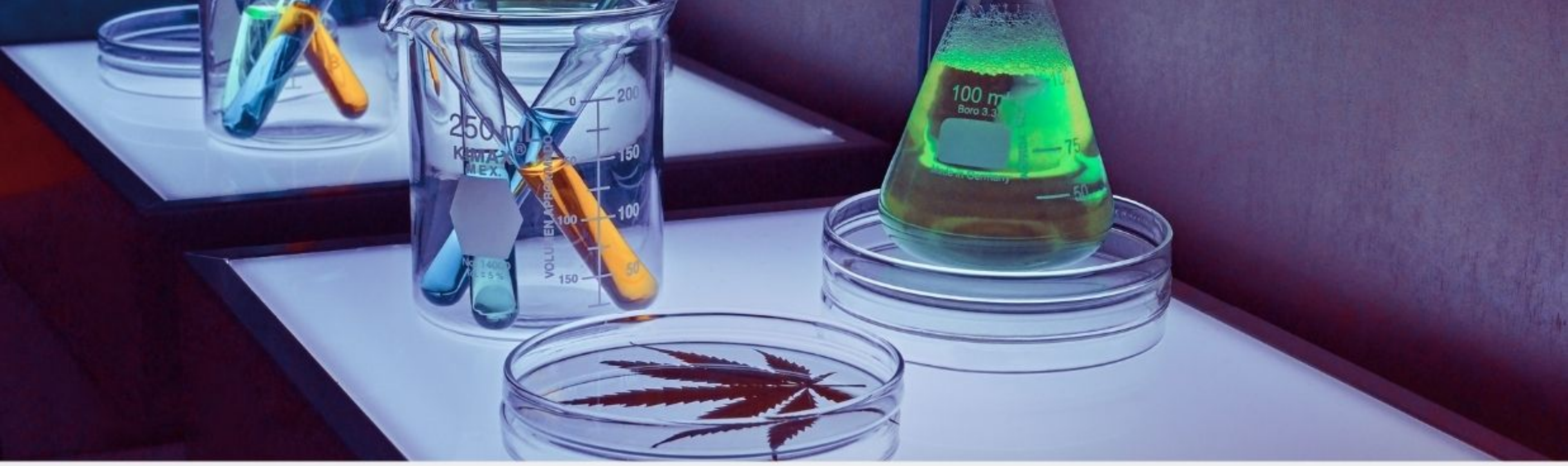

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COMPREHENSIVE REVIEWS IN FOOD SCIENCE AND FOOD SAFETY

Comprehensive REVIEWS in Food Science and Food Safety WILEY

High-pressure processing of fish and shellfish products: Safety, quality, and research prospects

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Abstract

Seafood products have been one of the main drivers behind the popularity of high-pressure processing (HPP) in the food industry owing to a high demand for fresh ready-to-eat seafood products and food safety. This review provides an overview of the advanced knowledge available on the use of HPP for production of wholesome and highly nutritive clean label fish and shellfish products. Out of 653 explored items, 65 articles published during 2016–2021 were used. Analysis of the literature showed that most of the earlier work evaluated the HPP effect on physicochemical and sensorial properties, and limited information is available on nutritional aspects. HPP has several applications in the seafood industry. Application of HPP (400–600 MPa) eliminates common seafood pathogens, such as *Vibrio* and *Listeria* spp., and slows the growth of spoilage microorganisms. Use of cold water as a pressure medium induces minimal changes in sensory and nutritional properties and helps in the development of clean label seafood products. This technology (200–350 MPa) is also useful to shuck oysters, lobsters, crabs, mussels, clams, and scallops to increase recovery of the edible meat. High-pressure helps to preserve organoleptic and functional properties for an extended time during refrigerated storage. Overall, HPP helps seafood manufacturers to maintain a balance between safety, quality, processing efficiency, and regulatory compliance. Further research is required to understand the mechanisms of pressure-induced modifications and clean label strategies to minimize these modifications.

KEYWORDS
high-pressure processing, crustaceans, clean-label foods, mollusks, meat separation, nonthermal processing of fish

1 | INTRODUCTION

The world's appetite for seafood increased significantly in the past decades with total production and consumption reaching an all-time high in 2018. The basic seafood category includes fish, shellfish (mollusks and crustaceans), and other invertebrates. According to the Food and Agriculture Organization (FAO), the average annual growth rate of total food fish consumption increased by 3.1% in the period between 1961 and 2017. About 88% of the 179 million tonnes of total fish production was utilized for direct human consumption. The aquaculture accounted for 52% of this global fish consumption and capture fisheries contributed about 48% (FAO, 2020). The per capita fish consumption is projected to increase in all regions except Africa (3% reduction) and the highest growth rates are projected for Asia (9%), Europe (7%), and Latin America and Oceania (6% each) (FAO, 2020). However, a sizable portion of the fisheries and aquaculture production (35% of the global harvest) is either lost or wasted. The rise in global seafood consumption would benefit from technical developments in terms of processing and logistics and reduction of wastage through optimal utilization of raw material.

Seafood is a rich source of proteins, long-chain omega-3 fats, iodine, vitamin D, and minerals such as iron, calcium, and zinc. Seafood has less connective tissues compared to meat. However, a high water activity, neutral pH, and active autolytic enzymes make it highly susceptible to the development of rancid flavors and undesirable sensory changes during frozen or refrigerated storage (Oliveira et al., 2017). The degradation of seafood quality is associated with endogenous enzymatic autolysis, oxidation, and fast microbial growth (Figure 1). Recently, there has been an increase in the proliferation of pathogens (especially *Vibrio*, *Salmonella*, and *Listeria* spp.) due to increasing temperatures of seas and oceans (WHO, 2020). The consumption of raw or undercooked seafood has been reported to cause several health hazards, necessitating that the industry uses proper cooking and preservation methods to safeguard consumer health and safety. Traditionally, seafood is preserved by methods such as chilling, freezing, drying, salting, smoking, fermentation, and canning, which control water activity, enzymatic and oxidative changes, and microbial activities (Ghaly et al., 2010). However, there are undesirable effects associated with most of these methods. For example, freezing causes denaturation of fish muscle proteins and degrades functional and sensory properties, such as texture, water-holding capacity (WHC), and color, preventing its use as a raw material for further processed products such as minced fish, fish balls, and fish cakes (Alizadeh et al., 2007). Further, fish and muscle products containing high levels of unsaturated fatty acids and pro-oxidants are highly susceptible to development of rancidity during frozen storage (Jamwal et al., 2015; Suh, Kim, Shin, & Ko, 2017). To avoid these undesirable effects, several chemical preservatives are added to these products, such as nitrite (Chiesa et al., 2019), sulfite (Viji et al., 2018), formaldehyde (Jinadasa et al., 2022; Mohanty et al., 2018), salts of ethylenediaminetetraacetic acid (Abdel-Tawwab et al., 2017), nitrofuran derivatives (Wang et al., 2018), and synthetic antioxidants (butylated hydroxyanisole, butylated hydroxytoluene, and tertiary butylhydroxyquinone) (Tsironi et al., 2020). In addition to these undesirable changes in product quality (e.g., lipid oxidation), the traditional methods of preservation add high processing and storage costs (Banerjee & Maheswarappa, 2019; Singh et al., 2014a). Further, consumer preferences for clean label ingredients and natural foods, and concerns about the safety of the chemical additives and preservatives, have prompted the food industry to search for green food preservation technologies (Bhat et al., 2020a, b; Roobab et al., 2022; Singh et al., 2015a, 2015b). Table 1 shows some quality issues in commercial seafood processed using conventional preservation methods.

Several nonthermal and green technologies are available such as pulsed-electric field and ultrasonication (Bhat et al., 2019a, 2019b, 2018a); however, HPP is gaining more popularity than other technologies in the seafood industry. This technology allows production of healthier seafood with a high level of nutritional and functional quality. Pressures applied during treatment usually range from 100 to 600 MPa but pressures as high as 1200 MPa have been used for spore inactivation (sterilization) (Bhat et al., 2021a). HPP results in similar benefits in terms of microbial and enzymatic inactivation as those achieved during thermal treatments and has been projected as the

TABLE 1 Quality issues in seafood processed using conventional preservation methods

Traditional preservation method	Practice	Advantages	Limitations	Reference
Brining	The cleaned fish were placed inside plastic jars of 5 liters and brine (20% salt solution) was added until the fish was completely covered.	Inexpensive when salt is cheap, no energy required, storage at room temperature, reasonable quality, long storage life, and nutritional value is reasonable.	Lots of salt and salty drippings. Higher pH and microbial values compared to dry salting. Excess salting allows growth of salt-tolerant bacteria, causing pink eye spoilage of fish flesh.	(Bonoco & Kurt Kaya, 2018)
Canning	Heat treatment of fish in sealed containers made of tin plates, aluminum cans, or glass, till the product was fully sterilized.	Relatively long shelf-life when stored at ambient temperatures. Produce commercial sterility. The resulting product is fully cooked.	Time-consuming. Improper methods can be dangerous. When jars fail to seal, spoilage will occur. Most species used for canning are caught in large quantities and canneries must store the raw material before it is processed. However, inadequate processing or poor sanitation can result in deadly *Clostridium botulinum* contamination. Canning leads to much loss of vitamin B1, pantothenic acid, vitamin-C, and pteroxylglutamic acid.	(Mills-Gray, 2015)
Chilling/Freezing	Covering the fish with layers of ice or packed separately in polyethylene bags and frozen by the freezer compartment of domestic refrigerators at a temperature of −18°C for different times (0–8 weeks).	Increases shelf-life, high organoleptic quality, and highly attractive for consumers. Simplest, most convenient, and most highly recommended method of fish preservation.	Susceptible to microbial safety problems due to the temperature range since psychrotrophic pathogens can grow and proliferate without an obvious sensorial impact during chilling. Freezing brings about denaturation of flesh. Ice crystals formed during freezing cause mechanical damage to the muscles. Cell walls burst, structure gets deformed, and the flesh loses much of flavor and taste. The flesh also becomes dehydrated and loses texture.	(Sharaf, 2013; Tavares et al., 2021)
Drying	Practiced under the sun, on the sand of the beach, on elevated bamboo rack and on the bamboo covering. It takes about 1 week depending on temperature, humidity, and air velocity, and so on.	Inexpensive; no energy required; little equipment needed; dry and/or airtight storage required; quality and nutritional value reasonable with good storage.	Insect infestation (blow fly and beetle larvae), presence of dirt, filth, pesticide residue, microbial, and fungal growth. Drying reduces weight, nutritive value, and the digestibility of the flesh.	(Rasul et al., 2020)

(Continues)

TABLE 1 (Continued)

Traditional preservation method	Practice	Advantages	Limitations	Reference
Marination/ Fermentation	Fresh or thawed frozen fish was placed in jars filled with the solution of marinating bath containing 6% NaCl and 5% acetic acid. Or prepared by mixing salt with fish and placing it inside large earthen fermentation jars. Left to ferment for 30–90 days with occasional stirring to make sure the salt is spread evenly.	Inexpensive; no energy required, gives typical marinated odor and flavor, limited shelf-life (semiconserve), high-grade raw material, and strict hygiene are prime requirements. Useful strategy for fish waste valorization, improves taste and used to obtain antioxidant compounds and preservatives, and so on.	Lower yield of semimarinades from frozen materials, caused mainly by lower water-holding capacity and higher losses in the form of brine suspension dry mass. Fermentation is an anaerobic process, therefore can occur even when there is insufficient oxygen. If proper hygienic measures are not taken during the processes like washing, guttation, and evisceration, more harm would be done to the preserved material, owing to increase in the bacterial population.	(Laub-Ekgreen et al., 2018; Szymczak, 2011; Marti-Quijal et al., 2020)
Salting/Drying	Salt was poured into plastic jars of 5 liters. The fish were rubbed with dry salt and placed in the jars. The concentration of salt was adjusted to be 20% of the fish's weight. Arranged on a stainless-steel wire rack and dried in a chiller room at 4°C for 20 days.	Inexpensive, no energy required, long storage life, inhibits the decomposing process. Salt-dried salmon has a higher amount of unsaturated fatty acids compared to saturated fatty acids. Cholesterol and tocopherol contents were reduced, while the astaxanthin and lutein contents were increased.	Drying time affect color, the nutritional composition, and the microbiological stability. Using a fish with a lower fat concentration would give better results in salting process. The salt content is too high and sometimes contaminated with heavy metals, excessive consumption of salted fish can increase risk of hypertension.	(Bonoco & Kurt Kaya, 2018; Bunga et al., 2021)
Smoking and smoke drying	Fish being suspended in the kiln over slowly smoldering wood shavings. The fish were left overnight to be naturally infused with smoke. Smoked (hot smoking) and then dried in a traditional barrel kiln.	Inexpensive, little energy required, wood must be present, little equipment needed, widely used to increase the shelf-life due to bactericidal and antioxidant properties of smoke and nutritional value.	Smoked fish and smoked-dried fish produced using barrel kiln and wood fuel are highly contaminated by carcinogenic polycyclic aromatic hydrocarbons. Long processing time, unwanted color, and risk of protein denaturation. Salting combined with smoking results in loss of protein, about 1–5% due to salting and 8–30% due to smoking. Smoking also accelerates rancidity of fat and so reduces digestibility of fat products.	(Adeyeye, 2019; Assogba et al., 2022)

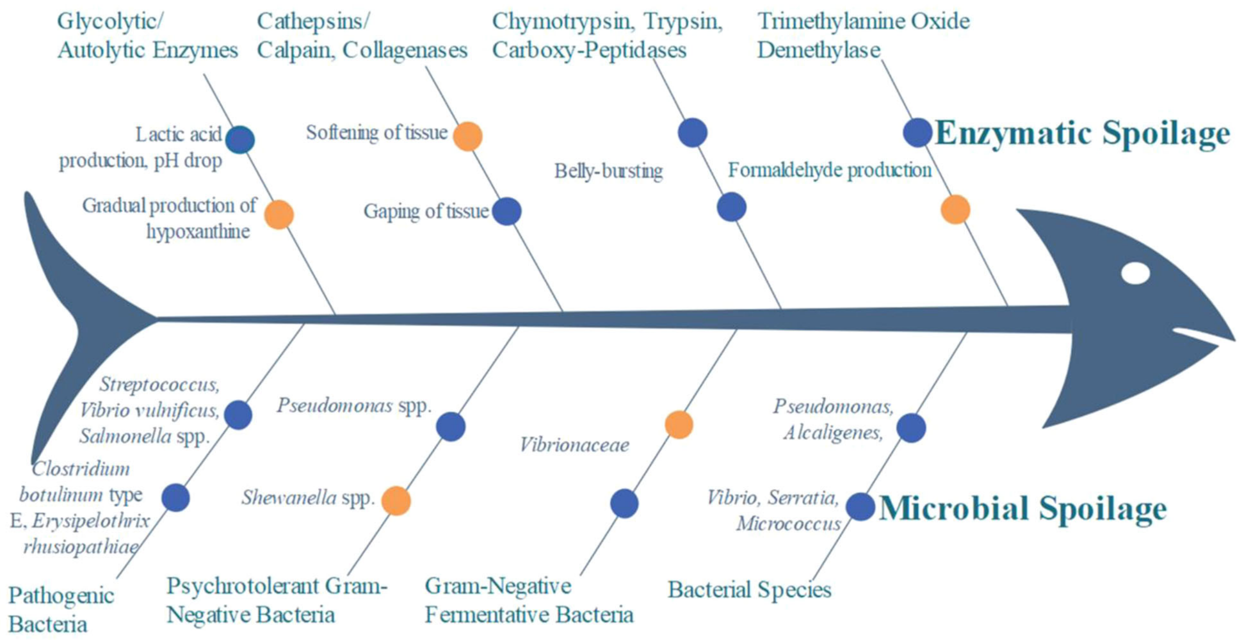

FIGURE 1 Enzymes and microorganisms responsible for fish quality degradation

fastest-growing technology for the next decade in North America and Europe (Kontominas et al., 2021). Using this technology, the packaged products are introduced in a pressure chamber and are generally subjected to hydrostatic pressures up to 600 MPa using a liquid transmitter. The microorganisms present in both solid and liquid foods are inactivated without using heat or additives, making the foods microbiologically stable and generally increasing their shelf-life (Bhat et al., 2021b, 2021c). For instance, HPP extended the shelf-life of freshly picked and cooked crabmeat from 7 to 21–30 days without addition of chemical preservatives (Ye et al., 2021a, 2021b). This stabilizing effect of HPP on microbial quality of seafood extends their shelf-life that allows a greater distribution range, increases profit margins, and reduces product wastage. The HPP eliminates or slows the growth of common seafood pathogens without adversely affecting their sensory and nutritional qualities. HPP is also used to shuck shellfish like oysters, crabs, clams, scallops, mussels, and lobsters, increasing yield up to 25%. HPP treatments (275 MPa for 3 min and 300 MPa for 2 min) have been reported to denature adductor muscle proteins responsible for closing shells in oysters, resulting in 100% release of oyster adductor muscles (Rong, Ling, Huihui, & Qi, 2018). This review examines the studies published on HPP over the period of 2016–2021 and discusses the progress this technology has made in the seafood industry. The prospective applications of this technology in seafood processing and preservation of value-added seafood products are discussed in detail.

2 | REVIEW METHODOLOGY

The paper followed the PRISMA (preferred reporting items for systematic reviews and meta-analyses) framework to review the literature (Page et al., 2021). A scoping technique was adopted to extract the most relevant articles on clean label processing of HPP-treated seafood. A comprehensive literature overview and the most prominent and reliable research databases such as Web of Science, Scopus, Springer Nature, and PubMed were used. The PICO strategy “Population-Patient, Intervention, Comparison-Control, Outcome” with the following definitions was used:

- Population-Patients: Seafood (fresh or frozen produce, fishery, shellfish, mollusks, crustaceans);
- Intervention: HPP alone or in combination/comparison with other technologies;
- Control: Without HPP; and
- Outcomes: Seafood quality and shelf-life.

The PICO strategy was used to answer the research question on the use of HPP for seafood as an alternative to traditional technologies: “Does the use of HPP maintain the quality of seafood products and increase the shelf-life?” The set of keywords: (“high-pressure processing” OR “high hydrostatic pressure” OR “HPP” OR “HHP”) AND (“fish” OR “seafood”) AND (“quality” OR “safety” OR “shelf-life”) were used in each database search to collect the relevant literature. Each database filter confirmed the predefined quality standard and inclusion and exclusion measures (Figure 2). Initially, 653 research articles written in English from 1993 to 2021 were found. The language selected was "only English" and was limited to "research articles only." The selected articles were segregated into results, abstracts, and conclusions sections. Moreover, cited references in the literature were also explored. The search documents were reviewed several times and irrelevant articles were excluded to maximize the desired results. The final literature search resulted in 65 documents (2016–2021) that were considered for the review, which included fish (49%), shellfish, crustaceans and mollusks (51%), the latter were further categorized into oysters, shrimp and prawns, squid, crabs, lobster, clams, and mussels. The information included publication year, first author name, title, abstract, seafood type, processing/preservation method, HPP conditions or experimental setup, and results.

3 | RESULTS AND DISCUSSION

Figure 3 shows the ongoing citation trend of HPP during the last 6 years and includes scientific publications on seafood research (identified from the Scopus database). The majority of the articles were related to various applications of HPP for most types of seafood with a special focus on pressure-assisted freezing and thawing, and the combinations of different nonthermal treatments for shelf-life extension. Extensive research has been done around fish gelation aiming at various textural improvements (HPP-treatments induce a smooth and glassier appearance compared to heat-induced gels). Substantial evidence in the literature dating back to the 1970s shows HPP as a clean-label option for several foods including seafood.

3.1 | Historical evolution of HPP and developments in seafood processing

While the concept of using pressure for food applications dates back to 1899, most of the research on HPP received an impetus during the last 20 years. Ohshima et al. (1993) and Lanier (1998) were the pioneers and studied the effects of HPP on fish but did not cover other seafood. In 2000, Matser, Stegeman, Kals, & Bartels (2000) studied the effects of HPP (150–200 MPa for 5 min) on color and texture of several seafood species including pollack (*Pollachius virens*), mackerel (*Scomber scombrus*), tuna (*Thunnus thynnus*), cod (*Gadus morhua*), salmon trout (*Salmon trutta*), carp (*Cyprinus carpio*), plaice (*Pleuronectus platessa*), octopus, and anglerfish (*Lophius piscatorius*). All the pressurized samples resulted in a cooked appearance except the octopus that maintained a raw appearance up to 400–800 MPa. Until 2003, HPP technology was best known for its lethal effects on microorganisms, ensuring food safety and quality. However, unwanted side effects such as changes in texture and color were also observed. Jiménez-Colmenero and Borderia (2003) discussed the problems and shortcomings associated with HPP treatments on myosystems and provided a brief analysis of pressurized products. The effects of HPP depend on both applied pressure/temperature levels and the preparation of the raw material for homogenous pressurization. For thermolabile products, like muscle-based foods, there is a need for more specific experimental designs to ensure safety and quality of the finished products. HPP has been evaluated for several applications for shellfish processing, such as shucking or opening of shellfish, inactivation of microorganisms, and maintaining sensory and nutritional properties (Murchie et al., 2005).

From 2005–2010, the impact of HPP on physicochemical properties of different fish species were evaluated (Chéret, Delbarre-Ladrat, Verrez-Bagnis, & De Lamballerie, 2007; Sequeira-Munoz, Chevalier, LeBail, Ramaswamy, & Simpson, 2006; Yagiz, Kristinsson, Balaban, & Marshall, 2007). Several studies examined HPP-based inactivation of proteolytic enzymes (Chéret, Delbarre-Ladrat, De Allerie-Anton, & Verrez-Bagnis, 2005) and pathogens (Basaran-Akgul et al., 2010; Collins et al., 2005; Fletcher, Youssef, & Gupta, 2008; Ritz, Jugiau, Federighi, Chapleau, & De Lamballerie, 2008) in seafood. Studies also explored the advantages of HPP for shelf-life extension (Gou, Lee, & Ahn, 2010) and inactivation of biogenic amines (Gou, Xu, Choi, Lee, & Ahn, 2010) in seafood. During the last decade, studies have determined the HPP-induced physicochemical changes in Atlantic salmon muscle (Ojagh, Núñez-Flores, López-Caballero, Montero, & Gómez-Guillén, 2011), herring (*Clupea harengus*), and haddock (*Melanogrammus aeglefinus*) (Karim et al., 2011), horse mackerel (*Trachurus trachurus*) (Pazos, Méndez, Vázquez, & Aubourg, 2015; Torres, Saraiva, Guerra-Rodríguez, Aubourg, & Vázquez, 2014), sea bass (*Dicentrarchus labrax*) (Teixeira et al., 2014), Atlantic mackerel (Fidalgo, Saraiva, Aubourg, Vázquez, & Torres, 2014; Pazos, Méndez, Fidalgo, et al., 2015), hilsa (*Tenualosa ilisha*) (Chouhan, Kaur, & Rao, 2015), mild-smoked rainbow trout (*Oncorhynchus mykiss*) and fresh European catfish (*Silurus glanis*) (Mengden, Röhner, Sudhaus, & Klein, 2015), and farm-raised abalone (*Haliotis rufescens*) (Hughes, Greenberg, Yang, & Skonberg, 2015). Good overviews of the earlier work were prepared by Truong, Buckow, Nguyen, and Stathopoulos (2016) and Oliveira et al. (2017) and covered the effects on physicochemical, microbial, and sensory qualities of the preserved seafood.

Recently, HPP has been evaluated for its role in reducing allergenicity associated with seafood proteins. With

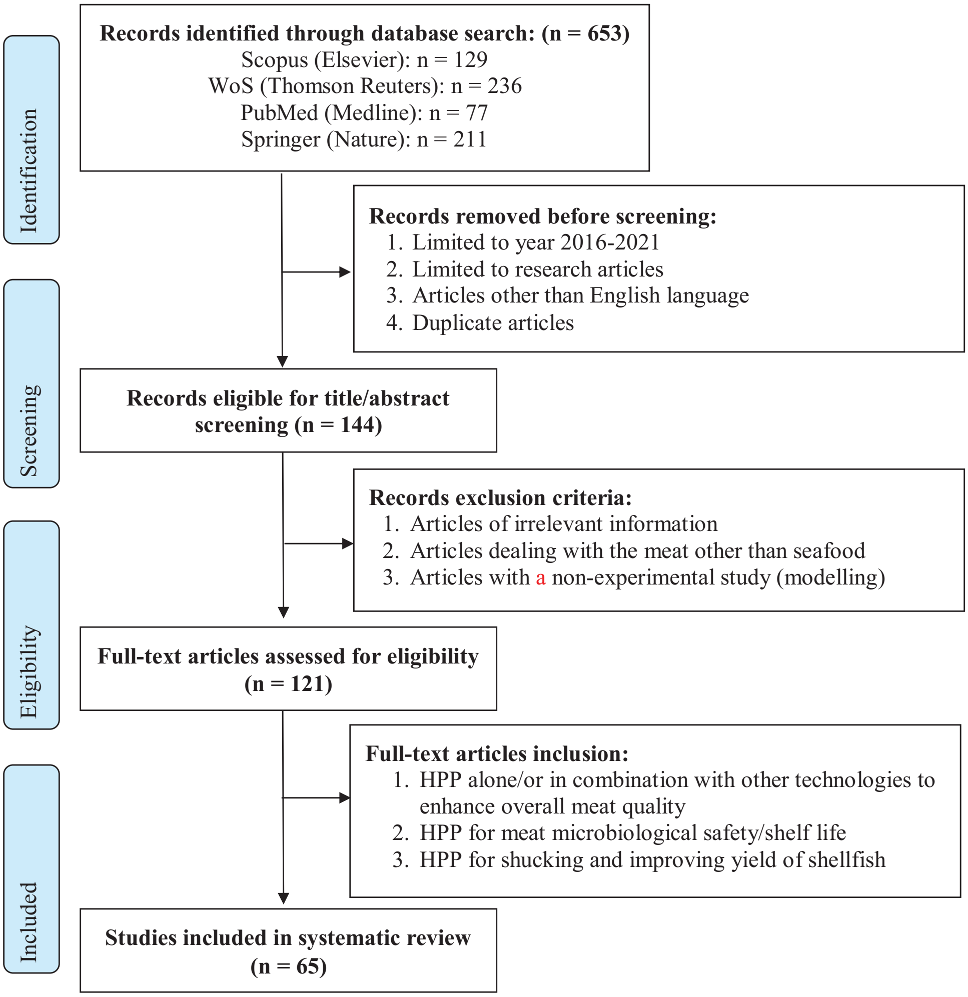

FIGURE 2 PRISMA (preferred reporting items for systematic reviews and meta-analyses) framework

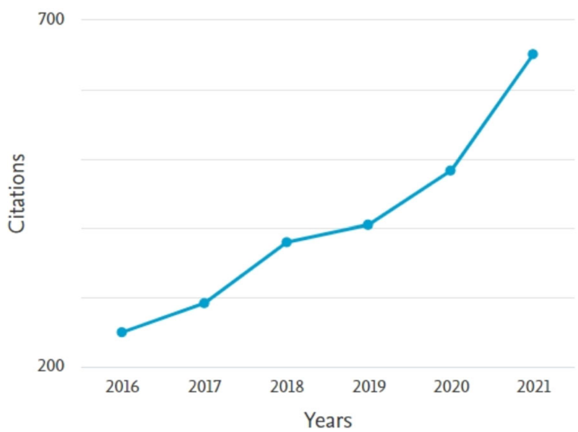

FIGURE 3 Citation overview (identified from the Scopus database)

symptoms such as angioedema, gastrointestinal distress, asthma, rhinitis, and anaphylaxis, seafood allergies have been shown to be the most dangerous food allergies (Tsabouri et al., 2012). Studies have evaluated the effectiveness of HPP treatments for reducing the allergenicity and improving the digestibility of seafood proteins, such as squid (Zhang, Deng, & Zhao, 2017) and cod proteins (Zhang, Bi, Wang, Cheng, & Chen, 2019). HPP treatments (200–600 MPa for 20 min) have been reported to reduce the allergenic potential of seafood proteins by inducing structural (secondary and tertiary) modifications, thereby affecting the epitopes and binding capacities of immunoglobulins E and G (Zhang et al., 2017). The inactivation of tropomyosin (a major allergen found in crustaceans) was achieved in 10 min at 500 MPa (55°C) by Long, Yang, Wang, Hu, and Chen (2015). Zhang et al. (2019) used HPP treatment (200 MPa for 20 min at 25°C) to reduce allergenicity of cod proteins. The processing-induced shear effects caused denaturation of the proteins and liberation of free amino acids and peptides. The treatment also increased the solubilization and oxidation of the proteins.

HPP has been used in combination with other technologies to induce some synergestic and useful effects. Hurdle approaches combining HPP (600 MPa for 10 min) with annatto and bixin (the main carotenoid of annatto seeds) have been reported (Figueirêdo, Bragagnolo, Skibsted, & Orlien, 2015) to inhibit oxidation of cholesterol in chilled minced herring and minced Atlantic mackerel stored for 2 weeks. The effects of HPP (500 Mpa for 5 min at 4°C), microwave (900 W for 1 min), marination, and vacuum packaging were used in combination for Atlantic mackerel, a low-value species with a high nutritional value. Results showed that the effect of the combined technologies helped preserve the MUFA and PUFA contents of the samples and resulted in higher nutritional quality indices (Fiore et al., 2019).

HPP treatments (450 and 600 MPa for 1–5 min) were used to produce protein-denatured tuna loins with high water-holding capacity and the ability to retain water, resulting in a product with higher yield and moisture content compared to steam-cooked loins (Jiranuntakul et al., 2018). Therefore, HPP treatments higher than 450 MPa have a potential to replace the energy-intensive steam precooking step, which is traditionally required in the canned tuna production process. The combined effect of HPP (210–400 MPa for 5 min at 110°C) and sous-vide cooking has been reported to extend the shelf-life of salmon loins up to 6 days (Picouet, Cofan-Carbo, Vilaseca, Ballbè, & Castells, 2011).

Another hurdle approach involved use of HPP (300 MPa at 20°C for 15 min) along with gelatin-based bioactive edible films to extend the shelf-life of cold-smoked sardines (*S. pilchardus*). The films were incorporated with an extract of oregano (*Origanum vulgare*), rosemary (*Rosmarinus officinalis*), or chitosan, and effectively reduced oxidation and microbial growth (Gómez-Estaca, Montero, Giménez, & Gómez-Guillén, 2007). The combined use of HPP (300 MPa for 10 min at 5 or 40°C) and fish gelatin–lignin films improved the quality of salmon fillets in ready-to-eat (RTE) or semiprepared dishes compared to conventional thermal treatment (90°C for 10 min) (Ojagh et al., 2011). HPP combined with edible chitosan/clove oil-based films were successfully used for microbial inactivation of trout fillets (Albertos et al., 2015). It is important to mention that the use of edible films is an emerging green technology for preservation of muscle foods and is currently being studied (Sharma et al., 2021a, 2021b; Kalem et al., 2018a, 2018b).

Recently, Kumar, Rao, Purohit, and Kumar (2019) reported that HPP at a low pressure (100–300 MPa at 30°C for 10 min) improved the freshness and microbiological quality (2 log units reduction in the total plate count values) of acid pretreated (0.01% potassium sorbate solution for 5 min) hilsa fillets. The combined effect of HPP and acid pretreatment on hilsa fillets resulted in the highest antimicrobial activity, which was observed by the reduction of the total volatile basic nitrogen (TVB-N) and trimethylamine-nitrogen (TMA-N) values (strongly correlated to microbial activity). However, higher pressure levels (300 MPa) were reported to induce negative effects on important biochemical and sensory properties, such as the increased oxidation and hardness values (Kumar et al., 2019). Increasing the pressure levels and acid solution concentration also resulted in acid hydrolysis of the fillets and increased free fatty acid contents (Kumar et al., 2019). The increase of lipid oxidation at 300 MPa was attributed to declining electrostatic, Van der Waals, hydrogen bond, and hydrophobic forces between myofibrillar proteins (Kumar et al., 2019). Lipid oxidation is an important factor that determines the acceptance of the muscle foods (Bhat et al., 2019c, 2018b; Mahajan et al., 2016). Combined use of HPP and natural antioxidants, such as plant extracts and phytochemicals, may help reduce the lipid oxidation of muscle foods (Dua et al., 2015a, 2015b). Studies have successfully used plant extracts to improve the lipid stability of muscle foods through direct addition to food matrices or to packaging films (Kalem et al., 2017; Kaur et al., 2021, 2015; Singh et al., 2014b).

4 | APPLICATIONS FOR RAW AND FROZEN FISH AND FISH PRODUCTS

Fish freshness degradation is a major problem for the seafood industry. Loss in fish freshness is directly correlated with quality defects, such as protein denaturation, texture loss, and off-odor development. Research has been focused on providing solutions to this problem using HPP. The commercial shelf-life of fish products could be extended while retaining their unique odor and aroma using appropriate HPP conditions. Figure 4 shows the advantages of application of HPP to seafood products. HPP inactivates microorganisms and reduces autolytic enzymes activities and formation of biogenic amines associated with seafood (Matějková, Křížek, Vácha, & Dadáková, 2013). For instance, HPP treatments of half-dried fish (*Gwamegi*, stored for 28 days) showed a decrease of cadaverine and spermidine while showing increased tyramine and spermine levels (Doeun, Shin, & Chung, 2016). Accumulation of the biogenic amines is a good indicator of fish spoilage.

4.1 | Quality of raw and processed fish

Several studies have used HPP to improve the storage quality of fish and seafood. Nagarajarao (2016) used a low-intensity treatment (220 MPa for 30 min) for processing of tuna muscle. The treatment was effective in prolonging the shelf-life and decreasing the proteolytic activities, texture degradation, and formation of TVB-N

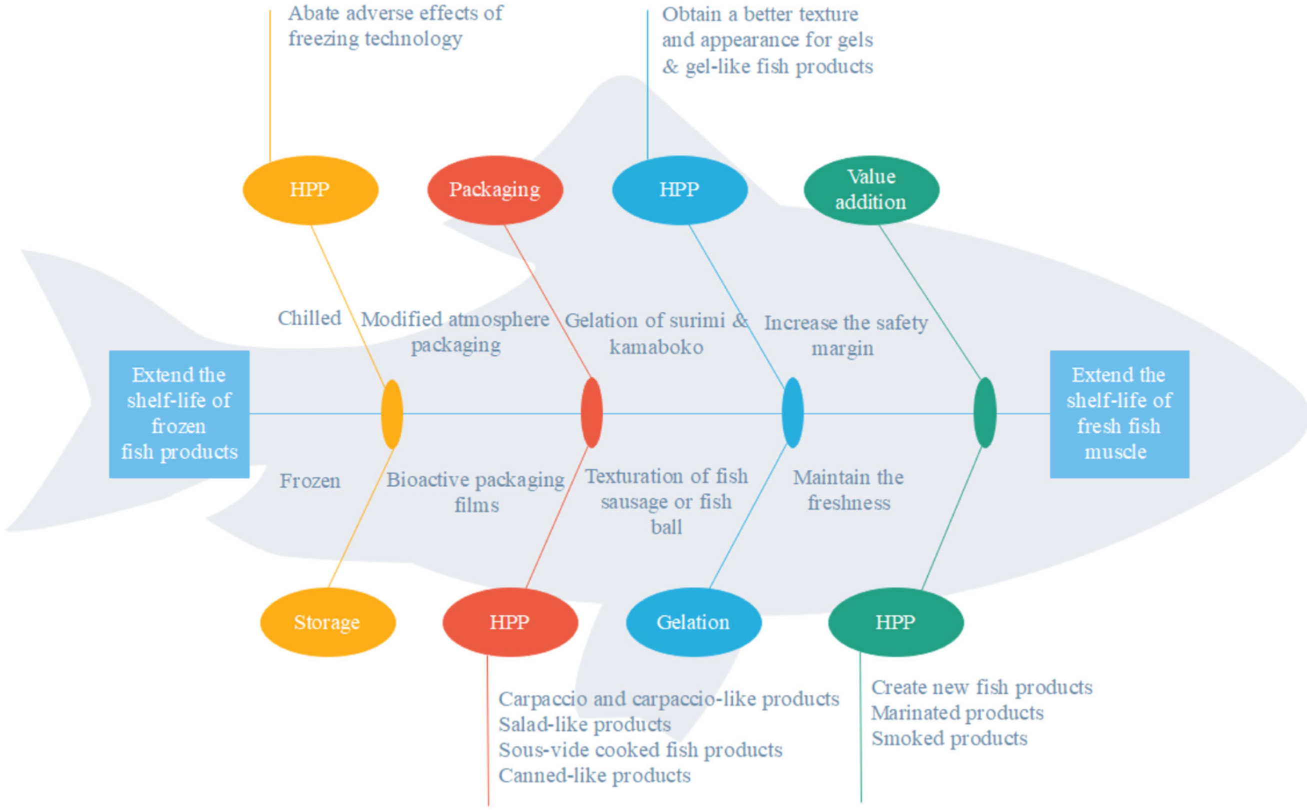

FIGURE 4 Possible applications of HPP for fishery products

and histamines. Similarly, low-intensity HPP (200–300 MPa) for a shorter treatment time (1 or 3 min) also increased the shelf-life of herring and haddock (*M. aeglefinus*) to 13 days on ice compared to control samples which spoiled after 4 days (Karim et al., 2011). HPP-treatment (150 and 450 MPa for 2 min) of European hake (*Merluccius merluccius*) resulted in an increase of luminosity (a color parameter), changed texture properties (increased hardness, adhesiveness, and springiness), and showed better organoleptic properties after transformation into fishcakes (Pita-Calvo et al., 2018a). These effects have also been observed in other studies, confirming the effectiveness of combining HPP and frozen storage for improving the sensory and functional qualities of fish and fish products (Fidalgo etal., 2014; Torres et al., 2014). However, HPP treatments >250 MPa for 3 min have been reported to increase the drip loss and also cause a loss in visual freshness of barramundi (*Lates calcarifer*) during frozen storage (Truong et al., 2016). The results suggested that the efficiency of HPP was dependent on the fish species, processing, and storage conditions. The main results of the research studies done in the fish sector from 2016 to 2021 are summarized in Table 2.

HPP as a pretreatment has been reported to affect the activity of endogenous enzymes. Recently, the inactivation of the pro-oxidative enzymes was observed in lean and fatty fish using HPP as a pretreatment (200–300 MPa) before freezing (Cropotova et al., 2020). Truong et al. (2016) observed an increased hardness and delayed lipid oxidation in barramundi muscle pretreated with HPP (150–200 MPa for 3 min) before frozen storage at −18°C for 18 weeks. While pretreatment at 150–450 MPa (before freezing) maintained expressible water in European hake at adequate levels for up to 6 months (Pita-Calvo et al., 2018a), treatments at 250 and 350 MPa for 10 min improved texture, prevented lipid hydrolysis, retained lower viable counts, and prolonged the shelf-life of raw hilsa fillets to 25 days compared to thermally treated samples (75°C for 5 min), showing 10 days of shelf-life (Chouhan et al., 2015). While HPP at 500 MPa increased the activity of cathepsins in fresh sea bass (*D. labrax*) fillets (Chéret, Delbarre-Ladrat, De Allerie-Anton, & Verrez-Bagnis, 2005), treatment at 400 MPa caused disruption of lysosomes and induced denaturation, aggregation, and fragmentation of sarcoplasmic proteins. This behavior could be related to the activity reduction of degradative enzymes such as cathepsins, acid phosphatase, lipases, and calpains, observed in fresh sea bass fillets (Teixeira et al., 2013). Qiu, Xia, and Jiang (2014) studied the effect of HPP on quality of silver carp (*Hypophthalmichthys molitrix*) and reported damage to the secondary structures like α-helices treated at 400 MPa for 10 min. The conformational stability of myofibrils was

TABLE 2 Research and developments in HPP in fish sector during 2016–2021

Sample	Experiment	Compared/ Combined	Findings	Reference
Albacore (*Thunnus alalunga*)	200 MPa for 0–6 min	Frozen and stored (−20°C) for up to 12 months. Thawed (4°C; 24 h)	200 MPa for 6 min minimized thawing loss inherent to freezing and frozen storage and decreased TBARS (53.9%) for the control. It resulted in color changes (higher *L**, *b**, and Δ*E* values) and texture (higher adhesiveness and springiness) and decreased the salt-soluble protein content	(Cartagena, Puértolas, & Martínez de Marañón, 2020a;b)
Albacore (*T. alalunga*) fresh steaks	0.1-500 MPa for 2 min	Stored at 4°C for 24 h	250 MPa decreased weight loss by 50.1% compared to the controls but produced minor color changes. 500 MPa provoked the maximum reduction of weight loss for the controls (59%), although it caused marked differences in all quality parameters.	(Cartagena, Puértolas, & Martínez de Marañón, 2019)
Atlantic chub mackerel (*Scomber colias*)	200–600 MPa for 2 min	Freezing (−30°C for 48 h), frozen storage (−18°C for 6 months), canning, and canned storage (3 months at 20°C)	HPP decreased potassium, magnesium, calcium, barium, manganese, iron, lead, and phosphorus contents in fish canned after the freezing step; HPP provoked additional decreases in calcium, barium, and manganese levels in samples corresponding to 6-month frozen storage. HPP increased cadmium, sulfur, and selenium contents in all canned samples. A marked inhibitory effect on free fatty acid content, higher average polyene values, increased peroxides and fluorescent compounds contents were observed.	(Prego et al., 2020;2021)
Barramundi (*Lates calcarifer*)	150–300 MPa at 11°C for 3 min.	Before and after immediate blast freezing and storage at -18°C for up to 18 weeks.	200 MPa increased hardness and delayed lipid oxidation during frozen storage (for up to 18 weeks) without resulting in a cooked appearance. 250 MPa for 3 min resulted in the loss of visual freshness and increased drip loss.	(Truong et al., 2016)
Cod (*Gadus morhua*)	200 MPa/min at 25°C for 20 min.	Compared to control (25 °C for 20 min), baked and steamed (100 °C for 20 min).	Reduced allergenicity, avoided protein oxidation, and improved the digestibility.	(Zhang et al., 2019)
Cod (*G. morhua*) and salmon (*Salmo salar*), frozen and re-thawed	150–450 MPa for 5 min at 20°C.		HPP allows the shelf-life of the raw product at 4°C to be increased with minimal changes in the organoleptic characteristics and to enable crude consumption.	(Arnaud, de Lamballerie, & Pottier, 2018)
Cod and salmon meat (washed)	193 MPa at subzero temperature - 20°C (without freezing of water).		Myofibril proteins solubility increased at pressure above 60 MPa. The salmon and cod gels pressurized at 193 MPa and −20°C then heated were much harder than only pressurized or heated gels.	(Malinowska-Pańczyk, 2017)
European hake (*Merluccius merluccius*)	150–450 MPa.	Frozen stored at −21°C for 12 months.	150 MPa allowed adequate expressible water for raw muscle up to 2.5 months of frozen storage time. A pressure level of 300 MPa and 5 months of frozen storage showed adhesiveness values for raw muscle like that of nontreated samples.	(Pita-Calvo et al., 2018a;b)

(Continues)

TABLE 2 (Continued)

Sample	Experiment	Compared/ Combined	Findings	Reference
	150–450 MPa for 2 min.	Frozen (up to 5 months at −10°C).	Degradation after applying a pressure ≥ 430 MPa was observed for phosphoglycerate mutase-1, enolase, creatine kinase, fructose bisphosphate aldolase, triose phosphate isomerase, and nucleoside diphosphate kinase; contrary, electrophoretic bands assigned to tropomyosin, glyceraldehyde-3-phosphate dehydrogenase, and beta parvalbumin increased their intensity.	(Carrera, Fidalgo, Saraiva, & Aubourg, 2018)
	150 MPa for 2 min.	Frozen (−10, −18 and −30°C).	A pressure level of 150 MPa inhibited the formation of degradative molecules such as DMA, FA, TMA, and FFA during the frozen storage at −18°C (maximum recommended) and −10°C. Lowering the storage temperature showed to be more effective than the current HPP.	(Carrera, Fidalgo, Vázquez, Saraiva, & Aubourg, 2020)
European sea bass (*Dicentrarchus labrax*)	600 MPa for 5 min at 25°C.		HPP led to more than a 5-log reduction in initial TVC and altered the bacterial microbiome, reducing the proportion of food spoilage genera. HPP increased lightness and hardness with fibers appearing fused and more compact in comparison to the unprocessed control. Sensory evaluation indicated a shelf-life of 11 days for untreated control samples and 2 months for the HPP-treated fillets.	(Tsironi et al., 2019)
Fish gels	250 MPa for 12 min and a setting condition of 25°C for 30 min.		The synergistic effect of HPP and MTGase enhanced the textural and functional properties of fish gels when compared with conventional cooking. It enhanced conformational stability and produce stronger networks through the formation of nonsulfide bonds between proteins and setting reinforced these networks.	(Kunnath et al., 2020)
Fish ham prepared with farmed meager (*Argyrosomus regius*)	350 and 500 MPa at 30°C.		Good textural properties and reduce the MTGase (2.5 g/kg). WHC and folding properties of hams were not affected by HPP, compared with heat-processed hams. Whiteness was lower in HPP hams, and values increased with pressure level.	(Ribeiro et al., 2018)
Fish salad with mayonnaise	450 or 600 MPa for 5 min.	Stored for 26 days at 5 and 10°C.	The salad contained diced smoked trout fish, mayonnaise, and different kinds of spices. At both storage temperatures, the HPP-treated samples showed enhanced safety and increased shelf-life up to 3 weeks.	(Salamon et al., 2016)
Herring (*Clupea harengus*)	100–500 MPa for 5 min.	Vacuum-packed stored at 4°C up to 21 days.	500 MPa delayed the growth of *Photobacterium phosphoreum* and *Morganella psychrotolerans* until the 12th and 7th days, respectively, as compared to the controls. 300 MPa and above could help the industry for commercial production of microbiological-free fish and fish products.	(Ucak, Gokoglu, Toepfl, & Galanakis, 2018)
Haddock (*Melanogrammus aeglefinus*) and herring (*C. harengus*)	200–300 MPa for 1–3 min.	Stored for 14 days.	Effectively slows the conversion of inosine to hypoxanthine, delaying the undesirable flavor that develops in spoiling fish.	(Karim et al., 2019)

(Continues)

TABLE 2 (Continued)

Sample	Experiment	Compared/ Combined	Findings	Reference
Haddock and mackerel mince (frozen storage, and fishcakes)	200 and 300 MPa.	Frozen storage at −40°C.	Fish minces become slightly lighter and softer at 200 MPa due to denaturation of proteins, thus enhancing sensory properties of fishcakes prepared thereof.	(Cropotova et al., 2020)
Hilsa (*Tenualosa ilisha*) curry RTE	300–500 MPa for 5–15 min at 40–60°C.	Compared with heating at 75°C for 5 min.	500 MPa for 5 min at 50°C found to be the most suitable treatment to retain the physicochemical parameters and reduce the microbial load. All the HPP showed retention of quality attributes in terms of physical, chemical, and microbiological characteristics of ready-to-eat hilsa curry.	(Singha, Swami Hulle, Deb, & Rao, 2020)
Mackerel fillets	100–500 MPa for 2–5 min.		A significant reduction in TVC and H_2S-producing bacteria was detected at 300 MPa for 5 min and 500 MPa for 2- or 5-min. Lightness (L^*) increased and redness (a^*) decreased at the highest treatment intensities. HPP significantly decreased levels of EPA, PUFA, HUFA, DHA, CLA and increased MUFAs and SFA.	(de Alba et al., 2019)
	500 MPa for 5 min at 4°C.	Combined with marinating, vacuum packaging (98°C for 1 min), and microwave (900 W of power for 1 min)	Preserved more monounsaturated fatty acids and polyunsaturated fatty acids, reducing the atherogenic and thrombogenic indexes.	(Fiore et al., 2019)
Tuna (Skipjack, *Katsuwonus pelamis*)	150–600 MPa for 1–5 min.	Compared with steam cooking for 10 min.	Protein denaturation in HPP-treated loins increased with increasing pressure level, but these loins retained between 1.1% and 2.4% more water than steam-cooked loins. WHC decreased from 57% to 44% at 600 MPa. Steam cooking and HPP at 150, 300, 450, and 600 MPa decreased the total aerobic counts by 4.75, 0.12, 1.20, 4.69, and 6.08 log CFU/g, respectively.	(Jiranuntakul et al., 2018)
Tilapia (*Oreochromis niloticus*)	100–400 MPa for 1–3 min.	Stored at 5°C for 1 week.	Color parameters L^* and whiteness at 300 and 400 MPa were significantly higher than control samples. Psychrotrophic microorganisms were significantly reduced at 300 and 400 MPa. A pressure level of 200 MPa was preferred by assessors on sensory evaluation of fillet's appearance. 400 MPa for 3 min was efficient for preservation but the color modifications may cause difficulty in its commercialization.	(Suemitsu & Cristianini, 2019)
Red tilapia (*O. niloticus*), black tilapia (*Oreochromis mossambicus*), grouper (*Epinephelus areolatus*), and threadfin bream (*Nemipterus tambuloides*)	250 MPa for 10 min.	Pretreatment either in citric acid solution or during thermal extraction.	Increase in the yield of gelatin and the concentration of gelatin extract. Pretreatment time was reduced.	(Jaswir, Yusof, Jamal, & Jami, 2017)

(Continues)

TABLE 2 (Continued)

Sample	Experiment	Compared/ Combined	Findings	Reference
Rainbow trout fish	400 MPa for 3 min, 600 MPa for 6 min, and 100 MPa for 3 min, 200 MPa for 6 min.		The use of lower pressure levels is beneficial to the structural quality preservation of the fillets but less effective concerning the microbial inactivation.	(Cioca, Dan, Lupău, Colobatiu, & Mihaiu, 2018)
Salmon (*Salmo salar*), cod (*G. morhua*), and mackerel (*Scomber scombrus*)	200 and 500 MPa for 2 min.	Stored for 26 days.	200 MPa did not have any effect on the oxidation level in salmon during the storage period while this was observed for cod. The TBARS level in mackerel was high, independent of pressure treatment. For salmon both control and 200 MPa samples showed a decrease in acid phosphatase at day 11 compared with day 0.	(Rode & Hovda, 2016)
Salmon (*Oncorhynchus nerka*), dry-cured cold-smoked	450 MPa for 2 min (N450) and 600 MPa (N600).	Nisin (10 μg/g)	*Listeria. innocua* in N450 and N600-treated samples reduced 2.63 and 3.99 log CFU/g, respectively, immediately after HPP and spoilage growth were not observed during 36-day storage at 4°C.	(Lebow et al., 2017)
Sardine (*Sardina pilchardus*)	125–200 MPa for 0 min.	Frozen (−18°C for 9 months).	Inhibition of lipid hydrolysis development (lower free fatty acid formation and lipase activity). It caused only minor modifications in biochemical indicators of deterioration throughout the subsequent frozen storage of samples for up to 9 months.	(Méndez et al., 2017)
Swai-fish-based emulsions containing mixed fermented soybeans	600 MPa for 20 min at 25°C.	Stabilized by either konjac flour or CMC (0.1–0.3%). Compared with heating (72°C for 30 min).	Both hydrocolloids enabled the improvement of the color of fish emulsions. HPP gave rise to products with greater WHC and higher sensorial scores than the thermal treatments. Thermal treatments increased the gel strength and elasticity of the products more than pressurization. Both processes equally inhibited bacterial cells and some spores of *Bacillus subtilis*.	(Techarang et al., 2019)

Abbreviations: TBARS: Thiobarbituric acid reactive substances, WHC: Water holding capacity, TMA: Trimethylamine, DMA: Dimethylamine, FA: formaldehyde, FFA: Free fatty acids, TVC: Total viable counts, EPA: Eicosapentaenoic acid, PUFA: Polyunsaturated fatty acids, HUFA: Highly unsaturated fatty acids, DHA: Docosahexaenoic acid, CLA: Conjugated linoleic acids, MUFA: Monounsaturated fatty acids, SFA: Saturated fatty acid, RTE: Ready-to-Eat, MTGase: Microbial transglutaminase, CMC: carboxymethylcellulose

reduced at >200 MPa and the pressure levels >300 MPa increased sulfhydryl content, hydrophobic regions, and free amino acids (Bhat et al., 2021d).

HPP has shown potential industrial applications involving the freezing and thawing processes. The potential of HPP (500 MPa for 2 min or 300–500 MPa for 5 min) to improve the quality of mackerel by controlling the spoilage and enhancing the shelf-life by reducing microbial growth has been evaluated as compared to frozen fish (de Alba et al., 2019). HPP pretreatment (200 MPa for 6 min) was reported to minimize the thawing loss of albacore tuna samples after freezing and frozen storage. The treatment decreased the TBARS values and affected the color and texture (Cartagena et al., 2020a). No differences were observed in color and texture between HPP-treated and control samples after cooking (Cartagena et al., 2020b). The authors (Cartagena et al., 2020a,b) concluded that a pressure level of 200 MPa would be an option for reducing thawing loss while minimizing changes in the quality as compared to a 600 MPa pretreatment, which led to sharp changes in color (higher L^* and b^* values) and texture (higher hardness and chewiness).

HPP inhibited lipid hydrolysis and oxidation, and reduced breakdown of trimethylamine oxide during frozen storage of fatty and lean fish species (Vázquez, Fidalgo, Saraiva, & Aubourg, 2018). A marked inhibitory effect of HPP was observed on free fatty acid content of canned Atlantic chub mackerel and the effect showed an increase with applied pressure (Prego, Fidalgo, Saraiva, Vázquez, & Aubourg, 2021). Cropotova et al. (2020) applied HPP (200 and 300 MPa for 5 min) to lean and fatty fish species before freezing for reduction of microbial growth. HPP pretreatment of lean haddock and fatty Atlantic mackerel minces was shown to be a clean label approach to control microbial growth. Treatment increased the fluid drain and protein carbonylation while decreasing the protein solubility of frozen fish mince. Samples treated at 200 MPa showed lighter color, softer texture (due to the denatured proteins), and enhanced sensory quality of fishcakes as compared to control samples (Cropotova et al., 2020). The degree of lipid oxidation decreased with increased pressure, possibly due to the inactivation of pro-oxidative endogenous enzymes (Cropotova et al., 2020). Other studies have also reported a similar decrease in the lipid oxidation of fish meat treated at 150–200 MPa for 3 min before freezing at −18°C without any change in muscle appearance compared to control samples (Truong et al., 2016).

HPP affected the mineral content of the fish and seafood products. Marine organisms accumulate minerals from the diet and deposit them in their skeletal tissues and organs in the form of chlorides, sulfates, or organic salts such as citrates, lactates, or pyruvates. The majority of these accumulated macroelements and toxic trace elements in commercially available fish and fish products can present some health risks to the consumers. Prego, Vázquez, Cobelo-García, and Aubourg (2020) evaluated the effect of HPP treatment (200–600 MPa for 2 min) on the mineral content of brine-canned Atlantic chub mackerel during freezing (−30°C, 48 h) and frozen storage (−18°C, 6 months). The treatment-induced protein structural changes led to a decrease of WHC that resulted in a substantial liquid loss, thereby affecting the mineral retention of the muscle. The impact of HPP on overall quality of fish is schematically shown in Figure 5.

HPP treatments have significant benefits in terms of microbial stability and sensory quality. HPP treatment (600 MPa for 5 min) slowed the recovery of microbial counts (<5 log CFU/g) in RTE fish salad (vacuum packaged smoked fish with mayonnaise and spices) during 26 days of refrigerated storage (5°C) and temperature abusive conditions (10°C) (Salamon et al., 2016). HPP-treated samples remained acceptable to sensory panelists even after 21 days regardless of the storage temperature (Salamon et al., 2016). Lebow et al. (2017) evaluated the sensory and microbiological quality of cold smoked salmon after HPP and nicin (a bacteriocin) treatments. Low-temperature HPP significantly increased lightness (L^*) and decreased the peelability (the ability to separate individual slices), leading to a decrease of consumer preference for salmon. However, the combined treatment of Nisin (10 μg/g) and HPP (600 MPa for 120 s) within an ice slurry was effective in controlling *L. innocua* (decreasing it 4 log CFU/g) and the samples were highly preferred by the panelists compared to control. Similarly, HPP treatments at 150–300 MPa improved the quality (textural properties) of frozen cooked hake, which were comparable to freshly cooked ones (Pita-Calvo et al., 2018b).

4.2 | HPP-mediated gelation of fish muscle proteins

HPP can have a significant role in improving the gelation properties of fish muscle proteins. The treatment can increase the accessibility of the proteins to transglutaminase enzyme, which can lead to texturizing effects by improving the intermolecular cross-links and gel strength. In Japan, HPP is used to induce gelation of surimi from different fish products, such as sardines, pollock, tuna, and skipjack tuna. Ribeiro et al. (2018) used HPP (350–500 MPa for 10 min at 30°C) treatments as an alternative to heat-induced gelation (82°C for 1 h 50 min) and observed a significant increase in gelation of meager (*Argyrosomus regius*) hams while using low levels of microbial transglutaminase (MTGase, 2.5 g/kg). The HPP-treated ham showed good textural properties, improved elasticity, and cohesiveness than the control hams prepared using high levels of MTGase (5.0 g/kg). MTGase is used in the food industry to induce cross-linking among proteins to form a porous protein matrix that can absorb water and increase WHC. The reduction of MTGase results in a decreased value of WHC. HPP (350 MPa for 20 min at 30°C) treatment damaged the cross-linking and ionic bonds between proteins and countered MTGase functionality. However, the synergistic effect of MTGase and HPP enhanced the gel network making it uniform with smaller and more evenly distributed pores (Ribeiro et al., 2018). The WHC was unaffected using HPP (300 MPa for 10 min at 10°C) in combination with MTGase for development of Alaskan pollock low-salt (0.3%) surimi gels (Cando, Borderías, & Moreno, 2016). The reduction in sodium chloride content requires special strategies for adequate gelation and solubilization. Using pressure >400 MPa induced the breakdown of surimi gel 3D networks (protein cross-linking) and decreased WHC, which resulted in the transfer of free water from inside to the outside of the gel networks (Ma, Yi, Yu, Li, & Chen, 2015). However, Uresti, Velazquez, Vázquez, Ramírez, and Torres (2006) combined MTGase and HPP (600 MPa for 5 min) to improve the mechanical properties of gels made from arrowtooth flounder (*Atheresthes stomias*) paste set at 25°C. The combined effects of MTGase and HPP improved the conformational stability and produced stronger networks due to the formation of nonsulfide bonds between the protein molecules (Kunnath, Jaganath, Panda, Balange, & Gudipati, 2020). Low-

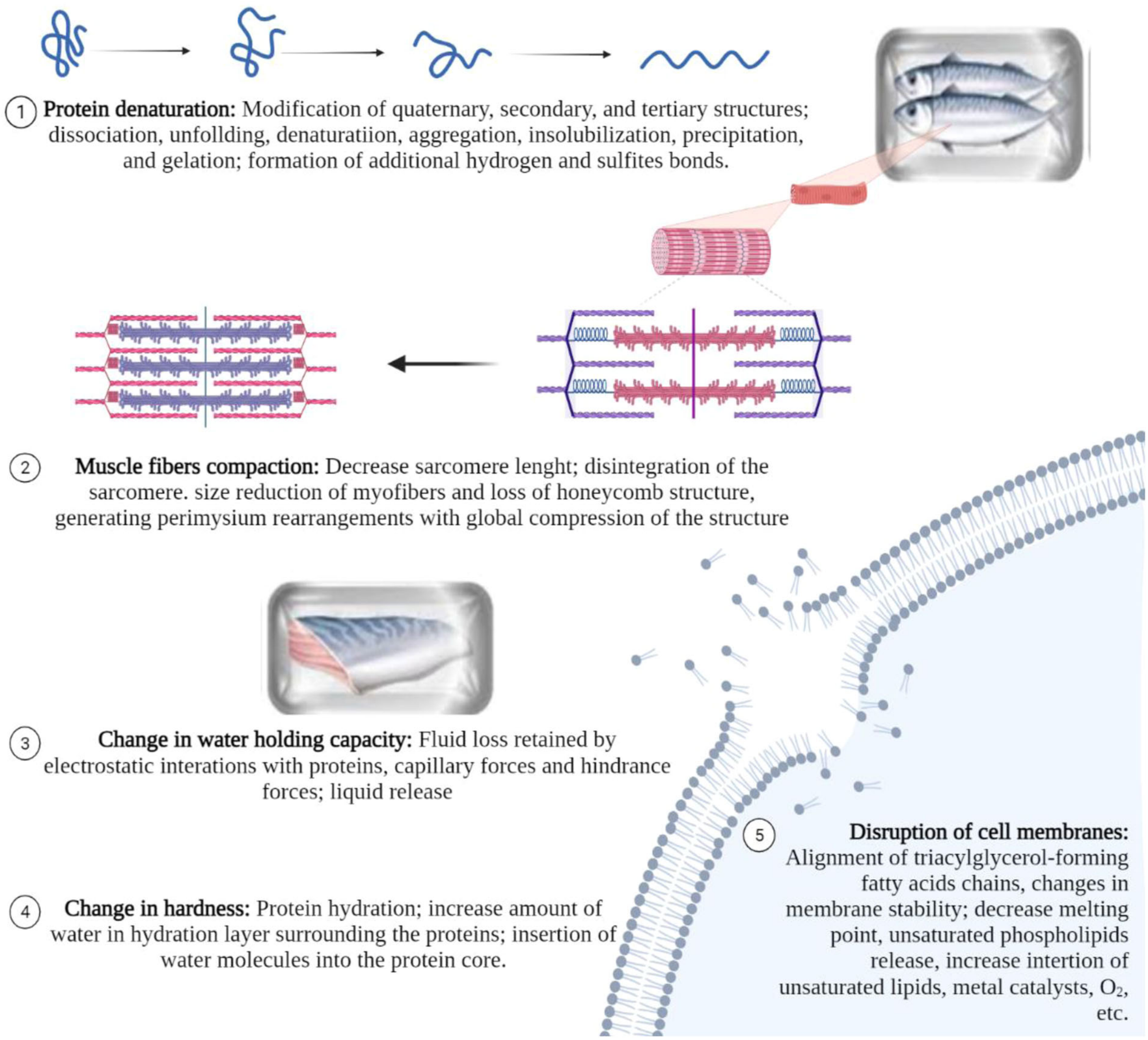

FIGURE 5 The impact of HPP on the quality of fish meat

intensity HPP (40–200 MPa for 10 min) induced structural transformations in flying fish (*Parexocoetus brachyterus*) surimi gels showing more α-helix and fewer β-structures compared to untreated controls (Moreno et al., 2015).

5 | HPP APPLICATIONS WITH SHELLFISH

The two main categories of shellfish, that is, crustaceans and mollusks have been mostly treated with a pressure level of 100–600 MPa for a processing time of a few seconds to 10–15 min. A treatment of 275 MPa for 3 min or 300 MPa for 2 min achieved a 100% release of the oyster adductor muscle necessary to optimize the shucking process (Rong et al., 2018). Pressures >300 MPa caused damage to the shells. An overview of the application of HPP to shellfish is given in Table 3, showing species and pressurization conditions (time, pressure level, and temperature).

5.1 | Quality and safety of HPP-treated shellfish

The risk of bacteria is high in seafood (*Salmonella*, *Listeria monocytogenes*, *Escherichia coli*, and *Vibrio*). According to the data collected by the National Outbreak Reporting System (NORS), 67.4% of the cases of food *Vibriosis* in the United States can be attributed to oyster consumption. However, the risk of contracting *Vibriosis* from crabs, prawns, and lobsters (4–10% of incidents) was significantly lower since they are usually cooked (Cook, 2003). The World Health Organization (2015) reported a higher incidence of outbreaks and cases of foodborne diseases attributed to pathogenic *Vibrio* spp. in seafood due to the increased seawater temperature. The presence of *Vibrio* spp. threatens consumer health (i.e., induces septicemia), and has a direct financial impact on seafood manufacturers and healthcare agencies worldwide. While

TABLE 3 Overview of the applications of HPP for shellfish, crustaceans, and mollusks (2016–2021)

Sample	Experiment	Compare/ Combined	Findings	References
Oysters (*Crassostrea hongkongensis*)	400 MPa for 3 min at 20°C.	Stored at −20°C and compared with steamed at 100°C for 8 min.	In raw, HPP, and steamed oysters, the equivalent umami concentration was 8.80, 3.66, and 1.44 g MSG/100 g, respectively, with significant differences observed among various treatments.	(Liu et al., 2021)
Oysters (Pacific, *C. gigas*), shelled oysters and oyster homogenate	100–300 MPa for 2–5 min at 0–5°C.		The murine norovirus inactivation was best in buffer (decreased to 1.8 log PFU/ml), followed by oyster homogenate and shelled oysters (decreased to 2.8 log PFU per oyster at 275 MPa for 5 min).	(Takahashi et al., 2019)
Oysters (Pacific, *C. gigas*)	100–350 MPa for 1–3 min.	Stored at 4 °C.	275 MPa for 3 min or 300 MPa for 2 min achieved 100% release of oyster adductor muscle and decrease aerobic bacterial count by 1.27 log units. Pressures higher than 350 MPa caused excessive release as the shells of oysters were broken.	(Cao et al., 2017)
Oysters (Pacific, *C. gigas*)	300 MPa for 2 min.	Stored at 4°C.	Shelf-life of 6–8 days for control and 12 days for HPP-treated oysters was observed. *Psychrobacter* was dominant in the HPP-treated spoiled oysters and its proportion was 42.3%, while *Pseudoalteromonas* (32.2%) and *Shewanella* (19.5%) were dominant in the spoiled oysters without HPP treatment.	(Rong et al., 2018)
Oysters (*C. gigas*)	400 MPa for 5 min at 10–25°C.		HPP is a promising process of inactivation of infectious human noroviruses in oysters.	(Imamura et al., 2017;2018)
Oysters (*C. virginica*)	300–500 MPa for 2 min at 25°C.		Lipid oxidation values were higher for 500 than 300 MPa at 0°C. 500 MPa decreased unsaturated fatty acid percentage. The glycogen content of control oysters at 3 weeks was significantly higher when compared to HPP treated oysters [300 MPa (25 °C); 450 MPa (0°C); and 500 MPa (0°C)].	(Lingham et al., 2016)
Prawn (Indian White, *Fenneropenaeus indicus*)	250 MPa for 6 min at 25°C.		Muscle fibers were shrunk, and extracellular space apparently reduced while myofibrillar proteins denatured and sarcoplasmic proteins aggregated after HPP. Protein activity was decreased through the WHC, solubility, viscosity, and Ca^{2+} ATPase, whereas foam expansion, the volume of foam, and protein turbidity improved.	(Joseph et al., 2020)
Prawn (Banana, *F. merguiensis*)	600 MPa for 5–10 min at 40–120°C.		HPP for 10 min at 120°C decreases tropomyosin antigenicity by 65%, while at 40 and 80°C increases antigenicity by almost double. Pepsin enzyme digestion significantly reduces antigenicity in HPP-treated samples.	(Faisal et al., 2019)
Shrimp (*Penaeus monodon* carapace)	150–250 MPa for 10–20 min.	Acetone–methanol mixture, 7:3, vol/vol (3–7 mL).	HPP achieved higher extraction astaxanthin yield of 95.17 μg/gdw at 238.54 MPa for 16.29 min and 59.9744 μg/gdw at 210 MPa for 10 min as compared to 29.44 μg/gdw using chemical extraction. Total carotenoid was increased from 46.95 μg/ml using chemical extraction to 68.26 μg/ml using HPP. The sample of astaxanthin demonstrated a significant increase in DPPH radical scavenging activity (25.47 to 87.90%), reducing activity of Ferrum redox reaction (2.86 μmol TE/g to 8.13 μmol TE/g) and oxygen radical absorption capacity (2,000 μmol TE/100 g to 4,000 μmol TE/100 g) compared to the chemical extraction sample.	(Irna et al., 2018a;2018b;c)

(Continues)

TABLE 3 (Continued)

Sample	Experiment	Compare/ Combined	Findings	References
Shrimp (*P. vannamei*)	HPP-vacuum-freeze-drying (550 MPa for 10 min).	Compared with hot air drying (50°C for 22 h) and vacuum freeze-drying.	HPP pretreatment shortens the relaxation time, improved drying efficiency, and moisture migration was from the exterior to the interior part with increasing drying time as well as no significant damage of muscle fibers was observed.	(Ling et al., 2020)
Shrimp (Black Tiger, *P. monodon*)	300–600 MPa for 0–15 min at 30–60°C.		HPP and temperature favored the inactivation of *Escherichia coli, Listeria innocua, and Staphylococcus aureus*. The optimized conditions targeting at least 6 logs reductions of *S. aureus* with moderate changes in quality attributes were obtained at 361 MPa for 12 min, 46°C.	(Kaur & Rao, 2017a;2017b; 2017c)
Shrimp (Black Tiger, *P. monodon*)	361 MPa for 12 min at 46°C.	Packed in LDPE, EVOH, and MMP pouches and stored at 4, 15, and 25°C for 30 days.	The estimated shelf-life of pressure-treated samples were 30 days for EVOH and MMP samples and 18 days for LDPE samples at 4°C. The control and HPP samples at 15°C reached the unacceptable limit by the 3rd and 9th day of storage, respectively. However, the samples at 25°C showed shelf-life of fewer than 3 days. EVOH film was adjudged to be the best in maintaining the quality of shrimp.	(Kaur & Rao, 2018)
Shrimp (White, *Litopenaeus vannamei*)	200–500 MPa for 2–20 min.		With the increase in HPP processing conditions, the rate of inactivation of TPC and PPO have all increased. Hardness of 300–500 MPa-treated samples was higher than that of control. HPP-treated samples turned slightly pink for a long time and high pressure.	(Li et al., 2016)
Shrimp (*L. vannamei*), shelled fresh	200–400 MPa for 5–15 min.	Acidic electrolyzed water (NaCl concentration to electrolysis 1.5 g/L)	Acidic electrolyzed water dramatically increased the effectiveness of HPP for inactivation of *V. parahaemolyticus* and *Listeria monocytogenes* up to 6.08 and 5.71 logs respectively compared to single HPP treatment, which reduced 4.74 and 4.31 log^{s} respectively.	(Du et al., 2016)
Crab (Chinese Mitten, *Eriocheir sinensis*), shucked	300 MPa for 20 min at 25°C.	Super chilled storage at 4°C.	Upon 3-week storage, the lightness and whiteness of HPP-meat start to decline. The aerobic plate count, total volatile base nitrogen, and histamine content of crab meat reached 5.71 logs, 24.50, and 0.99 mg/100 g, respectively, on the 8th day. The shelf-life was evaluated to be 6 days and *Clostridium* was dominant in the spoiled meat.	(Ye et al., 2021a;b)
Crab (Blue, *Callinectes sapidus*) meat gels	100–600 MPa for 5 min, 40°C for 30 min.	90°C for 20 min before thermal gelling.	HPP gels were lighter and reddish color as compared to the control. 100 and 300 MPa increase the meat extraction. 600 MPa produced considerable protein aggregation of gels, whereas at 300 MPa protein functionality can be modified to produce crab meat gels with adequate brightness, texture profile analysis values, and a fresh, high-quality appearance. Higher sensory scores were obtained in 300 and 600 MPa.	(Martínez-Maldonado et al., 2020;2017)
Squid (*Illex argentinus*) pen	500 MPa for 10 min.	Acetate 1% (*w*/w).	HPP-sample chitosan reached maximum yield of 81.9%, which had a rough surface with high porosity, compared to smooth surface of control sample. The HPP-chitosan had significantly higher DPPH radical scavenging activity, greater reducing power, and a stronger ferrous ion chelating effect than did chitosan of untreated sample.	(Huang & Tsai, 2020)

(Continues)

TABLE 3 (Continued)

Sample	Experiment	Compare/ Combined	Findings	References
Squid (Jumbo, *Dosidicus gigas*)	100–400 MPa.	Salt (15 g/100 ml) for 30 s.	With increasing pressure levels, the color parameters L^* (Lightness) have increased; b^* (yellowish) and a^* (reddish) have decreased. Samples thus had a brighter aspect and a mildly cooked look.	(Lemus-Mondaca et al., 2018)
Squid (*Todarodes pacificus*)	200–600 MPa for 20 min.		Decreased the band intensity of hemocyanin when increasing pressure from 200 and 400 MPa to 600 MPa. The α-helix and random coil contents of the 600 MPa treated samples were 23.67% and 37.54%, respectively, compared to 32.37% and 32.02% in the control, respectively. The IgE and IgG-binding capacities decreased after HPP, show a significant decrease in the allergenicity.	(Zhang et al., 2017)
Squids (*T. pacificus*), Fresh	200–600 MPa for 10 min at 20°C.		200 MPa improved umami and volatile aroma compounds during shelf-life. Essential free amino acids and succinic acids were lower on Day-0 than on Day-10. At 600 MPa, inosine monophosphate and volatiles were maximally reduced on Day 10.	(Yue et al., 2016)
Squids (*T. pacificus*)	200–600 MPa for 20 min at 25°C.		Two-cycle 600 MPa gave the highest in vitro protein digestibility (84.42%). HPP resulted in significantly higher anti-inflammatory values compared to control. Modified the protein and functional properties of squids and gave the relevant chemical shifts in NMR signals, either migrated or disappeared.	(Zhang, Dai, et al., 2016)
Squids (*T. pacificus*) muscles	200–600 MPa for 10 min at 20°C.		Pressurization and storage did not affect the taurine, EPA, DHA, Mn, and Cu levels. 600 MPa caused maximum loss of cholesterol, hypoxanthin, adenine, and Fe after 10 days of storage and produce small reduction in guanine, vitamin B2, DPPH, reducing power, and TBARS. Cholesterol, reducing power, or vitamin A showed no obvious differences at 200 and 400 MPa.	(Zhang, Wang, et al., 2016)
Clam (Fresh Razor, *Sinonovacula constricta*)	200–400 MPa for 1–10 min.		Increased shelling efficiency, WHC, pH, conductivity, and lipid oxidation, as well as showed lower levels of microorganisms and drip loss than untreated razor clam. Levels of TBARS in HPP samples were greatly increased (up to 0.93 ± 0.09 mg MDA/kg at 400 MPa for 10 min) which was caused by the formation of hydroperoxides during HPP treatment.	(Xuan et al., 2018)
Lobster (*Homarus americanus*) tails, raw and sous vide cooked	150 or 350 MPa for 5 or 10 min.	Stored for 28 days at 4 °C.	150 MPa for 10 min decreased the hardness of raw lobsters compared to controls. 350 MPa for 5 or 10 min increased the shear force. Significantly lower microbial counts, total volatile base nitrogen, and biogenic amine levels. HPP increased the L^* values but did not affect moisture content, WHC, or weight loss.	(Humaid et al., 2020;2019)
Blue Mussel, *Mytilus edulis*) homogenates	250–450 MPa for 1–3 min at 25°C.		To achieve a reduction of >5 log in mussel homogenates, pressure treatment needs to be (i) 350–450 MPa for ≥1 min at 25°C for both *V. alginolyticus* and *V. cholerae*, (ii) 250 MPa for ≥3 min or 350–450 MPa for ≥1 min for *V. vulnificus* and (iii) 350 MPa for ≥3 min or 450 MPa for ≥1 min for *V. parahaemolyticus*.	(Vu et al., 2018)

Abbreviations: TBARS: Thiobarbituric acid reacting substances, PPO: Polyphenol oxidase, LDPE: Low-density polyethylene, EVOH: Ethylene vinyl alcohol, MMP: Multilayer metalized polyester, WHC: Water holding capacity, EPA: Eicosapentaenoic acid, DHA: Docosahexaenoic acid, PFU: Plaque-forming units.

traditional thermal methods are available for microbiological inactivation, HPP is a time-saving and energy-efficient preservation technique for the seafood industry for opening shellfish or crustaceans (Ling et al., 2020). Using HPP (200–350 MPa), the bivalve shells opened with ease and allowed efficient meat extraction without affecting the product while avoiding cooking. Moreover, HPP avoids manual handling of shellfish or crustaceans, reducing the cost, time, and risk of contamination. The application of HPP has led to good results for microbiological inactivation and a consequent increase of shelf-life (Arnaud, de Lamballerie, & Pottier, 2018; Tsironi et al., 2019).

Studies have shown the efficiency of HPP as an effective nonthermal technology for microbiological inactivation of fish and seafood products. The Interstate Shellfish Sanitation Conference (USA) has suggested a reduction level of >3.52 log of *Vibrio* spp., as the safety standard for shellfish processing, which is likely to be achieved using HPP technology at relatively mild pressures (150–350 MPa). For example, processing at 293 MPa for 2 min reached or exceeded a 3.52 log reduction of *V. parahaemolyticus* (pressure-resistant strains) present in Pacific oysters (*Crassostrea gigas*), which represented a shelf-life extension of 6–8 days (stored at 5°C) or 16–18 days (stored in ice) (Ma & Su, 2011). A reduction of 5 log units of *V. parahaemolyticus* was obtained using a pressure >350 MPa at 1–35°C for 2 min (Campus, 2010). Another potential foodborne pathogen is human norovirus (HuNov), which has traditionally been the cause of outbreaks linked to the consumption of fresh oysters or crustaceans. The available scientific evidence indicates that HPP treatments reduced the risk of virus exposure associated with raw oyster consumption. Leon et al. (2011) observed no cases of HuNov infections from HPP (600 MPa for 5 min at 6°C) treated oysters. Imamura et al. (2017) obtained 1.9–2.0 log reductions of the genomic equivalent virus after HPP treatment (400 MPa for 5 min at 25°C) of naturally contaminated oysters. HPP treatments inactivated parasites such as *Anisakis*, Hepatitis A virus, and calicivirus from raw shellfish (Kingsley, Hoover, Papafragkou, & Richards, 2002). However, *E. coli* showed some resistance to HPP treatments and a reduction of only 1.9–4.7 logs was achieved in raw black tiger shrimp at 500 MPa for 3–9 min whereas a treatment of 600 MPa for 6–9 min was required to achieve 4–6 log reductions (Kaur et al., 2016).

In addition to microbial inactivation, HPP has been evaluated for its potential to reduce the production of amine compounds during storage of fish and seafood products. In general, seafoods are highly susceptible to formation of amine compounds during storage (refrigerated or frozen) due to enzymatic and microbial activities, which leads to off-flavors and sometimes intoxication (Biji, Ravishankar, Venkateswarlu, Mohan, & Gopal, 2016; Cheng, Sun, Zeng, & Pu, 2014). HPP treatment of raw squid (200–400 MPa) reduced the concentration of dimethylamine (DMA) and TMA by 20–51% after 20 days of chilled storage (Gou, Choi, He, & Ahn, 2010). Paarup, Sanchez, Peláez, and Moral (2002) found a concentration of 40 mg TMA/100 g of nontreated squid mantle stored for 7 days, whereas HPP treatments (300–400 MPa) significantly slowed TMA formation, giving 20–35 mg TMA/100 g after 28 days. Processing of black tiger shrimp with HPP at 300–600 MPa for 3–9 min reduced TMA concentration by 20–63% (Kaur, Rao, & Nema, 2016). HPP treatments induced changes in composition and other components of shellfish. Liu et al. (2021) reported some slight modifications in the biochemical composition and nonvolatile sensory compounds of raw oysters treated with HPP (400 MPa for 3 min at 20°C) compared to a steam process. Higher concentration of inorganic ions such as sodium, potassium, phosphate, and chloride were found in raw and HPP-treated oysters compared to steamed samples. These changes were attributed to easy dissolving and leaching of glycogen and inorganic ions into the water during steam heating.

5.2 | HPP-assisted shucking of shellfish

While shellfish processing may include thermal treatments, such as steaming or boiling to separate meat from the shell, HPP processing offers some advantages over these conventional methods. The severe thermal treatments break covalent bonds and produce new degradation compounds. While HPP can break weak hydrophobic and electrostatic bonds present in macromolecules (Cheftel, 1995), it does not alter covalent bonds, which are the backbone of important chemical compounds, such as those associated with important nutritional and sensory properties. The changes induced in the quaternary and tertiary protein structures mainly depend on the intensity of the pressure levels and holding times used in the treatments. HPP reduced the stress levels of both mollusks and crustaceans compared to other meat-extraction techniques. High pressure induces several changes in neurological processes at the cellular and physiological level (e.g., reducing the influx of calcium ions and inhibiting neurotransmitter release), which may inhibit the pain and distress of animals (Grossman, Colton, & Gilman, 1991). Besides, HPP cycles are done in a short time and at low temperature, two relevant factors to minimize pain in crustaceans. Although there is no study of the welfare of crustaceans that were alive at the start of HPP processing, the available scientific literature suggests that meat extraction using HPP does not lead to suffering during the process, that is, death is rapid (Cheftel, 1995; Grossman, Colton, & Gilman, 1991).

Further, pressure treatment at 200–300 MPa for 45–90 s at 5–15°C opens the shells of the bivalves efficiently with a 100% recovery rate of extracted meat (Tonello, 2011). Additionally, HPP shucking with seawater infuses salt into the meat, which improves the flavor and juiciness without affecting the quality of mollusks and crustaceans. HPP separates the meat from the shell of lobsters and crabs, allowing 100% meat extraction and making the process quicker, safer, and easier, and allowing a clean label (e.g., 100% natural and additive free) product. The process also enables easy collection of smaller parts, such as the crustacean legs, otherwise a challenging task. At the same time, it avoids the need to cook the product to maintain its color, texture, and flavor profile. However, intense pressure levels can alter the color and other descriptive quality attributes. Hence, the process must be optimized based on the raw material, such as species, growing conditions, and handling practices (He, Adams, Farkas, & Morrissey, 2002). Compared to HPP, the traditional methods of shucking or manually removing the shells of oysters, lobsters, crabs, mussels, clams, and scallops are time-consuming and difficult, and require expertise and extreme patience.

Industrial blue crab processing also includes thermal treatments, such as steaming or boiling, to separate meat from the shell. These thermal treatments allow the meat to cook, which produces the primary flavor compounds and inactivates pathogenic microorganisms. These severe conditions contribute to a significant loss in moisture and extraction yield. HPP treatment (100–300 MPa) improved the gelling properties of crab meat proteins and enhanced meat extraction yield compared to the thermal treatment (90°C for 20 min) (Martínez-Maldonado et al., 2020, 2017). This was attributed to HPP that induced conformational changes, structural transformations, and partial denaturation of myofibrillar proteins, leading to an increase of WHC. Martínez et al. (2017) recovered between 24 and 27% (w/w meat) of blue crab consisting of jumbo lump, backfin, special, and claw cuts after HPP (400–600 MPa) treatment. However, hand extraction of cooked crabs resulted in 15% (w/w) recovery, whereas the extraction from raw, non-treated crabs yielded 18% (w/w) meat recovery. Mohamed, Endan, Aniza, and Shamsudin (2015) highlighted the ease of shell removal for whole mud crabs processed at 345 MPa compared to unprocessed samples; however, they reported no differences for shrimp peeling. The treatment reduced waste and crab meat losses during processing. Martínez et al. (2017) confirmed the benefit of using HPP (100–600 for 5 min at 10°C) for extraction of blue crab retaining its functional quality such as fresh appearance, higher springiness and juiciness values, and retention of the natural sweetness. HPP-shucked crab meat can be preserved for up to 3 weeks with good acceptance, although a negative influence on the drip loss has been reported (Ye et al., 2021a,b). The HPP-assisted shucking combined with super-chilling can be an effective way to preserve the crab meat.

6 | CONSUMER ACCEPTANCE, MARKET TRENDS, AND INDUSTRIAL CHALLENGES

HPP offers several advantages over traditional preservative methods, although rapid cooling, freezing, and purification techniques retain the characteristics of the "fresh" product. These methods are slow processes that increase the chance of microbial survival (Oliveira et al., 2017; Suh et al., 2017). The same issue can be observed with chemical preservation methods, where the survival of pathogens is highly possible. Sometimes, additives produce undesirable effects, such as lipid oxidation with some strong oxidative agents (Bhat & Pathak, 2012, 2009; Tsironi et al., 2020). Although irradiation offers similar benefits to food quality and safety, it is not generally accepted by consumers and is legally restricted in some countries (Castell-Perez et al., 2021). Similarly, thermal processing is negatively associated with quality loss of the final products (Ojagh et al., 2011; Pita-Calvo et al., 2018a).

HPP has been used for a wide range of food-related applications. Several companies have taken advantage of the effortless pressure-assisted meat extraction using a semiautomatic HPP system to collect the meat (Cao et al., 2017; Xuan et al., 2018). The highly valuable end product can be used for developing some value-added dishes or be used as minced meat for soups or fillings (Martínez-Maldonado et al., 2017; 2020; Vu et al., 2018). HPP has been used for opening the shells of crustaceans. It may open the shells but they remain in place, making it easier to extract the meat from crustaceans at the time of consumption (Takahashi et al., 2019). However, HPP-assisted shucking should be done when lobsters are alive or shortly after their death, since the lack of oxygen hardens the muscles and eliminates the process' benefits (Humaid et al., 2019; 2020). However, this technology has been associated with some undesirable product characteristics. HPP (250–275 MPa for 50–60 s) caused an undesired blue color in live crabs due to polyphenol oxidase activation. Therefore, crab killing is generally recommended before shucking (Martínez et al., 2017). Moreover, higher pressure levels can break the bivalve shells and contaminate the meat, indicating the importance of process optimization for a successful adductor release rate (Rong et al., 2018).

This technology is commercially used for processing various foods with good success including seafood. Ocean Choice International was the first to install an HPP unit in 2002, in North America, for seafood products and used a pressure-assisted process for lobster meat extraction (Hiperbaric, 2018). Several other companies, such as Bacalaos Alkorta (Spain), Cinq-Degrés Ouset (France), Seafarer's Inc., and Greenhead Lobster (USA) have used this technology for processing seafood. USA seafood processors of fresh and RTE precooked crabmeat, for example, Seafarer's Inc. turned to HPP to control *Vibrio* and other pathogens in their products. This technology helped to achieve a shelf-life (free of pathogens such as *Listeria* and *Vibrio*) of up to 30 days without the use of chemicals and preservatives. Similarly, Accua HPP Solutions (Spain) achieved 40 days of shelf-life without any chemical preservative for RTE premium seafood products. Previously, this company used modified atmosphere packaging (with additives) to minimize the risk of pathogens (*Listeria* or *Salmonella*) and achieved 20 days of shelf-life for cod products, such as fillets, bellies, jowls, and carpaccio. Delpirre (France) preserved the natural texture and flavor of fish fillets using HPP (500 MPa), which they called a "novel high-pressure stabilization technology or cold pasteurization."

The HPP-based global food market has reached a value of >15.5 billion (USD) in 2019 and is expected to grow substantially until 2025 (Market Study Report, 2020). HPP aids seafood manufacturers to obtain an adequate balance between safety, quality, and regulatory compliance. The versatility of the process allows manufacturers to commercialize seafood in multiple products. HPP has helped companies to meet the rising demand of consumers by expanding the production capacity and lowering the processing time (Tsevdou, Gogou, & Taoukis, 2019). The acceptance of nonthermal processes increases as they ensure the inactivation of microorganisms, food preservation, freshness, and longer shelf-life (Roobab et al., 2018). One of the benefits of HPP is that food products are treated rapidly, irrespective of their shape and size, which is the main limiting factor for thermal processing. The process only uses pure cold water under pressure and does not cause variations in texture and taste as induced by heat, irradiation, or chemicals. Advantages of HPP include fresher and more delicious foods compared to thermal processing, extended shelf-life compared to raw food, cleaner product labels, improved management of food sustainability, and reduced food waste (Roobab et al., 2021a, 2021b). However, these benefits have to be considered on a case-by-case basis as there are several variables which can affect the outcome while using HPP (e.g., high temperatures, hurdle technology used, or adiabatic temperature increases during processing). While thermal processing is inexpensive, sustainable, and also yields a clean label and limits food waste, it affects the freshness attributes that are important for fish and seafood processing. Initial capital and energy requirements and processing costs are higher for HPP processing compared to thermal processing (Bolumar et al., 2021; Rodriguez-Gonzalez, Buckow, Koutchma, & Balasubramaniam, 2015). The higher energy requirements of HPP are mainly due to the batch nature of the technology, energy used to build up the pressure, and nonrecovery of the energy applied (Bolumar et al., 2021). However, the water requirements and environmental impact of HPP processing are lower than thermal processes (such as conventional pasteurization) and the water used in the process can be recylcled (Cacace, Bottani, Rizzi, & Vignali, 2020).

While HPP has several technological benefits, there are some hurdles for commercial uptake of the technology. HPP is still a batch process in most cases and expensive, which prevents universal acceptance compared to thermal processing. The initial capital and cost of the equipment is higher than other techniques and is considered a potential drawback for uptake of this technology. There are relatively few companies that manufacture the equipment and the average machine costs between 0.5 and 4 million USD (Young, 2020). However, as the industrial uptake of the technology will increase, the costs will likely go down. Meanwhile, an already-existing tolling system allows manufacturers to avoid a large capital investment and only pay using an as-a-service model. Larger companies which are already taking full advantage of this technology can further exploit its benefits by adding increasing automation levels in the production process or partnering with reliable automation parts suppliers (Tsevdou et al., 2019). When temperature is not used, HPP is more energy-efficient than other nonthermal alternatives such as synthetic chemicals or preservatives. Once the required pressure is reached, it can be maintained without additional energy input (Ye et al., 2021a, b). The water used in the pressurization process is recycled and thus produces no waste. Since the foods are processed within the packaging, treated products are usually refrigerated, which is generally considered a more environmentally friendly method than freezing due to relatively lower energy consumption (Svendsen et al., 2022). However, refrigeration produces more food waste compared to freezing methods and in the long run may have a higher environmental impact. Overall, HPP increases productivity, lowers labor costs, and eliminates foodborne pathogens (Rong et al., 2018; Ye et al., 2013). Further, by offering significant shelf-life extensions, it can help with food waste reduction (Huang & Tsai, 2020; Tsironi et al., 2020). A wider use of this technology in the area of fish and seafood will result in additional products and applications, some of which have been discussed in this manuscript, and may lead to new markets for these products.

7 | CONCLUSIONS

Nonthermal food preservation technologies and postpackaging strategies offer important benefits such as shelf-life extension and safety assurance without compromising sensory and nutritional quality of fresh and processed foods. While there is a range of available nonthermal technologies, HPP has recently gained popularity in the fish and seafood industry. This technology increases the safety and quality of fish and seafood products and offers several benefits without using any additives. HPP can extend the shelf-life of seafood during chilled and frozen storage by inactivating spoilage microorganisms and enzymes. Accompanied with other clean-label technologies, HPP offers numerous advantages to the fish and seafood industry such as improved texture, freshness and WHC; reduced drip loss and allergenicity; maintenance of pH; and inhibiting the production of TVB-N and biogenic amines. Studies have explored several nonmicrobiological applications of HPP such as tenderization, gelation, marination, and cooking, with the purpose of developing new products. This review has discussed in detail the successful applications of HPP in the seafood industry with a special focus on those studies that have provided effective and innovative interventions for retaining nutrients during processing. While there are some hurdles in the commercial uptake of HPP, rising investments in food production, advancements in the equipment, and expanding knowledge will create opportunities for growth in the near future.

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AUTHOR CONTRIBUTIONS

Ume Roobab: Writing—original draft. **Liliana G. Fidalgo**: Writing—review & editing. **Rai Naveed Arshad**: Methodology; Writing—review & editing. **Abdul Waheed Khan**: Methodology; Writing—review & editing. **Xin-An Zeng**: Conceptualization; Supervision. **Zuhaib F. Bhat**: Methodology; Writing—review & editing. **Ala El-Din A. Bekhit**: Methodology; Writing—review & editing. **Zahra Batool**: Writing—review & editing. **Rana Muhammad Aadil**: Conceptualization; Supervision

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

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