REVIEW

Turkish Journal of FISHERIES and AQUATIC SCIENCES

Pretreatment and Non-thermal Processing Technologies for Quality Maintenance and Shelf-life Extension of Seafoods

Mohamed Tagrida[1], Suriya Palamae[1,*], Soottawat Benjakul[1,2,*]

[1]International Center of Excellence in Seafood Science and Innovation, Faculty of Agro-Industry, Prince of Songkla University, Hat Yai, Songkhla, 90110, Thailand
[2]Department of Food and Nutrition, Kyung Hee University, Seoul 02447, Republic of Korea.

How to Cite

Tagrida, M., Palamae, S., Benjakul, S. (2024). Pretreatment and Non-thermal Processing Technologies for Quality Maintenance and Shelf-life Extension of Seafoods. *Turkish Journal of Fisheries and Aquatic Sciences*, *24(7)*, *TRJFAS24817.* https://doi.org/10.4194/TRJFAS24817

Article History
Received 04 October 2023
Accepted 20 May 2024
First Online 04 June 2024

Corresponding Author
E-mail: suriya.pal@psu.ac.th

Keywords
Microbial contamination
Non-thermal process
Pretreatment seafood
Shelf-life extension

Abstract

The seafood industry faces significant challenges in preserving the quality and extending the shelf-life of its products to meet the demands of consumers for fresh, safe, and nutritious seafood. Apart from traditional pretreatments such as washing, sorting, and deheading, several emerging technologies like ozonized water (OW), acidic electrolyzed water (AEW), and plasma-activated water (PAW) have drawn attention for seafood industry. These innovative technologies not only improve quality of seafood but also effectively reduce contaminated microorganisms and enzymatic activity, thereby delaying spoilage. Furthermore, non-thermal processing technologies, including high pressure processing (HPP), cold plasma (CP) treatment, and modified atmosphere packaging (MAP), offer promising alternatives to conventional heat-based processes. These technologies are characterized by their ability to inactivate microorganisms and enzymes, while preserving the sensory attributes and nutritional value of seafood. HPP and MAP particularly have demonstrated their profound ability to extend the shelf-life of seafood products without compromising their quality or sensorial attributes. Furthermore, the synergistic effects of combining pretreatment and non-thermal processing techniques, have potential to prolong shelf-life and improve safety of seafood products. Thus, the integration of these pretreatments and technologies offers a promising avenue for enhancing the quality and safety of seafood products.

Introduction

Seafood products are among the most globally traded food items with high value due to their high nutrients and delicacy. Nevertheless, the quality of raw seafood can be deteriorated rapidly caused by various physicochemical alterations, enzymatic activity, and microbial proliferation (Ekonomou & Boziaris, 2021; Gram & Huss, 1996). To ensure seafood safety and quality, it is essential to prevent contamination from hazardous chemicals and pathogenic microorganisms during post-harvest handling or storage (Ekonomou & Boziaris, 2021). Therefore, pretreatment methods are crucial as the starting point for exploring innovative technologies in seafood production. Among these emerging technologies, ozonized water (OW), acidic electrolyzed water (AEW), and plasma-activated water (PAW) have demonstrated remarkable potential in recent years for microbial inactivation and shelf-life extension of fresh seafoods. These technologies align with the food industry's trends owing to their cost-effectiveness, environmentally friendly nature, and sustainability.

Traditional techniques for seafood preservation include intense heat (such as pasteurization or cooking), salting, drying, rehydration, acidification, and the use of synthetic preservatives (Kipcak et al., 2021; Ozyalcin et al., 2022; Sevim et al., 2023). Since those harsh

processes might cause severe health issues for consumers (Andoni et al., 2021), non-thermal technologies have been adopted for the preservation of food products. They do not rely on high heat or chemical additives to achieve preservation. Non-thermal processes can preserve sensitive nutrients and flavor compounds better than traditional techniques. Moreover, they can help maintain the texture and color of food products more effectively, enhancing their acceptability to consumers. Thus, alterations in the quality attributes resulting from microbial contamination or the usage of conventional preservation techniques can be reduced. Additionally, economic losses can be minimized, and premium-quality safe products can be obtained (Olatunde et al., 2021a). Non-thermal inactivation techniques for food preservation have been extensively studied because of the increased consumer demand for fresh, nutritious, and safe food products with accepted organoleptic quality and an extended shelf-life (Olatunde & Benjakul, 2018). Among the important foods preserved via non-thermal techniques, seafood including fish, crustaceans, and mollusks are the main target commodities. Such products are highly prone to spoilage due to high lipid and protein contents. Consequently, different biochemical reactions and microbial contamination, particularly after catching and the death of these products, occur rapidly. This can lead to a quick deterioration of seafood, hence shortening its shelf-life (Olatunde et al., 2021b). Recently, novel non-thermal preservation techniques including high-pressure processing (HPP), cold plasma (CP), modified atmosphere packaging (MAP), etc., have been intensively investigated (Jan et al., 2017).

Pretreatment Technologies for Seafoods

Ozonized Water (OW)

Ozone is an appealing option for seafood processing and preservation due to its rapid antimicrobial action, strong oxidative properties, and natural decomposition into molecular oxygen, without leaving hazardous halogenated compounds in foods (Pandiselvam et al., 2017: Liao et al., 2018). In general, ozone is generated through the interaction of electrical discharge and unadulterated oxygen during ventilation (Güzel-Seydim et al., 2004). The generation of ozone involves breaking the O-O bond in oxygen molecules (O_2) to separate into free oxygen atoms (O), resulting in the formation of ozone molecules (O_3) (Bocci, 2006; Chawla et al., 2007). Ozone is an unstable triatomic oxygen molecule and subsequently decomposes into hydroxide radical (•OH), hydroperoxide (•HO_2), and superoxide (•O_2^-) radicals. Those radicals have powerful oxidizing properties, which can be applied in food industry (Figure 1) (Blogoslawski & Stewart, 2011; Gonçalves, 2016).

Antimicrobial Efficacy of OW

OW treatments have been used for extending the shelf-life of seafood. The use of ozone at 0.6 ppm in a 3% NaCl solution reduced viable bacterial cell counts in the skin of gutted fish. It had the potential to enhance the shelf-life of fish by 20% to 60%, particularly when applied periodically (every 2 days) for jack mackerel (*Trachurus trachurus*) and shimaaji (*Caranx mertensi*) fish, respectively (Powell et al., 1979). The use of ozone

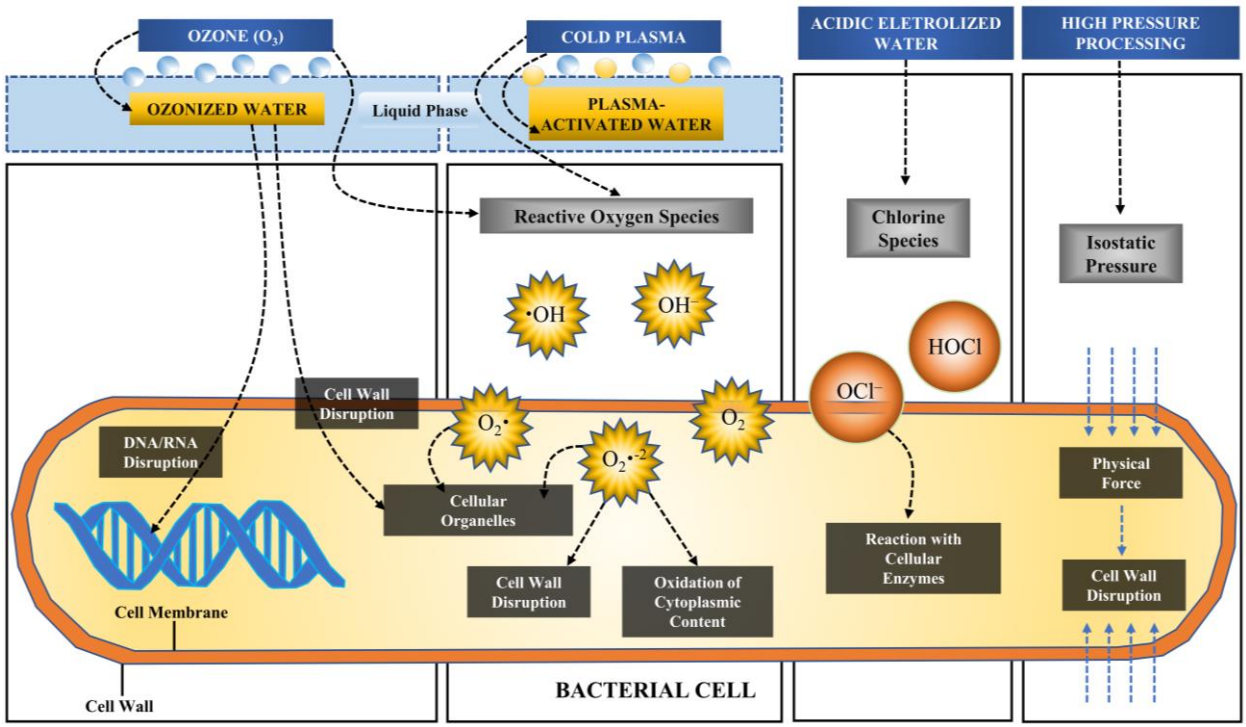


Figure 1. Antimicrobial mechanisms of ozonized water (OW), plasma-activated water (PAW), acidic electrolyzed water (AEW) and high-pressure processing (HPP).

in distilled water at a concentration of 6 ppm effectively deactivated pathogenic microorganisms such as *Escherichia coli*, *Staphylococcus aureus*, *Salmonella* Typhimurium, and *Vibrio parahaemolyticus*, resulting in the preservation of the quality attributes of fresh fish. As a result, treated fish could be stored up to one month at 0 °C and 5 °C (Gelman et al., 2005; Nash, 2002). Combining ozone pretreatment with cold storage at 0 °C is therefore an effective method for extending the storage life of fish. Additionally, washing fish with aqueous ozone reduced the microflora without adversely affecting fish quality (Gelman et al., 2005; Ravesi et al., 1988). However, ozone treatments, whether through washing or direct exposure, were found to be ineffective against *L. monocytogenes* contaminated in frozen shrimp. To enhance the efficacy of ozone treatments, it is recommended to treat fresh fish with OW, since bacterial attack occurs thoroughly on fish skin over time (Paranjpye et al., 2008).

Application of OW for Seafood Preservation

Seafood products pretreated with OW have been demonstrated to have the reduced bacterial counts and extended shelf-life, while maintaining high-quality attributes that meet consumer expectations. Okpala (2015b, 2015a) reported that the adhesiveness, springiness, and fracturability of OW-treated shrimp remained relatively unchanged after storage. Additionally, the hardness of sequentially ozonized water-washed shrimp was consistent, when compared to untreated shrimp, suggesting that washing shrimp with OW had no significant impact on the textural attributes of the shrimp. Moreover, OW washing has been documented to inhibit the activity of proteolytic enzymes, in which textural quality of shrimp could be retained (Zhang et al., 2013). Shrimps subjected to ozone treatment exhibited a slower softening rate, compared to untreated shrimps (Liao et al., 2018). Ozone treatment in seafood processing minimizes washing time and enhances the color of dark-fleshed fish surimi, contributing to the overall quality improvement of the resulting surimi (Chen & Lao, 1997). de Mendonça Silva and Gonçalves (2017) also found that OW pretreatment at 1.5 ppm for 15 min resulted in an 88.25% reduction in microbiological contamination while preserving the characteristic pigmentation of whole tilapia.

Limitation of OW

Ozone, recognized as a potent oxidizing agent, is commonly employed for disinfecting wastewater and eliminating organic substances as well as offensive odors (Epelle et al., 2023). However, a notable limitation of ozone treatment is its diminished effectiveness in preventing post-treatment contamination since it undergoes reduction with organic matters (Olatunde & Benjakul, 2018). While ozone can effectively reduce microbial loads before and during treatment, it offers limited protection against microbial contamination after the treatment process due to the short life span (Pandiselvam et al., 2017). Moreover, it can trigger oxidation in seafood, potentially resulting in an undesirable odor and taste for consumers (Manousaridis et al., 2005). Ozone-induced protein oxidation can also lead to a decrease in the protein functionality of seafood, negatively affecting the overall quality of seafood and its products.

Acidic Electrolyzed Water (AEW)

Over the previous two decades, the usage of AEW has gradually expanded to agriculture and the food industry (Yan et al., 2021). AEW is produced by electrolyzing an electrolyte solution, and the type of AEW generated can vary, depending on the presence or absence of a diaphragm in the electrolytic cell. In a diaphragm-containing electrolytic cell, the electrolyte solution typically consists of chloride salt (usually NaCl) (Esua et al., 2021a). During electrolysis, the negatively charged ions (OH^- and Cl^-) move toward the anode, where electrons are released and hypochlorous acid (HOCl), hypochlorite ion (OCl^-), hydrochloric acid (HCl), oxygen gas (O_2) and chlorine gas (Cl_2) are released (Rahman et al., 2016). Simultaneously, water molecules lose electrons at the anode, generating H^+ ions and O_2 gas. As a result, the pH of the solution near the anode decreases, leading to the formation of AEW having chlorine ions of at least 20 ppm, a pH below 3.0, and an oxidation-reduction potential (ORP) exceeding +1000 mV (Wang et al., 2022a). In recent years, slightly acidic electrolyzed water (SAEW) with a pH ranging from 5.0 to 6.5 and an ORP between 700 and 900 mV as well as neutral electrolyzed water (NEW) with a pH of 7.0 – 8.0 and an ORP of 750 – 900 mV can be generated using an electrolytic cell without a diaphragm, providing variations of electrolyzed water (Zhang et al., 2021). The widespread popularity of AEW in various food industry is attributed to its environmentally friendly and non-toxicity. It generally does not compromise the quality of food products and presents no hazards to consumers. Additionally, the cost-effectiveness leads to its wider applications in the food industry (Chakka et al., 2021; Esua et al., 2021a).

Antimicrobial Efficacy of AEW

AEW exhibits potent antimicrobial activity against common foodborne pathogens, spores, fungi, and viruses in both foods and food processing environments, while exhibiting minimal impact on physicochemical and sensory qualities of treated food products (Ekonomou & Boziaris, 2021). Several factors in AEW including chlorine ions, pH, and oxidation-reduction potential (ORP) directly contribute to distinct antimicrobial activity of AEW. High ORP can disrupt bacterial metabolic processes and ATP synthesis by altering electron flow

(Liao et al., 2007). Low pH (<2.6) sensitizes the outer membrane of bacterial cells, allowing hypochlorous acid (HOCl) to enter and inhibit glucose oxidation through the oxidation of sulfhydryl groups in carbohydrate metabolism enzymes (Luo and Oh, 2015). Chlorine and reactive oxygen species (ROS) can disrupt microbial cell membranes and induce DNA oxidation, resulting in reduced microbial growth (Park et al., 2004). This effect is associated with the formation of hypochlorous acid (HOCl) and the low pH of AEW, which damage microbial cell membranes (Figure 1) (Veasey & Muriana, 2016). Various AEW with elevated ORP and chlorine concentrations (10–50 mg/L), could inhibit some common foodborne pathogens found in seafoods and processing environments, including *E. coli* O104:H4, *L. monocytogenes*, *A. hydrophila*, *V. parahaemolyticus*, and *Campylobacter jejuni*, particularly those found in aqua-cultured bivalves to some extent (Al-Qadiri et al., 2016; Ovissipour et al., 2013; Palamae et al., 2023). Therefore, combination of AEW with mild thermal treatments at varying temperatures and durations has been explored to reduce *L. monocytogenes* in Atlantic salmon (*S. salar*). For instance, an application of NEW at 65 °C for 10 min led to a substantial reduction of *L. monocytogenes* counts by 5.60 log CFU/g (Ovissipour et al., 2018). Additionally, the combination of AEW (pH 2.7; ORP 1150 mV; free chlorine 60 ppm) with mild heating (40 °C for 10 min) resulted in significant reductions of *L. monocytogenes* retaining on the surface of cold-smoked salmon fillets to 2.85 log CFU/g (Ghorban Shiroodi et al., 2016). For shrimps inoculated with *V. parahaemolyticus*, pretreatment using basic electrolyzed water (BEW) followed by treatment with AEW at 50 °C for 5 min and 1 min, respectively, demonstrated the most significant antimicrobial activity against the pathogens (Xie et al., 2012). Increased reductions in microbial populations were observed with higher temperatures, potentially due to variations in microbial cell physicochemical characteristics that facilitated EW entry into the cells (Fabrizio & Cutter, 2003).

Application of AEW for Seafood Preservation

Various types of AEW have shown significant antimicrobial effectiveness in pretreating seafoods and their products to ensure food safety. Nevertheless, the balance between the retention of quality and sensory attributes must be considered. The use of AEW ice has been demonstrated to have the potential as a post-harvest treatment for preserving the quality of shrimp (*L. vannamei*), highlighting its positive impact on seafood quality (Wang et al., 2014). To maintain shrimp quality, AEW ice exhibited bactericidal effects on TVC, reduced the formation of total volatile basic nitrogen (TVB-N), and decreased polyphenol oxidase (PPO) activity in raw shrimp during a 6-day storage period (Lin et al., 2013; Wang et al., 2014). Similarly, lower TVB-N, trimethylamine (TMA), and thiobarbituric acid reactive substance (TBARS) values were reported for raw puffer fish (*Takifugu obscurus*) stored at 4°C after treatment with weakly acidic electrolyzed water (WAEW) and MAP (Li et al., 2020). Khazandi et al. (2017) demonstrated that shelf-life of refrigerated Southern Australian King George Whiting and Tasmanian Atlantic salmon fillets was prolonged by 2 and 4 days, when NAEW at concentrations of 15% and 50%, respectively, was used for washing fillets. A variety of electrolyzed waters have been studied for their capacity to preserve the physicochemical and sensory attributes of seafoods (Ekonomou and Boziaris, 2021).

Limitation of AEW

AEW treatment alone has shown limited effectiveness in sanitizing raw seafood. Reductions of *L. monocytogenes* counts on raw salmon ranged from 1.1 to 1.3 log CFU/g) with AEW treatments for 1 to 10 min (Al-Holy & Rasco, 2015). In some cases, AEW treatments did not inhibit the growth of *L. monocytogenes* on raw salmon kept at 4°C, even with a 5-min immersion (McCarthy & Burkhardt, 2012). Longer AEW treatments, such as 64 min on salmon fillets, only resulted in reductions of *L. monocytogenes* counts by 0.8 to 1.1 log CFU/g (Ozer & Demirci, 2006). AEW are more effective in reducing microbes on fish skin compared to fish fillet tissue, achieving reductions of 2.0 and 2.8 log CFU/g for carp fillet and skin, respectively, after 15 min of treatment (Mahmoud et al., 2004). The presence of organic matter from the fish may reduce AEW efficiency, as it can react with free chlorine to form combined available chlorine, which has lower bactericidal activity (Al-Holy & Rasco, 2015; Oomori et al., 2000). The raw fish tissue matrix, which strongly attaches bacterial cells, may also contribute to lower bacterial reduction efficacy of AEW (Mahmoud et al., 2004). To overcome these limitations, combining two or more decontamination methods has been suggested to enhance disinfection effectiveness (Rahman et al., 2016; Rasco & Ovissipour, 2015). Palamae et al. (2023) documented that the total viable count and *V. parahaemolyticus* in Asian green mussels were more effectively inactivated with the combination of AEW and sous vide cooking compared to using AEW alone. In another study, AEW depuration combined with HPP effectively eliminated spoilage bacteria and pathogens in blood clams (*Tegillarca granosa*) during cold storage. HPP treatment at 300 MPa for 3 min completely inactivated various bacterial types, with this sample maintaining low bacterial counts to day 9. On the other hand, the samples treated with HPP alone were spoiled within 6 days (Palamae et al., 2024a).

Plasma-Activated Water (PAW)

In contrast to AEW, the utilization of PAW in seafood processing is a relatively recent development (Han et al., 2023). Plasma is recognized as the fourth state of matter, extending beyond gas, liquid, and solid phases. It consists of a mixture of photons, electrons,

ions, molecules, and free radicals (Pankaj & Keener, 2017). Plasma is generated through the excitation of neutral gas using energy sources such as electricity, radiation, laser, or extremely rapid compression (Punia Bangar et al., 2022). PAW is generated by subjecting water to a nonthermal plasma generated by devices like atmospheric pressure jet devices (APPJ), dielectric barrier discharge devices (DBD), and gliding arc discharge devices (GAD). The interaction of O_2 atoms with water molecules in the gas-liquid interface during nonthermal plasma exposure leads to dissociation and ionization processes. This results in the acidification of the solution and the production of ROS including OH^- and H_2O_2 (Han et al., 2023). Additionally, exposure to nonthermal plasma generates reactive nitrogen species (RNS) such as NO_2^- and NO_3^- (Esua et al., 2021a). The ROS and RNS species generated in the PAW are responsible for microbial inactivation (Figure 1) (Liu et al., 2021a). They can spread inside the cell, leading to the cellular accumulation of ROS and RNS. These reactive species in the internal environment oxidize and degrade cell components, including DNA, RNA, and proteins (Han et al., 2023). They primarily cause protein denaturation and cell leakage, affecting both spores and cells equally (Critzer et al., 2007). Additionally, they exhibit a synergistic effect with high oxidation-reduction potential (ORP) and low pH, which has been proven to possess antimicrobial activity. A lower pH is more favorable for the reactive species to penetrate cell walls (Sun et al., 2012). ORP is considered an important factor affecting microbial inactivation, as it damages the cell membrane of microbes and their defense mechanisms (Thirumdas et al., 2018). PAW has demonstrated its efficacy in activating microorganisms in various forms, including bacterial suspension (Ikawa et al., 2010), biofilm (Ercan et al., 2013), and spores (Sun et al., 2012). PAW has been reported as a promising alternative method for food decontamination, with the advantage of a prolonged bactericidal effect, depending on storage temperature, making it a valuable candidate for industrial implementation (Zhao et al., 2021).

Antimicrobial Efficacy of PAW

PAW treatment has emerged as a promising approach for the decontamination of microorganisms and preservation of seafoods and their products. Esua et al. (2021b) observed a reduction in populations of *Shewanella putrefaciens* and *E. coli* by 0.92 and 0.88 log CFU/g, respectively, on grass carp after a 4-min pretreatment with PAW. Increased voltage application during PAW pretreatment enhanced the inactivation effect. Furthermore, the combination of PAW and ultrasound showed more effective for microbial inactivation than PAW treatment alone. It resulted in the reduction of 1.49 and 1.39 log CFU/g for *S. putrefaciens* and *E. coli*, respectively. The use of PAW for 10 min resulted in a reduction of 0.15 and 0.24 log CFU/g in total mesophilic bacteria count and total psychrotrophic bacteria count, respectively, on raw mackerel fillets. When PAW pretreatment was combined with ultrasound, the reduction in total mesophilic bacterial counts and total psychrotrophic bacterial counts on raw mackerel fillets increased to 0.38 and 0.27 log CFU/g, respectively (Zhao et al., 2021). Additionally, Liao et al. (2018) proposed that PAW ice could serve as an alternative preservation for fresh shrimp. It showed a superior antimicrobial effect to conventional tap water ice, resulting in an impressive extension of the storage for shrimp by 4–8 days. Ultrasound shows antimicrobial properties by leveraging mechanisms such as sonolysis and cavitation, which involve the generation of rarefaction, mechanical shockwaves, and compression (Han et al., 2023). Consequently, ultrasound in combination with PAW exhibited highly effective microbial inactivation, offering innovative approaches to food preservation and safety assurance (Han et al., 2023).

Application of PAW for Seafood Preservation

Color is one of the most essential aspects of seafood products. Fresh and colorful seafood is a good indicator of freshness and high quality. The maintenance of natural color of seafood is a critical consideration for seafood producers and sellers. In the case of yellow river carp fillets, PAW pretreatment resulted in an elevation of the *L** value (lightness) and a reduction in the *a** value (redness), with no significant changes observed in the *b** value (yellowness), texture characteristics, and sensory attributes (Liu et al., 2021a). Mackerel fillets subjected to PAW pretreatment and PAW-ultrasound pretreatment showed no significant differences in *a** (redness), *b** (yellowness), *L** (lightness) values, and peroxide value. In shrimp, PAW-pretreated samples still had a pH below 7.7 during storage, leading to the delayed changes in color and firmness as well as lipid oxidation. Additionally, the TVB-N value in PAW-treated samples exhibited a significant reduction compared to other treatment methods, and this decrease did not adversely affect the protein content (Liao et al., 2018).

Limitation of PAW

There have been several documented improvements in the development and application of PAW. During PAW generation, the increased quantities of acidogenic molecules (NO_2^- and NO_3^-), such as nitrous, singlet oxygen, and nitric acids, and their derivatives are produced. When those molecules combine with water, nitric acid is produced and lowers the pH of food (Yong et al., 2015). Lower pH and acidity could determine the processing requirements necessary for inactivation of some microorganisms in foods. Nevertheless, drastic alteration may have an undesirable impact on product texture, flavor, and shelf life. PAW treatment of golden pompano fillets showed a

decrease of *a** value (redness), which could result from the damage of myoglobin caused by ROS. The ROS and/or RNS derive from cold plasma readily promote lipid and protein oxidation especially form fish and seafood (Olatunde et al., 2019). The combination of polyphenol antioxidant, e.g. coconut exocarp flavonoids, and PAW exerted synergistic effect on the quality preservation of fillets. The polyphenol antioxidant marinating followed by PAW soaking significantly inhibited microbial spoilage, maintained sensory quality, and lowered lipid and protein oxidation (Gao et al., 2024). PAW-pretreated grass carp exhibited the significant increases in lipid oxidation, total volatile basic-nitrogen, and protein degradation. However, these values remained within acceptable limits. Although PAW-ultrasound pretreatment was more effective in preserving hardness, it adversely impacted color of the treated sample (Esua et al., 2021b). Moreover, the limitations of PAW for the use in seafood products in the low bacterial inactivation. As a consequence, it must be combined with other emerging nonthermal technologies to achieve adequate food quality and safety. This comprehensive method can improve the safety and quality of food products by minimizing microbial growth on their surfaces or interior portions (Han et al., 2023).

Non-thermal Processing Technology for Seafoods

High-pressure Processing (HPP)

The growing consumer demand for high-quality foods characterized by fresh sensory attributes and absence of additives has driven the advancement of non-thermal food processing technologies as choices instead of traditional thermal processing (Huang et al., 2017). HPP is a non-thermal technique that utilizes high-pressure to inactivate pathogens and extend the shelf-life of food products. The pressure is applied uniformly from all sides, ensuring an effective inactivation of microorganisms, while maintaining the sensory quality of the processed food. During HPP treatment, the food product is exposed to pressures ranging from 100 to 1000 MPa for a short period, typically 2-3 min, and at temperatures between –20 to 121°C (Ekonomou & Boziaris, 2021; Koutchma, 2014). The process involves placing the sealed food product in a pressure vessel filled with a pressure-transmitting liquid medium (usually water), in which all the air inside the chamber is expelled. The pressure-transmitting medium ensures that the pressure is evenly distributed throughout the product. The process is usually carried out in batch or semi-continuous mode using specialized equipment designed for specific types of food products (Koutchma, 2014). HPP is based on the *Pascal* (isostatic) and *Le Chatelier* principles. The first principle asserts the uniform and nearly immediate transmission of pressure throughout food, without regard for its mass, dimensions, or composition**.** Another principle highlights HPP's ability to promote reactions, leading to volume reduction, while inhibiting those reactions causes the increases in volume (Medina-Meza et al., 2014). However, the presence of a minimal moisture content is required for effective pressure propagation. This principle, as described by Barbosa-Cánovas and Rodríguez (2002) and Cheftel (1995), states that any process involving a reduction in volume, including phase transitions, molecular conformation alterations, or chemical reactions, is enhanced under elevated pressure condition, while the decreased pressure can minimize these volume-reducing transformations.

Antimicrobial Efficacy of HPP

The utilization of HPP has demonstrated its benefits in terms of microbiological inactivation. The efficacy of HPP treatment on bacterial inactivation depends on several factors such as the type of microbe, growth phase, applied pressure level, process temperature, and duration (Tao et al., 2014). Generally, increasing pressure, holding time, or temperature lead to greater inactivation of microorganisms. Gram-negative bacteria are typically more sensitive to high-pressure than Gram-positive bacteria (Ekonomou & Boziaris, 2021). Bacterial spores are more resistant, but certain conditions, such as high-pressurization temperatures, can lead to their inactivation (Bhat et al., 2021a). Using HPP within the pressure range of 150–350 MPa has the potential to achieve a significant reduction of *Vibrio* spp. over 3.52 log units, thus meeting the safety standards required for shellfish processing (Roobab et al., 2022). HPP has its capability to effectively control and reduce *V. parahaemolyticus*, a pathogenic bacterium, in Pacific oysters (*Crassostrea gigas*). HPP treatments at 293 MPa for 2 min achieved a reduction of at least 3.52 log units, extending the shelf-life significantly when stored at 5°C or on ice (Ma & Su, 2011). Additionally, HPP at pressure exceeding 350 MPa for 2 min led to an impressive reduction of 5 log units of *V. parahaemolyticus*, highlighting the potential of HPP for enhancing the safety of seafood products (Ma & Su, 2011; Campus, 2010). *Escherichia coli* displayed the resistance to HPP treatments, with reductions ranging from 1.9 to 4.7 log units observed in raw black tiger shrimp when exposed to pressures of 500 MPa for 3 to 9 min. Achieving higher reductions of 4 to 6 log units necessitated more intense HPP conditions, specifically at 600 MPa for 6 to 9 min, as reported by Kaur et al. (2016). The isostatic principle behind bacterial inactivation during HPP treatment is the modifying cell membranes through structural changes in proteins and membrane phospholipids (Figure 1) (Patterson, 2014).

Application of HPP for Seafood Preservation

Apart from microbial inactivation, HPP has the capability to maintain the original color, flavor, aroma, quality, and nutritional value of treated seafood

products (Arnaud et al., 2018; Tsironi et al.,2019). The effectiveness of HPP in preserving seafood products is influenced by many factors (Table 1). The application of HPP at pressures ranging from 200 to 300 MPa led to the inactivation of pro-oxidative enzymes in both lean and fatty fish, particularly when applied prior to freezing (Cropotova et al., 2020). Truong et al. (2016) reported that pretreatment of barramundi muscle with HPP at pressures ranging from 150 to 200 MPa for 3 min, increased muscle hardness and effectively delayed lipid oxidation during frozen storage at –18°C for a duration of 18 weeks. HPP exhibits a diverse range of effects on the quality and shelf-life of various fish species. It can maintain water in food matrix and extend shelf-life in European hake at 150 –450 MPa (Pita-Calvo et al., 2018a). HPP also improved texture, preventing lipid hydrolysis, and prolonged shelf-life of raw hilsa fillets at 250 and 350 MPa for 10 min (Chouhan et al., 2015). Conversely, HPP at 500 MPa could increase the activity of cathepsins in fresh sea bass fillets. This potentially linked to the reduction in activity of degradative enzymes such as cathepsins, acid phosphatases, lipases, and calpains, as observed in fresh sea bass fillets (Chéret et al., 2005; Teixeira et al., 2013). HPP at pressure levels exceeding 200 MPa was found to reduce the conformational stability of myofibrils, while pressures above 300 MPa increased the sulfhydryl content, hydrophobic regions, and free amino acids within the fish muscle tissue (Bhat et al., 2021b).

HPP-based inactivation of endogenous enzymes in seafood has been reported. HPP has been observed to effectively inhibit lipid hydrolysis and oxidation, while reducing the breakdown of trimethylamine oxide during the frozen storage of both fatty and lean fish species, as demonstrated by Vázquez et al. (2018). Cropotova et al. (2020) found that fish cake subjected to a pressure treatment of 200 MPa exhibited improved sensory quality as witnessed by lighter color, softer texture resulting from denatured proteins, and a decreased degree of lipid oxidation, possibly attributable to the inactivation of pro-oxidative endogenous enzymes. HPP has been documented to offer advantages in terms of extending the shelf-life of seafood and effectively inactivating biogenic amines during refrigerated storage (Matějková et al., 2013). In general, some fish products are prone to the formation of biogenic amines during refrigerated storage, primarily due to enzymatic and microbial activities, which result in undesirable off-flavors. In some cases, biogenic amines can cause intoxication, (Biji et al., 2016; Cheng et al., 2014). HPP applied to raw squid at pressures ranging from 200 to 400 MPa resulted in a substantial reduction in the concentrations of dimethylamine (DMA) and TMA, in which the decrease of 20 – 51% was observed after 20 days of chilled storage (Gou et al., 2010), while HPP applied to black tiger shrimp at pressures ranging from 300 to 600 MPa for 3 – 9 min resulted in a substantial reduction in TMA concentration by 20 – 63% (Kaur et al., 2016). Moreover, HPP treatments induced slight modifications in chemical compositions and nonvolatile sensory compounds of raw oysters, as reported by Liu et al. (2021b). These obvious changes occurred after HPP treatment at 400 MPa for 3 min at 20°C was applied, compared to a traditional steam processing method. HPP has been used in combination with other technologies to obtain some synergistic effects. The synergistic application of HPP at 500 MPa for 5 min at 4°C, microwave treatment at 900 W for 1 min, marination, and vacuum packaging effectively maintained the monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFAs) contents of Atlantic mackerel samples, leading to a notable improvement in their overall nutritional quality (Fiore et al., 2019).

In crustaceans and mollusks, the main function of HPP application involves treatment at pressure levels ranging from 100 to 600 MPa for 3 – 15 min. Rong et al. (2018) found that HPP at 275 MPa for 3 min or 300 MPa for 2 min resulted in the complete release of oyster adductor muscles, thus optimizing the shucking process. Shucking mollusks and crustaceans with HPP not only enhance flavor and juiciness but also facilitates 100% meat removal by separating the meat from the shell in blood clams, lobsters and crabs. (Palamae et al., (2024a, 2024b) reported that HPP at 300 MPa for 3 min was easily shucked and had a high expanding rate. It was also recommended for blood clam processing to preserve color, heme iron content, and fatty acid profiles. This process offers clean label product claimed "100% natural" and "additive-free" (Roobab et al., 2022).

Limitation of HPP

Different microorganisms have varying degrees of resistance to HPP, and some factors e.g., growth phase, pH, and food matrix composition can influence their susceptibility (Farkas and Hoover, 2000). Furthermore, HPP equipment and operational costs are relatively high. There has been an increasing investment in industrial HPP units due to the technology's potential benefits in terms of food safety and quality improvement. While HPP can effectively reduce or inactivate several microorganisms, it may not be sufficient for complete pathogen reduction (Huang et al., 2017). The isostatic compression and subsequent release of pressure during HPP showed a negative impact on sensitive small molecules such as vitamins and flavor components to some extent (Linton et al., 2000). However, HPP under the extreme condition brings about the changes in quality attributes or acceptability, e.g., textural alteration, color changes, etc. (Bhat et al., 2021a; Roobab et al., 2022). A pressure of 400 MPa may potentially disrupt lysosomes, leading to denaturation, aggregation, and fragmentation of sarcoplasmic proteins (Teixeira et al., 2013). Palamae et al. (2024a) and Palamae et al. (2024b) also reported that HPP >400 MPa damaged hemolymph and caused gaps, increased lipid oxidation and destruction of tissue of

Table 1. Applications of HPP for seafood preservation

Seafood product	Condition	Finding	Reference
Fish:			
European sea bass (*Dicentrarchus labrax*)	600 MPa for 5 min at 25°C.	- Reduction of >5 log CFU/g of initial TVC - Increase in lightness and hardness with compacting fibers. - Extension of shelf-life: 11 days for untreated fillets, 2 months for HPP-treated fillets	Tsironi et al. (2019)
Mackerel fillets	100-500 MPa for 2-5 min.	- Reduction of TVC and H_2S-producing bacteria at 300 MPa for 5 min and 500 MPa for 2- or 5-min. - Increase in lightness (*L**) and decrease in redness (*a**) at 500 MPa - Decrease in EPA, PUFA, HUFA, DHA, CLA levels - Increase in MUFAs and SFA levels	de Alba et al. (2019)
Tuna (Skipjack, *Katsuwonus pelamis*)	150-600 MPa for 1-5 min.	-Increase in protein denaturation with higher HPP pressure - Decrease in water holding capacity from 57% to 44% at 600 MPa. - Reduction of total aerobic counts by 4.75, 0.12, 1.20, 4.69, and 6.08 log CFU/g at 150, 300, 450, and 600 MPa of HPP pressures, respectively	Jiranuntakul et al. (2018)
Tilapia (*Oreochromis niloticus*)	100-400 MPa for 1-3 min combined with storage at 5°C for 7 days.	- Increase in *L** and whiteness in treated samples at 300 and 400 MPa compared to control samples - Reduction of psychrotrophic bacteria at 300 and 400 MPa - Maintain sensorial properties at 200 MPa of HPP treatment - Effective preservation: HPP at 400 MPa for 3 min, but color changes may reduce commercial viability.	Suemitsu and Cristianini (2019)
Salmon (*Salmo salar*), cod (*G. morhua*), and Mackerel (*Scomber scombrus*)	200 and 500 MPa for 2 min combined with stored for 26 days.	- No effect on salmon oxidation with HPP at 200 MPa (unlike cod). - Mackerel had consistently high TBARS levels, regardless of pressure. - Reduction of acid phosphatase for both control and 200 MPa treated salmon at day 11 compared to day 0.	Rode and Hovda (2016)
Mollusks:			
Oysters (Pacific, *C. gigas*)	100-350 MPa for 1-3 min with stored at 4°C.	- HPP at 275 MPa for 3 min or 300 MPa for 2 min: 100% release of oyster adductor muscle. - This process decreased aerobic bacterial count by 1.27 log CFU/g. - Pressures above 350 MPa led to excessive oyster shell breakage.	Cao et al. (2017)
Oysters (Pacific, *C. gigas*)	300 MPa for 2 min combined with stored at 4°C.	- Control oysters had a shelf-life of 6–8 days, while HPP-treated oysters lasted 12 days. - Spoiled HPP-treated oysters were dominated by *Psychrobacter* (42.3%). - Spoiled oysters without HPP treatment were dominated by *Pseudoalteromonas* (32.2%) and *Shewanella* (19.5%).	Rong et al. (2018)
Blue Mussel, (*Mytilus edulis*) homogenates	250-450 MPa for 1-3 min at 25°C.	- For >5 log CFU/g reduction: *V. alginolyticus* and *V. cholerae*: 350–450 MPa for ≥1 min at 25 °C. *V. vulnificus*: 250 MPa for ≥3 min or 350–450 MPa for ≥1 min. *V. parahaemolyticus*: 350 MPa for ≥3 min or 450 MPa for ≥1 min.	Vu et al. (2018)
Blood clam edible portion, *Tegillarca granosa*	100-600 MPa for 3 min	- HP-P at 300 MPa did not affect hemocyte, heme iron and redness of blood clam edible portion. - HP-P > 400 MPa damaged hemolymph and caused gaps of tissue of blood clam edible portion. - HP-P at 600 MPa reduced lipid globular structure diameter from 16 µm to 3 µm. - Lipid oxidation of blood clam edible portion was enhanced with increasing pressure levels.	Palamae et al. (2024b)
Squid (Jumbo, *Dosidicus gigas*)	100-400 MPa combined Salt (15 g/100 ml) for 30 s.	- Increasing pressure levels raised *L** (Lightness) and *b** (yellowish) but lowered *a** (reddish) in color parameters. - Samples appeared brighter and exhibited a mildly cooked appearance.	Lemus- Mondaca et al. (2018)
Crustaceans:			
Shrimp (Black Tiger, *P. monodon*)	300-600 MPa for 0-15 min at 30-60°C.	- HPP and temperature enhanced inactivation of *E. coli*, *L. innocua*, and *S. aureus*. - Reduction of 6 log CFU/g of *S. aureus* with moderate quality changes at optimal conditions (361 MPa for 12 min at 46°C)	Kaur and Rao (2017a, and b)
Shrimp (*L. vannamei*), shelled fresh	200-400 MPa for 5-15 min combined AEW	- Single HPP treatment reduced *V. parahaemolyticus* and *L. monocytogenes* by 4.74 and 4.31 log CFU/g, respectively. - AEW greatly enhanced HPP for *V. parahaemolyticus* and *L. monocytogenes* inactivation (up to 6.08 and 5.71 log CFU/g).	Du et al. (2016)
Crab (Chinese Mitten, *Eriocheir sinensis*)	300 MPa for 20 min at 25°C combined chilled storage at 4°C.	- Decrease in lightness and whiteness for HPP-treated meat after 3 weeks of storage On day 8, crab meat had an aerobic plate count of 5.71 log CFU/g, total volatile base nitrogen of 24.50, and histamine content of 0.99 mg/100 g. - The shelf-life was extended to 6 days, and the dominant spoilage organism was *Clostridium*.	Ye et al. (2021a and b)

blood clam edible portion. Thus, it is often used in combination with other technologies to ensure microbiological safety in seafoods and maintain the original quality and flavor of their products.

Cold Plasma (CP)

CP is a relatively new technology with high antimicrobial potential, which has been developed for treatment of different fresh and ready-to-eat food products (Ganesan et al., 2021). This technology is based on the application of high voltage electricity or other energy inputs to ionize gaseous atoms. Free electrons naturally present in the gas will absorb the energy at a more accelerated rate than the other ions, in which they will transfer the absorbed energy to heavier molecules through elastic and inelastic collisions. This imparts reactive properties on the gas, which further undergoes excitation, phase reactions-ionization, and dissociation to generate several reactive species (free radicals, ROS, new electrons, ions, etc.) (Misra et al., 2016). These generated reactive species have the ability to interact with microorganisms or enzymes, causing their inhibition and inactivation (Tagrida et al., 2021). Therefore, this technique can show promising aspects to be used for sanitizing food surfaces and the packages (Olatunde & Benjakul, 2018). No discoloration or dehydration took place in CP treated products (Sharma, 2020). CP can be generated via different devices, depending on the electric field source, pressure, gas flow, and gas type. It can provide a wide range of active species, depending on adjustable parameters (Schlüter et al., 2013). For the pressure involved in the process of CP generation, either low or atmospheric pressure, can be used (Misra & Jo, 2017).

Low-pressure CP System

A comprehensive low-pressure CP system includes a vacuum chamber, gas removal pump, gas feeders, controllers, gauges, and multi-frequency electrodes for diverse deposition techniques (Garvey & Rowan, 2019). Low-pressure CP systems offer precise control over gas quantity and composition due to their operation in a closed vacuum vessel, ensuring a balanced distribution of plasma throughout the enclosure (Okyere et al., 2022). There are several low-pressure systems used for CP generation.

Glow Discharge CP

In this system, an electric current (≥100 V) either alternating current (AC) or direct current (DC), is applied through a gas over a series of electrodes. Due to excitation and collisions, electrons and other reactive species are generated with sufficient energy, which results in generation of other reactive species including the photons responsible for the visible glow (Campelo et al., 2020). Glow discharge plasma has been used in food applications such as seed germination, agronomic traits, enzymatic activities, and nutritional properties (Sohan et al., 2022).

Radio Frequency (RF) Discharge CP

This kind of plasma typically operates at a radio frequency range between 1 and 100 MHz. The plasma is generated when an oscillating electromagnetic field produced either by inductive or capacitive discharge, is applied on a gas (Obileke et al., 2022). It is a highly effective method for preventing food spoilage under specific controlled conditions (Jiang et al., 2022). RF discharge CP can inactivate microorganisms, in which products can meet microbial food safety standards.

Microwave Plasma

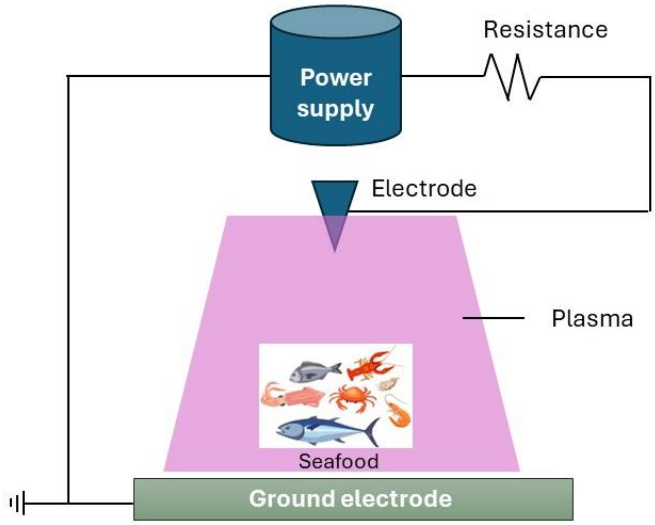
Like RF discharge CP, this technique functions by oscillating electrons, which in turn generate ions and other free radicals by colliding with gas atoms and molecules (Ganesan et al., 2021). Microwave plasma is usually created through capacitive coupling by employing a magnetron to generate microwave power, which is then transmitted through coaxial waveguides to a hollow coaxial electrode (Ivanov et al., 2019). The gas, typically argon or nitrogen, is capacitively infused with microwave energy via the electrode to generate plasma (Misra et al., 2016). It has been used for many food packages and other industrial applications due to its ability to penetrate bacterial cells and cause oxidative stress, plasma membrane alterations, and DNA modifications.

Atmospheric-pressure CP System

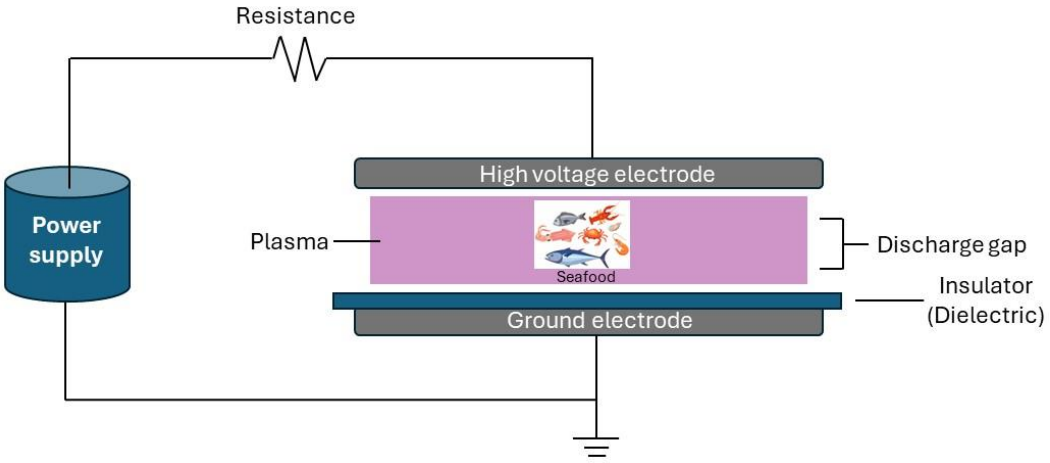
These systems are commonly operated at a high voltage using either AC or DC (Figure 2). They provide a continuous treatment to the product (Okyere et al., 2022). The most notable atmospheric-pressure CP systems have been documented.

Corona Discharge

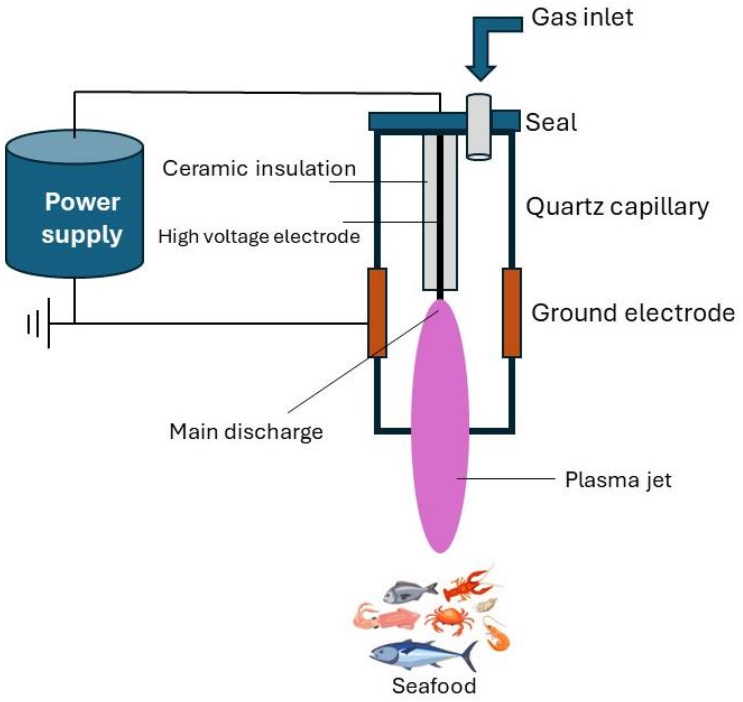
This type of plasma is generated when a strong electric field ionizes the air around a conductor, usually appearing at atmospheric pressure close to sharp points or thin wires having sufficiently large electric field (Puač et al., 2018). The instrument setup typically comes in the shape of two contrasting electrodes, positioned apart by a space that holds the gas used to produce plasma. These electrodes are linked to a high-voltage source (Darvish et al., 2020). These configurations are energized by high, continuous, or pulsed DC or AC voltages. Gases employed to generate corona discharge can include air, N_2, Ar, a mixture of He and O_2, or Ar and O_2 (Dobrynin et al., 2011). Corona discharge has been used for improving the quality of many foods (Lee et al., 2018).



A. Corona discharge



B. Dielectric barrier discharge (DBD)



C. Plasma jet

Figure 2. Atmospheric-pressure cold plasma systems.

Dielectric Barrier Discharge

The setup of the system usually consists of electrodes covered with dielectric materials such as quartz, ceramic, or plastic. The gases (air, N_2, Ar, and He) enclosed between two electrodes are ionized by the application of a high voltage to the electrodes, leading to the generation of plasma (Thirumdas et al., 2015). Electrodes are typically positioned within the sealed container, allowing for direct sample treatment and preventing the escape of generated plasma species (Feizollahi et al., 2021). Additionally, round-edged electrodes, dielectric materials used, and the application of high voltage are utilized to avoid arcing during the generation of plasma (Okyere et al., 2022). Currently, this technique has been extensively used for the destruction of vegetative cells and spores of several microorganisms that can grow on different food materials (Guo et al., 2021).

Plasma Jets

Plasma jet systems feature a generator with an outer casing serving as a ground and an inner electrode crafted from materials like stainless steel, pyrex, or glass (Okyere et al., 2022). The generator is connected to two electrodes, one serving as the ground electrode and the other linked to the power supply, facilitating the generation of the plasma jet. This system also contains airflow monitor, and gas inlet (Deng et al., 2020). The supplied gas is ionized by applying high voltage between the electrodes. Thereafter it expands to the surroundings outside a nozzle. Compressed air, or mixture of Ar/N_2 and O_2 were reported to be the most suitable gases used in this kind of system with better preservation properties (Sharma, 2020).

Microbial Activity and Enzyme Deactivation Efficacy of CP

Basically, CP can efficiently destroy or inhibit the growth of numerous bacteria, fungi and other pathogens or spoilage microorganisms (Lacombe et al., 2015) (Figure 3). CP can instantly react with microbial macromolecules, such as polysaccharides, lipids, proteins, and DNA causing their oxidation and altering their nature (Deng et al., 2020). These particles and radicals in plasma have the tendency to affect the integrity of the microbial cellular membranes because of their ability to adhere to the microbial cell surface (Wu et al., 2021). As a consequence, their permeability and their functional activities are affected, resulting in the eventual inhibition of their growth (Olatunde & Benjakul, 2018). Reactive species can induce the formation and accumulation of intracellular oxidative stress, affecting the cytoplasmic and nuclear responses, which consequently result in DNA damage, cell cycle alterations and apoptosis (Panieri et al., 2013). CP treatment affected the microbial proteins abundancy and genes responsible for the functions of cell wall, membrane, motility, chemotaxis, stress resistance, prophages formation and sporulation (de Souza Pedrosa et al., 2021).

CP has been reported to inactivate a wide range of enzymes such as polyphenol oxidase, peroxidase, and lysozyme (Misra et al., 2016). The generation of plasma can degrade enzymes via damaging their active sites by reactive species (Misra et al., 2019). It can also slow down the metabolic activity of the tissue, thus halting their enzymatic activities (Tappi et al., 2016). Peroxidase and polyphenol oxidase are the enzymes found widely in various foods. Peroxidases are commonly linked to reactions that could negatively impact the quality of food, including the oxidation of lipids and phenols, leading to changes in flavor and surface browning (Wang et al., 2023a). Rapid deactivation of peroxidase in many foods was achieved when exposed to CP, denoting its importance in preventing such negative impacts (Mayookha et al., 2022). Most CP uses nitrogen and oxygen gas mixtures to generate plasma that contains considerable amounts of nitrogen oxides molecules, which are responsible for decreasing the activities of several enzymes by altering their structure (Misra et al., 2016). When amino acids such L-alanine and L-valine were directly exposed to CP, degradation of COOH group and NH_2 group was observed and by-products such as formic acid, acetone, acetic acid, pyruvic acid, and erythro-methlyaspartic acid were formed (Li et al., 2014; Wang et al., 2023b). Free oxygen atoms along with other free radicals generated by CP have the ability to abstract hydrogen from the enzyme's backbone, thus generating more radical, which leads to subsequent radical chain process. This results in the cleavage of the entire enzyme chain and the formation of volatile compounds (Birania et al., 2022).

CP led to a significant diminishment in the number of α-helices, signifying the loss of enzyme activity. Similarly, Segat et al. (2016) reported that the loss in the activity of alkaline phosphatase after treatment with CP was attributed to the loss of α-helix structure along with a decrease in the β-sheet content. The decomposition of different bonds in the enzymes resulting from oxidation by reactive species of oxygen containing plasma leads to loss of β-structure, thereby inactivating these enzymes (Iqbal et al., 2019). Thus, the alterations in the structure of enzymes are strongly attributed to the chemical interactions between the enzyme polymer units and the reactive species generated by CP. Therefore, CP can be used to inactivate the activity of enzymes linked with adverse effects in different foods (Pankaj et al., 2013).

Application of CP for Seafood Preservation

Majorly, CP was used to decontaminate food products such as agricultural crops, cheese, meat, eggs, and dairy products (Ganesan et al., 2021). Due to its effectiveness in microbial decontamination, the use of CP was extensively studied for the preservation and

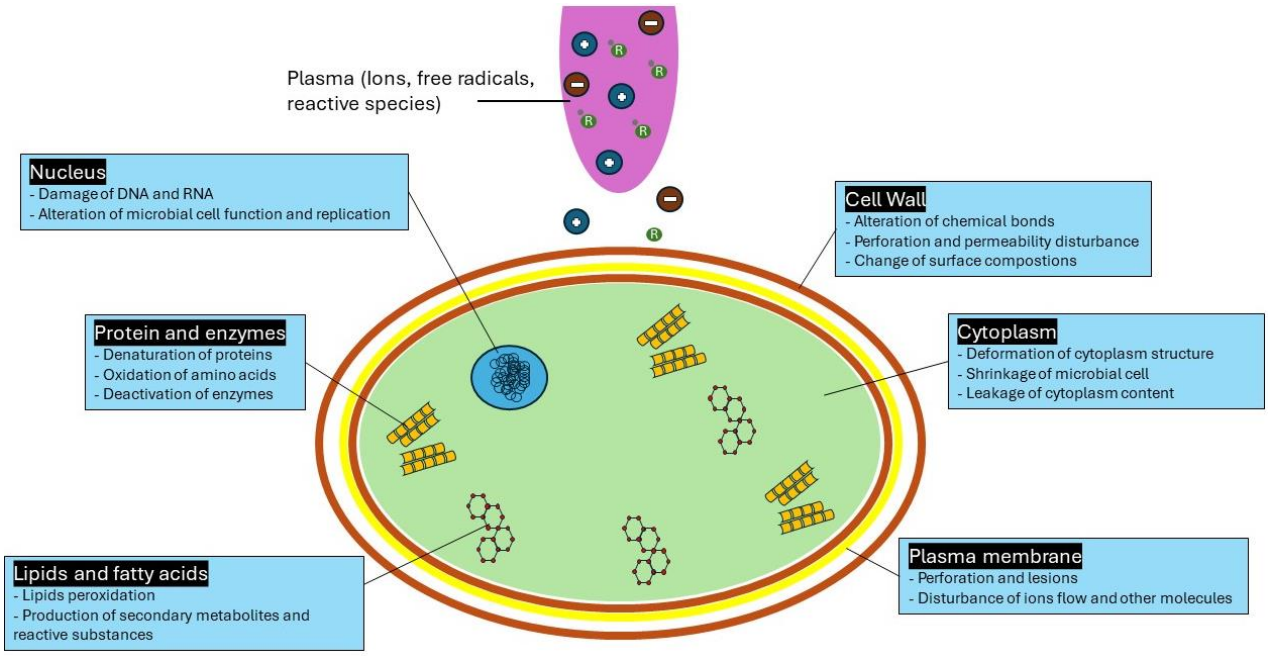


Figure 2. Impact of cold plasma on the activity of microbial cells.

shelf-life extension of seafood (Rathod et al., 2022). In general, seafood is rich in PUFAs, that are easily susceptible to lipid oxidation. This can lead to rancid odor, inedible taste, loss of nutrients, formation of unhealthy molecules and color changes (Olatunde et al., 2021c). CP generated from air using DBD technique at 40 kV, and 500Hz for 10 min was able to reduce bacterial count and extend the shelf-life of Pacific white shrimp up to 14 days (da Silva Campelo et al., 2019). The physicochemical properties and sensorial attributes were improved during the storage compared to the control samples which showed rapid spoilage. Asian seabass slices had the prolonged shelf-life (15 days) when treated with CP at 80 kV for 5 min using the mixture of CO_2, Ar, and O_2 (60:30:10) (Olatunde et al., 2020). Lower total volatile nitrogen base content and total bacterial count were found in the treated slices, compared to the untreated slices, which showed the elevated spoilage. CP markedly changed the biophysical properties and induced aggregation of the protein which further strengthened the gel formation of surimi made from threadfin bream muscles (Olatunde et al., 2021c). Color attributes, water holding capacity, and textural properties of the myofibrillar proteins from Largehead hairtail were enhanced significantly after treatment with CP generated from air using DBD at 50 kV for 300 s (Koddy et al., 2021). Recent applications of CP for seafood preservation are summarized in Table 2.

Limitation of CP

Cold plasma has shown promise as a novel technology for food preservation, but it also comes with certain limitations and challenges which can include limited penetration depth into certain food matrices. This can affect its ability to treat and inactivate microorganisms that may be present in the inner layers of certain food products (Tagrida et al., 2021). Cold plasma is often more effective in surface treatments rather than penetrating deep into porous or structured food items. This limitation may impact its ability to treat foods with complex surfaces or irregular shapes thoroughly (Koddy et al., 2021). While cold plasma is effective against many pathogenic microorganisms, its efficacy against spoilage microorganisms may vary. Some spoilage microorganisms may be more resistant to the effects of cold plasma, additionally the efficacy of cold plasma can be influenced by factors such as the composition and properties of the treated food, the type of microorganisms present, and environmental conditions. This variability makes it challenging to establish consistent inactivation levels (Olatunde et al., 2020). Moreover, cold plasma treatments may have an impact on the sensory attributes, nutritional quality, and overall organoleptic properties of treated foods (Tagrida & Benjakul, 2022). The equipment required for generating cold plasma can be complex and expensive. Additionally, operational costs may be higher compared to some traditional preservation methods. Also, cold plasma systems may require a significant amount of energy, and the associated energy consumption can be a concern in terms of sustainability and cost-effectiveness. This can be a limitation for small-scale or resource-limited food processing facilities (Rathod et al., 2022).

Modified Atmosphere Packaging (MAP)

MAP involves the use of gas barrier materials to enclose food products while modifying the gas

Table 2. Applications of cold plasma for seafood preservation

Seafood product	Type of cold plasma	Gas used and working conditions	Findings	References
Fish balls	Corona discharge cold plasma	Sterile dry air, 75 Hz and air flow of 6.5 L/min	- Reduction of bacterial load - Deformation and rupture of bacterial cells - Maintain physical appearance of the products	Zhang et al. (2019)
Pacific white shrimp	In-bag dielectric barrier discharge	Ar/air (80/20), 16 kVRMS, for 10 min	- Reduction in bacterial count - Improvement of physicochemical properties - Shelf-life extension up to 15 days at 4°C	Shiekh and Benjakul (2020)
Tilapia fillets	Dielectric barrier discharge	Atmospheric air, 60 kV for 4 min	- Reduction of enzymatic activity, total sulfhydryl (TSH) and carbonyl contents - Retardation of bacterial growth - Shelf-life extension for 10 days at 4°C	Mohamed et al. (2021)
Tilapia slices	In-bag dielectric barrier discharge	CO_2: Ar: O_2 (60:30:10), 80 kVRMS for 300 s+ pretreatment with betel ethanolic extract	- Retardation of bacterial growth - Reduction of lipid oxidation and total nitrogenous compounds content - Maintain sensorial properties - Shelf-life extension for 12 days	Tagrida et al. (2021)
Seafood product	**Type of cold plasma**	**Gas used and working conditions**	**Findings**	**References**
Blue swimming crab lump meat	In-bag dielectric barrier discharge	O_2 and Ar (10:90), 80 kVRMS for 15 min	- Reduction of spoilage bacteria - Maintain physical and sensorial properties - Shelf-life extension for 9 days	Olatunde et al. (2021a)
Bigeye Tuna Slices	In-bag dielectric barrier discharge	Atmospheric air, 40 kVRMS for 90 s	- Retain volatile freshness compounds - Maintain sensorial properties for 7 days of storage at 4°C - Preserve the flavor of the slices	Pan et al. (2022)
Tilapia Fillets	Dielectric barrier discharge	Atmospheric air,70 kV for 60, 120, 180, 240, and 300 s	- Reduction of microbial load - Increase lipid oxidation with increase the treatment time - Maintain physical properties	Wang et al. (2022b)
Fresh sea bass	Dielectric barrier discharge	He/air, 20 kHz and 30 kV for 10 min	- Reduction of total nitrogenous compounds and lipid oxidation - Retardation of bacterial growth - Improve sensorial properties after 5 days of storage	Mol et al. (2023)

environment within the package to inhibit the growth of spoilage microorganisms and extend shelf life. As a consequence, higher quality can be maintained, and shelf life of perishable food can be extended during storage (Tagrida et al., 2021). Two major forms of MAP include vacuum packaging and gas flush or gas exchange packaging. Vacuum packaging involves placing the food product in a package that has low gas permeability. Thereafter the air is removed from the package and the hermetic seal is applied (Cenci-Goga et al., 2020). This technique is based on the principle that both aerobic microorganisms and oxidation reactions based on oxygen can be inhibited. Therefore, it can impede spoilage, maintain product quality, and extend shelf-life (Conte-Junior et al., 2020). Despite these effects, vacuum packaging may lead to some deterioration due to the proliferation of anaerobic or microaerophilic microorganisms and the occurrence of non-oxidative reactions. Additionally, vacuum packaging will lead to product compression which is unavoidable and can result in consumer rejection of the packaged products (Fidalgo et al., 2020).

Gas exchange packaging is similar to vacuum packaging, but the key difference is that after removal of air from the package, a specific mixture of gases is introduced to that package, in which the atmosphere of the package can be controlled (Olatunde et al., 2019a). This technique was designed to overcome some drawbacks of vacuum packaging by inhibiting a wider range of spoilage microorganisms and avoid the compression of food products (Tabassum & Khan, 2020). The inhibition effect of this technique depends on the gases used for the process. Keeping the packaged product in refrigerated conditions is general practice, which can maximize the inhibition effect.

Antimicrobial Efficacy of MAP

Several gases have been commonly used in MAP. Each has specific function to retard the spoilage of the packaged products (Tagrida et al., 2021). Oxygen (O_2) removal from the package is vital to ensure the inhibition of the aerobic microbes and the retardation of oxidation of seafoods. Moreover, O_2 is important for packaging of red meat or seafood meat such as tuna which requires myoglobin to be preserved in its oxygenated form (oxymyoglobin) with the preferable bright red color (Conte-Junior et al., 2020). For salmon, appropriate gas mixture can help maintain the astaxanthin, a major pigment of salmon meat (Conte-Junior et al., 2020) To achieve these demands, the O_2 must be controlled within the packages to avoid the strictly anaerobic condition, which promote hazardous pathogens e.g., *Clostridium botulinum* (Cenci-Goga et al., 2020).

Carbon dioxide (CO_2) has been extensively used in MAP because of its immense importance in the inhibition of many spoilage microorganisms, particularly after dissolution into the packaged product (Masniyom et al., 2002). The inhibitory effect of CO_2 is linked to the amount used. Nevertheless, CO_2 at levels higher than 60% was found to show no significant difference in its inhibitory effect towards several microorganisms (Floros & Matsos, 2005). The package volume, surface area, and the permeability of the packaging material are important factors to be considered as they will affect the dissolution of CO_2 into the product, thus affecting the inhibition activity of CO_2 (Qu et al., 2022). Additionally, low storage temperature is found to enhance the solubility of CO_2. Thus, it can have synergistic effects by increasing its inhibition effect (Simpson et al., 2009). Carbonic acid is formed after the dissolution of CO_2, which is believed to cause the inhibition effect towards many microorganisms by altering the pH of the environment and consequently affecting their permeability and other metabolic reactions in bacterial cells (Tagrida & Benjakul, 2022). Nevertheless, the accumulation of carbonic acid will lead to an increase in the acidity of the products, which can be rejected many consumers. Furthermore, the increased intake of the gas by the packaged product will lead to pack collapse which change its appearance and may contribute to sealing problem or material fault (Masniyom et al., 2002). CO_2 was reported to increase the duration of the lag phase. Bacteria can remain dormant during this period, thus increasing the inhibitory effects (Spilimbergo & Bertucco, 2003).

Nitrogen (N_2) is used as a balance or filler usually to replace O_2 in packaging and if the product is highly prone to oxidation. It also can be used to limit pack collapse caused by the absorption or dissolution of CO_2 (Rashvand et al., 2023). This inert gas is tasteless, odorless, and colorless. Therefore, it will not lead to notable changes in the organoleptic or biochemical properties of the packed foods, thus maintaining the quality of the packed foods, retarding spoilage, and prolonging the shelf-life (Olatunde et al., 2019a). Additionally, N_2 cushions protect fragile foods within the package from being crushed during handling. Nonetheless, the amount of N_2 used in MAP should be optimized to provide sufficient protection and to allow space for additional expansion due to pressure changes during handling and storage (Kalpana et al., 2019).

Argon (Ar) is another inert gas that was used recently in MAP due to its characteristics and inability to react with the packed food products in harmful way. It does not cause notable changes on the chemical or sensorial properties of the packed food products (Olatunde et al., 2020). The effectiveness of Ar was demonstrated when a MAP system containing Ar was managed successfully in maintaining the quality of pomegranate arils (Tinebra et al., 2021). These keeping effects of Ar on pomegranate quality could be owing to the presence of Ar clathrate hydrate, which is formed when an inert gas is dissolved in water at a suitable temperature and pressure (Shen et al., 2019). Clathrate hydrate is a three-dimensional crystal structure compound consisting of two molecular sup-structures,

the primary molecule forms a cage-like structure through bonding, while the other molecule is enclosed in the cage-like structure (Lagnika et al., 2011). Water molecules align in clathrate hydrates to form complexes through the hydrogen bonds, and gas molecules are localized in the clathrate. These complexes are stable at temperatures around 0°C (Park et al., 2020). Formation of clathrate hydrate limits the water fluidity and several enzymatic reactions, thus maintaining the quality and physicochemical characteristics of packed products for prolonged periods (Shen et al., 2019).

Application of MAP for Seafood Preservation

Due to its preservative efficiency, MAP was used for the preservation of different seafoods. Nevertheless, to achieve maximum activity, MAP was usually used along with other preservative technology to cause a synergistic effect for the better preservation of the seafood (Olatunde & Benjakul, 2018). Skinless salmon fillets packaged in chitosan films enriched with pink pepper residue extract under MAP had the reduced lipid oxidation, compared to the control (Merlo et al., 2019). The packaged slices had lower bacterial count, lower total volatile nitrogen content, and better sensorial properties. The shelf-life could be extended up to 28 days. Masniyom et al. (2002) found that CO_2 proportion played a major role in shelf-life extension of refrigerated Asian seabass slices. Different gas compositions containing high CO_2 proportion in the range of 80–100%, showed the highest efficacy in shelf-life extension. In addition, the pretreatment of slices using pyrophosphate could exhibit the synergistic effect with MAP in inhibition of *Listeria monocytogenes* and *Escherichia coli* (Masniyom et al., 2006). Olatunde et al. (2019b) reported that MAP containing Ar showed superior preserving activity on Asian sea bass slices, in which the packaged samples had an extended shelf-life of 9 days, compared to 6 days for the control samples kept in air. A MAP system containing hydrogen (H_2) as reducing gas was also found to significantly reduce the quantity of biogenic amines in rainbow trout and horse mackerel (Sezer et al., 2022). The reduction rates were higher than that of a normal MAP system without the usage of H_2, denoting the significance of this gas in preserving seafood for longer period. Other applications of MAP for seafood preservation are shown in Table 3.

Limitation of MAP

While MAP has proven effective in preserving many types of foods, it also has certain limitations. MAP is more effective for certain types of foods and specific microorganisms. Its efficacy may vary depending on the food product and the microbial load present (Sezer et al., 2022). MAP is generally more effective against aerobic spoilage microorganisms than anaerobic ones. Oxygen-sensitive spoilage organisms may still proliferate in a modified atmosphere, affecting the overall quality of the product (Olatunde & Benjakul, 2018). The choice of packaging materials is crucial in MAP. If the packaging material is not sufficiently impermeable to gases, the modified atmosphere within the package may not be maintained, leading to a shortened shelf life, furthermore, implementing MAP requires specialized equipment to control gas composition within the packaging. The initial investment in this equipment, along with ongoing operational costs, can be a limitation for small-scale or resource-limited food processing facilities (Merlo et al., 2019). The effectiveness of MAP can be sensitive to temperature fluctuations during storage and transportation. Inconsistent temperature conditions may compromise the preservation benefits provided by the modified atmosphere (Park et al., 2020). Some microorganisms may adapt to the modified atmosphere over time, reducing the efficacy of MAP. This adaptation can lead to the survival and proliferation of spoilage or pathogenic microorganisms, in addition, MAP may create conditions that promote anaerobic respiration in certain microorganisms, leading to the growth of anaerobic spoilage bacteria. (Tinebra et al., 2021). Additionally, MAP may affect the sensory attributes, color, texture, and flavor of certain food products. The altered atmosphere can impact the oxidation of fats, which might result in changes to the product's overall quality (Qu et al., 2022).

Conclusions

Emerging non-thermal technologies for seafood processing encompass various stages, starting with pretreatment involving ozonized water, plasma-activated water, and acidic electrolyzed water. In general, pretreatment can reduce initial microbial loads. Subsequent non-thermal processes like high-pressure processing, cold plasma, and MAP are applied under suitable conditions to enhance microbial inactivation, while minimizing adverse effects. Finally, advanced packaging technologies, particularly MAP, play a crucial role in extending the shelf-life of seafood products. It is essential to store these pretreated/processed seafood products at low temperatures to enhance their shelf-life extension. The combined advantages of these technologies make them a promising approach for microbial inactivation while preserving sensory attributes and nutritional value. Safety of seafood and products can also be assured for consumers

Ethical Statement

Ethics approval was not required for this research.

Funding Information

This study was funded by Prachayacharn Grant from Prince of Songkla University, Hat Yai, Thailand (Grant no. AGR6602079N). This research was also supported by the Postdoctoral Fellowship from Prince of Songkla University to Dr. Suriya Palamae

Table 2. Applications of modified atmospheric packaging for seafood preservation

Seafood product	Gas composition and other hurdles	Findings	References
Asian Seabass slices	CO_2: O_2: N_2 (80: 10: 10) and CO_2 (100)	- Reduction of TVB-N, TMA, NH_3 and formaldehyde contents - Maintain sensorial properties Extension of shelf-life for 21 days at 4°C	Masniyom et al. (2002)
Pacific white shrimp	CO_2: O_2: N_2 (40:10:50) + weakly acidic electrolyzed water ice-glazing	- Inhibition of total aerobes and *S. aureus* - Reduce lipid oxidation and maintaining lower TVB-N and TMA - Retard the degradation of the physical structure of shrimp meat	Zhang et al. (2015)
Half-Smooth Tongue Sole fillets	CO_2: N_2 (70: 30) + edible coating based on Rosmarinic acid and ε-Polylysine	- Maintain the qualities and freshness - Reduction of nitrogenous volatile compounds - Extension of shelf life for 8–12 days during refrigerated storage	Li et al. (2018)
Salmon fillets	CO_2 (100%) + Chitosan films added with pink pepper residue extract	- Reduction of lipid oxidation - Retardation of microbial load - Reduction of formation of nitrogenous compounds - Maintain sensorial properties of the samples - Extension of shelf-life for 21 days compared to less than 14 days for the control samples	Merlo et al. (2019)
Seafood product	**Gas composition and other hurdles**	**Findings**	**References**
Farmed puffer fish	CO_2: O_2: N_2 (60: 5: 35) + weakly acidic electrolyzed water	- Inhibition of total viable counts (TVC), H_2S-producing bacteria, *Pseudomonas* spp., and lactic acid bacteria (LAB) - Maintain lower TVB-N, TMA, and retarding lipid oxidation - Reduce the relative content of fishy flavor compounds - Extending shelf-life to 18 days compared to 8 days for the untreated samples	Li et al. (2020)
Asian sea bass slices	CO_2: Ar: O_2 (60:30:10) + In-bag dielectric barrier discharge	- Reduction of microbial loads - Reduction of TVB-N and TMA - Extend shelf-life to 15 days compared to 6 days for the control samples	Olatunde et al. (2020)
Gray Triggerfish Fillets	N_2: CO_2: O_2 (30: 40: 30)	- Inhibition of increase in TVB-N and pH - Retardation of microbial counts - Maintain physicochemical and sensorial attributes - Extension of shelf-life for 12 days,compared to less than 10 days in the control samples	Esteves et al. (2021)

Author Contribution

Mohamed Tagrida: Conceptualization and Writing-original draft; Suriya Palamae: Conceptualization, Writing-original draft and Writing-review and editing; and Soottawat Benjakul: Conceptualization, Supervision and Writing-review and editing. All authors read and approved the final manuscript.

Conflict of Interest

The authors declare no conflict of interest

Acknowledgements

The authors gratefully acknowledge the International Center of Excellence in Seafood Science and Innovation, Faculty of Agro-Industry, Prince of Songkla University for all the supports.

References

Al-Holy, M. A., & Rasco, B. A. (2015). The bactericidal activity of acidic electrolyzed oxidizing water against *Escherichia coli* O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes* on raw fish, chicken and beef surfaces. *Food Control*, 54, 317 – 321. https://doi.org/10.1016/j.foodcont.2015.02.017

Al-Qadiri, H. M., Al-Holy, M. A., Shiroodi, S. G., Ovissipour, M., Govindan, B. N., Al-Alami, N., Sablani, S. S., & Rasco, B. (2016). Effect of acidic electrolyzed water-induced bacterial inhibition and injury in live clam (*Venerupis philippinarum*) and mussel (*Mytilus edulis*). *International Journal of Food Microbiology*, 231, 48–53. https://doi.org/10.1016/j.ijfoodmicro.2016.05.012

Andoni, E., Ozuni, E., Bijo, B., Shehu, F., Branciari, R., Miraglia, D. & Ranucci, D. (2021). Efficacy of non-thermal processing methods to prevent fish spoilage. *Journal of Aquatic Food Product Technology,* 30**,** 228-245.

Arnaud, C., de Lamballerie, M., & Pottier, L. (2018). Effect of high pressure processing on the preservation of frozen and re-thawed sliced cod (*Gadus morhua*) and salmon (*Salmo salar*) fillets. *High Pressure Research*, 38(1), 62–79.

Barbosa-Cánovas, G. V, & Rodríguez, J. J. (2002). Update on nonthermal food processing technologies: Pulsed electric field, high hydrostatic pressure, irradiation and ultrasound. *Food Australia*, 54(11), 513–520.

Bhat, Z. F., Morton, J. D., Bekhit, A. E. A., Kumar, S., & Bhat, H. F. (2021a). Emerging processing technologies for improved digestibility of muscle proteins. *Trends in Food Science and Technology*, 110, 226–239.

Bhat, Z. F., Morton, J. D., Bekhit, A. E. D. A., Kumar, S., & Bhat, H. F. (2021b). Thermal processing implications on the digestibility of meat, fish and seafood proteins. *Comprehensive Reviews in Food Science and Food Safety*, 20, 4511–4548. https://doi.org/10.1111/1541- 4337.12802

Biji, K. B., Ravishankar, C. N., Venkateswarlu, R., Mohan, C. O., & Gopal, T. K. S. (2016). Biogenic amines in seafood: A review. *Journal of Food Science and Technology*, 53(5), 2210–2218

Birania, S., Attkan, A. K., Kumar, S., Kumar, N. & Singh, V. K. (2022). Cold plasma in food processing and preservation: A review. *Journal of Food Process Engineering,* 45**,** e14110.

Blogoslawski, W. J., & Stewart, M. E. (2011). Some ozone applications in seafood. *Ozone: Science and Engineering*, 33(5), 368–373. https://doi.org/10.1080/01919512.2011.602006

Bocci, V. A. (2006). Scientific and medical aspects of ozone therapy "State of the art". *Archives of Medical Research*, 37(4), 425–435. https://doi.org/10.1016/j.arcmed.2005.08.006

Campelo, P. H., Alves Filho, E. G., Silva, L. M., De Brito, E. S., Rodrigues, S. & Fernandes, F. A. (2020). Modulation of aroma and flavor using glow discharge plasma technology. *Innovative Food Science and Emerging Technologies,* 62**,** 102363.

Campus, M. (2010). High pressure processing of meat, meat products and seafood. *Food Engineering Reviews*, 2(4), 256–273.

Cao, R., Zhao, L., & Liu, Q. (2017). High pressure treatment changes spoilage characteristics and shelf life of Pacific oysters (*Crassostrea gigas*) during refrigerated storage. *Journal of Ocean University of China*, 16(2), 351–355. https://doi.org/10.1007/s11802-017-3087-0

Cenci-Goga, B. T., Iulietto, M. F., Sechi, P., Borgogni, E., Karama, M. & Grispoldi, L. (2020). New trends in meat packaging. *Microbiology Research,* 11**,** 56-67.

Chakka, A. K., Sriraksha, M. S., & Ravishankar, C. N. (2021). Sustainability of emerging green non-thermal technologies in the food industry with food safety perspective: A review. *LWT-Food Science and Technology*, 151, 112140. https://doi.org/10.1016/j.lwt.2021.112140

Chawla, A., Bell, J. W., & Janes, M. E. (2007). Optimization of ozonated water treatment of wild-caught and mechanically peeled shrimp meat. *Journal of Aquatic Food Product Technology*, 16(2), 41–56. https://doi.org/10.1300/J030v16n02_05

Cheftel, J. C. (1995). Review: High-pressure, microbial inactivation and food preservation. *Food Science and Technology International*, 1(2–3), 75–90. https://doi.org/10.1177/108201329500100203

Chen, H. U., & Lao, I. C. (1997). Washing process during the manufacture of dark fleshed fish surimi: The effects of washing methods and conditions on the color and gel-forming ability of surimi prepared from Layanscad (*Decapterus macarellus*). *Food Science of Taiwan*, 24, 56–67.

Cheng, J. H., Sun, D. W., Zeng, X. A., & Pu, H. Bin. (2014). Non-destructive and rapid determination of TVB-N content for freshness evaluation of grass carp (*Ctenopharyngodon idella*) by hyperspectral imaging. *Innovative Food Science and Emerging Technologies*, 21, 179-187. https://doi.org/10.1016/j.ifset.2013.10.013

Chéret, R., Delbarre-Ladrat, C., Verrez-Bagnis, V., & De Lamballerie, M. (2007). Effect of high pressure on the calpain-calpastatin system in fish muscle. *Journal of Food Science*, 72(6), 313-316. https://doi.org/10.1111/j.1750-3841.2007.00410.x

Chouhan, A., Kaur, B. P., & Rao, P. S. (2015). Effect of high-pressure processing and thermal treatment on quality of hilsa (*Tenualosa ilisha*) fillets during refrigerated storage. *Innovative Food Science and Emerging Technologies*, 29,

151-160. https://doi.org/10.1016/j. ifset.2015.03.016

Conte-Junior, C. A., Monteiro, M. L. G., Patrícia, R., Mársico, E. T., Lopes, M. M., Alvares, T. S. & Mano, S. B. (2020). The effect of different packaging systems on the shelf life of refrigerated ground beef. *Foods,* 9**,** 495.

Critzer, F. J., Kelly-Wintenberg, K., South, S. L., & Golden, D. A. (2007). Atmospheric plasma inactivation of foodborne pathogens on fresh produce surfaces. *Journal of Food Protection*, 70(10), 2290–2296. https://doi.org/10.4315/0362-028X-70.10.2290

Cropotova, J., Mozuraityte, R., Standal, I. B., Ojha, S., Rustad, T., & Tiwari, B. (2020). Influence of high-pressure processing on quality attributes of haddock and mackerel minces during frozen storage, and fishcakes prepared thereof. *Innovative Food Science and Emerging Technologies*, 59, 102236.

Da Silva Campelo, M. C., Rebouças, L. D. O. S., De Oliveira Vitoriano, J., Junior, C. A., Da Silva, J. B. A. & De Oliveira Lima, P. (2019). Use of cold atmospheric plasma to preserve the quality of white shrimp (*Litopenaeus vannamei*). *Journal of Food Protection,* 82**,** 1217-1223.

Darvish, F., Sarkari, N. M., Khani, M., ESlami, E., Shokri, B., Mohseni, M., Ebrahimi, M., Alizadeh, M. & Dee, C. F. (2020). Direct plasma treatment approach based on non-thermal gliding arc for surface modification of biaxially-oriented polypropylene with post-exposure hydrophilicity improvement and minus aging effects. *Applied Surface Science*, 509,144815.

de Alba, M., Pérez-Andrés, J. M., Harrison, S. M., Brunton, N. P., Burgess, C. M., & Tiwari, B. K. (2019). High pressure processing on microbial inactivation, quality parameters and nutritional quality indices of mackerel fillets. *Innovative Food Science and Emerging Technologies*, 55, 80–87.

de Mendonça Silva, A. M., & Gonçalves, A. A. (2017). Effect of aqueous ozone on microbial and physicochemical quality of Nile tilapia processing. *Journal of Food Processing and Preservation*, 41(6), e13298. https://doi.org/10.1111/jfpp.13298

De Souza Pedrosa, G. T., Pimentel, T. C., Gavahian, M., De Medeiros, L. L., Pagán, R. & Magnani, M. (2021). The combined effect of essential oils and emerging technologies on food safety and quality. *LWT-Food Science and Technology*, 147, 111593.

Deng, L.-Z., Mujumdar, A. S., Pan, Z., Vidyarthi, S. K., Xu, J., Zielinska, M. & Xiao, H.-W. (2020). Emerging chemical and physical disinfection technologies of fruits and vegetables: A comprehensive review. *Critical Reviews in Food science and Nutrition*, 60, 2481-2508.

Dobrynin, D., Friedman, G., Fridman, A. & Starikovskiy, A. (2011). Inactivation of bacteria using dc corona discharge: Role of ions and humidity. *New Journal of Physics*, 13, 103033.

Du, S., Zhang, Z., Xiao, L., Lou, Y., Pan, Y., & Zhao, Y. (2016). Acidic electrolyzed water as a novel transmitting medium for high hydrostatic pressure reduction of bacterial loads on shelled fresh shrimp. *Frontiers in Microbiology*, 7, 1–12.

Ekonomou, S. I., & Boziaris, I. S. (2021). Non-thermal methods for ensuring the microbiological quality and safety of seafood. *Applied Sciences*, 11(2), 833. https://doi.org/10.3390/app11020833

Epelle, E. I., Macfarlane, A., Cusack, M., Burns, A., Okolie, J. A., Mackay, W., Rateb, M., & Yaseen, M. (2023). Ozone application in different industries: A review of recent developments. *Chemical Engineering Journal*, 454, 140188. https://doi.org/10.1016/j.cej.2022.140188

Ercan, U. K., Wang, H., Ji, H., Fridman, G., Brooks, A. D., & Joshi, S. G. (2013). Nonequilibrium plasma-activated antimicrobial solutions are broad-spectrum and retain their efficacies for extended period of time. *Plasma Processes and Polymers*, 10(6), 544–555. https://doi.org/10.1002/ppap.201200104

Esteves, E., Guerra, L. & Aníbal, J. (2021). Effects of vacuum and modified atmosphere packaging on the quality and shelf-life of gray triggerfish (*Balistes capriscus*) fillets. *Foods*, 10, 250.

Esua, O. J., Cheng, J.-H., & Sun, D.-W. (2021a). Functionalization of water as a nonthermal approach for ensuring safety and quality of meat and seafood products. *Critical Reviews in Food Science and Nutrition*, 61(3), 431 – 449. https://doi.org/10.1080/10408398.2020.1735297

Fabrizio, K. A., & Cutter, C. N. (2003). Stability of electrolyzed oxidizing water and its efficacy against cell suspensions of *Salmonella* Typhimurium and *Listeria monocytogenes*. *Journal of Food Protection*, 66(8), 1379–1384. https://doi.org/10.4315/0362-028X-66.8.1379

Farkas, D. F., & Hoover, D. G. (2000). High pressure processing. *Journal of Food Science*, 65(s8), 47-64.

Feizollahi, E., Misra, N. & Roopesh, M. (2021). Factors influencing the antimicrobial efficacy of dielectric barrier discharge (DBD) atmospheric cold plasma (ACP) in food processing applications. *Critical Reviews in Food Science and Nutrition*, 61, 666-689.

Fidalgo, L. G., Simões, M. M., Casal, S., Lopes-Da-Silva, J. A., Carta, A. M. S., Delgadillo, I. & Saraiva, J. A. (2020). Physicochemical parameters, lipids stability, and volatiles profile of vacuum-packaged fresh Atlantic salmon (*Salmo salar*) loins preserved by hyperbaric storage at 10 C. *Food Research International*, 127, 108740.

Fiore, A. G., Palmieri, L., Orlando, I., De Giorgi, A., Derossi, A., & Severini, C. (2019). Comparison of different combined processes of preservation on the nutritional and sensory changes of "ready to eat" mackerel fillets. *Journal of Food Processing and Preservation*, 43(3), 1–13.

Floros, J. D. & Matsos, K. I. (2005). Introduction to modified atmosphere packaging. *Innovations in food packaging*, 159-172.

Ganesan, A. R., Tiwari, U., Ezhilarasi, P. & Rajauria, G. (2021). Application of cold plasma on food matrices: A review on current and future prospects. *Journal of Food Processing and Preservation*, 45, e15070.

Gao, C., Zhao, M., Wang, X., Wang, J., Li, C., Dong, X., Liu, Z., & Zhou, D. (2024). Plasma-activated water in combination with coconut exocarp flavonoids emerge as promising preservation technique for golden pompano: Impact of the treatment sequence. *Food Chemistry*, 447, 138981. https://doi.org/10.1016/j.foodchem.2024.138981

Garvey, M. & Rowan, N. (2019). Pulsed UV as a potential surface sanitizer in food production processes to ensure consumer safety. *Current Opinion in Food Science*, 26, 65-70.

Gelman, A., Sachs, O., Khanin, Y., Drabkin, V., & Glatman, L. (2005). Effect of ozone pretreatment on fish storage life at low temperatures. *Journal of Food Protection*, 68(4), 778–784. https://doi.org/10.4315/0362-028X-68.4.778

Ghorban Shiroodi, S., Ovissipour, M., Ross, C. F., & Rasco, B. A.

(2016). Efficacy of electrolyzed oxidizing water as a pretreatment method for reducing *Listeria monocytogenes* contamination in cold-smoked Atlantic salmon (*Salmo salar*). *Food Control*, 60, 401–407. https://doi.org/10.1016/j.foodcont.2015.08.020

Gonçalves, A. A. (2016). Ozone as a safe and environmentally friendly tool for the seafood industry. *Journal of Aquatic Food Product Technology*, 25(2), 210-229. https://doi.org/10.1080/10498850.2013.841785

Gou, J., Xu, H., Choi, G. P., Lee, H. Y., & Ahn, J. (2010). Application of high-pressure processing for extending the shelf life of sliced raw squid. *Food Science and Biotechnology*, 19(4), 923-927.

Gram, L., & Huss, H. H. (1996). Microbiological spoilage of fish and fish products. *International Journal of Food Microbiology*, 33(1), 121-137. https://doi.org/10.1016/0168-1605(96)01134-8

Guo, L., Yao, Z., Yang, L., Zhang, H., Qi, Y., Gou, L., Xi, W., Liu, D., Zhang, L. & Cheng, Y. (2021). Plasma-activated water: An alternative disinfectant for S protein inactivation to prevent SARS-CoV-2 infection. *Chemical Engineering Journal*, 421, 127742.

Güzel-Seydim, Z., Bever, P. I., & Greene, A. K. (2004). Efficacy of ozone to reduce bacterial populations in the presence of food components. *Food Microbiology*, 21(4), 475–479. https://doi.org/10.1016/j.fm.2003.10.001

Han, Q.-Y., Wen, X., Gao, J.-Y., Zhong, C.-S., & Ni, Y.-Y. (2023). Application of plasma-activated water in the food industry: A review of recent research developments. *Food Chemistry*, 405, 134797. https://doi.org/10.1016/j.foodchem.2022.134797

Huang, H.-W., Wu, S.-J., Lu, J.-K., Shyu, Y.-T., & Wang, C.-Y. (2017). Current status and future trends of high-pressure processing in food industry. *Food Control*, 72, 1-8. https://doi.org/10.1016/j.foodcont.2016.07.019

Ikawa, S., Kitano, K., & Hamaguchi, S. (2010). Effects of pH on bacterial inactivation in aqueous solutions due to low-temperature atmospheric pressure plasma application. *Plasma Processes and Polymers*, 7(1), 33-42. https://doi.org/10.1002/ppap.200900090

Iqbal, A., Murtaza, A., Hu, W., Ahmad, I., Ahmed, A. & Xu, X. (2019). Activation and inactivation mechanisms of polyphenol oxidase during thermal and non-thermal methods of food processing. *Food and Bioproducts Processing*, 117, 170-182.

Ivanov, I., Tikhonov, V. & Tikhonov, A. (2019). Microwave complex for obtaining low-temperature plasma at atmospheric pressure. *Journal of Physics*: *Conference Series*. IOP Publishing, 012042.

Jan, A., Sood, M., Sofi, S. & Norzom, T. (2017). Non-thermal processing in food applications: A review. *International Journal of Food Science and Nutrition*, 2, 171-180.

Jiang, H., Lin, Q., Shi, W., Yu, X. & Wang, S. (2022). Food preservation by cold plasma from dielectric barrier discharges in agri-food industries. *Frontiers in Nutrition*, 9, 1015980.

Jiranuntakul, W., Nakwiang, N., Berends, P., Kasemsuwan, T., Saetung, T., & Devahastin, S. (2018). Physicochemical, microstructural, and microbiological properties of skipjack tuna (*Katsuwonus pelamis*) after high-pressure processing. *Journal of Food Science*, 83(9), 2324–2336. https://doi.org/10.1111/1750-3841.14318

Esua, O. J., Cheng, J.-H., & Sun, D.-W. (2021b). Novel technique for treating grass carp (*Ctenopharyngodon idella*) by combining plasma functionalized liquids and ultrasound: Effects on bacterial inactivation and quality attributes. *Ultrasonics Sonochemistry*, 76, 105660. https://doi.org/10.1016/j.ultsonch.2021.105660

Kalpana, S., Priyadarshini, S., Leena, M. M., Moses, J. & Anandharamakrishnan, C. (2019). Intelligent packaging: Trends and applications in food systems. *Trends in Food Science and Technology*, 93, 145-157.

Kaur, B. P., & Rao, P. S. (2017a). Modeling the combined effect of pressure and mild heat on the inactivation kinetics of *Escherichia coli*, *Listeria innocua*, and *Staphylococcus aureus* in black tiger shrimp (*Penaeus monodon*). *Frontiers in Microbiology*, 8, 1311. https://doi.org/10.3389/fmicb.2017.01311

Kaur, B. P., & Rao, P. S. (2017b). Process optimization for high-pressure processing of black tiger shrimp (*Penaeus monodon*) using response surface methodology. *Food Science and Technology International*, 23(3), 197–208. https://doi.org/10.1177/ 1082013216673460

Kaur, B. P., Rao, P. S., & Nema, P. K. (2016). Effect of hydrostatic pressure and holding time on physicochemical quality and microbial inactivation kinetics of black tiger shrimp (*Penaeus monodon*). *Innovative Food Science and Emerging Technologies*, 33, 47–55. https://doi.org/10.1016/j.ifset.2015.12.002

Khazandi, M., Deo, P., Ferro, S., Venter, H., Pi, H., Crabb, S., Amorico, T., Ogunniyi, A. D., & Trott, D. J. (2017). Efficacy evaluation of a new water sanitizer for increasing the shelf life of Southern Australian King George Whiting and Tasmanian Atlantic salmon fillets. *Food Microbiology*, 68, 51–60. https://doi.org/10.1016/j.fm.2017.06.008

Kipcak, A. S., Derun, E. M., Tugrul, N., & Doymaz, İ. (2021). Drying characteristics of blue mussels by traditional methods. *Chemical Industry and Chemical Engineering Quarterly*, 27(3), 279–288. https://doi.org/10.2298/CICEQ200920046K

Koddy, J. K., Miao, W., Hatab, S., Tang, L., Xu, H., Nyaisaba, B. M., Chen, M. & Deng, S. (2021). Understanding the role of atmospheric cold plasma (ACP) in maintaining the quality of hairtail (*Trichiurus Lepturus*). *Food Chemistry*, 343, 128418.

Koutchma, T. (2014). Emerged HPP Commercial Applications. In *Adapting High Hydrostatic Pressure for Food Processing Operations* (pp. 29–34). Elsevier: Amsterdam, The Netherlands.

Lacombe, A., Niemira, B. A., Gurtler, J. B., Fan, X., Sites, J., Boyd, G. & Chen, H. (2015). Atmospheric cold plasma inactivation of aerobic microorganisms on blueberries and effects on quality attributes. *Food Microbiology*, 46, 479-484.

Lagnika, C., Zhang, M. & Wang, S. (2011). Effect of high argon pressure and modified atmosphere packaging on the white mushroom (*Agaricus bisporus*) physico-chemical and microbiological properties. *Journal of Food and Nutrition Research*, 50, 167-176.

Lee, T., Puligundla, P. & Mok, C. (2018). Intermittent corona discharge plasma jet for improving tomato quality. *Journal of Food Engineering*, 223, 168-174.

Lemus-Mondaca, R., Zambra, C., Marín, F., Pérez-Won, M., & Tabilo- Munizaga, G. (2018). Mass transfer kinetic and quality changes during high-pressure impregnation (HPI) of jumbo squid (*Dosidicus gigas*) slices. *Food and*

Bioprocess Technology, 11(8), 1516–1526. https://doi.org/10.1007/s11947-018-2122-5

Li, N., Shen, Y., Liu, W., Mei, J. & Xie, J. (2018). Low-field NMR and MRI to analyze the effect of edible coating incorporated with map on qualities of half-smooth tongue sole (*Cynoglossus semilaevis* Günther) fillets during refrigerated storage. *Applied Sciences*, 8, 1391.

Li, P., Chen, Z., Tan, M., Mei, J., & Xie, J. (2020). Evaluation of weakly acidic electrolyzed water and modified atmosphere packaging on the shelf life and quality of farmed puffer fish (*Takifugu obscurus*) during cold storage. *Journal of Food Safety*, 40(3), e12773. https://doi.org/10.1111/jfs.12773

Li, Y., Kojtari, A., Friedman, G., Brooks, A. D., Fridman, A. & Ji, H.-F. (2014). Decomposition of L-valine under nonthermal dielectric barrier discharge plasma. *The Journal of Physical Chemistry B*, 118, 1612-1620.

Liao, L. B., Chen, W. M., & Xiao, X. M. (2007). The generation and inactivation mechanism of oxidation-reduction potential of electrolyzed oxidizing water. *Journal of Food Engineering*, 78(4), 1326 – 1332. https://doi.org/10.1016/j.jfoodeng.2006.01.004

Liao, X., Su, Y., Liu, D., Chen, S., Hu, Y., Ye, X., Wang, J., & Ding, T. (2018). Application of atmospheric cold plasma-activated water (PAW) ice for preservation of shrimps (*Metapenaeus ensis*). *Food Control*, 94, 307-314. https://doi.org/10.1016/j.foodcont.2018.07.026

Lin, T., Wang, J. J., Li, J. B., Liao, C., Pan, Y. J., & Zhao, Y. (2013). Use of acidic electrolyzed water ice for preserving the quality of shrimp. *Journal of Agricultural and Food Chemistry*, 61(36), 8695–8702. https://doi.org/10.1021/jf4019933

Linton, M., Patterson, M. F., & Patterson, M. F. (2000). High pressure processing of foods for microbiological safety and quality. *Acta Microbiologica et Immunologica Hungarica*, 47(2-3), 175–182.

Liu, C., Ji, W., Jiang, H., Shi, Y., He, L., Gu, Z., & Zhu, S. (2021b). Comparison of biochemical composition and non-volatile taste active compounds in raw, high hydrostatic pressure-treated and steamed oysters *Crassostrea hongkongensis*. *Food Chemistry*, 344, 128632. https://doi.org/10.1016/j.foodchem.2020.128632

Liu, X., Zhang, M., Meng, X., Bai, Y., & Dong, X. (2021a). Effect of plasma-activated water on *Shewanella putrefaciens* population growth and quality of yellow river carp (*Cyprinus carpio*) fillets. *Journal of Food Protection*, 84(10), 1722-1728. https://doi.org/10.4315/JFP-21-031

Luo, K., & Oh, D.-H. (2015). Synergistic effect of slightly acidic electrolyzed water and ultrasound at mild heat temperature in microbial reduction and shelf-life extension of fresh-cut bell pepper. *Journal of Microbiology and Biotechnology*, 25, 1502e1509.

Ma, L., & Su, Y. C. (2011). Validation of high-pressure processing for inactivating *Vibrio parahaemolyticus* in Pacific oysters (*Crassostrea gigas*). *International Journal of Food Microbiology*, 144(3), 469-474. https://doi.org/10.1016/j.ijfoodmicro.2010.10.037

Mahmoud, B. S. M., Yamazaki, K., Miyashita, K., Il-Shik, S., Dong-Suk, C., & Suzuki, T. (2004). Decontamination effect of electrolysed NaCl solutions on carp. *Letters in Applied Microbiology*, 39(2), 169-173. https://doi.org/10.1111/j.1472-765X.2004.01557.x

Manousaridis, G., Nerantzaki, A., Paleologos, E. K., Tsiotsias, A., Savvaidis, I. N., & Kontominas, M. G. (2005). Effect of ozone on microbial, chemical and sensory attributes of shucked mussels. *Food Microbiology*, 22(1), 1–9. https://doi.org/10.1016/j.fm.2004.06.003

Masniyom, P., Benjakul, S. & Visessanguan, W. (2002). Shelf-life extension of refrigerated seabass slices under modified atmosphere packaging. *Journal of the Science of Food and Agriculture*, 82, 873-880.

Masniyom, P., Benjakul, S., & Visessanguan, W. (2006). Synergistic antimicrobial effect of pyrophosphate on *Listeria monocytogenes* and *Escherichia coli* O157 in modified atmosphere packaged and refrigerated seabass slices. *LWT - Food Science and Technology*, 39(3), 302–307. https://doi.org/10.1016/j.lwt.2005.01.007

Matějková, K., Křížek, M., Vácha, F., & Dadáková, E. (2013). Effect of high-pressure treatment on biogenic amines formation in vacuum-packed trout flesh (*Oncorhynchus mykiss*). *Food Chemistry*, 137(1), 31–36. https://doi.org/10.1016/j.foodchem.2012.10.011

Mayookha, V., Pandiselvam, R., Kothakota, A., Ishwarya, S. P., Khanashyam, A. C., Kutlu, N., Rifna, E., Kumar, M., Panesar, P. S. & Abd El-Maksoud, A. A. (2022). Ozone and cold plasma: Emerging oxidation technologies for inactivation of enzymes in fruits, vegetables, and fruit juices. *Food Control*, 144, 109399.

McCarthy, S., & Burkhardt, W. (2012). Efficacy of electrolyzed oxidizing water against *Listeria monocytogenes* and *Morganella morganii* on conveyor belt and raw fish surfaces. *Food Control*, 24(1), 214–219. https://doi.org/10.1016/j.foodcont.2011.09.030

Medina-Meza, I. G., Barnaba, C., & Barbosa-Cánovas, G. V. (2014). Effects of high pressure processing on lipid oxidation: A review. *Innovative Food Science and Emerging Technologies*, 22, 1–10. https://doi.org/10.1016/j.ifset.2013.10.012

Merlo, T. C., Contreras-Castillo, C. J., Saldana, E., Barancelli, G. V., Dargelio, M. D. B., Yoshida, C. M. P., Junior, E. E. R., Massarioli, A. & Venturini, A. C. (2019). Incorporation of pink pepper residue extract into chitosan film combined with a modified atmosphere packaging: Effects on the shelf life of salmon fillets. *Food Research International*, 125, 108633.

Misra, N. & Jo, C. (2017). Applications of cold plasma technology for microbiological safety in meat industry. *Trends in Food Science and Technology*, 64, 74-86.

Misra, N., Pankaj, S., Segat, A. & Ishikawa, K. (2016). Cold plasma interactions with enzymes in foods and model systems. *Trends in Food Science and Technology*, 55, 39-47.

Misra, N., Yadav, B., Roopesh, M. & Jo, C. (2019). Cold plasma for effective fungal and mycotoxin control in foods: Mechanisms, inactivation effects, and applications. *Comprehensive Reviews in Food Science and Food Safety*, 18, 106-120.

Mohamed, E. E., Younis, E. R. & Mohamed, E. A. (2021). Impact of atmospheric cold plasma (ACP) on maintaining bolti fish (*Tilapia nilotica*) freshness and quality criteria during cold storing. *Journal of Food Processing and Preservation*, 45, e15442.

Mol, S., Akan, T., Kartal, S., Coşansu, S., Tosun, Ş. Y., Alakavuk, D. Ü., Ulusoy, Ş., Doğruyol, H. & Bostan, K. (2023). Effects of air and helium cold plasma on sensory acceptability and quality of fresh sea bass (*Dicentrarchus labrax*). *Food and Bioprocess Technology*, 16, 537-548.

Nash, B. (2002). Ozone effective in preserving seafood freshness. In *Marine Extension News* (Issue Spring). North Carolina Sea Grant.

Obileke, K., Onyeaka, H., Miri, T., Nwabor, O. F., Hart, A., Al-Sharify, Z. T., AL-Najjar, S. & Anumudu, C. (2022). Recent advances in radio frequency, pulsed light, and cold plasma technologies for food safety. *Journal of Food Process Engineering*, 45, e14138.

Okpala, C. O. R. (2015a). Physicochemical changes in minimal ozone-treated fresh shrimp stored on ice tandem with microbiological efficacy of treatment. *Nigerian Food Journal*, 33(2), 74-87.

Okpala, C. O. R. (2015b). Quality evaluation and shelf life of minimal ozone-treated Pacific white shrimp (*Litopenaeus vannamei*) stored on ice. *Journal Fur Verbraucherschutz Und Lebensmittelsicherheit*, 10(1), 49-57. https://doi.org/10.1007/s00003-014-0904-x

Okyere, A. Y., Rajendran, S. & Annor, G. A. (2022). Cold plasma technologies: Their effect on starch properties and industrial scale-up for starch modification. *Current Research in Food Science,* 5**,** 451-463.

Olatunde, O. O. & Benjakul, S. (2018). Nonthermal processes for shelf-life extension of seafoods: A revisit. *Comprehensive Reviews in Food Science and Food Safety*, 17, 892-904.

Olatunde, O. O., Benjakul, S. & Vongkamjan, K. (2019a). Combined effect of ethanolic coconut husk extract and modified atmospheric packaging (MAP) in extending the shelf life of Asian sea bass slices. *Journal of Aquatic Food Product Technology*, 28, 689-702.

Olatunde, O. O., Benjakul, S. & Vongkamjan, K. (2019b). Comparative study on nitrogen and argon-based modified atmosphere packaging on microbiological, chemical, and sensory attributes as well as on microbial diversity of Asian sea bass. *Food Packaging and Shelf Life*, 22, 100404.

Olatunde, O. O., Benjakul, S. & Vongkamjan, K. (2020). Shelf-life of refrigerated Asian sea bass slices treated with cold plasma as affected by gas composition in packaging. *International Journal of Food Microbiology*, 324, 108612.

Olatunde, O. O., Chantakun, K. & Benjakul, S. (2021a). Microbial, chemical qualities and shelf-life of blue swimming crab (*Portunus armatus*) lump meat as influenced by in-package high voltage cold plasma treatment. *Food Bioscience*, 43, 101274.

Olatunde, O. O., Shiekh, K. A. & Benjakul, S. (2021b). Pros and cons of cold plasma technology as an alternative non-thermal processing technology in seafood industry. *Trends in Food Science and Technology*, 111, 617-627.

Olatunde, O. O., Singh, A., Shiekh, K. A., Nuthong, P. & Benjakul, S. (2021c). Effect of high voltage cold plasma on oxidation, physiochemical, and gelling properties of myofibrillar protein isolate from Asian sea bass (*Lates calcarifer*). *Foods*, 10, 326.

Oomori, T., Oka, T., Inuta, T., & Arata, Y. (2000). The efficiency of disinfection of acidic electrolyzed water in the presence of organic materials. *Analytical Sciences*, 16(4), 365 – 369. https://doi.org/10.2116/analsci.16.365

Ovissipour, M., Rasco, B., Tang, J., & Sablani, S. S. (2013). Kinetics of quality changes in whole blue mussel (*Mytilus edulis*) during pasteurization. *Food Research International*, 53(1), 141–148. https://doi.org/10.1016/j.foodres.2013.04.029

Ovissipour, M., Shiroodi, S. G., Rasco, B., Tang, J., & Sablani, S. S. (2018). Electrolyzed water and mild-thermal processing of Atlantic salmon (*Salmo salar*): Reduction of *Listeria monocytogenes* and changes in protein structure. *International Journal of Food Microbiology*, 276, 10–19. https://doi.org/10.1016/j.ijfoodmicro.2018.04.005

Ozer, N. P., & Demirci, A. (2006). Electrolyzed oxidizing water treatment for decontamination of raw salmon inoculated with *Escherichia coli* O157:H7 and *Listeria monocytogenes* Scott A and response surface modeling. *Journal of Food Engineering*, 72(3), 234-241. https://doi.org/10.1016/j.jfoodeng.2004.11.038

Ozyalcin, Z. O., & Kipcak, A. S. (2022). The ultrasound effect on the drying characteristics of *Loligo vulgaris* by the methods of oven and vacuum-oven. *Journal of Aquatic Food Product Technology*, 31(2), 187–199. https://doi.org/10.1080/10498850.2021.2024634

Palamae, S., Temdee, W., Buatong, J., Zhang, B., Hong, H., & Benjakul, S. (2023). Enhancement of safety and quality of ready-to-cook Asian green mussel using acidic electrolyzed water depuration in combination with sous vide cooking. *Innovative Food Science and Emerging Technologies*, 87, 103391. https://doi.org/10.1016/j.ifset.2023.103391

Palamae, S., Temdee, W., Buatong, J., Suyapoh, W., Sornying, P., Tsai, Y.-H., & Benjakul, S. (2024a). Use of high pressure processing in combination with acidic electrolyzed water depuration for the shelf-life extension of blood clam (*Tegillarca granosa*). *Food Control*, 156, 110160. https://doi.org/10.1016/j.foodcont.2023.110160

Palamae, S., Temdee, W., Saetang, J., Patil, U., Suyapoh, W., Yingkajorn, M., Fan, X., Zhang, B., & Benjakul, S. (2024b). Impact of high-pressure processing on hemolymph, color, lipid globular structure and oxidation of the edible portion of blood clams. *Food Chemistry*, 447, 138948. https://doi.org/10.1016/j.foodchem.2024.138948

Pan, W., Benjakul, S., Sanmartin, C., Guidi, A., Ying, X., Ma, L., Weng, X., Yu, J. & Deng, S. (2022). Characterization of the flavor profile of bigeye tuna slices treated by cold plasma using E-Nose and GC-IMS. *Fishes*, 7, 13.

Pandiselvam, R., Sunoj, S., Manikantan, M. R., Kothakota, A., & Hebbar, K. B. (2017). Application and kinetics of ozone in food preservation. *Ozone: Science and Engineering*, 39(2), 115–126. https://doi.org/10.1080/01919512.2016.1268947

Panieri, E., Gogvadze, V., Norberg, E., Venkatesh, R., Orrenius, S. & Zhivotovsky, B. (2013). Reactive oxygen species generated in different compartments induce cell death, survival, or senescence. *Free Radical Biology and Medicine*, 57, 176-187.

Pankaj, S., Misra, N. & Cullen, P. (2013). Kinetics of tomato peroxidase inactivation by atmospheric pressure cold plasma based on dielectric barrier discharge. *Innovative Food Science and Emerging Technologies*, 19, 153-157.

Pankaj, S. K., & Keener, K. M. (2017). Cold plasma: Background, applications and current trends. *Current Opinion in Food Science*, 16, 49–52. https://doi.org/10.1016/j.cofs.2017.07.008

Paranjpye, R. N., Peterson, M. E., Poysky, F. T., & Eklund, M. W. (2008). Incidence, growth, and inactivation of *Listeria monocytogenes* in cooked and peeled cold-water shrimp. *Journal of Aquatic Food Product Technology*, 17(3), 266-284.

https://doi.org/10.1080/10498850802187118

Park, D. H., Park, J. J., Olawuyi, I. F. & Lee, W. Y. (2020). Quality of white mushroom (*Agaricus bisporus*) under argon-and nitrogen-based controlled atmosphere storage. *Scientia Horticulturae,* 265**,** 109229.

Park, H., Hung, Y.-C., & Chung, D. (2004). Effects of chlorine and pH on efficacy of electrolyzed water for inactivating *Escherichia coli* O157:H7 and *Listeria monocytogenes*. *International Journal of Food Microbiology*, 91(1), 13-18. https://doi.org/10.1016/S0168-1605(03)00334-9

Patterson, M. F. (2014). Food Technologies: High Pressure Processing. In Y. Motarjemi, G. Moy, & E. Todd (Eds.), *Encyclopedia of Food Safety* (1st ed., Vol. 3, pp. 196-201). Academic Press: Oxford, UK.

Pita-Calvo, C., Guerra-Rodríguez, E., Saraiva, J. A., Aubourg, S. P., & Vázquez, M. (2018a). Effect of high-pressure processing pretreatment on the physical properties and colour assessment of frozen European hake (*Merluccius merluccius*) during long term storage. *Food Research International*, 112, 233–240. https://doi.org/10.1016/j.foodres.2018.06.042

Powell, J. C., Moore, A. R., & Gow, J. A. (1979). Comparison of EC broth and medium A-1 for the recovery of *Escherichia coli* from frozen shucked snow crab. *Applied and Environmental Microbiology*, 37(5), 836–840. https://doi.org/10.1128/aem.37.5.836-840.1979

Puač, N., Gherardi, M. & Shiratani, M. (2018). Plasma agriculture: A rapidly emerging field. *Plasma Processes and Polymers,* 15**,** 1700174.

Punia Bangar, S., Trif, M., Ozogul, F., Kumar, M., Chaudhary, V., Vukic, M., Tomar, M., & Changan, S. (2022). Recent developments in cold plasma-based enzyme activity (browning, cell wall degradation, and antioxidant) in fruits and vegetables. *Comprehensive Reviews in Food Science and Food Safety*, 21(2), 1958–1978. https://doi.org/10.1111/1541-4337.12895

Qu, P., Zhang, M., Fan, K. & Guo, Z. (2022). Microporous modified atmosphere packaging to extend shelf life of fresh foods: A review. *Critical Reviews in Food Science and Nutrition,* 62**,** 51-65.

Rahman, S., Khan, I., & Oh, D.-H. (2016). Electrolyzed water as a novel sanitizer in the food industry: Current trends and future perspectives. *Comprehensive Reviews in Food Science and Food Safety*, 15(3), 471-490. https://doi.org/10.1111/1541-4337.12200

Rasco, B., & Ovissipour, M. (2015). Electrolyzed water applications in aquaculture and the seafood industry. *Journal of Aquaculture Research and Development*, 6, 293.

Rashvand, M., Matera, A., Altieri, G., Genovese, F., Fadiji, T., Opara, U. L., Mohammadifar, M. A., Feyissa, A. H. & Di Renzo, G. C. (2023). Recent advances in the potential of modeling and simulation to assess the performance of modified atmosphere packaging (MAP) systems for the fresh agricultural product: Challenges and development. *Trends in Food Science and Technology*, 136, 48-63.

Rathod, N. B., Kulawik, P., Ozogul, Y., Ozogul, F. & Bekhit, A. E. D. A. (2022). Recent developments in non-thermal processing for seafood and seafood products: Cold plasma, pulsed electric field and high hydrostatic pressure. *International Journal of Food Science and Technology*, 57, 774-790.

Ravesi, E. M., Licciardello, J. J., & Racicot, L. D. (1988). Ozone treatment of fresh fish Atlantic cod. *Marine Fisheries Review*, 49, 37-42.

Rode, T. M., & Hovda, M. B. (2016). High pressure processing extend the shelf life of fresh salmon, cod and mackerel. *Food Control*, 70, 242-248. https://doi.org/10.1016/j.foodcont.2016.05.045

Rong, C., Ling, Z., Huihui, S., & Qi, L. (2018). Characterization of microbial community in high-pressure treated oysters by high throughput sequencing technology. *Innovative Food Science and Emerging Technologies*, 45, 241-248. https://doi.org/10.1016/j.ifset. 2017.11.001

Roobab, U., Fidalgo, L. G., Arshad, R. N., Khan, A. W., Zeng, X.-A., Bhat, Z. F., Bekhit, A. E.-D. A., Batool, Z., & Aadil, R. M. (2022). High-pressure processing of fish and shellfish products: Safety, quality, and research prospects. *Comprehensive Reviews in Food Science and Food Safety*, 21(4), 3297-3325. https://doi.org/10.1111/1541-4337.12977

Schlüter, O., Ehlbeck, J., Hertel, C., Habermeyer, M., Roth, A., Engel, K. H., Holzhauser, T., Knorr, D. & Eisenbrand, G. (2013). Opinion on the use of plasma processes for treatment of foods. *Molecular nutrition and food research*, 57, 920-927.

Segat, A., Misra, N., Cullen, P. & Innocente, N. (2016). Effect of atmospheric pressure cold plasma (ACP) on activity and structure of alkaline phosphatase. *Food and Bioproducts Processing*, 98, 181-188.

Sevim, S., Ozyalcin, Z.O., & Kipcak, A.S. (2023). Drying and rehydration characteristics of microwave dried *Mytilus edulis*. *Turkish Journal of Fisheries and Aquatic Sciences*, 23, TRJFAS23601. http://doi.org/10.4194/TRJFAS23601

Sezer, Y. Ç., Bulut, M., Boran, G. & Alwazeer, D. (2022). The effects of hydrogen incorporation in modified atmosphere packaging on the formation of biogenic amines in cold stored rainbow trout and horse mackerel. *Journal of Food Composition and Analysis*, 112, 104688.

Sharma, S. (2020). Cold plasma treatment of dairy proteins in relation to functionality enhancement. *Trends in Food Science and Technology*, 102, 30-36.

Shen, X., Zhang, M., Devahastin, S. & Guo, Z. (2019). Effects of pressurized argon and nitrogen treatments in combination with modified atmosphere on quality characteristics of fresh-cut potatoes. *Postharvest Biology and Technology*, 149, 159-165.

Shiekh, K. A. & Benjakul, S. (2020). Effect of high voltage cold atmospheric plasma processing on the quality and shelf-life of Pacific white shrimp treated with Chamuang leaf extract. *Innovative Food Science and Emerging Technologies*, 64, 102435.

Simpson, R., Acevedo, C. & Almonacid, S. (2009). Mass transfer of CO_2 in MAP systems: Advances for non-respiring foods. *Journal of Food Engineering*, 92, 233-239.

Sohan, M. S. R., Hasan, M., Hossain, M. F., Sajib, S. A., Khalid-Bin-Ferdaus, K. M., Kabir, A. H., Rashid, M. M., Talukder, M. R., Elseehy, M. M. & El-Shehawi, A. M. (2022). Low-frequency glow discharge (LFGD) plasma treatment enhances maize (*Zea mays* L.) seed germination, agronomic traits, enzymatic activities, and nutritional properties. *Chemical and Biological Technologies in Agriculture*, 9, 18.

Spilimbergo, S. & Bertucco, A. (2003). Non-thermal bacterial inactivation with dense CO_2. *Biotechnology and Bioengineering*, 84, 627-638.

Suemitsu, L., & Cristianini, M. (2019). Effects of high-pressure processing (HPP) on quality attributes of tilapia (*Oreochromis niloticus*) fillets during refrigerated

storage. *LWT-Food Science and Technology*, 101, 92-99. https://doi.org/10.1016/j.lwt.2018.11.028

Sun, P., Wu, H., Bai, N., Zhou, H., Wang, R., Feng, H., Zhu, W., Zhang, J., & Fang, J. (2012). Inactivation of *Bacillus subtilis* spores in water by a direct-current, cold atmospheric-pressure air plasma microjet. *Plasma Processes and Polymers*, 9(2), 157-164. https://doi.org/10.1002/ppap.201100041

Tabassum, N. & Khan, M. A. (2020). Modified atmosphere packaging of fresh-cut papaya using alginate based edible coating: Quality evaluation and shelf-life study. *Scientia Horticulturae*, 259, 108853.

Tagrida, M. & Benjakul, S. (2022). Liposomes loaded with betel leaf (*Piper betle* L.) extract: Antibacterial activity and preservative effect in combination with hurdle technologies on tilapia slices. *Food Control*, 138, 108999.

Tagrida, M., Benjakul, S. & Zhang, B. (2021). Use of betel leaf (*Piper betle* L.) ethanolic extract in combination with modified atmospheric packaging and nonthermal plasma for shelf-life extension of Nile tilapia (*Oreochromis niloticus*) fillets. *Journal of Food Science*, 86, 5226-5239.

Tao, Y., Sun, D.-W., Hogan, E., & Kelly, A. L. (2014). Chapter 1 - High-Pressure Processing of Foods: An Overview. In D.-W. Sun (Ed.), *Emerging Technologies for Food Processing (Second Edition)* (Second Edition, pp. 3–24). Academic Press. https://doi.org/10.1016/B978-0-12-411479-1.00001-2

Tappi, S., Gozzi, G., Vannini, L., Berardinelli, A., Romani, S., Ragni, L. & Rocculi, P. (2016). Cold plasma treatment for fresh-cut melon stabilization. *Innovative Food Science and Emerging Technologies*, 33, 225-233.

Teixeira, B., Fidalgo, L., Mendes, R., Costa, G., Cordeiro, C., Marques, A., Saraiva, J. A., & Nunes, M. L. (2013). Changes of enzymes activity and protein profiles caused by high-pressure processing in sea bass (*Dicentrarchus labrax*) fillets. *Journal ofAgricultural and Food Chemistry*, 61(11), 2851–2860. https://doi.org/10.1021/jf3049643

Thirumdas, R., Sarangapani, C. & Annapure, U. S. (2015). Cold plasma: A novel non-thermal technology for food processing. *Food Biophysics*, 10, 1-11.

Tinebra, I., Scuderi, D., Sortino, G., Inglese, P. & Farina, V. (2021). Effects of argon-based and nitrogen-based modified atmosphere packaging technology on the quality of pomegranate (*Punica granatum L*. cv. Wonderful) Arils. *Foods*, 10, 370.

Truong, B. Q., Buckow, R., Nguyen, M. H., & Stathopoulos, C. E. (2016). High pressure processing of barramundi (*Lates calcarifer*) muscle before freezing: The effects on selected physicochemical properties during frozen storage. *Journal of Food Engineering*, 169, 72-78. https://doi.org/10.1016/j.jfoodeng.2015.08.020

Tsironi, T., Anjos, L., Pinto, P. I. S., Dimopoulos, G., Santos, S., Santa, C., Manadas, B., Canario, A., Taoukis, P., & Power, D. (2019). High pressure processing of European sea bass (*Dicentrarchus labrax*) fillets and tools for flesh quality and shelf-life monitoring. *Journal of Food Engineering*, 262, 83-91. https://doi.org/10.1016/j.jfoodeng.2019.05.010

Vázquez, M., Fidalgo, L. G., Saraiva, J. A., & Aubourg, S. P. (2018). Preservative effect of a previous high-pressure treatment on the chemical changes related to quality loss in frozen hake (*Merluccius merluccius*). *Food and Bioprocess Technology*, 11(2), 293-304. https://doi.org/10.1007/s11947-017-2010-4

Veasey, S., & Muriana, P. M. (2016). Evaluation of electrolytically-generated hypochlorous acid ('Electrolyzed water') for sanitation of meat and meat-contact surfaces. *Foods*, 5(2), 42. https://doi.org/10.3390/foods5020042

Vu, T. T. T., Alter, T., Braun, P. G., Dittrich, A. J., & Huehn, S. (2018). Inactivation of *Vibrio* sp. in pure cultures and mussel homogenates using high hydrostatic pressure. *Letters in Applied Microbiology*, 67(3), 220-225. https://doi.org/10.1111/lam.13044

Wang, F.-Q., Cheng, J.-H. & Keener, K. M. (2023a). Changing the IgE binding capacity of tropomyosin in shrimp through structural modification induced by cold plasma and glycation treatment. *Foods,* 12**,** 206.

Wang, H., Zhang, Y., Jiang, H., Cao, J., & Jiang, W. (2022a). A comprehensive review of effects of electrolyzed water and plasma-activated water on growth, chemical compositions, microbiological safety and postharvest quality of sprouts. *Trends in Food Science and Technology*, 129, 449-462. https://doi.org/10.1016/j.tifs.2022.10.017

Wang, J. J., Lin, T., Li, J. B., Liao, C., Pan, Y. J., & Zhao, Y. (2014). Effect of acidic electrolyzed water ice on quality of shrimp in dark condition. *Food Control*, 35(1), 207-212. https://doi.org/10.1016/j.foodcont.2013.07.005

Wang, J., Fu, T., Wang, Y. & Zhang, J. (2022b). Effects of high-voltage atmospheric cold plasma treatment on microbiological and quality characters of tilapia fillets. *Foods*, 11, 2398.

Wang, X., Li, S., Li, L., Ding, Y., Xu, T., Liu, J., Li, Q., Zhao, T. & Zhang, Y. (2023b). Mycotoxins degradation by reactive oxygen species in plasma: Reactive molecular dynamics insights. *LWT-Food Science and Technology*, 184, 115058.

Wu, Y., Cheng, J.-H. & Sun, D.-W. (2021). Blocking and degradation of aflatoxins by cold plasma treatments: Applications and mechanisms. *Trends in Food Science and Technology*, 109, 647-661.

Xie, J., Sun, X., Pan, Y., & Zhao, Y. (2012). Combining basic electrolyzed water pretreatment and mild heat greatly enhanced the efficacy of acidic electrolyzed water against *Vibrio parahaemolyticus* on shrimp. *Food Control*, 23(2), 320–324. https://doi.org/10.1016/j.foodcont.2011.07.019

Yan, P., Daliri, E. B.-M., & Oh, D.-H. (2021). New clinical applications of electrolyzed water: A review. *Microorganisms*, 9(1), 136. https://doi.org/10.3390/microorganisms9010136

Ye, T., Chen, X., Chen, Z., Yao, H.,Wang, Y., Lin, L., & Lu, J. (2021b). Quality and microbial community of high pressure shucked crab (*Eriocheir sinensis*) meat stored at 4°C. *Journal of Food Processing and Preservation*, 45(4), e15330.

Ye, T., Xing, C., Zhina, C., Rui, L., WanG, Y., Lin, L., & Lu, J. (2021a). Quality characteristics of shucked crab meat (*Eriocheir sinensis*) processed by high pressure during superchilled storage. *Journal of Food Biochemistry*, 45(4), e13708. https://doi.org/10.1016/j.foodcont.2020.107223

Yong, H. I., Kim, H.-J., Park, S., Kim, K., Choe, W., Yoo, S. J., & Jo, C. (2015). Pathogen inactivation and quality changes in sliced cheddar cheese treated using flexible thin-layer dielectric barrier discharge plasma. *Food Research International*, 69, 57–63.

https://doi.org/10.1016/j.foodres.2014.12.008

Zhang, B., Ma, L.-K., Deng, S.-G., Xie, C. & Qiu, X.-H. (2015). Shelf-life of pacific white shrimp (*Litopenaeus vannamei*) as affected by weakly acidic electrolyzed water ice-glazing and modified atmosphere packaging. *Food Control*, 51, 114-121.

Zhang, C., Zhao, Z., Yang, G., Shi, Y., Zhang, Y., Shi, C., & Xia, X. (2021). Effect of slightly acidic electrolyzed water on natural *Enterobacteriaceae* reduction and seed germination in the production of alfalfa sprouts. *Food Microbiology*, 97, 103414. https://doi.org/10.1016/j.fm.2020.103414

Zhang, W., Xiao, S., & Ahn, D. U. (2013). Protein oxidation: Basic principles and implications for meat quality. *Critical Reviews in Food Science and Nutrition*, 53(11), 1191-1201. https://doi.org/10.1080/10408398.2011.577540

Zhang, Y., Wei, J., Yuan, Y., Chen, H., Dai, L., Wang, X. & Yue, T. (2019). Bactericidal effect of cold plasma on microbiota of commercial fish balls. *Innovative Food Science and Emerging Technologies,* 52**,** 394-405.

Zhao, Y.-M., Oliveira, M., Burgess, C. M., Cropotova, J., Rustad, T., Sun, D.-W., & Tiwari, B. K. (2021). Combined effects of ultrasound, plasma-activated water, and peracetic acid on decontamination of mackerel fillets. *LWT-Food Science and Technology*, 150, 111957. https://doi.org/10.1016/j.lwt.2021.111957