Comprehensive REVIEWS in Food Science and Food Safety

Nonthermal Processes for Shelf-Life Extension of Seafoods: A Revisit

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Abstract: For the past two decades, consumer demand for minimally processed seafoods with good sensory acceptability and nutritive properties has been increasing. Nonthermal food processing and preservation technologies have drawn the attention of food scientists and manufacturers because nutritional and sensory properties of such treated foods are minimally affected. More importantly, shelf-life is extended as nonthermal treatments are capable of inhibiting or killing both spoilage and pathogenic organisms. They are also considered to be more energy-efficient and to yield better quality when compared with conventional thermal processes. This review provides insight into the nonthermal processing technologies currently used for shelf-life extension of seafoods. Both pretreatments such as acidic electrolyte water and ozonification and processing technologies, including high hydrostatic pressurization, ionizing radiation, cold plasma, ultraviolet light, and pulsed electric fields, as well as packaging technology, particularly modified atmosphere packaging, have been implemented to lower the microbial load in seafood. Thus, those technologies may be the ideal approach for the seafood industry, in which prime quality is maintained and safety is assured for consumers.

Keywords: nonthermal process, pretreatment, quality, shelf-life, seafood, spoilage

Introduction

Seafoods, including various species of fish, molluscs, crustaceans, and echinoderms, have served as nutritive foods for a long time and have become popular due to their delicacy. However, they are susceptible to spoilage. Different biochemical and microbial reactions after death bring about a rapid deterioration of seafoods, thereby shortening shelf-life (Kykkidou, Giatrakou, Papavergou, Kontominas, & Savvaidis, 2009). Time and temperature are key factors for perishable products, affecting quality, particularly during transportation or distribution throughout the supply chain and storage. In general, seafood quality rapidly deteriorates as a result of temperature abuse during distribution. In addition, nature of species, handling, and storage conditions of seafood directly affect the nutritional and microbial qualities of seafood (Olafsdottir et al., 1997). Ghislenia et al. (2016) reported that factors such as feeding, initial microbiological load, season, geographical origin, and handling conditions influenced the shelf-life of seafood. Approximately 25% of all food produced is lost during postharvest handling or storage, owing to microbial activity (Baird-Parker, 2000). Therefore, it is crucial for an improved science-based understanding of the growth and activity of spoilage microorganisms in seafood for the reduction of losses by microbial spoilage and preservation techniques (Gram & Dalgaard, 2002). The preservation of seafood can be achieved not only by refrigeration or freezing (Gomez-Guillen and Montero, 2007), but also by nonthermal processes to minimize economic losses and to provide good-quality and safe products (Kykkidou et al., 2009).

Traditionally, the microbiological safety of foods has depended on thermal food processing technologies (pasteurization, sterilization, drying, and evaporation). They have been implemented for ensuring food safety (Pereira & Vicente, 2010), in which foodborne pathogens (bacteria, viruses, and parasites) are killed. The thermal process involved in food preservation depends on the nature of the food. Basically, low-temperature long-time (LTLT), known as pasteurization, and high-temperature short-time (HTST), known as sterilization, are the most commonly used techniques for juice, milk, and other beverages, whereas sterilization, drying, and evaporation are used for meat and seafoods. However, this technique leads to undesirable changes in the foods, such as reduced nutritional value or undesirable sensory attributes, mainly as a result of overheating (Garcia-Gonzalez et al., 2007; Rastogi, 2003; Stoica, Bahrim, & Cârâc, 2011; Valizadeh, Kargarsana, Shojaei, & Mehbodnia, 2009).

Consumer demand for minimally processed food, such as precut greens or fruit, or seafoods with extended shelf-life and assurance of safety, is continuously increasing. As a consequence, research has been directed towards nonthermal processing methods, which are able to destroy pathogens and spoilage organisms while retaining the sensory attributes and nutritive value similar to fresh or raw products. These alternative processing methods for enhancing the potential to destroy pathogens and maintain the desired food quality are at various stages of development. Effective treatments or technologies that are effective at sublethal or ambient temperatures are referred to as "nonthermal processing." Microorganisms are inactivated to varying degrees by pulsed light, high hydrostatic pressure, pulsed electric fields, ultraviolet

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light, high-intensity ultrasound, oscillating magnetic fields, and ionizing radiation (Butz & Tauscher, 2002). The balance between minimal processing and safety, between acceptable superior quality and economic constraints, and between traditional processing resources and novel approaches can be achieved through the development of nonthermal processing technologies for food processing (Zhang et al., 2011). This review gives updated information on nonthermal processes and their applications for shelf-life extension of seafoods, focusing on the principle and on the impact of these processes on microbial safety and shelf-life extension.

Pretreatments of Seafoods

Any treatment administered to food beforehand with the aim of improving or maintaining the nutritional, sensory, and functional properties, but lowering microbial load, is known as "pretreatment" (Micali & Fiorino, 2016). After being caught, a fish is beheaded, eviscerated, and washed. In crustaceans such as shrimps, decapitation, peeling, and deveining are practically conducted as pretreatment. Furthermore, potential pretreatment such as the use of acidic electrolyte water and ozonification have been applied for seafoods to improve their microbial qualities.

Acidic Electrolyte Water

Electrolyte water (EW) is made from water without the addition of any hazardous chemicals except sodium chloride (Kim, Hung, & Brackett, 2000a). EW is known as either a sanitizer (EW containing HOCl, an acidic electrolyte water) or a cleaner (EW containing NaOH, an alkaline electrolyte water (Rahman, Khan, & Oh, 2016). The simplicity of EW production and application is the foremost reason for its popularity. In numerous fields such as medical sterilization, agriculture, food sanitation, livestock management, and further applications, EW is gaining attention because of its antimicrobial properties (Huang, Hung, Hsu, Huang, & Hwang, 2008; Kim et al., 2000a).

Principle. Dilute NaCl in an electrolysis chamber can form EW, as illustrated in Figure 1. The chamber is composed of a diaphragm (septum or membrane) with the primary purpose to separate the anode and cathode (Hricova, Stephan, & Zweifel, 2008). In an EW generator, current values and voltage are set at 8 to 10 A and 9 to 10 V, respectively. Current passes through the generator, whereas voltage is spawned between the electrodes. During the electrolysis process, diluted NaCl in water dissociates into negatively and positively charged ions (Cl^- and Na^+, respectively). Simultaneously, hydrogen (H^+) and hydroxide (OH^-) ions are also formed from the water molecules in the solution. The positively charged ions (H^+ and Na^+) migrate toward the cathode, where electrons are gained, resulting in the generation of hydrogen gas (H_2) and sodium hydroxide (NaOH). However, negatively charged ions (Cl^- and OH^-) migrate toward the anode and release electrons. Hypochlorite ion (−OCl), oxygen gas (O_2), hypochlorous acid (HOCl), chlorine gas (Cl_2), and hydrochloric acid (HCl) are generated (Al-Haq, Sugiyama, & Isobe, 2005; Hricova et al., 2008). At the end of the electrolysis process, acidic and alkaline electrolyte water are generated simultaneously. An acidic electrolyte water (AEW) or electrolyzed oxidizing water (EOW) with oxidation reduction potential (ORP) of >1,100 mV, available chlorine concentration (ACC) of 10 to 90 ppm, and pH between 2 and 3, is produced at the anode. Meanwhile, alkaline electrolyzed water (AlEW) or basic electrolyzed water (BEW) with ORP of −800 to −900 mV and pH between 10 and 13 is produced at the cathode.

Antimicrobial efficacy and application of acidic electrolyte water for seafood preservation. Oxidation reduction potential (ORP), chlorine concentration (Cl_2, HOCl, and −OCl), and pH highly influence the antimicrobial efficacy of EW (Len, Hung, Erickson, & Kim, 2000). The formation of various chlorine species is dependent on the pH of EW. Hypochlorous acid (HOCl) has strong chlorine, and exhibits 80 times superior sanitizing power to −OCl when the pH of the solution is 5.0 to 6.5 (Cao, Zhu, Shi, Wang, & Li, 2009). At high pH, HOCl dissociates to hypochlorite ions (−OCl), whereas at low pH, it dissociates to chlorine gas (Cl_2). In the metabolic frameworks, HOCl penetrates the membranes of microbial cells and produces hydroxyl radicals, which exhibit antimicrobial action through oxidation (Huang et al., 2008). As pH increases from the acidic to the basic region, the efficiency of ORP and ACC of EW decreases. At pH value greater than 8.99, the ability of EW to deactivate all microorganisms diminishes (Rahman, Ding, & Oh, 2010). The decreased microbial population, when treated with acidic electrolyte water, can be attributed to the low pH, which makes bacterial cells more prone to dynamic chlorine by rendering their cell membrane more vulnerable to HOCl (Park, Hung, & Chung, 2004).

The impact of pH and chlorine of AEW on the bacteriostatic activity against *Escherichia coli* O157:H7 (*E. coli* O157:H7), and *Listeria monocytogenes* (*L. monocytogenes*), was investigated by Park et al. (2004). AEW effectively inactivated these organisms in a varied range of pH (2.6 to 7.0) when sufficient amounts of available chlorine (>2 mg/L) were available. Moreover, antimicrobial activity of AEW is dependent on ORP (Huang et al., 2008; Kim, Hung, & Brackett, 2000b; Liao, Chen, & Xiao, 2007). Chow, Yang, Lee, and Ochiai (2009) investigated the effects of acid and alkaline electrolyte water as pretreatments on the rate of discoloration in myoglobin extract and dark muscle of skinned tilapia fillet during iced storage and they reported that the pretreatment significantly ($p < .05$) prevented the discoloration of the dark muscle and myoglobin extract. Pretreatment also extended the shelf-life of the resulting tilapia fillets by maintaining muscle color and texture during extended storage at 4 °C for 9 days.

Limitation. One of the basic tastes easily perceived by humans is saltiness. High concentration of NaCl for acidic electrolyte water production can lead to an increase in saltiness in pretreated seafood. This can be perceived by consumers, thereby lowering the sensory acceptability of pretreated products. Chlorine ion can interact with other major components in foods, thus affecting food texture and inducing some reactions occurring during processing. However, salt enhances protein hydration and binds with proteins and fats (Man, 2007).

Ozonification

The interaction of molecular diatomic oxygen (O_2) to an oxygen atom gives rise to ozone (O_3), which is a highly unstable triatomic oxygen molecule (De Mendonça Silva & Gonçalves, 2017). Ozone has been employed as an oxidizing agent in water treatment and in the food industry and is considered a powerful sanitizer (Blogoslawski & Stewart, 2011; Gonçalves, 2016). In recent years, ozonification has attracted more interest for use in fish preservation due to its ability to reduce spoilage organisms (Glatman, Sachs, Khanin, Drabkin, & Gelman, 2006; Pastoriza, Bernardez, Sampedro, Cabo, & Herrera, 2008). Good improvement in fish quality and safety by aqueous ozone has been demonstrated by various researchers using immersion techniques (Crowe, Skonberg, Bushway, & Baxter, 2012; Gonçalves, 2016).

Principle. In general, ozone is produced when there is a ventilation of electrical discharge of voltage in the presence of an unadulterated oxygen (Guzel-Seydim, Bever, & Grene, 2004). Oxygen

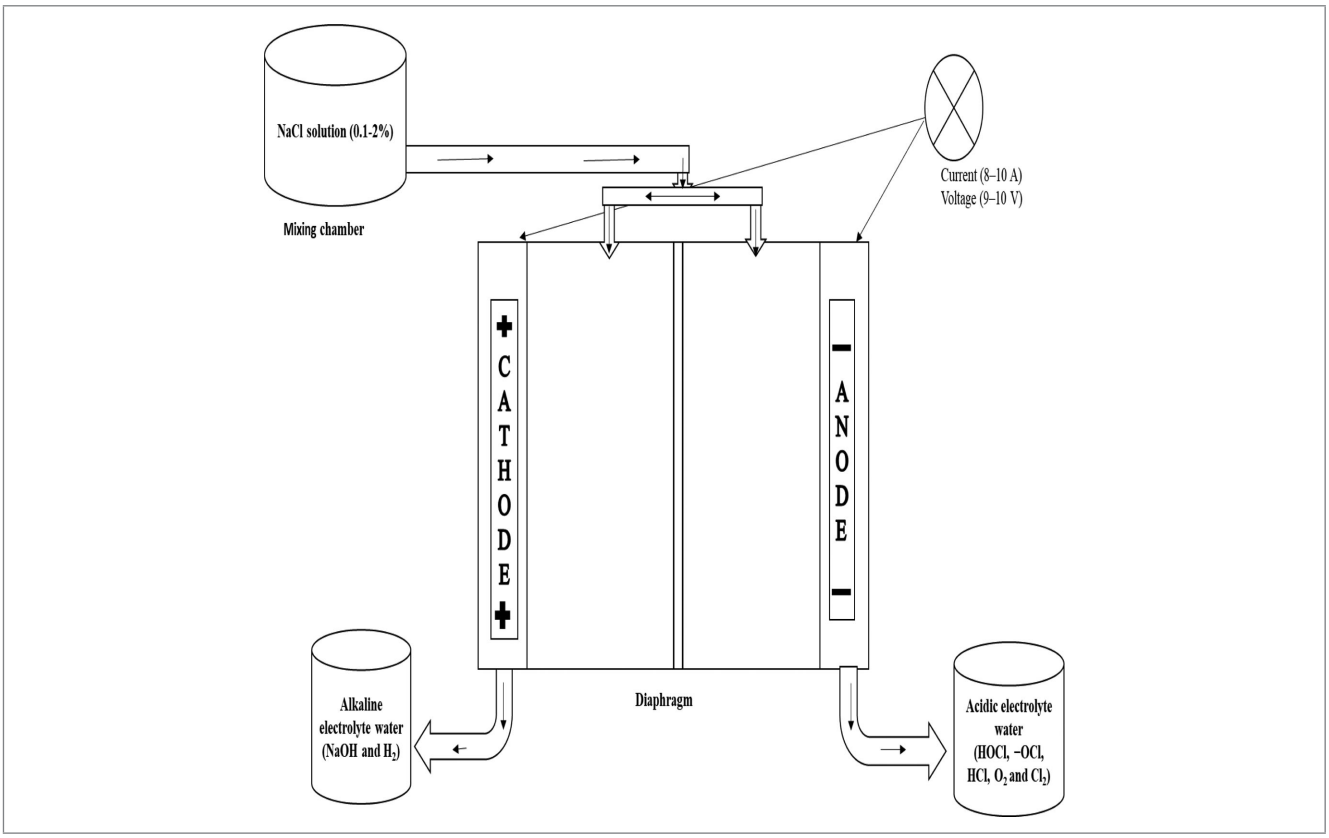

Figure 1–Electrolyte water production.

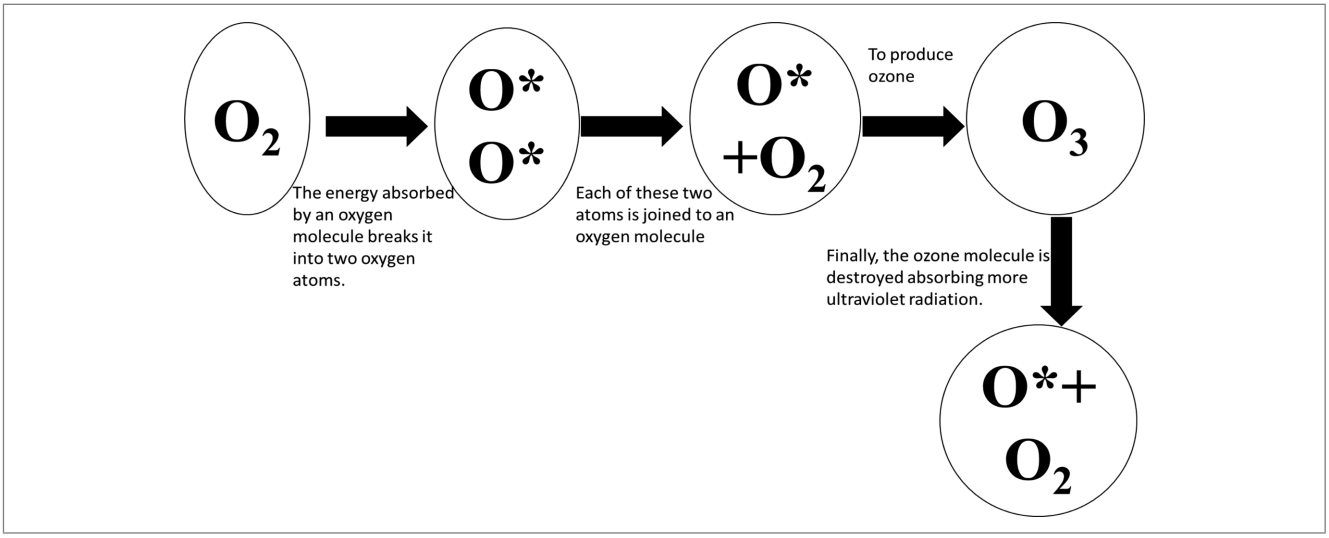

Figure 2–Ozone production using ultraviolet radiation.

molecules are separated or split into free oxygen atoms (O), and other oxygen molecules (O_2) can collide with these atoms. This leads to the formation of ozone molecules (O_3; Chawla, Bell, & Marlene, 2007; Duguet, 2004), as illustrated in Figure 2. However, a large amount of energy is essential to cleave the O–O bond (Bocci, 2006). Electrons of oxygen molecules are excited with high energy, such as chemi-nuclear sources, electrolytic processes, corona discharge (CD), and ultraviolet light (wavelengths less than 200 nm; Locke et al., 2006). For commercial purposes, ozone is potentially produced with the CD method (Ozone Solutions, 2007).

Antimicrobial efficacy and application of ozonification for seafood preservation. Gram-negative and Gram-positive bacteria, vegetative cells, and spores are significantly affected by ozonification (Guzel-Seydim et al., 2004; Pascual, Llorca, & Canut, 2007; Rong, Bang-Zhong, Qi, & Lan-Lan, 2010). Glycolipids, glycoprotein, and certain amino acids such as tryptophan in the bacterial membrane are first attacked by ozone. Alteration of sulfhydryl

groups results in bacterial cell disruption (da Silva, Franco, Sousa, & Goncalves, 2010), with enhanced cell permeability and lysis. This phenomenon often leads to bacterial death. Application methods and microbial population influence the antimicrobial efficacy of ozone (Crowe et al., 2012). Chemical composition, pH, additives, temperature, initial bacteria population, and ozone contact time with food and food surface type are factors determining the efficiency of ozone treatment on microbial reduction in seafoods (Campos, Losada, Rodríguez, Aubourg, & Barros-Velazquez, 2006; Crowe et al., 2012; Isikber & Athanassiou, 2015; Manousaridis et al., 2005; Pastoriza et al., 2008).

Gelman, Sachs, Khanin, Drabkin, and Glatman (2005) reported that pretreatment of tilapia slices with ozone prolonged shelf-life by 12 days and enhanced their quality attributes during storage at 0 °C for 30 days. The shelf-life of ozone-treated, shucked, and vacuum-packaged mussels was extended to 12 days, as compared with 9 days for untreated samples (Manousaridis et al., 2005). Dehkordi and Zokaie (2010) reported a 2 days extension in the shelf-life of trout fillets treated with ozone for 2 hr, as compared with untreated fillets. Japanese sea bass with different treatments, including (a) traditional flake ice (CK), (b) ozonized flake ice (OIce), (c) traditional flake ice (O), and (d) ozonized flake ice and ozonized water treatment (O + OIce), showed varying shelf-life as resolved by sensory evaluation, in which the shelf-life figures were 9, 15, 12, and more than 18 days, respectively (Lu, Liu, Liu, Ding, & Ding, 2012).

Freshly harvested shrimp treated with ozone for one minute was evaluated for bacterial count, TVB-N, TMA-N contents, and sensory characteristics. It could prolong the shelf-life of shrimps by 1.75 days, in comparison with the control (Okpala, 2014). Chen, Wang, Chen, Chen, & Huang (2014) reported that ozone water pretreatment could effectively extend the shelf-life and retain the quality of oysters. Shelf-life could be extended to 20 to 25 days when oysters were treated with ozone, whereas the control had a shelf-life of 5 to 10 days. Microbial contamination in whole tilapia was reduced by 88.25% by treating the fish with 1.5 ppm ozone for 15 min (De Mendonça Silva & Gonçalves, 2017).

Limitation. Although ozonification can prolong the shelf-life of seafoods by reducing the microbial load, pretreatment with ozone can induce oxidation in seafood. This may cause it to smell or taste less palatable to consumers. Due to the enhanced protein oxidation induced by ozone, the functionality of protein in seafoods can be decreased, leading to poor-quality products. Ozone is one of the strongest oxidizing agents widely used for disinfective of wastewater and removal of organic substances, and offensives odors (Boonduang & Limsuwan, 2013). There is usually a high risk of postcontamination, since ozone can only lower the microbial load before and during treatment but has less effect on prevention of contamination after treatment.

Processing Technologies for Seafood Preservation

Processing technologies such as high hydrostatic pressurization, ionizing radiation, cold plasma, ultraviolet light, and pulsed electric fields have several advantages, particularly for microbial inactivation, and they can be employed as alternatives for seafood preservation.

Pulsed Electric Field

Pulsed electric field (PEF) processing is a novel nonthermal preservation method that has the capability of producing foods with extended shelf-life, excellent nutritional quality, and acceptable sensory attributes (Kumar, Agarwal, & Pramod, 2016). PEF technology is considered superior to traditional heat treatment of foods based on food-quality attributes, because it avoids, or greatly lessens, unfavorable changes in physical and sensory properties (Mohamed & Eissa, 2012). Nevertheless, before the application of PEF in food processing, its effect on the nutritional and chemical properties of foods must be understood (Sotelo et al., 2014). PEF technology has been known to have more advantages than heat treatments, because it kills microorganisms with negligible impact on the nutritional value of food, and its flavor, original color, and texture (Kumar et al., 2016).

Principle. A source of high voltage, treatment chamber, switch, and capacitor bank make up the PEF processing system, and its production involves a rapid discharge of energy within a short duration. Microsecond high-voltage pulses in the order of 10 to 60 kV are involved in PEF processing (Kumar et al., 2016). The application of high-voltage pulses induces pores named "electroporation" in cell membranes, initiating a loss of barrier function, intracellular content leakage, and loss of vitality. The treatment is applied uninterruptedly in a chamber (setup of multiple electrodes). The product is exposed to the high-voltage pulses, into which liquid and semi-viscous liquid materials are pumped, while solid materials are transported through the treatment chamber. Treatment time required is less than a second. To ensure sufficient treatment, pulses are applied at repetition rates of up to 1000 per sec. PEF treatment intensity is affected, not only by electrical parameters such as specific energy input and field strength, but also by product composition and temperature. PEF can be applied at slightly above, below, or at ambient temperature in the form of bipolar, an exponentially decaying, oscillatory pulse, and square wave (Butz & Tauscher, 2002).

Antimicrobial efficacy and application of PEF for seafood preservation. External electrical field used for a few microseconds encourages rapid breakdown and structural changes of the cell membrane. Based on this phenomenon, called electroporation, many applications of high-intensity pulsed electric fields (HIPEF) in different food matrixes have been studied (Toepfla, Heinz, & Knorra, 2007: Faridnia et al., 2015). For irreversible breakdown of the cell membrane that consequently leads to microorganism inactivation or death can be possible with the utilization of PEF at higher treatment intensity (Figure 3). PEF processing offers good-quality, fresh, or raw-like liquid foods with excellent shelf-life, nutritional value, and flavor. Because PEF application on food involves no heat, the treated foods with PEF maintain their appearance, taste, and fresh aroma (Nagarajarao, 2016). PEF technology has been successfully applied for the pasteurization of foods such as fish soups, tomato juice, and liquid eggs.

Targeted microorganisms and their growth and physiological states are major factors influencing PEF efficacy. The intrinsic parameters of the microorganism such as shape, size, growth state, or species determine its susceptibility to PEF. In general, Gram-negtaive vegetative cells are less resistant to PEF when compared with Gram-positive bacteria. PEF sensitivity is higher in yeasts than bacteria (Mohamed & Eissa, 2012). The induction of electric fields into cell membranes of large cells is greater than small cells when exposed to PEF treatment (Zhang, Chang, & Barbosa-Cánovas, 1994). Most of the research studies pay attention to bacteria cell inactivation as affected by PEF, although only a few reports are accessible on the inactivation of spores, describing a limited effect of PEF. Pagan, Esplugas, Gongora-Nieto, Barbosa-Cánovas, and Swanson (1998) found that *Bacillus cereus* spores were not affected with PEF treatment of 60 kV/cm for 75 pulses at room temperature. However, Marquez, Mittal, and Griffiths (1997) reported

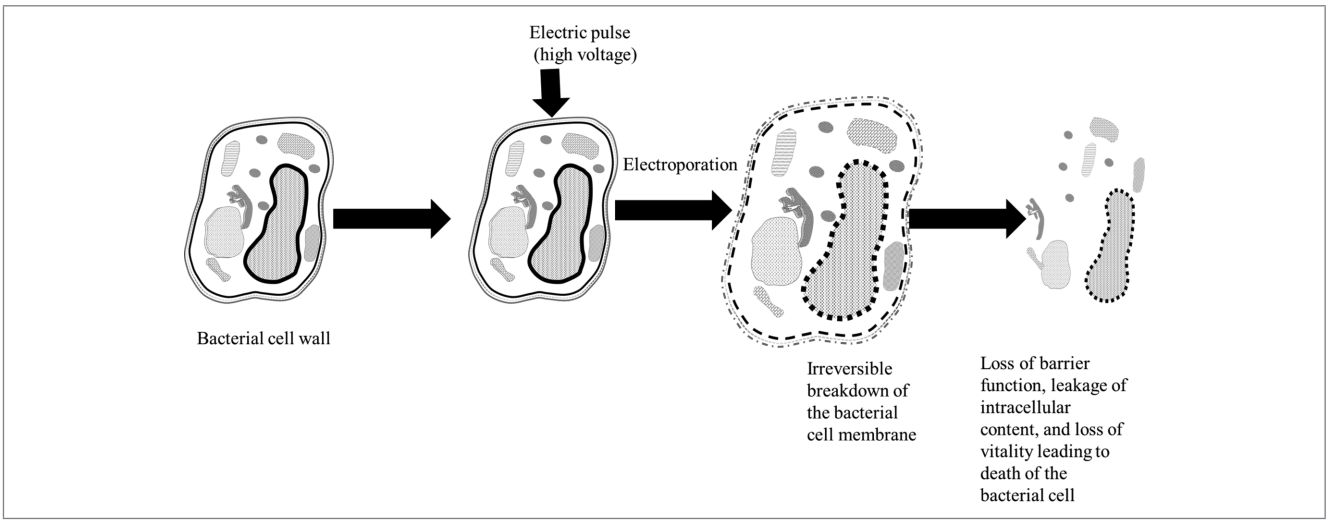

Figure 3–Bacterial inactivation by pulse electric field.

5 log and 3.42 log reductions of *Bacillus cereus* and *Bacillus subtilis* spores, respectively, with PEF treatment of 50 kV/cm for 50 pulses at 25 °C in salt solution. Gudmundsson and Hafsteinsson (2001) reported that an electric field as high as 18.6 kV/cm for 7 pulses at room temperature did not affect the primary structure of the treated salmon fish protein as compared with the control. However, PEF treatment (1.36 kV/cm for 40 pulses at room temperature) produced gaping in salmon samples. PEF treatment (2.0 kV/cm and 90 pulses/min) resulted in less water loss in fish samples (frozen cod loins, Iceland cyprine, cod fresh fillets, common whelk, frozen haddock loins, and pollock fillets), compared to the samples only injected with brine (Klonowski, Heinz, Toepfl, Gunnarsson, & Þorkelsson, 2006).

Limitation. High initial cost and the absence of any effect on enzymes are currently the major technical drawbacks of PEF. Also, application of PEF processing is limited to food products with low electrical conductivity and no air bubbles (Singh, 2012). PEF is a continuous processing method that may not be suitable for solid food products that cannot be pumped (Sabhapathi, 2013); therefore, the conveyor is important to include in the design of the machine.

High Hydrostatic Pressure

Since the early 1990s, high hydrostatic pressure (HHP) has earned more consideration among the group of nonthermal processing For over two decades, HHP has been employed for improving the nutritional, safety, functional properties, and quality of a wide variety of foods with negligible damaging effects on their nutritional and organoleptic characteristics (Jung, Tonello-Samson, & Lamballerie-Anton, 2011; Tewari, 2007).

Principle. Commercially, during HHP processing, food is exposed to pressure (200 to 1,000 MPa) for some period of time using water; an appropriate pressure-transmitting fluid (Neetoo & Chen, 2014). HHP depends on the isostatic principle, in which food products are uniformly and instantaneously compressed from all directions. When pressure is removed, food returns to its initial shape (Dahlia, Gourrierec, & Concepción, 2017). This hydrostatic compression is capable of inactivating microorganisms (Neetoo & Chen, 2014). Heat can be combined with HHP. Process temperatures can vary from sub-zero temperatures to temperatures beyond the boiling point of water (100 °C; Caner, Hernandez, & Harte, 2004). Pressurized vessel, system controls, an intensifier to produce higher pressures, and a low-pressure pump make up HPP equipment (Guan & Hoover, 2005). A temperature regulator device and product holding system are additional components (Mertens, 1995).

The structuring of the vessels is varied with diameter and vessel operating pressure. The three-cylindrical vessel designs include a monolithic chamber separately forged, a multiwall chamber shrunk-fit from a series of concentric tubes, and a wire-winded stainless steel core tube (Ting, 2010). The monoblock, or monolithic vessel, is usually fabricated for working pressures of 400 to 600 MPa for small-scale vessels with inner diameters not more than 15 cm. A wire-wound vessel or prestressed multilayered (multiwall) vessel is employed for higher pressures and longer dimensions. A commercial scale with larger capacity (525 L) is available and used for reducing microbial load in seafoods, particularly oysters (Collins et al., 2005; He, Adams, Farkas, & Morrissey, 2002). Rapid closing and opening systems that permit fast product stacking and unstacking are required for HPP. Breech-type, threaded closures, or pin closures are used for small-diameter or lower-pressure vessels (Ting, 2010).

Before and during processing, a siphoning heating/cooling medium in around pressure vessel can be used to control temperature in a large or more modern system, most especially where constant temperature is required (Fonberg-Broczek et al., 1999). Neetoo and Chen (2014) stated that a HHP system can treat either unpackaged liquids or slurries that can be siphoned in semi-continuous bulk mode or packaged food in batch mode. Reduced risk of large quantities of the product being contaminated by wear particles or lubricants of the machinery reflects increased productivity and less post-processing contamination. Those are the major advantages of batch mode over continuous bulk mode (Palou, Lopez-Malo, Barbosa-Canova, & Swanson, 2007).

Antimicrobial efficacy and application of HHP for seafood preservation. Mechanisms for the control and inactivation of microorganisms involve combined processes such as collapse of noncovalent bonds in macromolecules, biochemical effects, disruption and permeabilization of cell membranes, morphological alterations, and impacts on the genetic mechanisms of cells (Patterson, 2005). Viruses, bacteria, protozoa, parasites, and fungi in food when subjected to pressure can be greatly reduced. Microbial

groups and strains have different ranges of barotolerances (Vanlint, Rutten, Michiels, & Aertsen, 2012; Whitney, Williams, Eifert, & Marcy, 2007). The efficacy of HHP in different commodities by inactivating food-borne pathogens to enhance their microbiological safety has been investigated (Neetoo & Chen, 2014). The collaborative effect of antimicrobial and HHP has also been reported (Jofré, Garriga, & Aymerich, 2008).

The initial microbial load saw a 6-log reduction in fresh whole rainbow trout (*Oncorhynchus mykiss*) and an approximately 4-log reduction in mahi mahi (*Coryphaena hippurus*) at a pressure of 300 MPa (Yagiz, Kristinsson, Balabana, & Marshall, 2007). Erkan et al. (2011) studied physicochemical properties of horse mackerel (*Trachurus trachurus*) as affected by HHP treatment and reported that the best HHP conditions for horse mackerel treatment were 220, 250, and 330 MPa; 7, 15, and 25 °C for 5 and 10 min, in which color, TBA, and TMA-N values showed less change. Lipid hydrolysis was inhibited in frozen mackerel by increasing both the pressure level (150, 300, 450 MPa) and the pressure holding time (0.0, 2.5, 5.0 min) for HPP treatment as indicated by a marked inhibition of free fatty acid content throughout 3 months of frozen storage at −10 °C (Torres, Vázquez, Saraiva, Gallardo, & Aubourg, 2013). Shelf-life of abalone (*Haliotis discus hannai*) during refrigerated storage was extended by 10 days, compared to 3 days in the control after pretreatment with high-pressure (200 MPa) for a short time (5 min; Jo et al., 2014). Uçak and Gökoğlu (2016) reported that pressure between 100 and 300 MPa yielded marinated herring (*Clupea harengus*) with acceptable taste, texture, and appearance. Shelf-life extension by 3 wk was attained for fish salad with mayonnaise treated with HPP (450 or 600 MPa for 300 sec) and stored at 5 or 10 °C (Salamon et al., 2016). Oyster was treated with HPP (207 to 310 MPa for 0, 1, and 2 min) for shelf-life extension. The initial microbial load was reduced (2 to 3 logs) by HPP treatment, and remained at a reduced level throughout storage at 4 °C for 27 days (He et al., 2002).

Limitation. During processing, the organoleptic characteristic of HHP-treated food can be changed. This can be attributed to the ability of HPP to destabilize functional proteinaceous macromolecules, such as enzymes, by ionic and hydrophobic–hydrophobic interactions. Enzyme structure and function can be affected by HPP (Pandrangi & Balasubramaniam, 2005). However, HPP can accelerate lipid oxidation of treated seafoods during storage. This is caused by the release of inorganic transition metal ions from their respective compounds during the HPP process (Cheah & Ledward, 1997). HPP gives fish products a cooked appearance at high pressure (>200 Mpa). HPP can induce the formation of formaldehyde, which induces protein crosslinking, thus causing an increase in the hardiness of the treated fish (Matser, Stegeman, Kals, & Bartels, 2000). This is a drawback when HPP is employed for seafood treatment.

Cold Plasma Processing

Cold atmospheric plasma (CP) is a novel nonthermal process with great antimicrobial potential. Electricity and carrier gases such as oxygen, nitrogen, air, and argon are the key elements for this technology. Because of the charged particles, free radicals, photons, chemical reactive species, and ultraviolet radiations generated, CP can be used for sanitizing foods and containers. The antimicrobial efficacy of CP is beneficial to food retailers and producers for extending shelf-life and ensuring food safety of fresh commodities along the food chain (Smeu & Nicolau, 2014). Plasma treatment is an acceptable nonthermal process in the food industry because it does not cause discoloration or dehydration, nor does it affect the sensory and nutritive characteristics of food products (Schwabedissen, Łaciński, Chen, & Engemann, 2007). CP is a chemical-free, contactless, and waterless method that can prevent and reduce microbial growth (Niemira, 2012). It has been applied successfully to different food products for its antimicrobial effectiveness (Fernandez-Gutierrez, Pedrow, Pitts, & Powers, 2010; Grzegorzewski, Rohn, Kroh, Geyer, & Schluter, 2010).

Principle. Mixtures of ions, electrons, and free radical species in gaseous plasmas are responsible for microorganism destruction (Chirokov, Gutsol, & Fridman, 2005; Perni, Liu, Shama, & Kong, 2008). The gas becomes ionized, excited, or dissociated by the contact between ions or electrons. The respective gas leads to the creation of new active species when passed through plasma (Critzer, Kelly-Wintenberg, South, & Golden, 2007), as illustrated in Figure 4. Numerous CP jet devices have been installed for applying plasma to foods (Critzer et al., 2007; Deng, Cheng, Ni, Meng, & Cheng, 2008). However, the process is dependent on the diversity of devices and complexity (Moreau, Orange, & Feuilloley, 2008). Besides the working gases, the differences in plasma sources should be taken into account. In general, the frequency region (kHz) generates atmospheric pressure plasma by dielectric barrier discharge (DBD) or CD. The microwave region is generated by plasma torches, although radiofrequency (RF) regions are generated by an atmospheric pressure plasma jet or by inductive coupled plasma (ICP; Fröhling, Baier, Ehlbeck, Knorr, & Schlüter, 2012).

Antimicrobial efficacy and application of cold plasma for seafood preservation. The strong oxidizing agents, such as ozone and atomic oxygen, generated in plasma (Kelly-Wintenberg et al., 1999), as well as UV radiations, photons, chemical reactive species, and charged particles (Fröhling et al., 2012) affect the integrity of microbial cellular membranes and spawn the antimicrobial effect (Brandenburg et al., 2007; Perni et al., 2008). Depending on the plasma sources, the gases used, and processing parameters, the concentrations and the reactive species vary. Between plasma devices or the same device used, inactivation kinetics differs (Fröhling et al., 2012). Because of their ability to induce oxidation of microbial components and microbial cell membrane destruction, atomic oxygen species are the most effective. Oxidation of nucleic acids and amino acids causes changes which can lead to death or damage to microorganism (Smeu & Nicolau, 2014). Oxygen-reactive species affect lipid membranes, and this can be due to their ability to attach to the bacterial cell surface, which makes them more prone to attack by such strong oxidizing agents (Critzer et al., 2007). Agricultural products (mango, lettuce, almond, apple, and melon), real food systems (cheese and cooked meat), and egg surface have been decontaminated by CP in the food industry (Deng, Shi, Chen, & Kong, 2007).

A very limited attempt has been made at the use of plasma technology to enhance the quality and safety of seafoods. Lee, Noh, Yang, and Min (2011) showed that CP treatment for 2 min with helium gas (5 L/min) mixed with oxygen (100 mL/min) at 60 Hz and 30 kV/cm retarded the growth of *L. monocytogenes* on smoked salmon by 1 log CFU/g. Chiper, Chen, Mejlholm, Dalgaard, and Stamate (2011) reported that the population of *Photobacterium phosphoreum*, a bacterium associated with seafood spoilage in cold-smoked salmon, was significantly reduced (<3 log CFU/g) by CP (air and air + 7% CO_2 mixture) treatments operated at an applied voltage: 13 kV at 15 kHz frequency for in 60 to 120 sec. This inactivation effect was comparable between different gas compositions used (air and air + 7% CO_2). However, CP treatments did not significantly inactivate *L. monocytogenes* or *Lactobacillus sakei* in

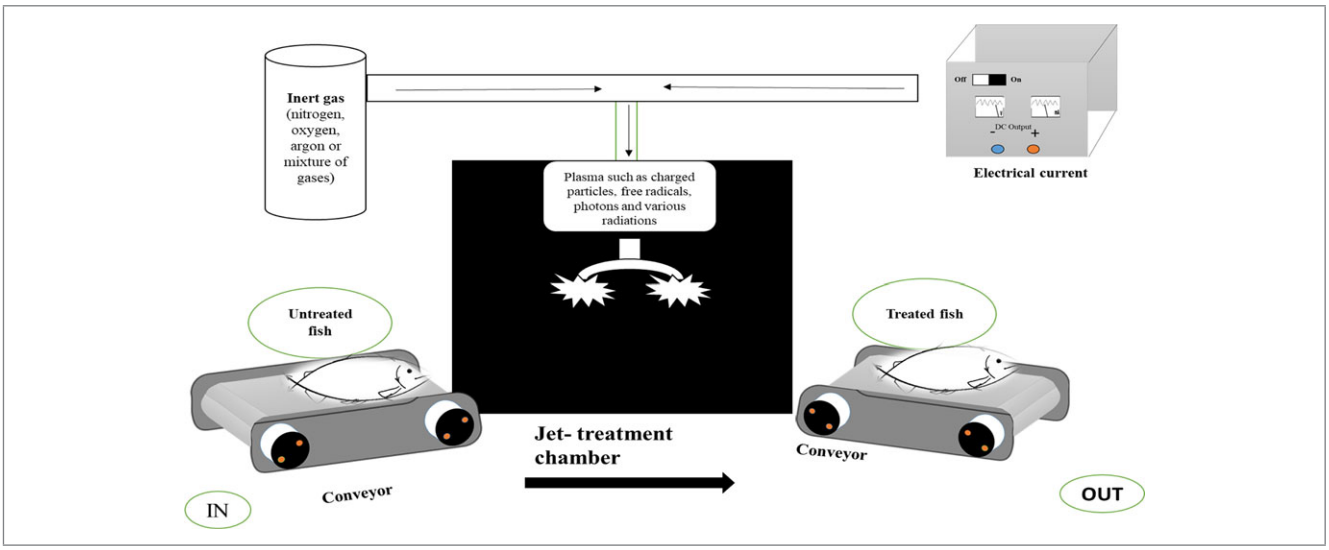

Figure 4–Cold plasma illustration in the treatment of seafood.

cold-smoked salmon, irrespective of the gas used. Park and Ha (2015) reported a significant decrease in the counts of *Cladosporium cladosporioides* and *Penicillium citrinum* on dried filefish fillets with increasing cold oxygen plasma (air subjected to high-energy deep-ultraviolet (UV) light with an effective radiation spectrum between 180 and 270 nm) with treatment times of 3 to 20 min.

Limitation. Treatment with CP can induce lipid oxidation in fatty foods and other food products susceptible to oxidation. This may lead to the creation of short-chain fatty acids, aldehydes, hydroxyl acids, and keto acids, thus causing off-flavors and off-odors during storage. (Ekezie, Sun, & Cheng, 2017). Undesirable textural properties, acidity, and discoloration of treated food can occur. Also, surface topography can be influenced by plasma treatment (Fernandez, Noriega, & Thompson, 2013). The high cost of installation is also a major drawback.

Ultraviolet (UV)

Disinfection of water in aquaculture and wastewater facilities is usually carried out by UV radiation (Bohrerova, Shemer, Lantis, Impellitteri, & Linden, 2008). The air quality within buildings can also be improved by UV radiation (Martin et al., 2008). If UV is used or handled improperly by operators, the intense UV radiation can be harmful. It can be mitigated by proper equipment and use. Recently, UV has been proved to be a promising method for extending the shelf-life of seafoods.

Principle. UV lamps are usually made of distinct quartz glass that allows 70% to 90% of UV rays to penetrate. Mercury vapor lamps contain a little amount of mercury inside the sealed glass tube and also an inert gas carrier. Mercury ionizes and vaporizes, thereby producing UV radiation when an electric arc is created. These basic components form the anatomy of a UV-emitting apparatus (Guerrero-Beltràn & Barbosa-Canovàs, 2011). UV-A with a wavelength of 320 to 400 nm, UV-B with a wavelength of 280 to 320 nm, and UV-C with a wavelength of 200 to 280 nm are the three regions in the UV spectrum (Sharma, 2010). UV treatment is a surface treatment because of its low depth of penetration (Neetoo & Chen, 2014).

Antimicrobial efficacy and application of ultraviolet radiation for seafood preservation. The germicidal property of UV-C is responsible for the 4-log reductions or more in viruses, yeasts, and bacteria at 1,000 J/m^2 dose rate (Neetoo & Chen, 2014). When a microbial cell is exposed to UV light, several modifications in the cellular components take place (Sharma, 2010). Neetoo and Chen (2014) reported that the lethality of the UV process depends on treatment time, target species, target species, and range of wavelengths used to irradiate the cells. The interaction between UV and the microbial nucleic acid results in microbial inactivation, which yield "photoproducts" of which pyrimidine dimers are the most important (Harm & Rupert, 1976). On the same strand of DNA, photoproducts such as pyrimidine dimers and pyrimidine adduct are formed between two neighboring pyrimidine bases such as thymine and cytosine. However the rate of formation of pyrimidine adduct is lower, compared to pyrimidine dimers. At sufficiently high UV doses, crosslinks between DNA and proteins are formed. At higher doses, breakage in the DNA strand may occur (Sharma, 2010). Apart from the wavelength, the concentration of hydrogen ions, the relative humidity, treatment temperature, and the microbial load also affect the effectiveness of UV light.

For food products, UV-C light technology application has been mostly confined to liquids and free-flowing foods. Bottino, Rodrigues, Ribeiro, Lázaro, and Conte-Junior (2016) reported that UV-C enhanced the shelf-life of *Piaractus mesopotamicus* and *Colossoma macropomum* fillets by at least 50% by retarding microbial growth. Lower growth rate and number of colonies in the stationary phase were noticeable in combination with decreased biogenic amine production. Putrescine content, mesophilic bacteria counts, total ammonia, psychrotrophic bacteria counts, and total volatile base nitrogen (TVB-N) content were reduced in UV-C radiation–pretreated rainbow trout (*Oncorhynchus mykiss*) fillets stored in MAP (106.32 mJ/cm^2: 20%N_2/80% CO_2), thereby extending the shelf-life by at least twice as compared with the control (Rodrigues et al., 2016).

Limitation. Accelerated senescence and surface discoloration in seafood can occur and deteriorate the treated seafood (Sharma, 2010). UV radiation can induce oxidation of lipids in treated seafoods since hydrogen peroxide, superoxide radicals, and lipid radicals are indirectly formed by UV light (Kolakowska, 2003). Peroxide created during extended UV light treatment can diminish the pigments and the fat-soluble vitamins (Krishnamurthy,

Irudayaraj, Demirci, & Yang, 2009). Also, cross-linking and fragmentation of protein, carbohydrate cross-linking, and peroxidation of unsaturated fatty acids in ultraviolet-treated seafood can be induced by superoxide radicals (Krishnamurthy et al., 2009). Protein, aromatic amino acids, and enzymes are denatured by UV radiation, which could affect the composition of seafoods (Neetoo & Chen, 2014).

Irradiation

Exposing materials to ionizing radiations (electron beams, X-rays, and gamma rays) is called irradiation. Level of radiation is one of prime factors determining efficacy. During irradiation, chemical bonds are broken to give free radicals or highly unstable and reactive ions when molecules absorb energy (Ohlsson & Bengtsson, 2002).

Principle. High-energy isotope sources to produce γ-rays are needed for irradiation, and cobalt-60 (60 Co) is used commercially to produce γ-rays. Less commonly, X-rays and high-energy electrons can be produced from machine sources (Arvanitoyannis & Tserkezou, 2010). Machine sources are electron accelerators, which consist of an evacuated tube and electrons are supplied by heated cathode, in which high-voltage electrostatic field excites an electron. Through amplifying the cascade of collisions, these electrons can ionize other atoms (Smeu & Nicolau, 2014). The absorbed dose, the overall economics of the process, food density, and food thickness determine the efficacy of the application (Arvanitoyannis & Tserkezou, 2010). The formation of reactive species induced by irradiation plays a paramount role in killing the microorganisms (Silva, Pereira, Junqueira, & Jorge, 2013). For personnel safety, an uncompromising procedure in the irradiation plant must be carefully followed (Fellow, 2000).

Antimicrobial efficacy and application of radiation for seafood preservation. DNA, proteins, or cell membranes can be disrupted by reactive species such as free radicals that are fractured typically from water molecules by high-energy electrons (Smeu & Nicolau, 2014). Cell genetic material is particularly prone to free radical damage during transcription or active replication (Snyder & Poland, 1995). The intrinsic factors, such as principal oxygen availability and dose of irradiation, affect the efficacy of irradiation (Lacroix et al., 2002). Bacterial cells are protected against inactivation during irradiation by reducing the water activity (Smeu & Nicolau, 2014). Reduction in the availability of reactive water molecules by freezing therefore increases microbial resistance to irradiation (Nicholson, Munakata, Horneck, Melosh, & Setlow, 2000). The characteristics inherent in the product, such as particle size and food thickness, product matrix and composition, and state of the food, have a bearing on product decontamination and they also affect the efficacy of radiation (Smeu & Nicolau, 2014). The sensitivity of microorganisms to ionizing radiation is in the ascending order of viruses < bacteria < parasites (Niemira, 2003).

The ability of irradiation to destroy spoilage microflora and food-borne pathogens in various plant-derived and animal-derived products has been investigated (Smeu & Nicolau, 2014). The shelf-life of foods can be extended by radurization (0.4 to 10 kGy), in which viable spoilage microorganisms, molds, and yeasts are destroyed, radicidation (0.1 to 8 kGy), where viable non–spore-forming food-borne pathogens are reduced, or radappertization (10 to 50 kGy), in which both spores and vegetative bacteria in food products are completely destroyed (Fellow, 2000). Crawford and Ruff (1996) used doses of up to 10 kGy on frozen poultry or shellfish (−18 °C) to destroy *Vibrio spp., E. coli* O157:H7, and *Campylobacter* spp. Przybylski, Finerty, Grodner, and Gerdes (1989) showed that the application of MAP and low-dose irradiation extended the shelf-life of fresh catfish fillet by 4 to 5-fold. Harewood, Rippey, and Montesalvo (1994) reported that irradiation doses of >0.5 kGy were significantly lethal for fecal coliforms, *E. coli,* and *C. perfringens,* in which the shelf-life of hard-shelled clams (*Mercenaria mercenaria*) could be extended. Oraei, Motalebi, Hoseini, and Javan (2011) investigated the effect of gamma-irradiation and frozen storage on the microbial quality of rainbow trout (*Oncorhynchus mykiss*) fillet and reported that for shelf-life extension, microbial control, and to ensure the safety of rainbow trout stored in the frozen state, an application of low-dose gamma irradiation (especially 3 kGy) is suitable. Dogruyol and Mol (2017) investigated the effect of irradiation (2.5 and 5.0 kGy) on the shelf-life and microbial quality of cold-stored sous vide (70 °C for 10 min) mackerel fillets. It was found that microbial loads were below the limits (6 log CFU/g) during 9 weeks of storage (2 ± 1 °C). Arshad, Sudha, Hatha, and Anilkumar (2015) investigated the synergistic effect of cold temperature storage and gamma-irradiation on the sensory properties of estuarine crab (*Scylla serrate*) and reported that frozen storage (−20 °C) and cold (4 °C) and gamma-irradiation (1.0 to 2.0 kGy) extended the shelf-life of the sample by maintaining sensory quality for the maximum duration of 28 and 14 days, respectively.

Limitation. Irradiation is harmful or noxious to humans (Moreira, 2010). However, the dose for seafood pretreatment is low, therefore making it safe for consumption. Excess accumulation as a result of constant exposure to irradiation is a major threat for the processors or workers. Some amino acids can be cleaved by high-dose irradiation, thereby changing the flavor and aroma of foods (Moreira, 2010). Lipid oxidation is enhanced in the irradiated product since irradiation can accelerate auto-oxidation of lipids, producing hydroperoxides and off-flavors in food, especially seafoods rich in polyunsaturated fatty acids (Neetoo & Chen, 2014).

Modified Atmosphere Packaging

Modified atmosphere packaging (MAP) is a preservation method that involves replacing the air in a packaging container by a mixture of gases or a specific gas different from the initial air composition (Çaklı, Kılınç, Dinçer, & Tolasa, 2006). Oxygen (O_2), nitrogen (N_2), and carbon dioxide (CO_2) are the main commercial gases used in MAP (Soccol & Oetterer, 2003). First, the mixture of gases is prepared. The packaging container is filled with the gas mixture, sealed, and stored with no additional control during storage (Rutherford et al., 2007).

Principle. Oxygen in the package is displaced by N_2, which is an inert and insipid gas with low lipid or water solubility, thereby lessening oxidative rancidity and hindering any aerobic microorganism's growth (Rawat, 2015). N_2, with its low solubility, is an important factor in preventing possible packaging collapse, whereas dissolution of CO_2 may bring about packaging collapse. The growth of aerobic bacteria is stimulated by O_2, which may retard obligate anaerobic bacteria growth, although sensitivity to oxygen differs among anaerobic microorganisms (Arashisar, Hisar, Kaya, & Yanik, 2004). Davis (1998) supported that for fish, O_2 should be included in MAP to reduce exudation or drip in fish throughout storage, and they also proposed that O_2 can be included in the gas composition of MAP for low-fat fish. During storage, because of the slow permeation of gases through the packaging materials, biochemical changes, and dissolved gases still take place in the packed product. Gaseous atmosphere composition continuously changes (Özogul & Özogul, 2006).

MAP with high levels of CO_2 generally promote fresh fish storage stability. Mixtures of 30% O_2, 30% N_2, and 40% CO_2 have been recommended for fish with low-fat content, and a 40% N_2 and 60% CO_2 gas mixture for fatty fish (Özogul & Özogul, 2006). Temperature has an impact on CO_2 bacteriostatic and bactericidal effects (Lopez-Caballero, Goncalves, & Nunes, 2002). At low temperature, CO_2 is trapped in the packing materials; at high temperature CO_2 gains kinetic energy and escapes from the packing materials. During storage, the lack of refrigeration may permit the growth of microorganisms stored under CO_2 atmosphere. For successful use of MAP, good or hygienic quality raw material is a key factor (Özogul & Özogul, 2006). Temperature control and good packaging material are also essential for MAP (Marcilene, Heidmann, & Marília, 2003).

Antimicrobial efficacy and application of MAP for seafood preservation. The solubility of CO_2 in water and lipids accounts for the bacteriostatic influence in MAP. During the logarithmic stage, CO_2 generally decreases growth of microorganisms (Motegi et al., 2013). Initial bacterial population, type of product, storage conditions, and concentration of CO_2 all have an influence on the bacteriostatic effect of MAP (Lopez-Caballero et al., 2002). The CO_2 is dissolved in the water of a sample, thereby forming carbonic acid (Sivertsvik, Jeksrud, & Rosnes, 2002). Penetration of acid in the bacterial membranes leads to alteration in cell membrane, a decrease in enzymatic reactions or direct inhibition of enzymes, and to changes in the intracellular pH. Direct alterations in the physico-chemical properties of proteins are the most important mechanisms explaining the influence of CO_2 on bacterial cells (Soccol & Oetterer, 2003).

At refrigerated temperatures, increase in shelf-life and inhibition of spoilage and pathogenic microorganisms in seafoods has been demonstrated by MAP (Sivertsvik et al., 2002). In the quest by manufacturers to meet consumer demand, this technology is gaining increasing attention in the food industry (Sveinsdottir, Martinsdottir, Hyldig, & Sigurgisladottir, 2010). MAP has been proven to possess an effective combination with superchilling in extending the shelf-life of fresh cod (*Gadus morhua*) loins (Lauzon, Magnusson, Sveinsdottir, Gudjonsdottir, & Martinsdottir, 2009) and Atlantic salmon (*Salmo salar*) fillets (Duun & Rustad, 2008). Hurtado, Montero, and Borderías (2000) assessed the shelf-life of vacuum-packaged (400 MPa) hake (*Merluccius capensis*) slices at refrigerated temperature (2 to 3 °C), and up to the 43rd day of storage hake slices were palatable to sensory panelists. Low trimethylamine content and a slight increase in drip were noted after 15 days of storage. Ordóñez, Lopez-Galvez, Fernandez, Hierro, and Hoz (2000) stored hake (*Merluccius merluccius*) in atmospheric air at 2 ± 1 °C, as well as in atmospheres containing 20% and 40% CO_2. Shelf-life was increased to 11 and 4 days under 40% and 20% CO_2, respectively. The 40% CO_2 atmosphere was more effective for refrigerated hake.

Masniyom, Benjakul, and Visessanguan (2002) reported that at 4 °C, the shelf-life of seabass slices in 80% to 100% CO_2 MAP could be extended to 12 days. Duun and Rustad (2008) reported that at storage of 2 °C, shelf-life superchilled salmon fillets in combination with MAP (CO_2:N_2 60:40) could be extended to more than 24 days by maintaining negligible microbial growth and good quality based on both microbial and sensory analyses, whereas a shelf-life of only 17 days was found for ice-chilled fillets without MAP. The synergistic effect of modified atmosphere and on shelf-life extension and quality of refrigerated seabass slices was reported by Masniyom, Benjakul, and Visessanguan (2005). Pretreatment of seabass slices by soaking them in 2% sodium pyrophosphate (PP) for 10 min prior to MAP (10% N_2, 10% O_2, and 80% CO_2) at 4 °C extended the shelf-life to 21 days, although the control stored in air had a shelf-life of 6 days. Moreover, the use of phosphate (2%) pretreatment in combination of MAP (80% CO_2, 10% N_2, and 10% O_2) could prevent the growth of *L. monocytogenes* and reduce the proliferation of *E. coli* O157 in stored seabass slices at 4 °C (Masniyom et al., 2005).

Effects of MAP on the microbiological properties of fresh common carp (*Cyprinus carpio L.*) were studied by Katarína, Hana, and Iva (2010). Shelf-life of carp could be extended by 5 and 6 days, as determined by total viable counts ($<10^6$ to 10^7 CFU/g considered the TVC limit of acceptability) when 30% CO_2/70% N_2 and 20% CO_2/80% O_2, respectively, were used. Maqsood and Benjakul (2010) reported that 200 ppm of tannic acid showed a synergistic effect with MAP (5% O_2, 35% CO_2, and 60% N_2) on microbial growth and retarded lipid oxidation, thus extending the shelf-life of striped catfish slices during refrigerated storage. Total color change (ΔE), mesophilic and psychrophilic aerobic bacterial growth were retarded for salmon sushi packaged in 100% CO_2, 50% CO_2, and 50% N_2 MAP, stored at 4 °C for 6 days (Mol, Alakavuk, & Ulusoy, 2014).

Limitation. Packaging collapse in MAP often occurs when there is an excessive absorption of CO_2 in food with high fat and/or moisture, such as poultry, beef, and fish (Marcilene et al., 2003). Drip or exudate may be increased in MAP, and this can be attributed to gases dissolution on the surface of muscles in atmospheres consisting of a high level of CO_2 (>60%). Carbonic acid formed can reduce pH, and, consequently, protein then undergoes denaturation with less water retention ability (Masniyom, 2011). Oxidative rancidity in fish with high lipid amounts can be promoted in the presence of O_2. Nevertheless, CO_2 can induce the release of non-heme iron in the muscle, acting as the pro-oxidant (Masniyom, 2011). Therefore, to minimize such a detrimental effect, a mixtures of gases for modified atmospheres with inclusion of O_2 is generally avoided with seafood. Moreover, the use of antioxidants can be a means to prevent lipid oxidation of seafood packaged under MAP.

Conclusion

Novel emerging non-thermal technologies for seafood processing start from pretreatment of seafoods using acidic electrolyte water or ozonification to reduce the initial microbial load. Further treatment using nonthermal processing, such as high hydrostatic pressure, ionizing radiation, cold plasma, ultraviolet light, and pulsed electric fields, can be applied under appropriate conditions to enhance the inactivation of microorganisms while lowering the detrimental effect associated with the harsh conditions. Finally, packaging technology, especially MAP, can be implemented to prolong the shelf-life of seafoods. Low storage temperature is recommended as a necessary tool to extend the shelf-life of treated/processed seafoods. Overall, the clear advantage of these technologies, especially in right combination, makes them a promising approach for inactivation of microorganisms while maintaining sensory attributes and nutritive value.

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Authors' Contributions

Olatunde Oladipupo Odunayo collected the data, compiled, and wrote the manuscript. Soottawat Benjakul planned, drafted, and corrected the manuscript.

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