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REVIEW

Postharvest Preservation Technologies for Marine-Capture Shrimp: A Review

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Abstract
Marine-capture shrimp is a general term for a type of shrimp that is different from marine-aquaculture shrimp. It is rich in protein, trace elements, and essential amino acids. It is an aquatic product with delicious meat and high nutritional and economic value. Most marine-capture shrimp are consumed fresh, with a small proportion subjected to processing. However, marine-capture shrimp is a highly perishable aquatic product, and hence, extensive preservation and processing methods have been developed to extend its shelf life. This review presents the current status of marine-capture shrimp in the world and the key issues (spoilage and melanization inhibition) regarding marine-capture shrimp preservation. Low-temperature preservation remains the predominant strategy for preserving marine-capture shrimp. Different preservation strategies combined with low temperature would maintain the quality of marine-capture shrimp more effectively, thereby extending the shelf life of the shrimp. The advantages and disadvantages of various preservation technologies are comprehensively considered and compared, as well as their scope of application. New processing technologies should be introduced, and various preservation technologies with complementary advantages should be organically combined to achieve the best preservation effect on marine-capture shrimp. This review provides a useful theoretical reference and a practical basis for future research on the shelf life extension of marine-capture shrimp.

Keywords Marine-capture shrimp · Postharvest preservation · Melanization · Quality change · Shelf life

Introduction

Shrimp is one of the most popular aquatic products in the world due to its rich taste (Rusanova et al., 2022) and high nutritional content (Lv et al., 2020; Yu et al., 2022a). In terms of species classification, shrimp belong to different families in the suborder Dendrobranchiata of Decapoda, and being different from the aquaculture shrimp species, the marine-capture shrimp (Fig. 1) have unique species, such as *Trachypenaeus curvirostris* (Stimpson, 1860), and *Parapenaeus longirostris* (Lucas, 1846) in the family Penaeidae, *Solenocera crassicornis* (Milne Edwards, 1837) and *Solenocera melantho* (de Man, 1907) in the family Solenoceridae, and *Acetes chinensis* (Hansen, 1919) in the family Sergestidae. According to different production sources, shrimp can be divided into two types: marine shrimp and freshwater shrimp (Li et al., 2011). Based on whether they are produced by aquaculture or not, marine shrimp and freshwater shrimp can be further divided into marine capture shrimp and marine aquaculture shrimp and into freshwater capture shrimp and freshwater aquaculture shrimp, respectively.

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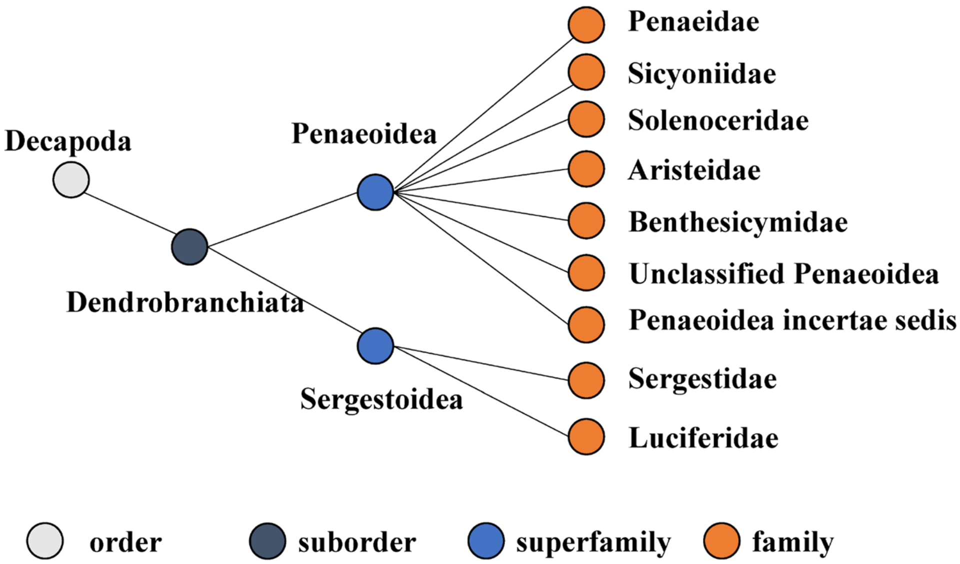

Fig. 1 Species classification of shrimps (from order to family) (adapted from Lifemap, 2023)

Shrimps that are mostly aquacultured and only partly caught in the ocean, such as the Pacific white shrimp (*Penaeus vannamei*, Boone, 1931), are not discussed in this review.

As one of the most important products among fishery trading commodities (Hou et al., 2018), shrimps have been widely integrated into consumer diets due to its high quality protein and have become an indispensable delicacy worldwide. According to the Yearbooks published by FAO (2021), shrimp accounts for 3.36−3.78% of all capture production and occupy a relatively important position by statistics by weight (ton). However, overfishing of offshore fishery resources has led to the beginning of a decline in the production of marine-capture shrimp. Therefore, fishing moratoriums were established as a sustainable conservation measure (Ding et al., 2021). China is the leading producer and exporter of shrimp in the world. Indeed, the marine-capture shrimp production in China in 2020 was nearly 1.21 million tons (Fishery Knowledge Service System,, 2022). Similarly, consumption and international trade demand are increasing annually, providing an advantageous market environment for the rapid development of shrimp foods and thus allowing the industry to have broad development prospects.

Shrimps are rich in water, protein, and highly active polyphenoloxidase (PPO) (Yu et al., 2022a); consequently, dead shrimps are easily degraded and spoiled during fishing, transportation, processing, and storage (Fan et al., 2022). The main causes of degradation include enzymatic autolysis (Huang et al., 2014), microbial spoilage (Broekaert et al., 2013), and lipid oxidation (Garcia-Soto et al., 2015). Lin et al. (2022) have conducted a detailed review of shrimp spoilage mechanisms. Shrimps will die soon after being caught due to being removed from their environment (Xu et al., 2017). At room temperature (25 °C), the shelf life of shrimp is approximately 1 day (Buyukcan et al., 2009), which can be extended to 4−6 days if placed at 4 °C. The shrimp will turn black over time, especially the head. Although the occurrence of blackening does not affect human health, it does greatly dissuade buyers. In order to solve these problems, researchers worldwide have conducted extensive research on how to preserve the freshness of marine-capture shrimp and how to minimize shrimp melanosis.

Based on the general concern about the preservation of marine-capture shrimp, this review aims to summarize the basic information about marine-capture shrimp in the world in recent years, analyze the production and species of marine-capture shrimp in China, the country with the highest consumption and production, and comprehensively present the current research trends (physical, chemical, and biological perspectives) on postharvest preservation of marine-capture shrimp. The characteristics and limitations of various preservation technologies used for marine-capture shrimp are objectively analyzed, and the direction of future technological development in marine-capture shrimp preservation is discussed. A theoretical reference and a practical basis are provided for future research on the shelf life extension of marine-capture shrimp.

Spoilage Mechanisms in Marine-Capture Shrimp

As with aquaculture shrimps, the mechanisms of spoilage in marine-capture shrimps include mainly biochemical reactions prior to stiffening, carcass lysis, and autolysis, and these were reviewed in detail by Peng et al. (2022). It is worth noting that marine-capture shrimps should focus on bacterial spoilage effects and blackening among these two most basic spoilage mechanisms.

Bacteria Spoilage Effects

Bacteria can cause spoilage of shrimps and also produce unpleasant odors. The main species associated with the spoilage of shrimps in sea catches include the genera *Shewanella* and *Pseudomonas* (Yu et al., 2022b). During shrimp spoilage, bacteria play a major role in the lysis phase of the carcass, including the production of various biogenic amines (which may cause allergies and other symptoms), the metabolisation of shrimp nutrients, and the production of unpleasant flavours (mainly trimethylamine and dimethylamine) (Peng et al., 2022).

Bacteria play a decisive role in the spoilage process, but often the shrimp muscle contains very few bacteria and more bacteria are enriched on the surface of the shell, so environmental and geographical factors are also key factors in determining the bacterial species contained in shrimp. Odeyemi et al. (2021) found that different environments and species determined the composition of the microbiota in shrimps. While excluding vacuum-packed shrimps, the storage environment also had an effect on the shrimp flora, and during this process, different bacterial populations underwent different changes at different stages of storage, which is considered a dynamic process.

Melanization

The bad appearance of fresh food will affect consumers' desire to buy, and the blackening of shrimp is one of the main reasons for affecting the desire to buy. The current blackening phenomenon is explained as follows (Sharifian et al., 2019): (1) prophenoloxidase (proPO) is activated, and phenoloxidase (PO) catalyzes the conversion of monophenolic substrates to bisphenols in vivo and then forms highly reactive quinones that can spontaneously polymerize to produce browning, and (2) these quinones react with amino acids and proteins to form melanin (Jiang & Kanost, 2000; Nirmal & Benjakul, 2011; Sritunyalucksana & Soderhall, 2000; Terwilliger & Ryan, 2006) (Fig. 2). These chemical reactions lead to spontaneous oxidation and blackening of shrimp after death.

Even if there are no reports to prove that black substances can cause harm to the human body, the production of melanin does cause great difficulties in the actual consumption process. Therefore, more and more scholars have begun to focus on how to solve the production of melanin or inhibit melanin.

Preservation Strategies for Marine-Capture Shrimp

Traditional Preservation Technology

Low-Temperature Preservation

Low-temperature preservation is mainly aimed at preserving and keeping fresh shrimp alive during transportation and storage. The principle is to keep shrimp at a low temperature such that shrimp corporal temperature becomes stabilized within a lower range, thereby reducing the activity, stress responses, oxygen consumption, and metabolic rate of the live shrimps (Guo et al., 2010; Qiu et al.,

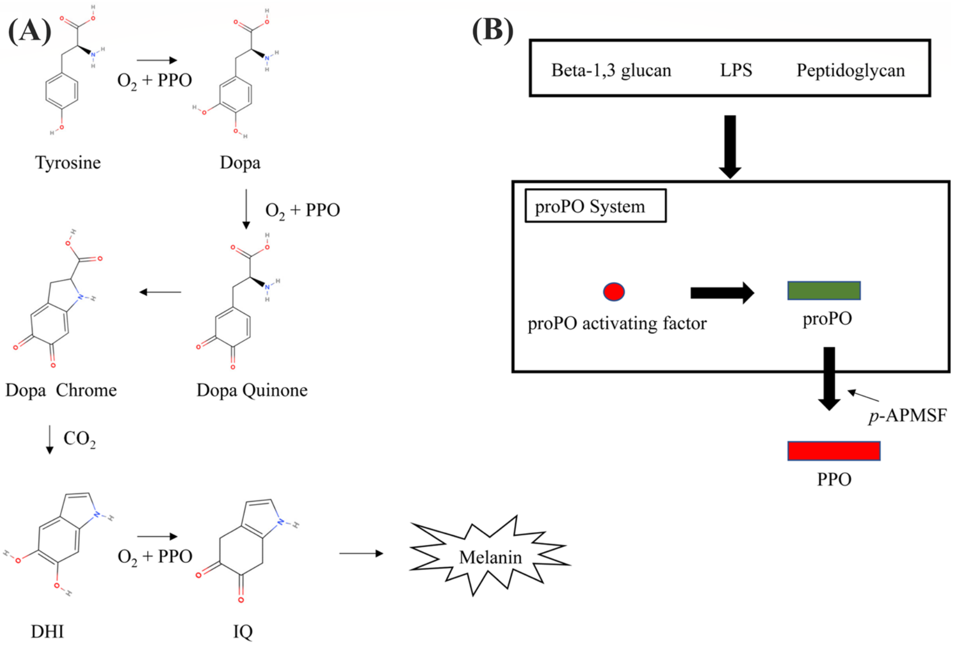

Fig. 2 The mechanism of shrimp melanization. **A** Melanin production pathway. **B** The mechanism of PPO activation. PPO, Polyphenoloxidase; DHI, 5,6-dihydtoxyindole; IQ, indole 5,6-quinone; proPO, prophenoloxidase; LPS, lipopolysaccharide; p-APMSF, 4-amidino phenyl methane sulfonyl fluoride (Jiang & Kanost, 2000; Nirmal & Benjakul, 2011; Sritunyalucksana & Soderhall, 2000; Terwilliger & Ryan, 2006)

2011; Ren et al., 2020), furthermore, inhibiting microbial metabolism and enzyme activity in dead shrimp (George, 1993; Pineiro et al., 2004). At present, low-temperature preservation is mainly divided into refrigerated preservation (0 to 4 °C), ice-temperature preservation (−2 to 0 °C), super-chilling preservation (−4 to −2 °C), and freezing preservation (−18 to −40 °C) (Leng et al., 2022; Pan et al., 2019). Ice-temperature and super-chilling preservation schemes are currently less used for economical shrimp, such as marine-capture shrimp because they have higher temperature control requirements, which results in excessively high costs. To our knowledge, some fishing vessels are now equipped with ultra-low-temperature equipment (< −60 °C); however, temperatures of −60 °C and below are more commonly used for laboratory preservation of precious biological samples, and the potential marginal gain in quality due to storage at −60 °C may be small for marine-capture shrimp (Ji et al., 2021). Nevertheless, most current research on freezing marine-capture shrimp for storage is mainly concentrated on the temperature range from −20 to −40 °C.

Parlapani et al. (2020) found that the shelf life of *P. longirostris* was extended from 2 days at 4 °C to 5 days at 0 °C, both temperatures at which the predominant microbes were *Psychrobacter* and *Carnobacterium*. Broekaert et al. (2013) found that *Psychrobacter* and *Pseudoalteromonas* were the predominant microbiota of *Crangon crangon* (Linnaeus, 1758) at 0 °C. The main volatile substances of *P. longirostris* at 0 °C were acetone and dimethyl sulfide, and at 4 °C, ethanol, 3-methyl-1-butanol, 2-ethyl-1-hexanol, 3-hydroxy-2-butanone, and indole (Parlapani et al., 2020). Compared with the *S. melantho* stored at 0, 3, and 6 °C, storing shrimp at −3 °C significantly inhibited spoilage (Xu et al., 2016). Furthermore, storage at −28 °C was more beneficial in slowing the deterioration of *S. melantho* than that at −20 °C or −12 °C (Xu et al., 2017). Overall, the lower the temperature, the less lipid oxidation was exhibited by *S. melantho* (Shi et al., 2017), which was also confirmed in *S. crassicornis* (Jin et al., 2018). At the same time, low temperature can effectively control the number of aerobic bacteria in marine-capture shrimp (Jin et al., 2018).

Among the preservation strategies of marine-capture shrimp, research on low-temperature preservation is the most in-depth; however, the actual effects achieved have not reached the ideal state. PPO in shrimp remains active at low refrigeration temperatures, even 0 to −20 °C (Montero et al., 2004; Nirmal & Benjakul, 2012), and can react slowly. Hence, this type of low-temperature storage cannot meet the requirements of shrimp storage during transportation and marketing, thereby affecting shrimp flavor and appearance. During freezing storage, moisture inside the shrimp is easily condensed into ice crystals that disrupt tissue structure, resulting in dry consumption, freezing denaturation, and other phenomena that strongly impact shrimp appearance, quality, and market value. Table 1 summarizes current preservation methods of marine-capture shrimp at low temperature combined with other methods (described in the following sections), aiming to provide more ideas for preserving marine-capture shrimp in the future.

Slurry Ice Preservation

Slurry ice, also known as liquid ice, is a natural and efficient cooling medium with a temperature of −1.5 to −0.5 °C (Liu et al., 2021). It is a homogeneous and stable two-phase mixture composed of an aqueous solution and ice crystals. Slurry ice shows the characteristics of small crystals and a large surface area (Huidobro et al., 2002). Aquatic products can be completely covered by slurry ice, and the temperature can be effectively lowered through its strong cooling capacity, inhibiting the reproduction of microorganisms and inactivating enzymes (Annamalai et al., 2018). In addition, slurry ice does not cause any mechanical damage to aquatic products during the preservation period (Lin et al., 2016) and can maintain the quality of aquatic products to the greatest extent (Annamalai et al., 2018). Currently, slurry ice is only suitable for pretreating fresh marine-capture shrimp on board. Generally, other preservation technologies, such as low-temperature preservation and MAP preservation, are more conducive to preserving marine-capture shrimp during transportation, processing, storage, and marketing. Huidobro et al. (2002) compared the effects of onboard slurry ice cooling and traditional flake-ice cooling on shrimp quality. Slurry ice can effectively inhibit the formation of nitrogen compounds and slow down the increase of pH and the growth of microorganisms. Slurry ice at −1.5 °C significantly extended the shelf life of *P. borealis* (Zeng et al., 2005).

In recent years, slurry ice has received much attention as a fast-cooling preservation technology. However, because it melts quickly, slurry ice may dissolve microorganisms and cause problems such as cross-contamination with shrimp meat. Therefore, special attention should be paid to draining the melted ice water as frequently as needed and replacing the slurry ice during the process of fresh shrimp preservation to achieve the best preservation results.

Chemical Preservation

Chemical preservation refers to a kind of preservation technology that uses the antibacterial and bactericidal effects of one or more drugs to be quantitatively added to the product according to the standard to achieve quality preservation and extension of the shelf life of the product. The mechanism underlying chemical preservation entails inhibiting the proliferation of harmful bacteria or their destruction with

Table 1 The low temperature preservation combined with other preservation strategies for marine-capture shrimp

Species	Strategy	Result	References
Acetes chinensis (Hansen, 1919)	Salt, vacuum package, 4 °C	Low salt and vacuum package delayed lipid oxidation, and vacuum package protected astaxanthin	(Qiu et al., 2020)
Aristaeomorpha foliacea (Risso, 1827)	MAP(N_2/CO_2), −35 °C	Prevented melanosis and spoilage	(Bono et al., 2016)
Crangon crangon (Linnaeus, 1758)	MAP(CO_2/O_2/N_2), 4 °C	O_2 stimulated microbial growth, and CO_2 inhibited microbial growth and metabolic activity	(Noseda et al., 2012)
Euphausia superba (Dana, 1850)	CC (sodium phytate), −2 °C	Suppressed microbial growth, the increases in pH value, total volatile basic nitrogen and sensory deterioration	(Liu & Pan, 2020)
Fenneropenaeus chinensis (Osbeck, 1765)	Bactericides, MAP(CO_2/O_2/N_2), 2 ± 1 °C	Prolonged the shelf life of fresh shrimps to 13 and 17 days	(Lu, 2009)
	Chitosan, ε-polylysine coating, 4 °C	Maintained the sensory characteristics and delayed the increases in TVB-N, hypoxanthine, *K* value	(Zhang et al., 2020)
Fenneropenaeus merguiensis (de Man, 1888)	Processing treatments (frying and boiling), acids, −20 °C	Acetic and HCl acids reduced antigenicity of tropomyosin by ~ 90%	(Faisal et al., 2019)
	Chitosan(γ-irradiated), 4 °C	Extended the shelf life	(Pati et al., 2021)
Litopenaeus stylirostris (Stimpson, 1871)	PA-LDPE, α-tocopherol, −20 °C	Reduced lipid oxidation, slowed hardness, and astaxanthin loss	(Zulema Valencia-Perez et al., 2015)
	MAP(CO_2/O_2/N_2), −22 °C/2 °C/5 °C/8 °C	Inhibited the growth of *Listeria monocytogenes*, 2 °C was the most suitable for shrimp delivery	(Mejlholm et al., 2005)
Pandalus borealis (Krøyer, 1838)	Ice maturation, steamed, −20 °C	Maturation time, freezing and steaming all affected the quality of the shrimps, whereas the peeling work was not affected	(Gringer et al., 2020)
	MAP(N_2), −18 °C/−17 °C	Improved the fading of shrimp, the production of rancidity, and the toughening of meat	(Bak et al., 1999)
Parapenaeopsis hardwickii (Miers, 1878)	Chlorogenic acid, gelatin, −5 °C	Inhibited growth of microorganism, lipid oxidation, and protein degradation	(Ge et al., 2020)
	4-HR based formula, 2 °C	Prevented melanosis, inhibited the growth of microorganisms (H_2S producers and pseudomonads) and extended the shelf life	(Elvira Lopez-Caballero et al., 2007; Lopez-Caballero et al., 2019; Martinez-Alvarez et al., 2008; Montero et al., 2004, 2006)
	4-HR based formula, −18 °C	Prevented melanosis, inhibited the growth of microorganisms, and extended the shelf life	(Martinez-Alvarez et al., 2020)
	MAP(CO_2/O_2), 4-HR, 2 °C	Made shrimps paler and softens the shell, inhibited melanosis, and the growth of microorganisms	(Martinez- Alvarez et al., 2005)
	MAP(CO_2/O_2), 2 °C	Delayed the microbial growth, the TMA and TVB-N production	(Lopez-Caballero et al., 2002)

Table 1 (continued)

Species	Strategy	Result	References
	MAP(N_2/CO_2), −18 °C	Completely inhibited lipid oxidation and maintained natural color for up to 6 months	(Bono et al., 2012)
Parapenaeus longirostris (Lucas, 1846)	Chitosan, sodium, metabisulphite, 4-HR, citric acid, rosemary extract, −18 °C/4 °C	The shrimp acceptability for at least 12 months. Slowed down biochemical reactions during refrigeration, extending shelf life up to twice as much, prevented melanosis	(Bingol et al., 2013, 2015; Varlik et al., 2014)
	Chitosan films, orange peel essential oil, 4 ± 1 °C	Prolonged the shelf life of fresh shrimps to 15 days	(Alparslan & Baygar, 2017)
	Chitosan solution (tapioca starch, cornstarch flour, locust bean gum), 4 °C	Positively improves the shelf life of shrimps	(Avola et al., 2011)
	CC, garlic oil, 4 °C	Reduced the total viable count, increased *L**, decreased *a** and *b**, extended the shelf life of shrimp,	(Asik & Candogan, 2014)
	Orange peel essential oil, gelatin coating, 4 °C	Prevented melanosis and extended the shelf life to 14 days	(Alparslan et al., 2017)
	Olive vegetation water phenolic extract, 2 °C	Prevented melanosis and inhibited the growth of microorganisms	(Miraglia et al., 2020)
Penaeus kerathurus (Forskål, 1775)	Sepia ink, −2 °C/0 °C	Extended shelf life by at least 10 days and slowed TVB-N and TMA increases	(Sadok et al., 2004)
Penaeus semisulcatus (De Haan, 1844)	Aloe vera coating, 4 °C	Prevented lipid oxidation and drip loss	(Soltanizadeh & Mousavinejad, 2015)
Pleoticus muelleri (Spence Bate, 1888)	Phosphates, −86 °C/−35 °C	Effectively reduced drip loss	(Goncalves & Duarte Ribeiro, 2008)
	Phosphates, −86 °C/−30 °C	Prevented large cooking-related yield losses and retained sensory attributes	(Goncalves & Duarte Ribeiro, 2009)
Solenocera crassicornis (Milne Edwards, 1837)	Sodium metabisulphite, −18 °C	1.5% SMB soaking to treat shrimp results in good antioxidant and antimicrobial effects	(Zhu et al., 2020)
Solenocera melantho (de Man, 1907)	EB irradiation, 4.0 ± 0.5 °C	L-lysine was downregulated, while 2′deoxyguanosine 5′-monophosphate and dihydroxyacetone phosphate acyl ester were upregulated during the refrigerated storage	(Yu et al., 2022a)
	Ice-glazing, rosemary extract, −20 °C	More effective in controlling quality changes	(Shi et al., 2019)
Xiphopenaeus kroyeri (Heller, 1862)	Ice-glazing, −18 °C	Demonstrated the effectiveness of the glazing process as a protecting agent for frozen shrimp	(Goncalves & Guidobono Gindri Junior, 2009)
Fresh shrimp (marine fished)	γ-irradiation, −18 °C/4 °C	5 kGy might enhance lipid oxidation and inhibited the growth of microorganisms and protein oxidation	(Hocaoglu et al., 2012)

MAP modified atmosphere packaging, *CC* chitosan coatings, *TVB-N* total volatile basic nitrogen, *PA-LDPF* polyamide low-density polyethylene film, *4-HR* 4-ethylresorcinol, *TMA* trimethylamine, *EB* electron beam chemical substances, which can react with oxidase in the organism to achieve an antioxidant effect (Torres-Arreola et al., 2007). In marine-capture shrimp, chemical preservation is mainly used to prevent melanization. The traditional chemical preservative is sodium metabisulfite, which can effectively delay the melanization of fresh shrimp and inhibit microbial reproduction and the physiological oxidation process. Zhu et al. (2020) found that sodium metabisulfite can significantly inhibit the blackening of *S. crassicornis*. However, the excessive use of sodium metabisulfite leads to excessive SO_2 residues, causing diseases such as gastrointestinal disorders, mucosal inflammation, and organ lesions (Rencuzogullari et al., 2001). Previous studies showed that 4-hexylresorcinol is an effective melanin inhibitor in marine-capture shrimp (Martinez-Alvarez et al., 2008; Montero et al., 2004) and that it tends to play a stronger role when combined with organic acids (citric, ascorbic, or acetic) and chelating agents (ethylenediaminetetraacetic acid and di-sodium di-hydrogen pyrophosphate) (Lopez-Caballero et al., 2019; Martinez-Alvarez et al., 2020); furthermore, the residual amount is relatively low (Montero et al., 2006). Other chemical preservatives can also act on marine-capture shrimp; for example, α-tocopherol maintained the muscle mass of *Litopenaeus stylirostris* (Stimpson, 1871) (Zulema Valencia-Perez et al., 2015), and phosphate treatment preserved the senses of *Pleoticus muelleri* (Spence Bate, 1888; Goncalves & Duarte Ribeiro, 2008).

Chemical preservation is advantageous due to its simplicity, efficiency, and low cost, although its application has certain limitations owing to the problems of SO_2, excessive antibiotic residues, and bacterial resistance in marine-capture shrimps. From the perspective of food hygiene and public health, the future chemical preservation technology for marine-capture shrimp should be developed in a natural, safe, and non-toxic direction. For example, chemicals can be combined with biological preservation technology to reduce the dosage of chemical reagents, effectively preserving the freshness of marine-capture shrimp and reducing harmful residues.

Novel Preservation Technology

High-Pressure Preservation

High-pressure processing (HPP), also known as high hydrostatic pressure (HHP) (Campus, 2010), is a common non-thermal food processing technology (Oliveira et al., 2017). The underlying principle is to place flexible packaged food in a pressure vessel containing a pressure-transmitting liquid (usually water or an aqueous solution) that can withstand 100 to 1000 MPa (Zhang et al., 2019). The pressure is usually called ultra-high pressure (UHP) when it is greater than 600 MPa. Sterilization using high pressure is achieved due to the destruction of bacterial cell walls and membrane structure, change in the permeability of the cell membrane, and inhibition of the replication and enzymatic activity of DNA (Wang et al., 2016). However, UHP treatment acts only on non-covalent bonds (e.g., hydrogen bonds, hydrophobic bonds, ionic bonds) in biological macromolecules, while covalent bonds are not affected (Campus, 2010). Therefore, the original quality, color, taste, and nutritional value of the food can be better maintained while arresting all microbial activity (Linton & Patterson, 2000).

At present, HHP has been widely used in fruits and vegetables. Reports of HHP-treated shrimp basically focus on the quality (Kaur et al., 2013, 2015) and PPO (Huang et al., 2014) of aquaculture shrimp, but reports on marine-capture shrimp are scarce. The study by Lv et al. (2020) showed that HHP treatment at 100−200 MPa was optimal for *S. melantho* preservation. The solubility of the myofibrillar protein in shrimp treated with 300 MPa was reduced, and the surface hydrophobicity was increased, whereby the structure of the myofibrillar protein was partially converted from α-helical structure to α-sheet structure, thereby exposing tryptophan residues.

HHP preservation technology is a fresh shrimp preservation technology that can maintain the nutrition and quality of fresh shrimp without producing adverse reactions caused by thermal processing (Kaur et al., 2013). However, at pressures less than 600 MPa, the relative activity of PPO remains greater than 88% (Huang et al., 2014), but switching to higher pressures is challenging for large-scale applications due to the high cost of UHP processing equipment. Moreover, since the HHP preservation technology does not produce a significant lethal effect on bacterial spores, other auxiliary factors, such as acidity, temperature, and bacteriostatic agents, should be supplemented with this technology to achieve a maximal lethal effect.

Irradiation Preservation

Irradiation is a physical cold sterilization method (Yu et al., 2020), and the main irradiation sources currently used for shrimp preservation include γ-rays, X-rays, and the electron beam (EB) (Huang et al., 2019). Some of the properties of the three types of radiation are listed in Table 2. Food irradiation can effectively inactivate bacteria and pathogens with little impact on food nutrition or quality (Yu et al., 2020). Currently, doses of 0−10 kGy are widely accepted for food processing purposes (EFSA, 2011; Kontominas et al., 2021; WHO, 1999).

Irradiation has also been used for the preservation of marine-capture shrimp. Yu et al. (2022a) treated *S. melantho* by irradiating with different doses of EB and screened for the optimal dose based on physiological and biochemical indicators and microbial diversity. Further, by comparing the protein changes before and after irradiation, the effect of EB irradiation on *S. melantho* proteins was revealed (Yu et al., 2022c). Additionally, changes in shrimp metabolites after irradiation were observed by refrigeration (Yu et al., 2022b). The results of the study by Sharma et al. (2007) indicated that γ-irradiation at 2 kGy did not alter the sensory value of *Solenocera chopri* (Nataraj, 1945) muscles.

However, there are also some limitations of irradiation preservation; most countries currently only allow doses below 10 kGy for food processing (Kontominas et al., 2021), as high-dose irradiation treatments may produce off-flavors and reduce the nutritional quality of foods (Rodrigues et al., 2021). Presently, the acceptance of irradiated food by consumers is not high, resulting in limited research on the preservation of marine-capture shrimp using this technology in recent years. Therefore, it is still necessary to strengthen public understanding of irradiation preservation technology so that this emerging food preservation technology can play a more important role in shrimp preservation. Irradiated food and food-containing irradiated ingredients are required to be affixed with a label declaring them as irradiated food (Kontominas et al., 2021). Because consumers are wary of irradiated food, some businesses do not use labels or make declarations for economic benefit. Hence, Xiong et al. (2016) developed the multispectral imaging (MSI) system to identify whether marine-capture shrimp were irradiated or not.

Modified-Atmosphere Packaging (MAP) Preservation

Commonly used gases for MAP preservation include CO_2, N_2, and O_2 (Sivertsvik et al., 2002). The general principle is to change the gas composition in the storage environment. For example, reducing O_2 content (the factor that accelerates melanization of shrimp) and increasing CO_2 and N_2 contents can reduce the respiration rate of microorganisms in fresh shrimp, inhibit the reproduction and metabolism of microorganisms (Bouletis et al., 2017), and reduce PPO activity in the body (Qian et al., 2014), thereby maintaining the quality of shrimp products and prolonging the shelf life (Bouletis et al., 2017).

Bono et al. (2012) found that under freezing preservation (−35 °C) and MAP (100% N_2) completely inhibited lipid oxidation in *P. longirostris* (better than 50%:50% N_2:CO_2) and inhibited melanosis for 6 months. This result was confirmed for *Aristaeomorpha foliacea* (Risso, 1827; Bono et al., 2016). Two MAPs (40%:30%:30% CO_2:O_2:N_2 and 45%:5%:50% CO_2:O_2:N_2) delayed microbial growth and production of trimethylamine and the total volatile nitrogen in *P. longirostris* (Lopez-Caballero et al., 2002); MAP involving 45%:5%:50% CO_2:O_2:N_2 was better (Goncalves et al., 2003). After *F. chinensis* were soaked in compound fungicides and processed by MAP, their shelf life was extended to 13 days under 40%:30%:30% CO_2:O_2:N_2 and 17 days under 100% CO_2 at 2 °C (Lu, 2009). All microbial growth in *Melicertus kerathurus* (Forskål, 1775) was effectively inhibited under MAP 60%:40% CO_2:N_2 (Arvanitoyannis et al., 2011). MAP preservation was considered to be effective in *C. crangon* (Noseda et al., 2010), and different gas ratios (CO_2:O_2:N_2) can inhibit microbial growth and reduce the metabolic effect of microorganisms, but the inhibitory effect will not be strong if the oxygen concentration is increased (Noseda et al., 2012). Under MAP involving 40%:60% CO_2:N_2, the predominant microorganisms in *C. crangon* at 4 °C were mainly *Carnobacterium*, *Shewanella*, and *Psychrobacter* (Calliauw et al., 2016). Nitrogen-filled packaging can effectively prolong the shelf life of *P. borealis* (Bak et al., 1999), and MAP treatment (50%:20%:30% CO_2:O_2:N_2) of *P. borealis* effectively inhibits the growth of *Listeria monocytogenes* (Mejlholm et al., 2005).

As one of the most effective aquatic-preservation technologies in the world, MAP has been widely used in marine-capture

Table 2 Some properties of the three irradiations (adapted from Pi et al., 2021)

	γ-irradiation	X-ray irradiation	EB irradiation
Irradiation source	^{60}Co and ^{137}Cs	X-ray machine	Electron accelerator
Irradiation species	Electromagnetic wave		High-speed electron flow
Penetrability	Very strong	Strong	Weak
Chargeability	Un-charge		Charge with 1 negative
Energy limit	5 MeV	5 MeV (US 7.5 MeV)	10 MeV
Utilization	Low		High
Output power	Low		High
Equipment cost	Very high	High	Low
Processing time	Slow		Fast
Equipment operating costs	High	General	Low
Processing mode	Single		Flexible
Environmental impact	Very radioactive contamination	Radioactive contamination	Safety and friendly

shrimp preservation. Currently, MAP is mostly based on research conducted on pathogenic bacteria and the inhibitory effect of bacteria in marine-capture shrimp, while research on the influence of pathogenic bacteria and spores is relatively insufficient. This may explain why, although this method maintains the sensory quality of marine-capture shrimp, the safety of the method cannot be guaranteed. Furthermore, due to the high technical requirements and complexity of operation of this preservation method, it has neither become very popular nor widely adopted.

Acidic Electrolyzed Water (AEW) Preservation

As a new type of preservation technology, AEW shows efficient sterilization effects, no pollution, and no residues due to its low pH, high effective chlorine concentration, and high redox potential (Esua et al., 2021). These observations account for the increase in its use for sterilization and preservation of aquatic products in recent years (Gao et al., 2021; Lan et al., 2022).

Although AEW has rarely been reported to be applied to marine-capture shrimp, it is reported to significantly inhibit the proliferation of *Vibrio parahaemolyticus*, thereby maintaining the quality of fresh aquaculture shrimp and reducing the health threat of the pathogen during storage and transportation (Wang et al., 2014; Xie et al., 2012). AEW ice reportedly inhibits the growth of bacteria in aquaculture shrimp (Lin et al., 2013), destroys the conformation of PPO, slows down browning (Sun et al., 2018), and does not cause any adverse effects on shrimp (Wang et al., 2015).

AEW is easy to prepare and inexpensive (Esua et al., 2021) and will not cause the loss of shrimp color, flavor, or nutritional components during use, thus effectively overcoming the negative impact of traditional preservation technology on food quality. AEW ice can be better used to preserve fresh shrimp during summer. More research on AEW preservation technology will enable a more effective reduction of the potential harm caused by pathogenic bacteria in shrimp tissues and, thus, better ensure shrimp quality and safety.

Chemical Preservation

As a new chemical preservation method, ozone (O_3) has been used to preserve the freshness of aquaculture shrimp (Goncalves & Lira Santos, 2019; Guo et al., 2013). Ozone destroys the bacterial cell wall, decomposes the membrane structure, and then diffuses into the interior of the cell, causing metabolic disorder and inhibiting growth (Kim et al., 2003). Ozone treatment is advantageous over traditional chemical preservatives for preserving marine-capture shrimp since the final product of ozone preservation is oxygen (Kim et al., 2003), which can effectively reduce the use of chemical preservatives, thereby improving food safety. At the same time, ozone sterilization is a non-thermal sterilization technology (Okpala, 2014), which can achieve the purpose of sterilization and anticorrosion without heating and thus save energy. However, it is vital to avoid high ozone concentrations to prevent its strong oxidizing power from adversely affecting shrimp quality (Okpala et al., 2016). There is currently little research on the application of ozone in preserving marine-capture shrimp despite ozone being able to prolong the shelf life of fresh shrimp effectively. Future preservation technology for marine-capture shrimp may possibly combine ozone preservation with low temperature, MAP preservation technology, and other technologies to enhance the preservation effect on fresh shrimp.

Biological Preservation

Biological preservation is an emerging research field derived from the theoretical study of biological sciences through integrating multiple disciplines. Its mechanism roughly includes (1) using related technologies to remove the air and inhibit enzyme activity so that oxidation is delayed and discoloration is prevented; (2) using substances with antibacterial, antioxidative, natural, and non-toxic properties to control the quality changes during food storage and transportation and to achieve anticorrosion and preservation effects; and (3) generating a protective film to prevent spoilage bacteria from breeding and contamination, slow down water loss, and maintain product quality. Recent research on biological preservatives mainly focuses on polyphenols, chitosan, and various biological extracts. Table 3 lists the relevant biological preservation methods currently used in marine-capture shrimp.

Although biological preservation has the potential to replace chemical preservation, the research and development of new biological preservation agents are not yet mature, and the research on the mechanism of biological preservation has not been studied in depth. Given the complex structure and composition of most biological preservatives, the low extraction rate, and the high technical requirements for the separation and purification process, the input cost is exceedingly high, greatly limiting its application in the actual storage and preservation process. In the future, it will still be necessary to strengthen further research on biotechnology and the development of new biological preservatives.

Other Preservation Technology

So far, there are also new preservation methods applied to various aquatic foods, including ultrasound, electrostatic fields, and magnetic fields (Abie et al., 2021). It is worth mentioning that Liu et al. (2022) applied a high-voltage electrostatic field to marine-capture shrimp, and the simulation diagram is shown in Fig. 3. Under the action of high-voltage

Table 3 The application of biological preservatives in marine-capture shrimp

	Substance	Features	Experimental results	References
Single strategy	Aloe vera gel	Antioxidation activity	Retarded lipid oxidation, reduced TBA, TVB-N, pH, and drip loss values	(Soltanizadeh & Mousavinejad, 2015)
	Chitosan (γ-irradiated)	Antibacterial and antioxidant activity	Extended the shelf life of shrimp	(Pati et al., 2021)
	Olive vegetation water phenolic extract	Antioxidant power combined with antibacterial activity	Reduced TVB-N, TBARS values significantly. Reduced bacterial counts and decreased the microbial development	(Miraglia et al., 2020)
	Rosemary extract	Food flavoring and antioxidant	Controlled quality changes in shrimp with lower TVB-N, drip loss, PV, FFA and higher lipid content and sensory scores	(Shi et al., 2019)
	Sepia	Preservative effect	Reduced TVB, TMA values	(Sadok et al., 2004)
	Chitosan, sodium phytate	Antibacterial, antioxidant activity and potent ion chelating ability	Suppressed microbial growth, the increases in pH value, TVB-N and sensory deterioration, extended the shelf life	(Liu & Pan, 2020)
Joint strategy	Chitosan, citric acid, rosemary extract	Antimicrobial, antioxidative, moisture retention, film-forming, and enzyme immobilization	Inhibited or slowed down melanosis	(Bingol et al., 2013; Varlik et al., 2014)
	Chitosan, garlic oil	Antibacterial and antioxidant activity	Reduced TVBN and TMA content, slowed lipid oxidation, and improved lightness (L^*)	(Asik & Candogan, 2014)
	Chitosan, ε-polylysine	Excellent film-forming and antibacterial characteristics	Sensory characteristics, TVB-N, ATP-related compounds, *K*-values, volatile components, and texture were regularly assessed	(Zhang et al., 2020)
	Chitosan, tapioca starch, cornstarch flour, locust bean gum	Film-forming	The effect of coating solutions on shrimps' shelf life was positive	(Avola et al., 2011)
	Chitosan, orange peel essential oil	Film-forming, antibacterial and antioxidant activity	Extended the shelf life of shrimp to 15 d	(Alparslan & Baygar, 2017)
	Chlorogenic acid, gelatin	Antioxidant, antibacterial, antiviral and anti-inflammatory properties	Inhibited growth of microorganism, lipid oxidation and protein degradation	(Ge et al., 2020)
	Orange peel essential oil gelatin	Antioxidant and antibacterial activities	Slowed the formation of blackening and maintained the quality of the shrimp	(Orlowska et al., 2009)

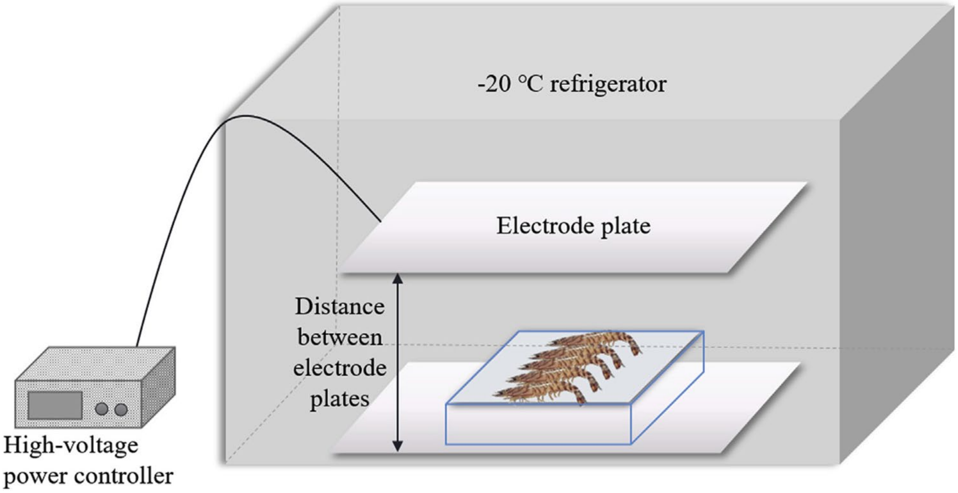

Fig. 3 Simulation diagram of high-voltage electrostatic field processing of marine-capture shrimp (Liu et al., 2022 with Elsevier permission)

electrostatic field, the ice crystal structure in the freezing process of red shrimp was improved, the freezing speed was increased, and the freezing quality of *S. melantho* was further improved, and the dose of the best electric field in the experiment was 15 kV/m.

Conclusions and Future Perspectives

Many of the preservation technologies for marine-capture shrimp described in this review can effectively prolong shrimp shelf life. However, each preservation technology shows its advantages and disadvantages. Therefore, in terms of the future practical application, the development of preservation technologies should comprehensively consider and compare the advantages and disadvantages of various preservation technologies and their applicability scope, and make reasonable use of the complementary advantages of various preservation technologies to combine different preservation technologies and achieve the best preservation effect on marine-capture shrimp.

In the future, the development of marine-capture shrimp preservation technology cannot be separated from preservatives. Presently, the main problem of preservatives is safety, followed by preservation efficacy and cost of use. Therefore, developing natural and efficient new preservatives is key to developing preservation technology. Due to the high cost and complexity of operation of many advanced preservation technologies, their development has been limited, and they are still in the research stage and have not yet been industrialized. At the same time, new processing and preservation technologies, such as voltage electrostatic fields and magnetic fields, have been applied to pork and fish, but no research has been reported on their application on marine-capture shrimp.

Therefore, future development of preservation technology for marine-capture shrimp should focus on safety, simplicity of operation, economy, and practicality to broaden the scope of application, thereby improving the economic and social benefits of shrimp preservation.

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Declarations

Conflict of Interest The authors declare no competing interests.

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