel production through enzymatic transesterification of fish oil. This type of biodiesel has become a newly trending nontoxic, biodegradable and renewable energy source [35].
2.3. Multi-Vitamins

Fish also contain the perfect balance of all essential vitamins which play an important role in human health. Fish is a rich source of vitamins (A and D) and a good source of B-group vitamins which are considered to be beneficial for the growth and development of children [36]. Vitamin A maintains cell development, the formation of bones and teeth and it also significantly contributes to improving weak eyesight as well as the treatment of various eye-related diseases [37]. Vitamin D present in fish was found in the form of vitamin D3 (cholecalciferol) which represents a three-fold higher potential efficiency ratio than that of vitamin D (ergocalciferol) and it was also found in the skin as 7-dehydrocholesterol after exposure to ultraviolet light [38]. Most children suffer from vitamin D deficiency that causes rickets but it is also found common in adults where many other diseases such as osteoporosis, osteomalacia, osteopenia, low bone mineral density and diabetes have been reported [39]. Vitamin B accelerates enzyme functioning which facilitates chemical processes in the human body whereas vitamin K is important for blood coagulation and helps to prevent internal bleeding in the body [8].

2.4. Minerals

Most micronutrients with high bioavailability are present in fish within the range of approximately 0.4 to 1.5%. Fish contain high-nutritional-value minerals in widely varying quantities including calcium, iron, zinc, selenium, iodine, phosphorus and potassium [40]. In particular, iodine and selenium are considered to have significant nutritional value due to their high bioavailability. Iodine is essential for hormone production, especially thyroxin which helps to regulate the body’s metabolism. It is also important for the psychological and growth development of children. Selenium possesses some antioxidant properties and is an important micronutrient in the human body that only performs various functions in the form of selenoproteins. These proteins are directly responsible for normal thyroid function and the inactivation of antioxidant enzymes such as glutathione peroxidase [41]. Calcium is significantly used for bone formation and mineralization, and the proper functioning of muscles and the nervous system [42]. Iron is directly involved in the synthesis of haemoglobin in red blood cells (RBCs) that can assist in the regulation of oxygen in every body part [43].

3. Preservation Technology Approaches of Fish

Fish are considered a most highly perishable food commodity. Fish spoilage can be caused by the following three reasons: enzymatic autolysis, microbial deterioration and chemical activities. Deterioration mainly caused by chemical and microbial activities has annually contributed approximately 25% of gross primary agricultural and fishery product losses [44]. Microbial activity contributed to one-fourth of the worldwide food supply losses and 30% of fish product losses. Recently, fish preservation techniques have gained increasing interest because the prevention of microbial spoilage of fish without adversely affecting its nutritional quality, prolonged shelf life, flavour and textural quality has also been improved [45].

3.1. Low-Temperature Preservation

Fish and fish-based products are usually used to preserved by various techniques at a very low temperature. There are several techniques such as cooling, freezing, icing and super-chilling that have been used to improve the preservation quality of fish [46] (Figure 2).
3.1.1. Cooling and Icing Technique

Fish handled at high temperatures is more susceptible to fish spoilage than that handled at low temperatures [47]. Cooling renders microbial growth at −1 °C to 4 °C and freezing requires temperatures of about −18 °C to −30 °C to inhibit bacterial growth but both enzymatic and non-enzymatic changes continue at a minimal rate [48]. Icing is used to store fish at high temperatures before using the freezing method but the rate of deterioration depends upon the harvesting and handling approach. The icing technique has been used to perform different functions including maintenance of uniform low temperatures, reducing autolysis and bacterial degradation and providing gentle washing and cleaning during melting [49]. In a cooling technique, both enzymatic and non-enzymatic activities remain and continue with microbial growth. Therefore, the freezing method is used to control microbial growth as well as enzymatic activity [50].

3.1.2. Freezing Technique

Freezing is the most efficient method used to control microorganisms and slow down the chemical changes that occur during storage. Fish contains 60–80% water that is converted into ice during the freezing process [3]. Freezing is a very fast process in which approximately 90–95% of water freezes at a temperature of −25 °C (75% of the water freezes at −5 °C in fish muscle). Approximately 10% of water remains unfrozen due to hydrogen bonding and chemically bonded water at a specific site such as the carbonyl and amino groups of protein [51]. The quality of frozen fish is significantly influenced by freezing time, i.e., fast and slow freezing. Freezing is a thermophysical phenomenon where fish are stored at low temperatures that affect fish quality due to varied ice crystal formation. Fast freezing (small ice crystals) produces better frozen fish quality than slow freezing (large ice crystals). Slow freezing causes tissue damage and denaturation of proteins [52].

During the freezing process, physical, chemical and biochemical reactions remain continuous in frozen fish and do not stop after cold treatment [53]. At a temperature of −12 °C, microorganism growth is minimal; below −18 °C, cellular metabolism is inhibited and at −55 °C quality changes are minimized [54]. Nevertheless, enzymatic and oxidative damage and ice crystallization lead to fish spoilage [55].

3.1.3. Super-Chilling

Super-chilling is another low-temperature preservation technology used to keep the fish between chilling and freezing temperatures. The super-chilling process keeps fish below their initial freezing point (1–2 °C) [56]. This technique is considered to be different from the cooling and freezing methods and has the ability to minimize storage and transport.
costs. In this process, ice is added inside the fish muscles to freeze internal water which then acts as a refrigeration source during transportation and distribution [3]. Super-chilling extends the shelf life of fish at least 1.4–5 times that make it a more promising technique than most traditional methods [57]. Super-chilling temperatures are used to reduce microbial growth and bacterial activity but physical and chemical changes may occur [58].

### 3.2. Antimicrobial Preservation

Several antimicrobial compounds including nitrites, sulfites and organic acids are used to control the microbial load [59] (Table 2). Nitrites along with sodium chloride are generally used as salt reservoirs (sodium nitrite and potassium nitrite) in fish products as antimicrobial agents for toxin-producing compounds (*Clostridium botulinum*) and used to improve colour [60]. Nitrites adversely affect the activity of microorganisms through several reactions including (a) reacting with an alpha-amino group of amino acids at low pH, (b) blocking the sulfhydryl group, (c) reacting with iron-containing compounds that inhibit the bacteria from using iron and (d) interfering with membrane permeability which limits transport across cells [61] (Figure 3).

![Figure 3. Antimicrobial mechanism of organic acids in a fish bacterial cell. ATP: Adenosine triphosphate; ADP: Adenosine diphosphate.](image)

Sodium chloride is commonly used in fish preservation at high concentrations and it is significantly used to inhibit microbial growth by increasing osmotic pressure and decreasing water activity. A combination of both sodium chloride and sodium lactate has a great impact on the quality, colour, fat stability and overall spoilage of fish [62].

**Table 2.** Application of natural antimicrobial and antioxidant preservatives from different fish and fishery products.

| Antimicrobial Preservatives | Fish/Fish Products | Storage Life | Main Effects | Reference |
|-----------------------------|--------------------|--------------|--------------|-----------|
| Wild mint leaf and cumin seed | Rainbow trout muscle | Up to 12–18 days | Total viable count and psychrotrophic bacteria ↓, peroxide value ↓, thiobarbituric acid reactive substances ↓, lipid oxidation ↓, sensory quality ↑ | [63] |
| Pure lemon essential oil (p-cymene 14.36%, D-limonene 52.85% and β-pinene 13.69%) | Fish spoilage bacteria | Shelf life increased | *Photobacterium damsela* ↓, *Vibrio vulnificus* ↓, *Proteus Mirabilis* ↓, *Serratia liquefaciens* ↓, *Enterococcus faecalis* ↓, *Pseudomonas luteola* ↓, shelf life ↑ | [64] |
Table 2. Cont.

| Antimicrobial                  | Preservatives                | Fish/Fish Products | Storage Life | Main Effects                                                                 | Reference |
|--------------------------------|-----------------------------|--------------------|--------------|-------------------------------------------------------------------------------|-----------|
| Cinnamon oil (Immersion 0.1%)  | Common carp muscle          | Up to 2 days       | Total volatile base nitrogen ↓, total viable count ↓, biogenic amines ↓, \( \text{H}_2\text{S} \) producing bacteria ↓, lactic acid bacteria ↓, *Pseudomonas and Aeromonas* ↓, shelf life ↑, sensory quality ↑ | [65]      |
| *Salvia officinalis* L.       | Rainbow trout muscle        | Shelf life increased (up to 25 days) | Total mesophilic count, *Pseudomonas*, *Enterobacteriaceae*, psychrophilic and \( \text{H}_2\text{S} \) producing bacteria, formation of total volatile base nitrogen and free fatty acid ↓, shelf life ↑ | [66]      |
| Marinated crayfish (Immersion 30 mL/L) | Rosemary and thyme | Up to 42–70 days | Thiobarbituric acid value ↓, total viable count ↓, total volatile basic nitrogen ↓, psychrotrophic bacteria count ↓, lactic acid bacteria ↓, moulds and yeast ↓, sensory score and shelf life ↑ | [67]      |
| Chitosan and lysozyme (Immersion 0.6 mg/mL) | Large yellow croaker | Shelf life increased (up to 15 days) | Lipid oxidation ↓, thiobarbituric acid value ↓, total volatile basic nitrogen ↓, total viable count ↓ (7.0 log CFU/g), *Salmonella, S. aureus, E. coli, P. aeruginosa* ↓, shelf life ↑ | [68]      |
| Animal origin                 | Grass carp                  | Up to 15–20 days   | Total viable count ↓, psychophilic bacteria counts ↓, *pseudomonads* ↓, H\(_2\)S producing bacteria, thiobarbituric acid value ↓, total volatile basic nitrogen ↓, shelf life ↑ | [69]      |
| Pomegranate peel extract-lysozyme, gelatin | Mackerel | Shelf life increased (up to 9 days) | Mesophilic and psychrotrophic count ↓, bacterial activity ↓, free fatty acids and thiobarbituric acid reactive substances ↓, sensory and shelf life ↑ | [70]      |
| Lactoperoxidase and whey      | Rainbow trout muscles       | Up to 12–16 days   | Mesophiles, *S. putrefaciens, pseudomonas* spp., *P. fluorescens* ↓, sensory quality and shelf life ↑ | [71]      |
| Lactic acid bacteria and essential oil | Sea bass                   | 14–21 days         | Psychrotrophic bacterial count ↓, mesophilic aerobic plate count ↓, total volatile basic nitrogen ↓, shelf life ↑ | [72]      |
| Bacteriocin 7293              | Pangasius fish fillets      | Up to 6–7 days     | Gram-positive (*S. aureus* and *L. monocytogenes*) ↓, Gram-negative (*A. hydrophila, S. typhimurium, P. aeruginosus* and *E. coli*) bacteria | [73]      |
| Reuterin isolated by *Lactobacillus reuteri* INIA P579 | Cold smoked salmon | Shelf life increased (up to 15 days) | *E. coli* K12 ↓, *L. monocytogenes* strains ↓, pathogenic bacterial growth ↓, shelf life ↑ | [74]      |
| Bacteriocin EFL4              | Fresh salmon fillets        | Shelf life increased (up to 7 days) | *S. aureus, E. coli, S. putrefaciens, P. fluorescens* and *L. monocytogenes* ↓, total viable count ↓, total volatile basic nitrogen ↓, shelf life ↑ | [75]      |
| Organic acids                 | European lake               | Shelf life increased (up to 15 days) | Aerobe and anaerobe ↓, psychrotrophic and *enterobacteriaceae* counts ↓, proteolytic activity ↓, sensory quality ↑ | [76]      |
| Citric and acetic acid (1 and 3%) | Bolti fish                  | Shelf life increased (up to 12 days) | Viable bacterial count ↓, coliform, yeast and mould count ↓, psychrophilic bacteria ↓, microbial load ↓ | [77]      |
| Acetic and ascorbic acid      | Silver carp                 | Shelf life increased (up to 9 days) | Total viable count ↓, peroxide value and pH ↓, bacterial activity ↓, sensory quality ↑, shelf life ↑ | [78]      |
Table 2. Cont.

| Antimicrobial Preservatives | Fish/Fish Products | Storage Life | Main Effects | Reference |
|-----------------------------|--------------------|--------------|--------------|-----------|
| Sodium lactate, sodium acetate, sodium citrate | Salmon | Shelf life extended (4–7 days) | Aerobic and psychrotrophic count ↓, total viable count ↓, Enterobacteriaceae bacteria ↓, H2S producing bacteria ↓, shelf life ↑ | [79] |
| Nisin | Rainbow trout | Shelf life extended (12–16 days) | Lipid oxidation ↓, total viable count ↓, psychrotrophic viable count ↓, bacteriostatic action ↓, total viable count ↓, peroxide value ↓, thiobarbituric acid value ↓, shelf life ↑ | [80] |
| Rosemary extract with nisin stored at 4 °C | Golden pompano fillet | Up to 6 days | Protein degradation ↓, nucleotide breakdown ↓, microbial count and lipid oxidation ↓, total volatile basic nitrogen ↓, colour, texture and sensory attributes ↑, shelf life ↑ | [81] |
| Ultracea dioica extract with whey protein contained poly (ε-caprolactone) | Rainbow trout fillet | Up to 15 days | Antimicrobial and antioxidant activity ↑, bacterial growth ↓, total volatile basic nitrogen and thiobarbituric acid values ↓, inhibition against mesophilic, psychrophilic, lactic acid bacteria and Enterobacteriaceae ↑ | [82] |
| Lactobacillus reuteri combined with modified atmosphere packaging | Tuna burger | Up to 12–13 days | Colour, odour and juiciness ↑, microbial quality ↑, product quality ↑, shelf life ↑ | [83] |
| Phenols | Salted silver carp | Up to 6 days | Oxidative stability ↑, thiobarbituric acid reactive substances ↓, lipoxygenase ↓, sensory quality ↑ | [84] |
| Ginger extract supercritical and essential oil (β sesquiphellandrene, α-Zingiberene, β-bisabolene, a-farnesene, a-carcuramine) | Nile tilapia burger | Up to 6–8 days | Thiobarbituric acid reactive substances ↓, antioxidant activity ↑, lipid oxidation ↓, reduced by enzymatic activities (Catalases-CAT, Total superoxide dismutase-SOD and Glutathione peroxidase-GSH-px), shelf life ↑ | [85] |
| Chitosan with essential oil (clava bud, cinnamon and lemongrass) | Grass carp fillets | Up to 7–11 days | Deterioration of physicochemical quality ↓, microbial growth ↓, oxidative stress ↓, lipid oxidation ↓, shelf life ↑ | [86] |
| Nisin coated with chitosan | Yellow croaker | Shelf life extended (6–9 days) | Microbial growth ↓, lipid oxidation ↓, protein oxidation ↓, shelf life ↑ | [87] |
| Nisin combination with high-pressure processing (450 and 600 MPa) at low temperature (−3 °C) | Dry-cured cold smoked salmon | Shelf life increased | Listeria spp. ↓, spoilage microbiota ↓, sensory quality and peelability ↑, consumer preference ↑ | [88] |
| Satureja thymbra extract (γ terpinene, p-cymene, carvacrol and trans-caryophyllene) | Gilthead seabream | Shelf life extended (25–35%) | Lipid oxidation (peroxide value) ↓, antimicrobial activity ↓, shelf life ↑ | [89] |
| Oregano essential oil | Hake burgers | Shelf life increased (up to 14 days) | bacterial count ↓, lipid oxidation ↓, shelf life ↑ | [90] |
| Halocnemum strobilaceum (Phenolic content 500 mg GAE/L) | Dolphin fish (Coryphaena hippurus) fillet | Shelf life increased (up to 6–9 days) | Lipid oxidation ↓, peroxide value ↓, malondialdehyde ↓, sensory properties ↑, shelf life ↑ | [91] |
Table 2. Cont.

| Antimicrobial                          | Preservatives                        | Fish/Fish Products | Storage Life | Main Effects                                                                 | Reference |
|----------------------------------------|--------------------------------------|--------------------|--------------|-------------------------------------------------------------------------------|-----------|
| Chitosan (2% w/v) and nano-chitosan    | Silver carp                          | Shelf life increased (3–6 days) | Antimicrobial activity ↓, total volatile basic nitrogen ↓, lipid oxidation ↓, thiobarbituric acid value ↓, mesophilic and psychrophilic bacteria count ↓ | [92]      |
| Chitosan oligosaccharides (COS)—nisin  | Colichthys niveatus                  | Shelf life increased (4 days)  | Sensory and texture deterioration ↓, total viable counts ↓, total volatile basic nitrogen ↓, oxidative spoilage ↓, shelf life ↑ | [93]      |

↓ Decrease or inhibit, ↑ Increase.

Sodium sulphites have antimicrobial activity against aerobic, Gram-negative bacilli, yeasts and moulds of fish and fish products. Sulphurous acid enters the cell and reacts with thiol groups of enzymes, proteins and cofactors [94]. Sulphite blocks cystine disulfide linkages because it reacts with cellular adenosine triphosphate (ATP) leading to yeast death [95].

Lactic acid is used as an antimicrobial agent against pathogenic microorganisms (Clostridium botulinum) due to a reduction in the pH level and transfer of protons across the cell membrane [96]. Lactic acid bacteria serve as the inoculum in a newly developed method for fish preservation. These bacteria are very efficient in removing undesirable microorganisms and species of psychrotrophic lactic acid bacteria by producing lactic acid and other organic acids [97].

3.3. Antioxidant Preservation

Oxidative deterioration in fish is mainly caused by the production of rancidity, off-flavours, discoloration and free radical catalyst due to the availability of oxygen in protein and lipid compounds [98]. Therefore, it is necessary to minimize the oxidation activity in fish products by using various antioxidant compounds (Table 2). Among them, the most commonly used lipid oxidation inhibitory additives include phenolic antioxidants (primary antioxidants) and phosphatase (a secondary antioxidant) [99]. Butylated hydroxyanisole (BHA) and ethylenediaminetetraacetic acid (EDTA) are considered to be derivatives of phenols that work as synthetic phenolic antioxidants. These antioxidants are widely used to dismiss chain-carrying peroxyl radicals and to inhibit the production of primary radicals and secondary radicals of lipids mainly to prevent, delay or inhibit the adverse effects of lipid peroxidation [100] (Figure 4).

![Figure 4](image-url)
Ethylenediaminetetraacetic acid (EDTA) is known as a sequestering agent, and is widely investigated for its ability to act as an antioxidant, chelating and metal complexing agent [101]. EDTA is a derivative of the polyaminocarboxylic acid group, added to fish to perform critical functions such as (a) acting as a pro-oxidant for the removal of trace metals through chelation, (b) acting as an inhibitor of lipid oxidation, (c) having antimicrobial activity by binding the divalent cations found in bacterial cell walls, (d) suppressing the growth of *Pseudomonas* species and (e) recovering the functional proteins by an acid solubilization process [102].

4. Processing Technology Approaches of Fish

A wide range of technologies is being used for the processing of commercially available fish products ranging from simple to advanced processing techniques including various treatments in order to meet consumer demands in terms of minimal processing and usage of chemical preservatives. However, the food industry is interested in developing non-thermal technologies including pulsed electric field (PEF), fluorescence spectroscopy, high-pressure processing (HPP) and thermal technologies such as canning.

4.1. Non-Thermal Technology

4.1.1. Pulsed Electric Field (PEF)

The pulsed electric field (PEF) technique is used as a new emerging non-thermal processing technology based on electrical currents between two electrodes where short electrical pulses are employed with high voltages that enable the thermal effects to remain low [103]. Such characteristics make it different from other thermal electrical techniques such as ohmic heating [104] and moderate electrical fields [105].

PEF is predominantly used to reduce microbial activity, for extraction of value-added compounds, make improvements in the extraction of plant materials, enhancement of mass transfer through cell disruption and reduce the induction of stress in cells and damage the biological cells without paying any adverse effects on marine food [106]. PEF operates continuously in a very short time duration (milliseconds to microseconds) which makes it a more desirable processing technique than traditional methods. Most recently, PEF has been applied for the extraction of high-value-added components and to study mass transfer phenomena [107]. Concerning the extraction process, the high intensity of PEF has the potential to extract calcium [106] and chondroitin sulfate [108] with a high extraction efficiency ratio in a very short period of time. Likewise, abalone viscera protein with extensive emulsifying properties was extracted with a conventional extraction technique and the viscosity and foaming properties of most of the extracted product were decreased when PEF was applied [109].

4.1.2. Fluorescence Spectroscopy

Fluorescence spectroscopy is known as a non-thermal processing technology since gaining interest due to efficient control of the quality and authenticity of fish and fish products [110]. Fluorescence spectroscopy is particularly applied to evaluate the freshness quality of most fish species stored under different light and vacuum packaging conditions and to monitor the access of lipid oxidation occurring in fatty and lean fish species during various storage and processing conditions such as canning, refrigerated and frozen storage [111]. The potential application of fluorescence spectroscopy was investigated to monitor the freshness quality among four groups of lean fish species; fish fillets stored for up to 12 days under various light and vacuum packaging conditions (dark/partial vacuum, dark total vacuum, light/partial vacuum and light/total vacuum) [111]. The findings of this study investigated that the fish fillets stored in dark and packed in a total vacuum had maximum quality characteristics compared to fillets kept in the other preservation conditions. Fluorescence spectroscopy has the potential to investigate the conformational changes that may occur in proteins as well as in the secondary and tertiary structures of proteins during processing [112]. In a recent study, [113] investigated the interaction
between myofibrillar protein and lipids using Schiff structures, formed during cooking process as a result of protein oxidation in farmed sturgeon (*Acipenser gueldenstaedtii*). The emission spectra have shown various patterns of spectra after obtaining excitation set at 360 nm as a result of cooking methods. The fluorescence intensity obtained from cooking methods (frying and roasting) was much greater than the fluorescence intensity of other cooking methods of heated samples [113]. Collectively, particular focus is being placed on the investigation of this technique as a highly sensitive and selective approach compared to other traditional and spectroscopic methods due to possessing the characteristics of rapid and non-destructive detection of quality parameters, extension of shelf life and analysis of marine food products [114].

4.1.3. Hyperspectral Imaging Technique (HSI)

Several spectroscopic techniques are used in fish and fish product analyses including near-infrared spectroscopy (NIR) and mid-infrared spectroscopy (MIR) [115], hyperspectral imaging (HSI) [116] and nuclear magnetic resonance spectroscopy (NMR) [117]. Recently, the hyperspectral imaging technique has been deployed as a rapid, non-destructive, smart and promising analytical tool to generate spatial and spectral information of the tested sample simultaneously [118]. Many recent reports have demonstrated the potential application of this technique to predict quality and authenticity issues in fish and meat products such as microbial spoilage, texture quality, colour attributes and discrimination between fresh and frozen/thawed products [119].

HSI has been used to determine the fish freshness quality parameters such as total volatile basic nitrogen TVB-N and K-value and basic nutritional composition (moisture, crude protein, crude fat and fat-related compounds). For instance, hyperspectral imaging wavelength (308–105 nm) was employed to determine the K-value in grass and silver carp, as a result obtained a coefficient of determination for prediction ($R^2_p = 0.94$) [120]. To determine textural quality, Ma et al. [121] evaluated textural (hardness, chewiness and gumminess) parameters of vacuum freeze-dried fishfillets using hyperspectral imaging in the VIS-NIR region.

4.1.4. High-Pressure Processing (HPP)

High-pressure processing (HPP) is another potential non-thermal processing technique progressively used to destroy microbial cells by disrupting noncovalent bonds, sustaining organoleptic properties and nutritional value without using high temperatures and increasing the shelf life of fish without compromising the sensory attributes [122].

In HPP, fish products are exposed to approximately 100–1000 MPa of pressure, fish products require very low temperatures (0–20 °C) to extend their shelf life and cannot be thermally processed while HPP allows for the application of high temperatures under cold conditions, resulting in an increased shelf life (by up to at least 300%) with reduced energy use and waste production [123]. Generally, HHP has extensively been utilized in the food processing industries in order to improve the nutritional quality of various kinds of food products such as dairy products, vegetables, fruits, including fish, meat and meat products, also including a variety of purposes such as prolonging the shelf lives, inhibit enzymatic and microbial degradation, modification in physicochemical properties, changes in microstructures and products development [103]. Greek national funds through the Operational Program “Competitiveness, Entrepreneurship and Innovation 2014–20” of the National Strategic Reference Framework (NSRF) (2016–19) investigated the effective application of HPP on fish physicochemical, microbiological and sensory attributes by assessing the quality and fingerprint recognition of microbial spoilage by using the “omics” technique. “Omics” technologies progressively identify and detect pathogens and bacteria to ensure the quality and safety of fish products by detecting the effect of protein-based processing in fish products [124].
4.2. Thermal Technology

Canning

Canning is the most widely used non-thermal technology for the preservation of fish over a prolonged period of time. Canned fish is typically processed at a specific heating temperature (113–160 °C) in a sealed airtight container for a specific time interval [124]. During the canning process, the product is processed in the centre of the can where the temperature increases slowly which affects the processed product for the shortest time duration [125].

Canned fish quality is based on the amino acid concentration, microbial activity, processing conditions and histamine concentration which play an important role in the investigation of fish quality. Appropriate handling of fish from harvesting to processing showed better initial fish quality with a great impact on final product quality and stability compared to insufficient handling. Additionally, Bifurcaria bifurcate extract was intentionally added to the packing of canned fish to enhance the product quality [126]. Heat treatment (a temperature of 90 °C) before canning led to fish with a lower liquid holding capacity and water content, resulting in a lower heating yield and a tough texture [127]. In thermal canning, safety parameters and prolonged shelf life are achieved by consuming a large amount of energy. Recently, many studies have investigated the progressive application of alternative energy sources in fish canning, among which thermo-solar heat pump sets are becoming popular in industrial processing [128].

In conclusion, traditional thermal processing methods provide acceptable information and well-tasting products. Despite this, they have many limitations such as long processing time, limited heat penetration and heterogeneous distribution of heat, which can lead to underheating or overheating problems [129]. Contrary to thermal technologies, non thermal technologies do not use direct heating as their main aim is to have minimal effects on the different quality parameters such as taste, texture, colour and aroma without changing the composition of nutritional components while achieving high-quality objectives and meeting consumer demands for minimally processed and without having any preservatives present in the food [130]. In contrast, non-thermal technologies showed greater advantages over traditional thermal technologies because of their reduce processing time, maximum extraction efficiency, nontoxicity, minimum solvent consumption and ecofriendliness [103]. In this regard, the advantages and disadvantages of non-thermal technologies are presented in Table 3.

Table 3. Advantages and disadvantages of various non-thermal processing technologies.

| Technologies               | Advantages                                      | Disadvantages                                      | Storage Life                                                                 | References |
|----------------------------|-------------------------------------------------|---------------------------------------------------|------------------------------------------------------------------------------|------------|
| Pulsed electric field      | Low energy consumption                         | High initial investment                            | Improve tenderization and water holding capacity, less physiological effects due to partial disruption of cellular tissues, increase shelf life of meat | [107]      |
|                            | Short processing time                           | Less efficient for spore inactivation              |                                                                               |            |
|                            | Waste-free process                              | Presence of bubbles effect                         |                                                                               |            |
|                            | Quick process                                   | Uniformity                                        |                                                                               |            |
|                            | Relatively uniform heating                      | High economic                                     |                                                                               |            |
|                            | More recovery yields                            | High initial cost                                  | Increased shelf life through reducing oxidative spoilage, microbial activity, improve textural properties | [131]      |
|                            | Low contamination                               | Relatively electrolytic effect                     |                                                                               |            |
|                            | High selectivity rate                           |-time consumption in sample preparation            |                                                                               |            |
|                            | High data achievement rate                      | Not suitable for solid material detection          | Improve protein functionality and conformational changes during protein denaturation | [112]      |
|                            | Simple and more economic                       | Highly selective method                            |                                                                               |            |
| Enzymatic treatment        | More recovery yields                            | High enzymes cost                                  |                                                                               |            |
|                            | Low contamination                               | Prolong processing time                           |                                                                               |            |
|                            | High selectivity rate                           | Low-efficiency rate                                |                                                                               |            |
| Fluorescence spectroscopy  | High data achievement rate                      | Time consumption in sample preparation            |                                                                               |            |
|                            | Simple and more economic                       | Not suitable for solid material detection          |                                                                               |            |
|                            |                                                  | Highly selective method                            |                                                                               |            |
### Table 3. Cont.

| Technologies                                      | Advantages                                                   | Disadvantages                                                        | Storage Life                                      | References |
|---------------------------------------------------|--------------------------------------------------------------|----------------------------------------------------------------------|---------------------------------------------------|------------|
| Nuclear magnetic resonance                        | High data evaluation                                         | High cost-effective                                                  | Improve sensory properties, chemical composition, nutritional and physicochemical properties | [132]      |
| Fermentation                                      | Non-destructive and non-intrusive                           | Highly expensive equipment                                           |                                                   |            |
|                                                   | More economical                                              |                                                                     |                                                   |            |
|                                                   | Environmentally friendly                                     |                                                                     |                                                   |            |
|                                                   | Useful for bioactive extraction                              |                                                                     |                                                   |            |
|                                                   | Poor energy consumption                                      |                                                                     |                                                   |            |
| High hydrostatic pressure                         | High preservative quality                                    |                                                                     |                                                   |            |
|                                                    | Easy to commercialize                                        |                                                                     |                                                   |            |
|                                                    | Wide range of microorganism inactivation                     |                                                                     |                                                   |            |
|                                                    | Rapid and reliable                                           |                                                                     |                                                   |            |
|                                                    | Sensitive to conformational changes under various conditions|                                                                     |                                                   |            |
|                                                    | Independent of the physical condition of samples             |                                                                     |                                                   |            |
|                                                    | Required small size sample                                   |                                                                     |                                                   |            |
| Raman spectroscopy                                | Non-linear problems of the curve                             | Higher instrumental costs                                           | Increase shelf life, improve protein and water contents, reduce microbial load | [114]      |
|                                                    | High cost                                                    | Stronger biological fluorescence interference                         |                                                   |            |
|                                                    | Heat effect generated by the laser                           | Accuracy depends on the reliability of the reference method          | Reduce microbial spoilage, predict compositional changes, reduce foodborne pathogens | [135]      |
| Near-infrared (NIR) spectroscopy                  | Rapid and non-destructive                                    | Does not provide spatial information on the sample                   |                                                   |            |
|                                                    | Non-contact and cost-effective                               | Contain unnecessary and redundant information                         |                                                   |            |
|                                                    | Non-destructive                                              | Non-independent requires samples with known analyte concentration    | Reduce oxidation, optimize product quality, increase shelf life | [136]      |
| Visible near-infrared (VIS/NIR) spectroscopy      | Non-contact                                                  | Specular highlights and uneven illumination under varying sample surface |                                                   |            |
| Nuclear magnetic resonance/magnetic resonance imaging (NMR/MRI) spectroscopy | Non-destructive | Slow process                                                   | Food authentication, detect alteration and unwanted compounds. | [138]      |
| Ultrafiltration                                   | Cost-effective                                               | High initial cost                                                   |                                                   |            |
|                                                   | Non-destructive                                              | Expensive equipment                                                 |                                                   |            |
| Supercritical fluid extraction                    | High energy efficiency                                       | Time-consuming                                                       | Extend shelf life, reduce disruption of cells, inhibit microbial spoilage | [139]      |
|                                                   | Better quality permeates                                     | Expensive membranes                                                 |                                                   |            |
|                                                   | Continuous recovery                                           |                                                                     |                                                   |            |
|                                                   | Environmentally friendly                                     |                                                                     |                                                   |            |
|                                                   | Rapidly penetrate in sample                                  |                                                                     |                                                   |            |
|                                                   | Mild processing conditions                                   |                                                                     |                                                   |            |
|                                                   | Low processing wastes                                         |                                                                     |                                                   |            |

#### 5. Utilization of Fish Processing By-Products

Increasing fish waste production has become a serious issue worldwide over the last few decades. Technical, biological, operational and economic factors influence fish processing by-product production [141]. According to recent studies, total fish production leads to approximately 20% to 80% fish waste and unwanted products that have been discarded as waste depends on the species and applied processing methods [142]. In terms of industrial production, 40% of fish products are used for human consumption and the remaining 60% are waste products that include fins, viscera, head, skin and trimmings [13]. Therefore, the disposal of fish by-products is a serious problem in many regions and causes
serious environmental pollution that could be overcome by using different techniques to utilize fish by-products [143] (Figure 5).

Figure 5. General processing steps involved in the extraction of bio-molecules and their various industrial applications.

5.1. Fish Meal

Fish meal can be obtained by drying or grinding whole fish or fish by-products. Among fish species, mostly menhaden, capelin and anchovy fishes are used for fish meal production, which are the best sources of animal feed [144]. Chemically, fish meal is composed of minerals (10%), protein (70%), water (8%), fat (9%), vitamins, ash, pantothenic and various other minerals. Fish meal quality depends upon the types of amino acids, freshness and solubility of the fish meal and the processing method [145]. Fish meal is used as a feed for marine fish, crustaceans, poultry, ruminants, pigs and pets [146].

5.2. Fish Oil

Fish oil is derived from fish by-products and other unwanted products are also the main constituent of animal feed. Fish oil is composed of fatty acid triglycerides, phospholipids, glycerol ethers and wax esters that can remove environmental contaminants [147]. Numerous studies have been recently conducted on the extraction of fish oil by chemical and enzymatic transesterification because fish waste is a good source of lipids (60% by weight) [148]. Transesterification of fish oil and pyrolysis of fish oil is the process of recycling fish waste and producing char in the form of activated carbon and pyrolytic oil.

Fish oil is also suitable for biogas production, oil extraction and transformation to biodiesel [149]. During anaerobic digestion, a large amount of ammonia is released from fish waste, which greatly involves alleviating the level of methanogenic bacteria and a co-fermentation process is used to optimize the carbon-to-nitrogen ratio of a batch. In biorefinery industries, the co-fermentation process is conducted to recycle the energy material with the purpose of producing primary products including concentrated liquid material, secondary product-purified water, solid fertilizer and carbon dioxide [150].

5.3. Fish Silage

Fish waste is also utilized for the production of fish silage by the complete mixing of fish or fish by-product enzymes with acids, microorganisms and other enzymes [151]. Fish silage can be used in large-scale production because it is inexpensive and simple and has the main advantage of removing the smell and drainage problems of the industry. The disadvantages of fish silage include consumption at the same production place and high product volumes [152]. Fish silage and fish protein hydrolysates are commonly produced from the digestive organs of fish as well as the spleen and gonads [153]. Most nitrogen for the production of feed for pets and aquaculture is derived from these organs.
5.4. Fish Protein Hydrolysate

According to a recent survey, most food industries are using fish protein hydrolysates as an animal feed source [154]. Protein hydrolysates are significantly recovered from fish by-products because they contain high functional and nutritional properties. Several techniques are efficiently involved in the recovery of protein hydrolysates and many other natural products or high-value functional ingredients that can be used for animal feeding [155]. Additionally, biopeptides are a promising ingredient derived from fish by-products that are currently gaining increasing interest in the food industry [156]. Biopeptides are used for food fortification and exhibited various bioactivities such as antihypertensive, antioxidant, antimicrobial, anticholesterolemic, anticancer and antidiabetic activities [157]. Most fish protein hydrolysate sources are used for animal feed specifically those for poultry and swine. Protein hydrolysates in fish wastes are fermented under uncontrolled conditions, resulting in the production of high total volatile nitrogen contents and fish silage. Sheep fed fish silage gained more weight than those in the control feeding group [158]. Another protein ingredient is collagen, which can be a resultant product of fish-processing by-products.

5.5. Collagen

Collagen is considered to be the structural protein of connective tissues providing growth and support to bones, cartilage, skin, etc. This protein has numerous applications in the food, cosmetic, biomedical and pharmaceutical industries [159]. Collagen is widely applied in processed meat to improve the stability of products by increasing protein functionality through holding free water, used as a binding and extending agent in sausages and is involved in increasing the holding and absorption of water [160]. Collagen has some biomedical applications as a biopolymer to increase biocompatibility and decrease immunogenicity, producing fibres by cross-linking and self-aggregation. This protein is used in a bioprosthetic heart valve and wound dressing and it is also used for drug delivery by gel formulation with liposomes, transdermal delivery, gene delivery via nanoparticles and as a cell culture matrix [161].

Collagen is widely used in cosmetic products as an anti-ageing agent due to its useful biological effects [162]. Gelatine is the resultant product of collagen derived from fish processing by-products such as skin, bones, scales and internal organs of various fish species through thermal denaturation and partial hydrolysis. Gelatine has versatile industrial applications to enhance the consistency, stability and elasticity of dairy products, confectionery and fruit juices [163]. Gelatine alleviates phenol concentrations (tannins and anthocyanogens) and is presented for clarification and precipitation of fruit juices. At low melting temperatures, fish gelatine exhibited better aroma and flavour than those of bovine gelatine [164] and for diabetic patients, fish-based gelatine is used in food to increase protein levels and decrease carbohydrate levels [165]. Gelatine is used to make edible films that are heated for the manufacturing of edible containers for condiments and fried foods. In place of highly efficient catalysts, enzymes have great advantages in processing and are being used as biological catalysts to speed up biological reactions [166].

5.6. Enzymes

Many enzymes have been isolated from fish processing by-products and used as an alternative source of many enzymes. Viscera is a by-product of fish processing and is considered to be a good source of many enzymes such as protease, lipase, cellulase, and collagenase [167]. Enzymes or enzymatic peeling are used in the food, pharmaceutical and cosmeceutical industries and also serve as processing aids for various food products at low cost. Moreover, enzymes are used for the exclusion of undesirable parts of highly nutritious fish species [168]. There is a wide range of potential applications of fish enzymes in the dairy industry, especially for cheese production and various other industrial applications have also been reported [169].
5.6.1. Proteases

Proteases are multifunctional enzymes that can be recovered from digestive enzymes (i.e., pepsin, chymotrypsin, elastase, gastricsin, trypsin, carboxylesterase and carboxypeptidase) of fish viscera and catalyse the hydrolytic degradation of proteins. Pepsin-rich sources are obtained from the stomach of several fish species such as cold- and warm-water fish, at optimal pH and temperature conditions [170]. Fish proteases and trypsin encode protein hydrolysate production from various fish species [171].

5.6.2. Lipases

Lipases are isolated from various digestive organs of by-products such as the liver, stomach, and intestine. The liver shows higher lipase activity than that of other organs at optimal pH and temperature conditions of 8.0 °C and 50 °C, respectively, in the presence of ρ-nitrophenyl palmitate (ρ-NPP) substrate [172]. The potential uses of fish lipases have been employed for the alteration of foods, biodiesel production, flavour enhancement and production of structural lipids and delivered for hydrolysis of PUFAs for the enrichment of DHA and EPA in marine oils [173]. Fish lipases are extensively used in the dairy industry for flavour enhancement of dairy products and to inhibit the production of trans-fat in margarine. Lipases with antioxidants are used in the food and cosmetic industries to provide product stability [174] and in pharmaceuticals, lipases are applied as drugs to produce low serum cholesterol levels [175].

5.7. Minerals

It is likely that fish bones eliminated as by-products during fish processing contain significantly high amounts of mineral components presented as “bonefish”. Fish bones are generally employed as phosphorus and various other mineral forms to fulfil the calcium and phosphorus requirements of animal growth [176]. Fish bones are used as a fertilizer and as an animal feed extracted from the thermal processing of meat and bone meal during valorisation. Among the different parts of fish, cartilage and backbones consist of a high level of calcium phosphate, minerals and 30% proteins. Using various enzymes with a fish backbone helps to attain minerals and these minerals are utilized for feed formation with high functional properties [177].

5.8. Antioxidants

Several antioxidants and germicides are derived from by-products to increase food quality [178]. Many components contributed to better human health such as phenols, flavanols, and flavanol glycosides, when used in food compositions. These antioxidants have further applications in agriculture, mainly applied in pet feed formation and used as fertilizer after making a mixture of fish with carbon sources such as seashells and fish bones. These by-products are delivered as dry, liquid, fresh or frozen forms used for trap-making to catch fish [6].

6. Conclusions

The current review has interestingly reviewed the nutritional composition of fish and discussed the various applications of the utilization of fish processing by-products as well as preservative technologies to extend the shelf life of fish. Various processing technologies are actively involved to preserve the fish for a longer time. Enzymatic autolysis, microbial spoilage and chemical deterioration are three main factors involved in the spoilage of fish. It is necessary to control these factors by employing suitable techniques such as freezing, antimicrobials and antioxidants and super-chilling to ensure that the fish will be preserved for a long time. Low-temperature treatments can also be used efficiently to control microbial growth and enzymatic and non-enzymatic degradation processes. Several antimicrobial chemicals are effectively being applied to control microbial growth, whereas antioxidants are also used to control lipid oxidation. A broad range of technologies, including thermal and non-thermal treatments, are employed in industries for processing most economical
fish products in such a way as to meet consumer demands with minimal quality damage. The main focus of these technologies is to extend the shelf life, enhance the nutritional value, extract high-value-added products and avoid any adverse effects on fish products with minimal processing and chemical preservative addition. The disposal of fish processing by-products has become a serious problem worldwide and is influenced by biological, technical, operational and economic factors. Environmental pollution caused by many by-products has received attention in order to utilize these by-products for various purposes. The main aim of by-product utilization is to overcome the disposal of by-products with the recovery of highly valuable products and other useful components from fish by-products. The nutritional value, preservative and processing technologies while utilization of fish processing by-products shall be discussed. Further, new studies should be focused on the optimization of processing technologies but also the evaluation of natural preservatives and by-product sources rich in all essential nutrients.

7. Future Perspectives

The future of fish with respect to preservation and processing depends upon the industrial utilization of new technologies and progressive management of the factors related to fish parameters such as quality, nutritional requirements, prolonged shelf life, new developmental products, freshness and high yield. In terms of future perspectives, more research is needed to understand the effects of processing and preservation parameters on fish and fish products and to make them more reliable and user-friendly for future development. To date, the discarding of various fish by-products is still considered a challenging factor that requires subsequent work and developmental technologies to recover highly valuable and new products for the long-term benefit of society and the environment.

Author Contributions: Conceptualization, S.L. and S.W.; funding acquisition, S.L.; investigation, S.L. and S.W.; methodology, A.A. (Ahtisham Ali) and I.K.; formal analysis, A.A. (Ahtisham Ali), S.W. and A.A. (Adnan Ali); data curation, Q.S., Q.X., Z.W., Z.H. and Y.L.; project administration, S.L.; writing—original draft preparation, A.A. (Ahtisham Ali) and S.W.; writing—review and editing, S.W., A.A. (Ahtisham Ali) and I.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by Guangdong Province Scientific and Technological Innovation Strategy (2022A05036), National Natural Science Foundation of China (62171143), and Guangdong Innovation Team of Seafood Green Processing Technology (2019KCGXDT011).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Frisch, A.J.; Cameron, D.S.; Pratchett, M.S.; Williamson, D.H.; Williams, A.J.; Reynolds, A.D.; Hoey, A.S.; Rizzari, J.R.; Evans, L.; Kerrigan, B.; et al. Key aspects of the biology, fisheries, and management of Coral grouper. Rev. Fish Biol. Fish. 2016, 26, 303–325. [CrossRef]
2. Pedro, S.; Nunes, M.L. Reducing salt levels in seafood products. In Reducing Salt in Foods, 2nd ed.; Woodhead Publishing: Thorston, UK, 2019; pp. 185–211.
3. Tavares, J.; Martins, A.; Fidalgo, L.G.; Lima, V.; Amaral, R.A.; Pinto, C.A.; Silva, A.M.; Saraiva, J.A. Fresh Fish Degradation and Advances in Preservation Using Physical Emerging Technologies. Foods 2021, 10, 780. [CrossRef] [PubMed]
4. Hassanien, H.A.; Al-Rashada, Y. Assessment of genetic diversity and phylogenetic relationship among grouper species Epinephelus spp. from the Saudi waters of the Arabian Gulf. Saud. J. Biol. Sci. 2021, 28, 1779–1786. [CrossRef]
5. Luo, J.; Amenyogbe, E.; Fu, W.-j.; Huang, J.-s.; Chen, G. Hepatic transcriptome profiles reveal the hepatoprotective effects of dietary quercetin and sodium quercetin-5′-sulphonates supplementation in hybrid grouper (Epinephelus fuscoguttatus♀× Epinephelus polypekadios♂). Aquaculture 2022, 2022, 738483. [CrossRef]
6. Ghaly, A.E.; Ramakrishnan, V.; Brooks, M.S.; Budge, S.M.; Dave, D. Fish Processing Wastes as a Potential Source of Proteins, Amino Acids and Oils: A Critical Review. J. Microb. Biochem. Technol. 2013, 5, 107–129. [CrossRef]
7. Innes, J.K.; Calder, P.C. Marine Omega-3 (N-3) Fatty Acids for Cardiovascular Health: An Update for 2020. Int. J. Mol. Sci. 2020, 21, 1362. [CrossRef] [PubMed]
8. Khalili Tilami, S.; Sampels, S. Nutritional Value of Fish: Lipids, Proteins, Vitamins, and Minerals. *Rev. Fish. Sci. Aquac.* 2018, 26, 243–253. [CrossRef]

9. Ekonomou, S.I.; Parlapani, F.F.; Kyritsi, M.; Hadjidjchristodoulou, C.; Boziaris, I.S. Preservation status and microbial communities of vacuum-packed hot smoked rainbow trout fillets. *Food Microbiol.* 2022, 103, 103959. [CrossRef]

10. Hematyar, N.; Rustad, T.; Sampels, S.; Kastrup Dalsgaard, T. Relationship between lipid and protein oxidation in fish. *Aquac. Res.* 2019, 50, 1393–1403. [CrossRef]

11. Rathod, N.B.; Nirmal, N.P.; Pagarkar, A.; Özogul, F.; Rocha, J.M. Antimicrobial Impacts of Microbial Metabolites on the Preservation of Fish and Fishery Products: A Review with Current Knowledge. *Microorganisms* 2022, 10, 773. [CrossRef]

12. Rathod, N.B.; Ranveer, R.C.; Benjakul, S.; Kim, S.K.; Pagarkar, A.U.; Patange, S.; Özogul, F. Recent developments of natural antimicrobials and antioxidants on fish and fishery food products. *Compr. Rev. Food Sci. Food Saf.* 2021, 20, 4182–4210. [CrossRef] [PubMed]

13. Dekkers, E.; Raghavan, S.; Kristinsson, H.G.; Marshall, M.R. Oxidative stability of mahi mahi red muscle dipped in tilapia protein hydrolysates. *Food Chem.* 2011, 124, 640–645. [CrossRef]

14. Rustad, T.; Storna, I.; Slizyte, R. Possibilities for the utilisation of marine by-products. *Int. J. Food Sci. Technol.* 2011, 46, 2001–2014. [CrossRef]

15. Ghosh, S.; Sarkar, T.; Pati, S.; Kari, Z.A.; Edinur, H.A.; Chakraborty, R. Novel Bioactive Compounds From Marine Sources as a Tool for Functional Food Development. *Front. Mar. Sci.* 2022, 9, 10-3389. [CrossRef]

16. Soyano, K.; Amagai, T.; Yamaguchi, T.; Mushirobira, Y.; Xu, W.-G.; Pham, N.T.; Murata, R. Endocrine Regulation of Maturation and Sex Change in Groupers. *Cells* 2022, 11, 825. [CrossRef]

17. Yeşilçuoğlu, A.F.; Özyurt, G. Oxidative stability of microencapsulated fish oil with rosemary, thyme and laurel extracts: A kinetic assessment. *J. Food Eng.* 2019, 240, 171–182. [CrossRef]

18. Ahmed, I.; Jan, K.; Fatma, S.; Dawood, M.A.O. Muscle proximate composition of various food fish species and their nutritional significance: A review. *J. Anim. Physiol. Anim. Nutr.* 2022, 106, 690–719. [CrossRef]

19. Sathivel, S.; Bechtel, P.J.; Babbitt, J.; Prinyawiwatkul, W.; Negulescu, I.I.; Reppond, K.D. Properties of protein powders from arrowtooth flounder (*Atheresthes stomias*) and herring (*Clupea harengus*) byproducts. *J. Agric. Food Chem.* 2004, 52, 5040–5046. [CrossRef]

20. Ryu, B.; Shin, K.H.; Kim, S.K. Muscle Protein Hydrolysates and Amino Acid Composition in Fish. *Mar. Drugs* 2021, 19, 377. [CrossRef]

21. Lees, M.J.; Carson, B.P. The Potential Role of Fish-Derived Protein Hydrolysates on Metabolic Health, Skeletal Muscle Mass and Function in Ageing. *Nutrients* 2020, 12, 2434. [CrossRef]

22. Mohanty, B.P.; Mahanty, A.; Ganguly, S.; Mitra, T.; Karunakaran, D.; Anandan, R. Nutritional composition of fish foods and their importance in providing food and nutritional security. *Food Chem.* 2019, 293, 561–570. [CrossRef] [PubMed]

23. Holma, K.A.; Maalekuu, B. Effect of traditional fish processing methods on the proximate composition of red fish stored under ambient room conditions. *Amer. J. Food Nutr.* 2013, 3, 73–82.

24. Mohanty, B.P.; Ganguly, S.; Mahanty, A.; Sankar, T.V.; Anandan, R.; Chakraborty, K.; Paul, B.N.; Sarma, D.; Syama Dayal, J.; Venkateshwarlu, G.; et al. DHA and EPA Content and Fatty Acid Profile of 39 Fish Foods from India. *BioMed Res. Int.* 2016, 2016, 402743. [CrossRef] [PubMed]

25. Jamshidi, A.; Cao, H.; Xiao, J.; Simal-Gandara, J. Advantages of techniques to fortify food products with the benefits of fish oil. *Food Res. Int.* 2020, 137, 109353. [CrossRef]

26. Mesias, M.; Holgado, F.; Sevenich, R.; Briand, J.; Márquez-Ruiz, G.; Morales, F. Fatty acids profile in canned tuna and sardine after retort sterilization and high pressure thermal sterilization treatment. *J. Food Nutr. Res.* 2015, 54, 171–178.

27. Suganthi, A.; Venkatraman, C.; Chezhian, Y. Proximate composition of different fish species collected from Muthupet mangroves. *Int. J. Fish. Aquat. Stud.* 2015, 2, 420–423.

28. Hantoush, A.; Al-Hamadany, Q.; Al-Hassoon, A.; Al-Ilbadi, H. Nutritional value of important commercial fish from Iraqi waters. *Int. J. Mar. Sci.* 2015, 5, 1–5.

29. Ariño, A.; Beltrán, J.; Herrera, A.; Roncalés, P. Fish and seafood: Nutritional Value. *Encycl. Human Nutr.* 2012, 2012, 254–261. [CrossRef]

30. Nirmal, N.P.; Santivarangkna, C.; Rajput, M.S.; Benjakul, S.; Maqsood, S. Valorization of fish byproducts: Sources to end-product applications of bioactive protein hydrolysate. *Compr. Rev. Food Sci. Food Saf.* 2022, 21, 1803–1842. [CrossRef]

31. Maulu, S.; Nawanzki, K.; Abdel-Tawwab, M.; Khalil, H.S. Fish Nutritional Value as an Approach to Children’s Nutrition. *Front. Nutr.* 2021, 8, 780844. [CrossRef]

32. Balami, S.; Sharma, A.; Karn, R. Significance of Nutritional Value of Fish for Human Health. *Malay. J. Halal Res.* 2019, 2, 32–34. [CrossRef]

33. Abraha, B.; Tessema, H.A.; Mahmud, A.; Tsighe, K.N.; Shui, X.; Yang, F. Effect of processing methods on nutritional and physico-chemical composition of fish: A review. *MOJ Food Process. Technol.* 2016, 6, 376–382. [CrossRef]

34. Bowen, K.J.; Harris, W.S.; Kris-Etherton, P.M. Omega-3 Fatty Acids and Cardiovascular Disease: Are There Benefits? *Curr. Treat. Opt. Cardiovascular Med.* 2016, 18, 69. [CrossRef] [PubMed]

35. Aworanti, O.; Ajani, A.; Agarry, S.; Babatunde, K.; Akinwumi, O. Evaluation of process parameters for biodiesel production from vegetable and palm waste frying oils using a homogeneous catalyst. *Int. J. Ener. Eng.* 2019, 9, 25–35.
36. Sangiia, F.; Martin, H.; Matemu, A. African nightshades (Solanum nigrum complex): The potential contribution to human nutrition and livelihoods in sub-Saharan Africa. *Conpr. Rev. Food Sci. Food Saf.* **2021**, *20*, 3284–3318. [CrossRef]
37. Hernandez, L.H.; Hardy, R.W. Vitamin A functions and requirements in fish. *Aquac. Res.* **2020**, *51*, 3061–3071. [CrossRef]
38. Hawk, J.L.M. Safe, mild ultraviolet-B exposure: An essential human requirement for vitamin D and other vital bodily parameter adequacy: A review. *Photodermatol. Photoinmunol. Photomed.* **2020**, *36*, 417–423. [CrossRef]
39. Lilly, T.T.; Jayasanta, I.; Jamila, P. Macro and micronutrients of selected marine fishes in Tuticorin, South East coast of India. *Int. Food Res. J.* **2017**, *24*, 191–201.
40. Marques, I.; Botelho, G.; Guiné, R.P.F. Comparative study on nutritional composition of fish available in Portugal. *Nutr. Food Sci.* **2019**, *49*, 925–941. [CrossRef]
41. Gorini, F.; Sabatino, L.; Pingitore, A.; Vassalle, C. Selenium: An Element of Life Essential for Thyroid Function. *Molecules* **2021**, *26*, 7084. [CrossRef]
42. Sihotang, M.; Sinuhaji, P.; Aisyah, D. Synthesis and characterization of pure natural hydroxyapatite from fishbone biowaste of coastal communities. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *305*, 012072. [CrossRef]
43. Antony Jesu Prabhu, P.; Schrama, J.W.; Kaushik, S.J. Mineral requirements of fish: A systematic review. *Rev. Aquac.* **2016**, *8*, 172–219. [CrossRef]
44. Getu, A.; Misganaw, K. Post-harvesting and Major Related Problems of Fish Production. *Fish. Aquac. J.* **2015**, *6*. [CrossRef]
45. Speranza, B.; Racioppo, A.; Bevilacqua, A.; Buzzo, V.; Mariglano, P.; Mocerino, E.; Scognamiglio, R.; Corbo, M.R.; Scognamiglio, G.; Sinigaglia, M. Innovative Preservation Methods Improving the Quality and Safety of Fish Products: Beneficial Effects and Limits. *Foods* **2021**, *10*, 2854. [CrossRef]
46. Casas-Godoy, L.; Arellano-Plaza, M.; Kirchmayr, M.; Barrera-Martinez, I.; Gschaedler-Mathis, A. Preservation of non-Saccharomyces yeasts: current technologies and challenges. *Compr. Rev. Food Sci. Food Saf.* **2019**, *20*, 3464–3503. [CrossRef]
47. Pan, C.; Chen, S.; Hao, S.; Yang, X. Effect of low-temperature preservation on quality changes in Pacific white shrimp, *Litopenaeus vannamei*: A review. *J. Sci. Food Agric.* **2019**, *99*, 6121–6128. [CrossRef]
48. Baboo, J.; Kilbride, P.; Delahaye, M.; Milne, S.; Fonseca, F.; Blanco, M.; Meneghel, J.; Gaddum, N.; Morris, G.J. The Impact of Varying Cooling and Thawing Rates on the Quality of Cryopreserved Human Peripheral Blood T Cells. *Sci. Rep.* **2019**, *9*, 3417. [CrossRef]
49. Amaral, R.A.; Pinto, C.A.; Lima, V.; Tavares, J.; Martins, A.P.; Fidalgo, L.G.; Silva, A.M.; Gil, M.M.; Teixeira, P.; Barbosa, J.; et al. Chemical-Based Methodologies to Extend the Shelf Life of Fresh Fish—A Review. *Foods* **2021**, *10*, 2300. [CrossRef]
50. Zhu, Z.; Li, T.; Sun, D.W. Pressure-related cooling and freezing techniques for the food industry: Fundamentals and applications. *Crit. Rev. Food Sci. Nutr.* **2021**, *61*, 2793–2808. [CrossRef]
51. Rosmini, M.; Perez-Alvarez, J.; Fernandez-Lopez, J. Operational processes for frozen red meat. In *Handbook of Frozen Foods*; Marcel Dekker Inc.: New York, NY, USA, 2004; pp. 177–191.
52. Hassoun, A.; Shumilina, E.; Di Donato, F.; Foschi, M.; Simal-Gandara, J.; Biancolillo, A. Emerging Techniques for Differentiation of Fish. *Aquac. J.* **2015**, *9*, 2068–2077. [CrossRef]
53. Prabhakar, P.K.; Vatsa, S.; Srivastav, P.P.; Pathak, S.S. A comprehensive review on freshness of fish and assessment: Analytical methods and recent innovations. *Food Res. Int.* **2020**, *133*, 109157. [CrossRef] [PubMed]
54. Tryggyason, R.I.; Margeirsson, B.; Karlsson, O.; Gudjonsdottir, A.; Gudjonsdottir, A.; Aarason, S. Effects of food container depth on the quality and yield of superchilled and iced Atlantic salmon. *Packag. Technol. Sci.* **2020**, *33*, 289–302. [CrossRef]
55. Magnusson, O.; Haugland, A.; Hemmingsen, A.; Johansen, S.; Nordtvedt, T. Advances in superchilling of food—Process characteristics and product quality. *Trends Food Sci. Technol.* **2008**, *19*, 418–424. [CrossRef] [PubMed]
56. Huan, T.; Wang, L. The microbial safety of fish and fish products: Recent advances in understanding its significance, contamination sources, and control strategies. *Compr. Rev. Food Sci. Food Saf.* **2021**, *20*, 738–786. [CrossRef]
57. Gokoglu, N. Novel natural food preservatives and applications in seafood preservation: A review. *J. Sci. Food Agric.* **2019**, *99*, 2068–2077. [CrossRef]
58. Sindelar, J.J.; Houser, T.A. Alternative Curing Systems. In *Ingredients in Meat Products: Properties, Functionality and Applications*; Tarté, R.; Ed.; Springer: New York, NY, USA, 2009; pp. 379–405. [CrossRef]
59. Ray, B. Control of Microorganisms in Foods. In *Fundamental Food Microbiology*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2004; pp. 439–534.
60. Rybicka, I.; Nunes, M.L. Benefit and risk assessment of replacing of sodium chloride by other salt/substances in industrial seafood products. *EFSA J.* **2022**, *20*, 200420. [CrossRef]
61. Raffaelli, S.; Quek, S.Y.; Ojahg, S.M.; Aliashahi, A.R. Effects of cumin (*Cuminum cyminum*) seed and wild mint (*Mentha longifolia*) leaf extracts on the shelf life and quality of rainbow trout (*Oncorhynchus mykiss*) fillets stored at 4 °C ± 1. *J. Food Saf.* **2016**, *36*, 271–281. [CrossRef]
62. Ozogul, Y.; Kuley, E. Antimicrobial influence of nanoemulsified lemon essential oil and pure lemon essential oil on food-borne pathogens and fish spoilage bacteria. *Int. J. Food Microbiol.* **2019**, *306*, 108266. [CrossRef]
Li, J.; Hui, T.; Wang, F.; Li, S.; Cui, B.; Cui, Y.; Peng, Z. Chinese red pepper (Capsicum annuum L.) during refrigerated storage. *Int. J. Food Microbiol.* **2017**, *249*, 1–8. [CrossRef] [PubMed]

Mehdizadeh, T.; Tajik, H.; Jafarie, S.; Kaboudari, A. Effect of *Salvia officinalis* L. extract on chemical, microbial, sensory and shelf life of rainbow trout fillet. *Food Sci. Biotechnol.* **2019**, *28*, 1499–1506. [CrossRef] [PubMed]

Duman, M.; Coban, O.E.; Ozpolat, E. Effects of rosemary and thyme oils on shelf life of marinated sauce crayfish. *J. Anim. Plant Sci.* **2015**, *25*, 1771–1778.

Wu, T.; Ge, Y.; Li, Y.; Xiang, Y.; Jiang, Y.; Hu, Y. Quality enhancement of large yellow croaker treated with edible coatings based on chitosan and lysozyme. *Int. J. Biol. Macromol.* **2018**, *120*, 1072–1079. [CrossRef] [PubMed]

Yu, D.; Jiang, Q.; Xu, Y.; Xia, W. The shelf life extension of refrigerated grass carp (*Ctenopharyngodon idella*) fillets by chitosan coating combined with glycerol monolaurate. *Int. J. Biol. Macromol.* **2017**, *101*, 448–454. [CrossRef] [PubMed]

Khodanazary, A. Quality characteristics of refrigerated mackerel *Scomberomorus commerson* using gelatin-polycaprolactone composite film incorporated with lysozyme and pomegranate peel extract. *Int. J. Food Prep.* **2019**, *22*, 2057–2071. [CrossRef]

Shokri, S.; Ehsani, A.; Josaur, M.S. Efficacy of lactoperoxidase system-whey protein coating on shelf-life extension of rainbow trout fillets during cold storage (4 °C). *Food Bioprod. Technol.* **2015**, *8*, 54–62. [CrossRef]

Boulares, M.; Ben Moussa, O.; Mankai, M.; Sadok, S.; Hassouna, M. Effects of lactic acid bacteria and citrus essential oil on the quality of vacuum-packed sea bass (*Dicentrarchus labrax*) fillets during refrigerated storage. *J. Aquat. Food Prod. Technol.* **2018**, *27*, 698–711. [CrossRef]

Woraproyote, W.; Pumpluang, L.; Tosukhowong, A.; Zendo, T.; Sonomoto, K.; Benjakul, S.; Visessanguan, W. Effect of cinnamon essential oil on bacterial diversity and shelf-life in vacuum-packed common carp (*Cyprinus carpio* L.) during refrigerated storage. *Food Control* **2017**, *84*, 218–224. [CrossRef]

Asensio, C.M.; Quiroga, P.R.; Huang, Q.; Nepote, V.; Grosso, N.R. Fatty acids, volatile compounds and microbial quality preservation with an oregano nanoemulsion to extend the shelf life of hake (*Merluccius hubbsi*) burgers. *Int. J. Food Sci. Technol.* **2019**, *54*, 149–160. [CrossRef]
91. Messina, C.M.; Bono, G.; Renda, G.; La Barbera, L.; Santulli, A. Effect of natural antioxidants and modified atmosphere packaging in preventing lipid oxidation and increasing the shelf-life of common dolphinfish ( Coryphaena hippurus ) fillets. LWT 2015 , 62 , 271–277. [CrossRef]

92. Ramezanizadeh, Z.; Zarei, M.; Raminzadeh, N. Comparing the effectiveness of chitosan and nanochitosan coatings on the quality of refrigerated silver carp fillets. Food Control 2015 , 51 , 43–48. [CrossRef]

93. Zheng, X.; He, Y.; Zhou, H.; Xiong, C. Effects of Chitosan Oligosaccharide–Nisin Conjugates Formed by Maillard reaction on the preservation of Collicthys natrix. J. Food Process. Preserv. 2019 , 43 , 14116. [CrossRef]

94. D’Amore, T.; Di Taranto, A.; Berardi, G.; Vita, V.; Marchesani, G.; Chiaravalle, A.E.; Iammarino, M. Sulfites in meat: Occurrence, activity, toxicity, regulation, and detection. A comprehensive review. Compr. Rev. Food Sci. Food Saf. 2020 , 19 , 2701–2720. [CrossRef]

95. Davidson, P.M.; Sofos, J.N.; Branen, A.L. Food Antimicrobials. In Antimicrobials in Food , 3rd ed.; CRC Press: Boca Raton, FL, USA, 2005; pp. 12–17, 29, 68, 116, 151, 460–469.

96. Bensid, A.; El Abed, N.; Houicher, A.; Regenstein, J.M.; Özogul, F. Antioxidant and antimicrobial preservatives: Properties, mechanism of action and applications in food—a review. Crit. Rev. Food Sci. Nutr. 2022 , 62 , 2985–3001. [CrossRef] [PubMed]

97. Matamoros, S.; Pilet, M.F.; Gigout, F.; Prévost, H.; Leroi, F. Selection and evaluation of seafood-borne psychrotrophic lactic acid bacteria as inhibitors of pathogenic and spoilage bacteria. Food Microbiol. 2009 , 26 , 638–644. [CrossRef] [PubMed]

98. Shahidi, F.; Ambigaipalan, P. Phenolics and polyphenolics in foods, beverages and spices: Antioxidant activity and health effects—A review. J. Funct. Foods 2015 , 18 , 820–897. [CrossRef]

99. Andrés-Lacueva, C.; Castanhete, I.; Cruz, J.; Paseiro, P.; Sanches-Silva, A. Analytical strategies to evaluate antioxidants in food: A review. Trends Food Sci. Technol. 2010 , 21 , 229–246. [CrossRef]

100. Simitzis, P.; Deligeorgis, S. Lipid oxidation of meat and use of essential oils as antioxidants in meat products. 2010. Available online: http://scitopics.com/Lipid_Oxidation_of_Meat_and_Use_of_Essential_Oils_as_Antioxidants_in_Meat_Products.html (accessed on 27 September 2022).

101. Estevez, A.Y.; Boateng, Y.; Lipps, J.; Stdler, B.; Erlichman, J.S. Analysis of the antioxidant enzyme-mimetic activity and neuroprotective effects of cerium oxide nanoparticles stabilized with varying ratios of citric acid and EDTA. FASEB J. 2018 , 32 , 740–743. [CrossRef]

102. Finnegan, S.; Percival, S.L. EDTA: An Antimicrobial and Antibiofilm Agent for Use in Wound Care. Adv. Wound Care 2015 , 4 , 415–421. [CrossRef]

103. Ali, A.; Wei, S.; Liu, Z.; Fan, X.; Sun, Q.; Xia, Q.; Liu, S.; Hao, J.; Deng, C. Non-thermal processing technologies for the recovery of bioactive compounds from marine by-products. LWT 2021 , 147 , 111549. [CrossRef]

104. Gavahian, M.; Farahnaky, A. Ohmic-assisted hydridostillation technology: A review. Trends Food Sci. Technol. 2018 , 72 , 153–161. [CrossRef]

105. Gavahian, M.; Chu, Y.-H.; Sastry, S. Extraction from Food and Natural Products by Moderate Electric Field: Mechanisms, Benefits, and Potential Industrial Applications. Compr. Rev. Food Sci. Food Saf. 2018 , 17 , 1040–1052. [CrossRef]

106. Mannozzi, C.; Fauster, T.; Haas, K.; Tylewicz, U.; Romani, S.; Dalla Rosa, M.; Jaeger, H. Role of thermal and electric field effects during the pre-treatment of fruit and vegetable mash by pulsed electric fields (PEF) and ohmic heating (OH). Innov. Food Sci. Emerg. Technol. 2018 , 48 , 131–137. [CrossRef]

107. Gómez, B.; Munekata, P.E.S.; Gavahian, M.; Barba, F.J.; Martí-Quijal, F.J.; Bolumar, T.; Campagnol, P.C.B.; Tomasevic, I.; Lorenzo, J.M. Application of pulsed electric fields in meat and fish processing industries: An overview. Food Res. Int. 2019 , 123 , 95–105. [CrossRef] [PubMed]

108. Chotphruethipong, L.; Aluko, R.E.; Benjakul, S. Effect of Pulsed Electric Field-Assisted Process in Combination with Porcine Lipase on Defatting of Seabass Skin. J. Food Sci. 2019 , 84 , 1799–1805. [CrossRef] [PubMed]

109. Franco, D.; Munekata, P.E.S.; Agregán, R.; Bermúdez, R.; López-Pedrouso, M.; Pateiro, M.; Lorenzo, J.M. Application of Pulsed Electric Fields for Obtaining Antioxidant Extracts from Fish Residues. Antioxidants 2020 , 9 , 90. [CrossRef] [PubMed]

110. Fan, K.; Su, W.-H. Applications of Fluorescence Spectroscopy, RGB- and MultiSpectral Imaging for Quality Determinations of White Meat: A Review. Biosensors 2022 , 12 , 76. [CrossRef] [PubMed]

111. Hassoun, A.; Karoui, R. Front-face fluorescence spectroscopy coupled with chemometric tools for monitoring fish freshness stored under different refrigerated conditions. Food Control. 2015 , 54 , 240–249. [CrossRef]

112. Wang, K.; Sun, D.-W.; Pu, H.; Wei, Q. Principles and applications of spectroscopic techniques for evaluating food protein conformational changes: A review. Trends Food Sci. Technol. 2017 , 67 , 207–219. [CrossRef]

113. Hu, L.; Ren, S.; Shen, Q.; Chen, J.; Ye, X.; Ling, J. Proteomic study of the effect of different cooking methods on protein oxidation in fish fillets. RSC Adv. 2017 , 7 , 27496–27505. [CrossRef]

114. Hassoun, A.; Sahar, A.; Lakhal, L.; Ait Kaddour, A. Fluorescence spectroscopy as a rapid and non-destructive method for monitoring quality and authenticity of fish and meat products: Impact of different preservation conditions. LWT 2019 , 103 , 279–292. [CrossRef]

115. Ozaki, Y. Infrared Spectroscopy-Mid-infrared, Near-infrared, and Far-infrared/Terahertz Spectroscopy. Anal. Sci. 2021 , 37 , 1193–1212. [CrossRef]
116. Feng, C.H.; Makino, Y.; Oshita, S.; García Martín, J. Hyperspectral imaging and multispectral imaging as the novel techniques for detecting defects in raw and processed meat products: Current state-of-the-art research advances. *Food Control* 2018, 84, 165–176. [CrossRef]

117. Antequera, T.; Caballero, D.; Grassi, S.; Uttaro, B.; Perez-Palacios, T. Evaluation of fresh meat quality by Hyperspectral Imaging (HSI), Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI): A review. *Meat Sci.* 2021, 172, 108340. [CrossRef][PubMed]

118. Cheng, J.H.; Nicolai, B.; Sun, D.W. Hyperspectral imaging with multivariate analysis for technological parameters prediction and classification of muscle foods: A review. *Meat Sci.* 2017, 123, 182–191. [CrossRef][PubMed]

119. Ropodi, A.; Panagou, E.; Nychas, G.-J. Multispectral imaging (MSI): A promising method for the detection of minced beef adulteration with horsemeat. *Food Chem.* 2016, 57–63. [CrossRef]

120. Cheng, J.-H.; Sun, D.-W.; Pu, H.; Zhu, Z. Development of hyperspectral imaging coupled with chemometric analysis to monitor K value for evaluation of chemical spoilage in fish fillets. *Food Chem.* 2015, 183, 245–253. [CrossRef]

121. Ma, J.; Sun, D.-W.; Qu, J.-H.; Pu, H. Prediction of textural changes in grass carp fillets as affected by vacuum freeze drying using hyperspectral imaging based on integrated group wavelengths. *LWT* 2017, 82, 377–385. [CrossRef]

122. Huang, H.-W.; Wu, S.-J.; Lu, J.-K.; Shyu, Y.-T.; Wang, C.-Y. Current status and future trends of high-pressure processing in food industry. *Food Control* 2017, 72, 1–8. [CrossRef]

123. Tsironi, T.; Maltezou, I.; Tsievou, M.; Katsaros, G.; Taoukis, P. High-pressure cold pasteurization of gilthead seabream fillets: Selection of process conditions and validation of shelf life extension. *Food Bioprocess Technol.* 2015, 8, 681–690. [CrossRef]

124. Tsironi, T.; Anjos, L.; Pinto, P.I.; Dimopoulos, G.; Santos, S.; Santa, C.; Manadas, B.; Canario, A.; Taoukis, P.; Power, D. High pressure processing of European sea bass (*Dicentrarchus labrax*) fillets and tools for flesh quality and shelf life monitoring. *J. Food Eng.* 2019, 262, 83–91. [CrossRef]

125. Martinez, S.; Armesto, J.; Gómez-Limia, L.; Carballo, J. Impact of processing and storage on the nutritional and sensory properties and bioactive components of *Brassica* spp. A review. *Food Chem.* 2020, 313, 126065. [CrossRef]

126. Barbosa, R.G.; Trigo, M.; Fett, R.; Aubourg, S.P. Impact of a packing medium with alga *Bifurcaria bifurcata* extract on canned Atlantic mackerel (*Scomber scombrus*) quality. *J. Sci. Food Agric.* 2018, 98, 3462–3467. [CrossRef]

127. Romotowska, P.E.; Gudjónsdóttir, M.; Kristinsdóttir, T.B.; Karlsson, M.G.; Arason, S.; Jónsson, Á.; Kristinsson, H.G. Effect of brining and frozen storage on physicochemical properties of well-fed Atlantic mackerel (*Scomber scombrus*) intended for hot smoking and canning. *LWT* 2016, 72, 199–205. [CrossRef]

128. Quijera, J.; Labidi, J. Different integration alternatives of thermostermal energy and heat pump technology in a fish canning process. *Chem. Eng. Trans.* 2013, 35, 511–516.

129. Dominguez-Hernandez, E.; Salasevicene, A.; Erbbjerg, P. Low-temperature long-time cooking of meat: Eating quality and underlying mechanisms. *Meat Sci.* 2018, 143, 104–113. [CrossRef]

130. De Aguiar Saldanha Pinheiro, A.C.; Marti-Quijal, F.J.; Barba, F.J.; Tappi, S.; Rocculli, P. Innovative Non-Thermal Technologies for Recovery and Valorization of Value-Added Products from Crustacean Processing By-Products—An Opportunity for a Circular Economy Approach. *Foods* 2021, 10, 2030. [CrossRef]

131. Addis, M. Major Causes Of Meat Spoilage and Preservation Techniques: A Review. *Food Sci. Qual. Manag.* 2015, 41, 101–114.

132. Xiaobo, Z.; Xiaowei, H.; Povey, M. Non-invasive sensing for food reassurance. *Analyst* 2016, 141, 1587–1610. [CrossRef][PubMed]

133. Marti-Quijal, F.J.; Remize, F.; Meca, G.; Ferrer, E.; Ruiz, M.-J.; Barba, F.J. Fermentation in fish and by-products processing: An overview of current research and future prospects. *Curr. Opin. Food Sci.* 2020, 31, 9–16. [CrossRef]

134. Tsironi, T.N.; Taoukis, P.S. Advances in Conventional and Nonthermal Processing of Fish for Quality Improvement and Shelf Life Extension. In *Reference Module in Food Science*; Elsevier: Amsterdam, The Netherlands, 2019.

135. Afseth, N.K.; Wold, J.P.; Segtman, V.H. The potential of Raman spectroscopy for characterisation of the fatty acid unsaturation of salmon. *Anal. Chim. Acta* 2006, 572, 85–92. [CrossRef][PubMed]

136. Cozzolino, D.; Murray, I. A review on the application of infrared technologies to determine and monitor composition and other quality characteristics in raw fish, fish products, and seafood. *Appl. Spectr. Rev.* 2012, 47, 207–218. [CrossRef]

137. Mathiassen, J.R.; Misimi, E.; Bonde, M.; Veliyulín, E.; Østvik, S.O. Trends in application of imaging technologies to inspection of fish and fish products. *Trends Food Sci. Technol.* 2011, 22, 257–275. [CrossRef]

138. Medina, S.; Perestrello, R.; Silva, P.; Pereira, J.; Cámara, J. Current trends and recent advances on food authenticity technologies and chemometric approaches. *Trends Food Sci. Technol.* 2019, 85, 163–176. [CrossRef]

139. Chemat, F.; Rombaut, N.; Meulemister, A.; Turk, M.; Perino, S.; Fabiano-Tixier, A.-S.; Abert-Vian, M. Review of Green Food Processing techniques. Preservation, transformation, and extraction. *Innov. Food Sci. Emerg. Technol.* 2017, 41, 357–377. [CrossRef]

140. Sánchez-Camargo, A.P.; Almeida Meireles, M.; Lopes, B.L.F.; Cabral, F.A. Proximate composition and extraction of carotenoids and lipids from Brazilian redspotted shrimp waste (*Farfantepenaeus paulensis*). *J. Food Eng.* 2011, 102, 87–93. [CrossRef]

141. Yang, H.; Wang, H.; Huang, M.; Cao, G.; Tao, F.; Shen, Q.; Zhou, G.; Yang, H. Repurposing fish waste into gelatin as a potential alternative for mammalian sources: A review. *Compr. Rev. Food Sci. Food Saf.* 2022, 21, 942–963. [CrossRef]

142. Ivanovs, K.; Spalvins, K.; Blumberga, D. Approach for modelling anaerobic digestion processes of fish waste. *Energy Procedia* 2018, 147, 390–396. [CrossRef]

143. Korkmaz, K.; Tokur, B. Investigation of the quality parameters of hydrolysates obtained from fish by-products using response surface methodology. *J. Food Process. Preserv.* 2022, 46, 16296. [CrossRef]
144. Usman, M.; Sahar, A.; Inam-Ur-Raheem, M.; Rahman, U.U.; Sameen, A.; Aadil, R.M. Gelatin extraction from fish waste and potential applications in food sector. *Int. J. Food Sci. Technol.* 2022, 57, 154–163. [CrossRef]

145. Menon, V. Enzymes from Seafood Processing Waste and Their Applications in Seafood Processing. *Adv. Food Nutr. Res.* 2016, 78, 47–69.

146. Mikolajczak, Z.; Rawski, M.; Mazurkiewicz, J.; Kierończyk, B.; Kołodziejski, P.; Pruszyńska-Osmałek, E.; Józefiak, D. The first insight into black soldier fly meal in brown trout nutrition as an environmentally sustainable fish meal replacement. *Animal* 2022, 16, 100516. [CrossRef]

147. Merkle, S.; Giese, E.; Rohn, S.; Karl, H.; Lehmann, I.; Wohltmann, A.; Fritsche, J. Impact of fish species and processing technology on minor fish oil components. *Food Control* 2017, 73, 1379–1387. [CrossRef]

148. Ivanovs, K.; Blumberga, D. Extraction of fish oil using green extraction methods: A short review. *Energy Procedia* 2017, 128, 477–483. [CrossRef]

149. Jung, J.-M.; Oh, J.-I.; Park, Y.-K.; Lee, J.; Kwon, E.E. Biodiesel synthesis from fish waste via thermally-induced transesterification using clay as porous material. *J. Hazard. Mater.* 2019, 371, 27–32. [CrossRef] [PubMed]

150. Bhatia, S.K.; Jagtap, S.S.; Bedekar, A.A.; Bhatia, R.K.; Rajendran, K.; Pugazhendhi, A.; Rao, C.V.; Atabani, A.E.; Kumar, G.; Yang, Y.H. Renewable biohydrogen production from lignocellulosic biomass using fermentation and integration of systems with other energy generation technologies. *Sci. Total Environ.* 2021, 765, 144429. [CrossRef] [PubMed]

151. Shanthi, G.; Premalatha, M.; Anantharaman, N. Potential utilization of fish waste for the sustainable production of microalgae rich in renewable protein and phycocyanin-Arthroptria platensis/Spirulina. *J. Clean. Prod.* 2021, 294, 126106. [CrossRef]

152. Ahuja, I.; Dauksas, E.; Remme, J.F.; Richardsen, R.; Lees, A.K. Fish and fish waste-based fertilizers in organic farming—With status in Norway: A review. *Waste Manag.* 2020, 115, 99–112. [CrossRef]

153. Kim, J.K.; Jung, H.Y.; Cho, J.Y.; Kim, N.Y. Production of biofuels, bioactive compounds, and fertilizers from fishery waste and wastewater. In *Advanced Technology for the Conversion of Waste into Fuels and Chemicals*; Woodhead Publishing: Thornton, UK, 2021; pp. 149–181.

154. Gao, R.; Yu, Q.; Shen, Y.; Chu, Q.; Chen, G.; Fen, S.; Yang, M.; Yuan, L.; Mc Clements, D.J.; Sun, Q. Production, bioactive properties, and potential applications of functional fish hydrolysates: Methodologies and challenges. *Trends Food Sci. Technol.* 2021, 110, 687–699. [CrossRef]

155. Yasaman, E. Development of animal/plant-based protein hydrolysate and its application in food, feed and nutraceutical industries: State of the art. *J. Cleaner Prod.* 2021, 278, 123219. [CrossRef]

156. Pérez-Gálvez, R.; Morales-Medina, R.; Espejo-Carpio, F.; Guadix, A.; Guadix, E.M. Modelling of the production of ACE inhibitory hydrolysates of horse mackerel under enzymatic and microbial hydrolysis. *Food Funct.* 2016, 7, 3890–3901. [CrossRef]

157. Harney, P.A.; Parthsarathy, V.; McLaughlin, C.M.; O’Keeffe, M.B.; Allsopp, P.J.; McSorley, E.M.; O’Harte, F.P.M.; FitzGerald, R.J. Blue whitening (*Micromesistius poutassou*) muscle protein hydrolysate with in vitro and in vivo anti diarrheic activities. *J. Funct. Foods* 2018, 40, 137–145. [CrossRef]

158. Rahmi, M.; Faid, M.; Elyachioui, M.; Berny, E.; Fakir, M.; Oubssine, M. Protein rich ingredients from fish waste for sheep feeding. *Afr. J. Microbiol. Res.* 2008, 2, 73–77.

159. Jafari, H.; Lista, A.; Siekapan, M.M.; Ghaffari-Bohiouli, P.; Nie, L.; Alimoradi, H.; Shavandi, A. Fish Collagen: Extraction, Characterization, and Applications for Biomaterials Engineering. *Polymers* 2020, 12, 2230. [CrossRef] [PubMed]

160. Subban, F.; Hussain, Z.; Tauseef, I.; Shehzad, A.; Wahid, F. A review on recent advances and applications of fish collagen. *Crit. Rev. Food Sci. Nutr.* 2021, 61, 1027–1037. [CrossRef] [PubMed]

161. Sibilla, S.; Godfrey, M.; Brewer, S.; Buddh-Raja, A.; Genovese, L. An Overview of the Beneficial Effects of Hydrolysed Collagen as a Nutraceutical on Skin Properties: Scientific Background and Clinical Studies. *Open Nutr. J.* 2015, 8, 29–42. [CrossRef]

162. Peres, D.; Hubner, A.; Oliveira, C.; Almeida, T.; Kaneko, T.; Consiglieri, V.; Pinto, C.; Velasco, M.; Baby, A. Hydrolyzed collagen interferes with in vitro photoprotective effectiveness of sunscreens. *Brazil. J. Pharm. Sci.* 2017, 53, e16119. [CrossRef]

163. Kaewdang, O.; Benjakul, S. Effect of ethanolic extract of coconut husk on gel properties of gelatin from swim bladder of yellowfin tuna. *LWT* 2015, 62, 955–961. [CrossRef]

164. Al-Nimry, S.; Dayah, A.A.; Hasan, I.; Daghamsh, R. Cosmetic, Biomedical and Pharmaceutical Applications of Fish Gelatin/Hydrolysates. *Mar. Drugs* 2019, 17, 145. [CrossRef] [PubMed]

165. Karim, A.A.; Bhat, R. Fish gelatin: Properties, challenges, and prospects as an alternative to mammalian gelatins. *Food Hydrocoll.* 2009, 23, 563–576. [CrossRef]

166. Tongnuanchan, P.; Benjakul, S.; Prodpran, T.; Pisuchpen, S.; Osaka, K. Mechanical, thermal and heat sealing properties of fish skin gelatin film containing palm oil and basil essential oil with different surfactants. *Food Hydrocoll.* 2016, 56, 93–107. [CrossRef]

167. Caruso, G.; Floris, R.; Serangeli, C.; Di Paola, L. Fishery Wastes as a Yet Undiscovered Treasure from the Sea: Biomolecules Sources, Extraction Methods and Valorization. *Mar. Drugs* 2020, 18, 622. [CrossRef]

168. Suresh, P.V.; Kudre, T.G.; Johny, L.C. Sustainable Valorization of Seafood Processing By-Product/Discard. In *Waste to Wealth*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 111–139.

169. Jesús-de la Cruz, K.; Álvarez-González, C.A.; Peña, E.; Morales-Contreras, J.A.; Ávila-Fernández, A. Fish trypsin: Potential applications in biomedicine and prospects for production. *Biotech* 2018, 8, 186. [CrossRef]

170. Nalinanon, S.; Benjakul, S.; Visessanguan, W.; Kishimura, H. Tuna Pepsin: Characteristics and Its Use for Collagen Extraction from the Skin of Threadfin Bream (*Nemipterus spp.*). *J. Food Sci.* 2008, 73, C413–C419. [CrossRef]
171. Idowu, A.T.; Benjakul, S. Bitterness of fish protein hydrolysate and its debittering prospects. *J. Food Biochem.* 2019, 43, e12978. [CrossRef] [PubMed]

172. Sae-leaw, T.; Benjakul, S. Lipase from liver of seabass (*Lates calcarifer*): Characteristics and the use for defatting of fish skin. *Food Chem.* 2018, 240, 9–15. [CrossRef] [PubMed]

173. Rodrigues, R.C.; Virgen-Ortiz, J.J.; Dos Santos, J.C.S.; Berenguer-Murcia, Á.; Alcantara, A.R.; Barbosa, O.; Ortiz, C.; Fernandez-Lafuente, R. Immobilization of lipases on hydrophobic supports: Immobilization mechanism, advantages, problems, and solutions. *Biotechnol. Adv.* 2019, 37, 746–770. [CrossRef]

174. Kurtovic, I.; Marshall, S.N. Potential of fish by-products as a source of novel marine lipases and their uses in industrial applications. *Lipid Technol.* 2013, 25, 35–37. [CrossRef]

175. Choudhury, P. Industrial application of lipase: A review. *BioPharm* 2015, 1, 41–47.

176. Lall, S.P.; Kaushik, S.J. Nutrition and Metabolism of Minerals in Fish. *Animals* 2021, 11, 2711. [CrossRef] [PubMed]

177. Yamada, S.; Yamamoto, K.; Nakazono, A.; Matsuura, T.; Yoshimura, A. Functional roles of fish collagen peptides on bone regeneration. *Dent. Mater. J.* 2021, 40, 1295–1302. [CrossRef]

178. Ucak, I.; Khalily, R.; Abuibaid, A.; Ogunkalu, O. Maintaining the quality of rainbow trout (*Oncorhynchus mykiss*) fillets by treatment of red onion peel extract during refrigerated storage. *Progr. Nutr.* 2018, 20, 672–678. [CrossRef]