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Mild processing of seafood—A review

Nanna Abel[1] | **Bjørn Tore Rotabakk**[2] | **Jørgen Lerfall**[1]

[1] Department of Biotechnology and Food Science, Norwegian University of Science and Technology, Trondheim, Norway

[2] Nofima AS, Stavanger, Norway

Correspondence
Jørgen Lerfall, Department of Biotechnology and Food Science, Norwegian University of Science and Technology, Sverresgate 10–12, 7012 Trondheim, Norway.
Email: jorgen.lerfall@ntnu.no

Abstract

Recent years have shown a tremendous increase in consumer demands for healthy, natural, high-quality convenience foods, especially within the fish and seafood sector. Traditional processing technologies such as drying or extensive heating can cause deterioration of nutrients and sensory quality uncompilable with these demands. This has led to development of many novel processing technologies, which include several mild technologies. The present review highlights the potential of mild thermal, and nonthermal physical, and chemical technologies, either used alone or in combination, to obtain safe seafood products with good shelf life and preference among consumers. Moreover, applications and limitations are discussed to provide a clear view of the potential for future development and applications. Some of the reviewed technologies, or combinations thereof, have shown great potential for non-seafood products, yet data are missing for fish and seafood in general. The present paper visualizes these knowledge gaps and the potential for new technology developments in the seafood sector. Among identified gaps, the combination of mild heating (e.g., sous vide or microwave) with more novel technologies such as pulsed electric field, pulsed light, soluble gas stabilization, cold plasma, or Ohmic heat must be highlighted. However, before industrial applications are available, more research is needed.

KEYWORDS

Hurdle technology, Mild processing technologies, Seafood, Seafood quality, Seafood safety

1 | INTRODUCTION

Fish and seafood are recognized for their health benefits and are widely accepted to be an essential part of a balanced, healthy diet (Carlucci et al., 2015; Mandal et al., 2020; Ahern et al., 2021). Despite this, surveys show that the average seafood consumption in Europe is considerably less than the recommended amount (Altintzoglou, Einarsdottir, et al., 2010; EUMOFA, 2019). Lack of knowledge, difficulty of preparation, cost, and inconvenience are often described barriers for the consumption of seafood (Altintzoglou, Hansen, et al., 2010; Govzman et al., 2021). A review by Carlucci et al. (2015) summarizes consumer purchase behavior toward fish and seafood products. This review concluded that consumers seem to appreciate new, convenient, processed fish products "when" the original characteristics are not significantly altered. However, an increasing level of processing (without further specification) caused consumers to perceive the modifications of the original product characteristics as a proportional loss of quality, safety, naturalness, healthiness, and nutritional value. This has driven the research and development of ready-to-eat and other convenient partially processed seafood products that comply with consumers' preferences for healthy, natural, high-quality, fresh or fresh-like products (Carlucci et al., 2015; Casini et al., 2015). In later years, several papers have reported the consumers' purchase decision and the willingness to pay for different labels such as sustainability (Zander & Feucht, 2018; Lawley et al., 2019; Maesano et al., 2019), social responsibility certifications (Del Giudice et al., 2018), and health and environmental benefits (Menozzi et al., 2020). In general, there is a consensus among today's consumers that eco-friendly and healthy labels are attractive.

Traditional food processing methods such as drying or extensive heating and salting cause nutrients and/or sensory quality deterioration. Alternatively, mild processing methods have been tested and improved and gained more interest from the industry and research (Boziaris, 2014; Özoğul, 2019; Ekonomou & Boziaris, 2021). Most of these technologies vary in multiple aspects; for instance, some have been used for centuries, whereas others are newly developed. Furthermore, the working mechanisms and the effect on food safety, shelf life, and sensory quality differ from technology to technology. A schematic presentation of mild processing technologies is presented in Figure 1. In the present review, thermal and physical nonthermal inactivation methods as well as mild inhibition methods applied to seafood products are thoroughly discussed. Due to the mild application of these technologies, applied alone, they are seldomly sufficient ensuring good food safety and shelf life. Hence, a combination of two or more technologies are often applied either simultaneously or consecutively, an approach known as hurdle technology (discussed in Section 4).

Knowledge regarding the potential impacts, applications, and limitations of these technologies has not previously been gathered in one place, especially with a focus on fish and seafood application. Hence, this review aims to provide an overview of existing mild postharvest processing technologies and how these can be combined (hurdle technology), including a description of working mechanisms and obtained results and evaluating each technology's applicability.

2 | METHODS

Technologies included in this review were chosen based on a systematic literature search (Mandal et al., 2020) in Web of Science using the following keywords: lightly/mildly/minimally processed food, light/mild/minimal processing technologies, nonthermal/minimal processing, or emerging/new/trends technologies/processing. In total, more than 75,000 unique publications were identified. Repeating the search by filtering seafood-related research, the number of unique publications was reduced to less than 6000, from which 327 met the criteria for the review process. No age restrictions were applied in the search, but for most technologies, the included studies focus on the last 5–10 years of research.

3 | MILD PROCESSING METHODS FOR SEAFOOD

Many published articles use the term lightly processed, or some variant thereof (minimally processed, mild preservation, etc.), but almost all fail to define what is meant by choice of terminology. Articles that do offer an explanation or definition are seldomly in agreement. The most commonly used explanation is nonthermal processing methods (Allende et al., 2006; de Oliveira et al., 2019; Mañas & Pagán, 2005). However, this definition eliminates technologies such as sous vide, which by many is considered the exemplification of mild processing. A more nuanced definition includes maximum temperatures applied, but even those tend to vary significantly, from "[...] mild temperature; <40°C" (Barba et al., 2017) (p. 20) to "[...] temperatures remain under 100°C" (Rodgers, 2016) (p. R2309). Rajkovic et al. (2009) (p. 889) use "sublethal" to describe mild processing and extends on it by writing "[...] so-called mild decontamination [...] treatments inactivate only a part of the present microbial population [...]." This explanation only takes in part of the issue the microbiology, forgetting about all the other aspects that make up a food product. This is included in the article by Jermann et al. (2015) (p. 14) that explains it as methods that are "[...] extending product shelf life without affecting the nutritional content, organoleptic attributes and products specification." Guillou and Membré (2019), Nierop Groot et al. (2019), and Timmermans et al. (2014) use similar descriptions. In this article, the following definition of mildly processed seafood will be used:

Mild processing methods extend product shelf life and food safety by, partly or totally, inhibiting spoilage and pathogenic microorganisms and/or enzymes while affecting organoleptic attributes, nutritional content, and product characteristics as little as possible.

The mild processing concept was developed to preserve fresh quality; however, the particular focus has been to secure food safety and product shelf life due to the mild processing condition.

Broadly speaking, these mild processing methods can be separated into two different groups: thermal and nonthermal inactivation methods, although it might be argued that some processing technologies may fall under both categories. Furthermore, an additional group of mild inhibition methods may be considered as not all suitable

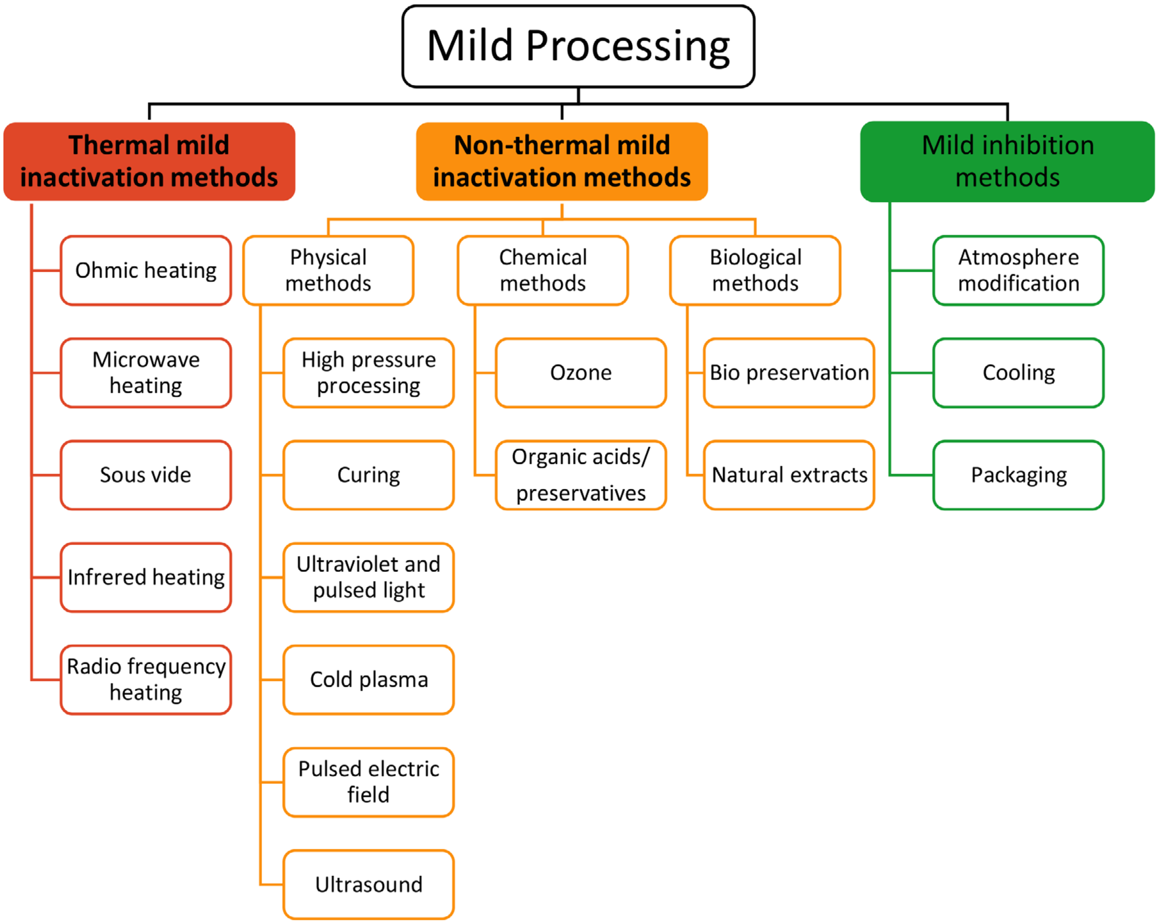

FIGURE 1 Examples of different approaches to mild processing of food separated based on working mechanisms. This review article focuses on thermal and physical nonthermal inactivation methods as well as mild inhibition methods applied to seafood products

methods exhibit inactivation effects. With the growing interest in developing and refining new production, the number of potential methods is endless. Therefore, the following work will focus on mild thermal, and nonthermal physical, and chemical technologies, either used alone or in combination (hurdle technology, discussed in Section 4), to obtain safe seafood products with good shelf life and preference among consumers. Nutritional aspects, and the preservation of seafood by additives, including biopreservation will not be discussed in this paper.

3.1 | Thermal mild inactivation methods

Thermal processing is the best-known preservation method and still dominates the food processing industry. The core inactivation mechanism in most thermal processing methods is the heat denaturation of the present microbiota, whereas the main difference is how the heat is applied. Besides the most used thermal processing technologies described in detail below, this group also includes radiofrequency heating, infrared heating, and Shaka technology (an agitated thermal process promoting heat transfer by forced convection).

3.1.1 | Ohmic heating

The concept of ohmic heating (OH) was first reported in the late 1800, followed by the first industrial application in the 1920s, where it was used for processing milk (Prescott, 1927). The technique has been known and researched for years, but the applications of OH are relatively new (Kumar, 2018).

Two mechanisms explain OH's effect: the thermal effect, which is the most dominant, and permeability enhancement, known as electroporation (Makroo et al., 2020). The thermal effect of OH is similar to that of conventional thermal inactivation. The difference between OH and conventional heating is that the heat is produced directly within the food itself during OH. When an electric current pass through an object, the object's electrical resistance causes electrical energy to be converted to heat, an effect known as Joule heating. This is why OH is also known as Joule heating or electrical resistance heating (Sastry, 2008). The working mechanism of OH causes an inside-out heating pattern resulting in rapid and uniform heating. Hence, no large temperature gradients will exist in the product, preventing overheating the surface, which preserves the sensory attributes of the treated food product (Tian et al., 2018). Electroporation occurs as high-voltage pulses induce and alter different electrical potentials between each side of the cell membranes. This causes hydrophilic pores and opening of transmembrane protein channels (Gómez et al., 2019; Yogesh, 2016). These pores allow intracellular content to leak from the cell, consequently losing cellular activity. The pores formed can be either reversible or irreversible depending on the extent of the treatment (Gómez et al., 2019).

The antimicrobial effect of OH has been studied intensively in products such as milk and juices (Tian et al., 2018); however, studies on seafood are limited. Bastías et al. (2015) found no difference in the microbial load of Chilean blue mussel (*Mytilus chilensis*) after being heated to a core temperature of 50, 70, or 90°C using either OH or conventional water bath. Furthermore, OH effectively inactivate *Listeria monocytogenes* in other food products (Makroo et al., 2020).

Experiments on shrimps (*Litopenaeus vannamei*) have found that processing with OH resulted in the same texture as conventional steam cooking. However, unlike steaming, OH achieved the core temperature faster (40 ± 1 s compared to 59 ± 2 s), and the temperature gradient within the shrimp was much smaller, regardless of the size of the shrimp or body part (head, body, or tail) (Lascorz et al., 2016). Similar findings were reported by Pedersen et al. (2016). This highlights the main advantage of OH compared to conventional heat treatment; it is possible to obtain the same characteristics but faster and without burning the surface.

Rajasekaran et al. (2021) reported OH at high voltage and short processing time (5 min to aim a core temperature of 72°C) to be beneficial regarding physiochemical and organoleptic quality. Moreover, they reported a reduction in total viable counts (TVC) up to 69% compared to untreated Green mussels (*Perna viridis*). The potential of high-frequency OH (20–50 kHz) has recently been highlighted, showing good water retention, low shrinkages, and beneficial textural properties of heat-treated scallops (Llave et al., 2018), as well as improved electrical conductivity during thawing of frozen tuna (Liu et al., 2017). Faster heating rates, such as those obtained through high-frequency OH, have been found protecting denaturation of actine (Llave et al., 2018), one of the major structural proteins influencing a product's water holding and textural properties. This highlights the potential of high-frequency OH to reduce the degradation of nutrients and to improve the retention of, for example, vitamins in seafood. However, to design a thermal process operation, the knowledge of temperature distribution within the processing unit and the thermal behavior of the product is required. Such knowledge can be obtained by developing three-dimensional models to predict the heating patterns of the product such as shown by Jin et al. (2020) for yellowtail (*Seriola quinqueradiata*) fillets.

3.1.2 | Microwave heating

For many years, microwave (MW) ovens have been an essential appliance in most kitchens. Typically, they have been used for reheating already processed foods, but nowadays, they are used more frequently to cook raw foods—both at home and in the industry.

MW technology uses electromagnetic waves, which affect the treated material in different ways. The varying electric field produced by the waveform causes dipolar molecules, such as water to oscillate back and forth. Due to the high frequencies applied in MW heating, this oscillation will occur several million times per second. Due to internal friction, these oscillations lead to volumetric heating of the food product. Second, as described for OH, when an electric current pass through an object, the object's electrical resistance causes electrical energy to be converted to heat (Chandrasekaran et al., 2013). MWs are part of the electromagnetic spectrum with a frequency range between 300 MHz and 300 GHz. The operating frequency for domestic appliances is typically 2450 MHz, whereas, for industrial applications, it is either 915 or 2450 MHz (Rosnes et al., 2011). Nevertheless, the frequencies vary in different regions of the world (Orsat et al., 2017).

MW pasteurization has mainly been applied to liquid food, such as milk and juices (Salazar-González et al., 2012), whereas the application in seafood is limited. A literature review by Tocmo et al. (2014) reported that only two studies were available regarding the inactivation of foodborne pathogens in seafood products. Sheen et al. (2013) evaluated the effect of MW cooking of catfish (*Sciades herzbergii*) fillets and found that 2 min at 1000 W were sufficient to eliminate (>5 log colony forming units [CFU]/g reduction) *Salmonella* spp. Similar results were obtained for *Escherichia coli* O157:H7 and *L. monocytogenes* at 750 and 875 W, respectively. Huang et al. (1993) reported that MW heating to a core temperature of 60°C resulted in up to 4-log CFU/g reduction in inoculated *L. monocytogenes*. In contrast, *Aeromonas hydrophila* was reduced by 5 log CFU/g. To the best of our knowledge, only one study in the past 5 years has investigated the specific effect of MW on foodborne pathogens in fish products concluding that even though MW had a significant effect on the microbial inactivation of *L. monocytogenes*, *Staphylococcus aureus*, and *E. coli* O157:H7, a treatment above 70°C core temperature was needed to ensure complete destruction of these pathogens (Ulusoy et al., 2019).

The fact that MW heats food products faster than conventional heating underlines the main advantage of MW heating; shorter heating and exposure times are less destructive (Thostenson & Chou, 1999). This has been demonstrated for Atlantic salmon color (Lerfall et al., 2018) and nutrient content (Ersoy & Özeren, 2009). Lerfall et al. (2018) found MW heating to be beneficial compared to conventional pasteurization for the Atlantic salmon color visualized by a darker (reduced *L**), more reddish (increased *a**), and yellowish (increased *b**) color. Moreover, MW-treated samples were slightly softer, but no differences were observed regarding the consumers' acceptability. In the study by Ersoy and Özeren (2009), the effect of different cooking methods on the mineral and vitamin content of African Catfish was studied. MW cooking (2450 MHz, 4 min) gave better retention of minerals and vitamin E compared to those baked in the oven (200°C, 15 min), in the grill oven (200°C, 10 min), or fried (200°C, 4 min). However, accounting for all results, the authors concluded the grilling method to be most suitable for heat processing of catfish due to better retention of vitamins (in total).

The applications of MW are versatile and include drying, blanching, baking, and extraction; however, industrial use of MW is limited (Orsat et al., 2017). This is partially explained by a series of limitations to the use of MW. MW only offers a limited penetration depth, which according to Metaxas and Meredith (1988) is about 10–20 mm at 2450 MHz. Furthermore, MW has been associated with significant uneven heating causing the formation of cold and hot spots leading to insufficient treatment or burns, respectively (Rosnes et al., 2011). The research focusing on these problems is growing rapidly, and the development of commercial systems for food processing has started (Brody, 2012; Orsat et al., 2017; Rosnes et al., 2011).

3.1.3 | Sous vide

Sous vide is defined as "Raw materials or raw materials with intermediate foods that are cooked under controlled conditions of temperature and time inside heat-stable vacuumized pouches" (Schellekens, 1996) (p. 256). Sous vide was first developed in 1974, yet the technique did not reach academic research until the 1990s, and later in the mid-2000s, it became widely known to ordinary people. From there on, it has been a fast journey, with sous vide cooking equipment becoming standard appliances in many restaurants and private kitchens (Baldwin, 2012; Gonzalea-Fandos & Laorden, 2020).

Despite sous vide relying on the same heating principle as traditional cooking, it differs in two fundamental ways: The raw ingredients are vacuum packaged in heat-stable plastic pouches, and second, the food is cooked using precise temperature control, often at low temperatures for a long time (Gonzalea-Fandos & Laorden, 2020). Both steps offer a range of advantages over traditional cooking. Vacuum packaging eliminates the risk of cross- or recontamination after the heat treatment, prevents the evaporation of water and loss of volatile compounds during the cooking, and reduces the access of oxygen (O_2), limiting lipid oxidation and reducing the growth of a series of aerobic bacteria. The precise temperature control offers increased reproducibility and potential to pasteurize food even at low temperatures (Baldwin, 2012).

Being developed in a restaurant, sous vide was first used as a cook-serve method, with no need for storage. As sous vide has shifted from a restaurant to an industrial application, there is an increased need for prolonged storage (distribution, selling, consumers' home, etc.).

The main advantage of sous vide cooking is the benefits to the sensory and nutritional quality. Sous vide cooking of fish cakes increased the sensory shelf life (based on juiciness, tenderness, flavor, appearance, and hedonic appeal) from 4 to 16 weeks compared to conventional cooking (Shakila et al., 2009). Similarly, sous vide cooking at 70°C for 10 min significantly increased the sensory shelf life of Atlantic bonito (*Sarda sarda*) while maintaining food safety (Mol et al., 2012). Furthermore, Díaz et al. (2011) found no detectable rancidity associated with lipid oxidation in sous vide cooked Atlantic salmon during storage. This is in agreement with other findings showing a delay in the onset of lipid oxidation due to sous vide treatment (Díaz et al., 2009; Schellekens, 1996). Additionally, Nishioka et al. (2011) showed no loss of vitamin B_{12} during sous vide cooking of herring (*Etrumeus teres*), whereas traditional cooking resulted in a loss of up to 62% of the content. The sensory and nutritional quality impact of sous vide cooking has been reviewed by Creed (1995).

The gentle heat treatment applied during sous vide cooking is insufficient to render food products safe for storage. Thus, the safety of sous vide cooked and chilled products relies heavily on fast cooling and maintaining cold storage (below 4°C) for the duration of the shelf life (Baldwin, 2012). Sous vide cooked and chilled mussels (*Mytilus galloprovincialis*) (85°C for 10 min) obtained a 50% increase in shelf life compared to conventional cooking (Bongiorno et al., 2018). Similar results were obtained on fish cakes (Shakila et al., 2009). On the other hand, González-Fandos et al. (2004) showed that although 90°C (15 min) was sufficient to injure the present microorganisms thermally, they were able to recover and multiply during refrigerated storage, especially under mild temperature abuse (10°C). This highlights the importance of proper cold storage. The shelf life of sous vide cooked and chilled fish products ranges from 6 to 42 days (Sampels, 2015).

Despite cold storage, various pathogens are still of concern for sous vide cooked fish products. Nonproteolytic *Clostridium botulinum* is one of these concerns as *C. botulinum* can form spores and survive after low or inadequate heat treatment and later start growing and producing toxins during refrigerated temperatures (Gonzalea-Fandos & Laorden, 2020). Experiments have shown that heat treatment in the temperature range of 65–90°C, including the typical temperature range of mild sous vide processing, has little effect on spores of nonproteolytic *C. botulinum*. Hence, the most efficient measure in the control of *C. botulinum* is fast cooling and refrigerated storage. Although *C. botulinum* can recover and grow at refrigerated temperature, the growth rate is slow under such conditions (Garcia et al., 1987).

Another concern is the survival and growth of *L. monocytogenes*. Generally, a heat treatment at 70°C for more than 2 min is recommended to ensure a 6-log reduction of *L. monocytogenes* (Baldwin, 2012). However, a 70°C heat treatment is seldomly applied to fish products due to the risk of protein precipitation at high temperatures. Recently, there has been an increase in low-temperature sous vide cooked seafood (42–60°C) (Gonzalea-Fandos & Laorden, 2020). However, there is a lack of data regarding the thermal inactivation of vegetative pathogens at such low temperatures (Stringer et al., 2012). This is one reason for recommending (re)heating of sous vide fish products before consumption. A sous vide treatment could potentially be combined with several other technologies such as pulsed electric field (PEF), pulsed light (PL), or soluble gas stabilization (SGS). Scant information about the combined effect of sous vide and PEF/PL is available on seafood. However, the combined effect of sous vide and SGS is discussed in Section 4.

Most of the other emerging mild processing technologies have become popular because they are fast, whereas the popularity of sous vide is derived from being slow but controlled. Sous vide combines vacuum packaging, low temperature–long time heat treatment, and fast cooling and storage to achieve safe products with high nutritional and sensory quality. Sous vide is one of the mild processing techniques that already have a wide existent in the industry and homes and restaurant kitchens worldwide.

3.2 | Nonthermal mild inactivation methods

Nonthermal processing methods are a diverse group of technologies, most of which rely on different inactivation mechanisms. Therefore, these methods are often separated into three different subgroups: physical, chemical, and biological. Besides the most used methods described below, the physical nonthermal group also includes ionized radiation, oscillating magnetic field, PEF, and ultrasound methods. Chemical food preservation has long been a well-established field. However, with the increasing demand for natural food products and green labels, there has been an increase in the use of so-called biological preservations, such as competitive microbiota (bio preservation) and use of essential oils or herb extracts (Banerjee & Verma, 2015; Rosnes & Skipnes, 2017). The use of chemical and biological preservation methods is outside the scope of this review and will not be described in further detail.

3.2.1 | High-pressure processing

High-pressure (HP) processing, also known as high hydrostatic pressure, uses pressure between 100 and 1000 MPa to inactivate or reduce microorganisms and enzymes to a safe level. The application of HP processing for food preservation was first tested more than a century ago when Hite (1899) reported increased shelf life of milk after pressure treatment. However, scientific development and industrial application are much newer and have evolved over the last few decades (Farr, 1990; Ekonomou et al., 2020; Ekonomou & Boziaris, 2021; Shynkaryk et al., 2020; Truong et al., 2015). Originally HP treatment was used for fruit products such as juices and jams, but the use has since expanded into almost all parts of the food processing industry. Despite several successful applications in the food industry, high equipment costs (30,000–770,000$) limit its use in smaller and medium-sized enterprises or low-production-volume applications (Pinto et al., 2020; van Wyk et al., 2018). However, contracting of such equipment has gained in popularity.

Application of HP causes a decrease in product volume (Martínez-Monteagudo & Balasubramaniam, 2016). This volume change affects all cellular components simultaneously due to the isostatic principle, which states that pressure is instantaneously and uniformly transmitted throughout the sample under pressure, regardless of shape and size (Smelt, 1998). The changes in product volume are accomplished by breaking molecular interactions, especially weaker interactions such as hydrogen bond, van der Waals forces, electrostatic force, and hydrophobic interactions (Tauscher, 1995). Consequently, proteins, including enzymes, polysaccharides, and nucleic acids may be subject to alteration in structure and functionality, whereas amino acids, vitamins, flavor compounds, and other small molecules remain relatively unaffected (Patterson, 2014). The ability to cause microbial inactivation while retaining quality showcases one of the main advantages of HP processing compared to conventional thermal treatment.

Multiple mechanisms have been suggested for the inactivation and/or death of vegetative bacterial cells caused by HP processing (Ferreira et al., 2016). These include changes in morphology, damage to the cell membrane (Ritz et al., 2002), and protein denaturation leading to changes in physiology, including synthesis of vital components and maintenance of intercellular conditions (Ferreira et al., 2016; Tholozan et al., 2000).

Regardless of the mechanisms, HP processing efficiently reduces microbial counts of various seafood species (Ekonomou & Boziaris, 2021; Truong et al., 2015). Generally, the application of 300 MPa for a few min at room temperature has been suggested as an adequate treatment to inhibit vegetative bacteria in many food products (Farkas & Hoover, 2000). This has been confirmed in multiple fish products (Erkan et al., 2010; Hurtado et al., 2000; Kamalakanth et al., 2011; Yagiz et al., 2007) as well as shellfish (Linton et al., 2003; López-Caballero, Pérez-Mateos, Bonderías, et al., 2000). Truong et al. (2015) reviewed the effect of various HP studies concerning microbial reduction and shelf life extensions. Although previous experiments agree on the overall effect, a direct comparison can be difficult. Chéret et al. (2005) and Teixeira et al. (2014) both performed experiments on sea bass (*Dicentrarchus labrax*), both at 400 MPa for 5 min, but obtained different bacterial reductions, 3.2 and 0.44 log CFU/g, respectively. The initial bacterial load (TVC of 6.0 and 4.4 log CFU/g in Chéret et al. [2005] and Teixeira et al. [2014], respectively) and the pressurization rate (3 and 14 MPa/s, respectively) did, however, affect the obtained results. Apart from treatment conditions, the effectiveness of HP processing on microbial inactivation is significantly affected by the characteristics of the microbiota. In general, it is assumed that Gram-negative (G^-) bacteria are more sensitive to pressure than Gram-positive (G^+). This is highlighted by the findings of Linton et al. (2003), who found G^+ to make up 58% of the total microbiota of mussels (*Mytilus edulis*) before treatment compared to 91% after HP processing (500 MPa for 2 min).

Oyster (*Crassostrea gigas*) is a seafood type for which HP processing has gained the most popularity. Both due to the ability to reduce the load of *Vibrio parahaemolyticus*, but equally important due to a series of quality aspects (Murchie et al., 2005). During HP processing, the adductor muscle of oysters detaches from the shell, opening the oyster, known as shucking. He et al. (2002) report 100% full release of adductor muscle after HP processing at 310 MPa. Similar findings were made by Rong et al. (2018). Furthermore, the HP-shucked oysters had a higher yield with fewer damages than traditionally hand-shucked oysters. Following HP processing, moisture content of the oysters had increased (Cruz-Romero et al., 2004; Rong et al., 2017), which explains the reports of more voluminous and juicy oysters after HP processing (López-Caballero, Pérez-Mateos, Montero, et al., 2000). Overall, sensory evaluation found HP-processed oysters to be more acceptable (Johnston et al., 2003) and with a lower quality index method (QIM) score (indicating fewer defects) (He et al., 2002; Yu et al., 2018).

The major drawback reported regarding the HP processing of oysters is the color change. At pressure above 300 MPa, increased whiteness (L^* value) and reduced transparency of the oysters were reported, resulting in a cooked appearance (Cruz-Romero et al., 2004). These observations also represent other molluscs (Gou et al., 2010; Hughes et al., 2016). HP-induced color changes have also been observed in HP-processed squid (*Loligo bleekeri*) (Nagashima et al., 1993), Atlantic cod (*Gadus morhua*), Atlantic salmon, mackerel (*Scomber scombrus*) (Christensen et al., 2017), and yellowfin tuna (*Thunnus albacares*) (Kamalakanth et al., 2011). Observed color changes in meat are often associated with three main mechanisms: (1) denaturation of myoglobin, (2) modification or disruption of the porphyrin ring, and (3) changes in the myoglobin redox chemistry (Bak et al., 2019). However, in seafood, increased lightness (L^*) is associated with HP-induced cold denaturation of globin and myofibril proteins. On the other side, changes in redness (a^*) are most likely affected by oxidative mechanisms (de Oliveira et al., 2017). The color of fish and shellfish products plays a vital role in consumers' perception of quality (Garber et al., 2003). These discolorations are therefore of great concern to the processing industry. Another concern regarding HP processing of seafood is the influence on water holding capacity (WHC). Decreased WHC as a function of treatment pressure (200–400 MPa) has been observed on sea bream (*Sparus aurata*) (Campus et al., 2010) and cold smoked Atlantic salmon (Lakshmanan et al., 2007). WHC highly depends on protein–water interaction, explaining the decrease following pressure-induced protein denaturation.

HP processing is a fast-expanding processing method gaining popularity in multiple parts of the food industry. The popularity primarily stems from the ability of HP processing to inactivate vegetative bacteria and most autolytic enzymes while causing minimal deterioration to the nutrient or sensory quality. Relying on protein denaturation as a mechanism for bacterial inactivation, it is inevitable to cause alterations to the product itself. This includes a cooked appearance due to surface protein denaturation or denaturation of color complexes and alterations to WHC, texture, and induction of lipid oxidation.

3.2.2 | Pulsed electric fields

PEF is an emerging nonthermal technology with great potential for cost-effective and eco-friendly applications in the food industry (Ekonomou & Boziaris, 2021). It is widely used on liquid and semiliquid food products. However, for seafood applications, further research is needed before applications can be commercialized. The basic principle of the PEF technology is the application of short pulses (a few nanoseconds to several milliseconds) of high-voltage electric fields between two electrodes with the intensity in the order of 0.1–80 kV/cm (Barba et al., 2017). The processing time is calculated by multiplying the number of pulses times with the effective pulse duration. The research on PEF related to seafood processing has increased in popularity due to its potential to inhibit microorganisms (Shiekh & Benjakul, 2020) and altering structural properties beneficial for, for example, salting (Cropotova, Tappi, Genovese, Rocculi, Laghi, et al., 2021). However, the number of high-quality publications focusing on seafood is restricted to less than 15 studies. One of the benefits of using PEF is the low impact on the sensory characteristics. Improved sensory characteristics after a PEF treatment have been reported on freshwater mussels (Zhou et al., 2017) and Asian seabass (Chotphruethipong et al., 2019). Cropotova, Tappi, Genovese, Rocculi, Laghi, et al. (2021) reported shorter brining times and increased salt uptake when PEF was used as a pretreatment before salting. The applied intensity of the current was set at 10 and 20 A (corresponding to a field strength of 0.3 and 0.6 kV/cm) before sea bass salting in brine with 5% and 10% salt concentration, respectively. However, the combination of PEF with brine salting resulted in an increase in primary and secondary lipid oxidation products expressed as peroxide value, conjugated dienes, and 2-thiobarbituric acid reactive substances in PEF-treated samples compared to untreated ones (Cropotova, Tappi, Genovese, Rocculi, Dalla Rosa, et al., 2021). In addition to the beforementioned applications, PEF can improve the extraction of nutritional and bioactive compounds. A few studies on seafood have recently been published, for example, on Pacific white shrimp (*Litopenaeus vannamei*) (Gulzar & Benjakul, 2020), fishbone (He et al., 2014), and sea bass and sea bream rest raw material (Franco et al., 2020), but the number of potential applications is considerable.

3.2.3 | Curing

Curing is a collective term for traditional processing methods such as drying, salting, smoking, pickling, marinating, or combinations thereof (Arason et al., 2014). Unlike most of the mild processing methods mentioned up until now, curing is not a new or emerging technology, but is in fact one of the oldest methods of preserving fish (Løvdal, 2015). According to Huss et al. (2003), cured products can be divided into four diverse groups: (1) mildly preserved seafood, including lightly salted, some marinated, and cold smoked seafood products; (2) fermented seafood; (3) semipreserved seafood, including salted and/or marinated fish and caviar; and (4) smoke-dried or heavily salted seafood products, including stockfish. The following will only focus on the physical methods within the mildly preserved seafood category in line with the overall topic.

Smoking

Smoked seafood includes two groups separated based on the temperature of processing: cold smoked or hot smoked. Cold smoked products are processed at temperatures below 33°C, classifying them as mildly processed (Løvdal, 2015).

A traditional cold smoking process involves salting, drying, and finally, smoking. The primary purpose of salting is to lower the water activity (a_w) to inhibit spoilage mechanisms (Sperber, 1983), and it can be done either by dry, brine, or injection salting. An additional decrease in a_w takes place during the drying and smoking steps. The smoking step further preserves the product through the release of formaldehyde and phenols known to inhibit the growth of multiple microorganisms and limit oxidative reactions (Kjällstrand & Petersson, 2001; Varlet, Prost, et al., 2007). Analyses have identified more than 200 different substances to be released during smoking (Arvanitoyannis & Kotsanopoulos, 2013), not all of which are beneficial. Especially polyaromatic hydrocarbon (PAH) compounds such as benzo(a)pyrene are of concern due to their link with cancer development.

Cold smoked seafood is very sensitive to deterioration and based on sensory evaluations it has a limited shelf life of 3–5 weeks when stored at 4°C (Leroi et al., 2001; Løvdal, 2015; Rørvik et al., 1991). The spoilage of cold smoked products is mainly ascribed to off-flavors resulting from microbial growth and metabolism (Leroi et al., 2001; Truelstrup Hansen et al., 1996). Several studies have shown that the microbiota of cold smoked products is dominated by lactic acid bacteria in combination with other spoilage bacteria such as *Photobacterium phosphoreum* or *Enterobacteriaceae* (Leroi et al., 1998; Olofsson et al., 2007; Truelstrup Hansen & Huss, 1998). One explanation for the high variability in the microbiota of cold smoked seafood is that the spoilage is highly dependent on the processing combinations. These variations include different salting methods, salt concentrations, degree of drying, and smoking method, just to name a few. For instance, Truelstrup Hansen et al. (1996) found *Brochothrix thermospacta* in brine-injected samples, but not in dry-salted samples, which, on the other hand, was found to be dominated by

P. phosphoreum. One of the biggest concerns about cold smoked seafood is the potential survival and growth of *L. monocytogenes* (Jami et al., 2014). A summary of *L. monocytogenes* prevalence in retail cold smoked Atlantic salmon is presented by Løvdal (2015), reporting results between 0% and 61%, averaging at 9.8%.

Although smoking traditionally was used to preserve and extend shelf life, nowadays it is primarily applied to develop favored sensorial characteristics. Different processing settings can have a significant impact on the quality of the final product. For instance, Martinez et al. (2012) found dry salting to result in firmer cold smoked products, compared to brine salting, in agreement with findings by Birkeland et al. (2004). The firmness is facilitated by the removal of water during the salting step. This again explains the differences in obtained yield due to different salting strategies (Birkeland et al., 2004; Birkeland & Bjerkeng, 2005; Bjørnevik et al., 2018). The additional drying of the surface obtained by dry salting also influences the surface color, which generally is found to be darker and less red (decreased L^* and a^*) compared to brine-salted smoked Atlantic salmon (Bjørnevik et al., 2018; Lerfall et al., 2011). Various settings within each of the methods mentioned (salting time and temperature, salt concentration, etc.) play a significantly role in determining the extent of the discussed effects (Birkeland & Bjerkeng, 2005; Goulas & Kontominas, 2005).

The most important factor influencing the characteristics of smoked fish products is the smoking process itself. Smoke can be generated by a variation of pyrolytic applications (Birkeland & Skåra, 2008) or by the application of liquid smoke, also known as purified condensed smoke (PCS) (Hattula et al., 2001). The previously mentioned concern over PAHs resulting from pyrolysis is one reason for the development of PCS. Smoke condensates are usually obtained from wood smoke produced by smoldering wood chips or sawdust followed by refining and rinsing steps to remove unwanted compounds (Guillén et al., 2000; Montazeri, Oliveira, et al., 2013). Despite the filtering, the active antimicrobial compounds are still the same and research has shown an inhibiting effect of several types of PCSs (Faisal et al., 2019; Guilbaud et al., 2008; Montazeri, Himelbloom, et al., 2013). PCS is used either by dipping the seafood product in a diluted PCS solution or by atomizing it and spraying the sample in a closed chamber.

Valø et al. (2020) compared traditional cold smoking with that of atomized PCS and found atomized PCS to result in lower aerobic plate count and better growth suppression than traditional cold smoking. Moreover, the PSC-processed salmon were firmer, darker, and slightly less reddish and yellowish than those smoked traditionally. On the other hand, de Araújo et al. (2020) found no significant differences in bacterial counts in catfish products in agreement with Özpolat and Patir (2016). Varlet, Serot, et al. (2007) compared sensory evaluations of pyrolysis-smoked and PCS-produced Atlantic salmon and found the samples to be significantly different, as PCS produced salmon was classified as "grassy" and "cold" compared to "buttery" for the traditionally smoked products. In contrast, Birkeland and Skåra (2008) found no significant differences in any of the evaluated sensory traits a week after processing with either PCS or traditional cold smoking. The different findings can easily be explained by using different condensates, as they differ significantly in flavor based on different production methods (Kostyra & Barłyko-Pikielna, 2006). This also highlights the possibility to adjust the use of different PCS to obtain the wanted flavor profile (Martinez et al., 2007; Martinez et al., 2012). Regardless of PCS type used, there is some characteristic of the traditionally wood-smoked products that are hard to mimic with PCS. This includes color, where PCS results in a lighter, paler surface color (lower L^*, lower a^*, and lower b^*) than wood-smoked fish products (Birkeland & Skåra, 2008; Cardinal et al., 2001; Hattula et al., 2001).

3.2.4 | Ultraviolet and pulsed light

The use of ultraviolet (UV) light treatment to preserve foods was first discovered in the 1930s and has since become a widespread disinfection method in multiple industries. The limitations to continuous UV treatment led to the development of flash lamps as an alternative for delivering UV radiation. The use was first reported in the late 1970s; however, PL treatment for microbial inactivation first reached the scientific literature in the 1990s (Bank et al., 1990; Mandal et al., 2020). Application of both for equipment, processing plant, and packaging material disinfection has long been used, but the use for direct processing of foods is relatively new, although fast growing (Mandal et al., 2020).

UV light is light in the electromagnetic spectrum region from 100 to 400 nm. However, the UV spectrum is often divided into three types based on wavelength: UV-A with 320–400 nm, UV-B with 280–320 nm, and UV-C with 200–280 nm, the latter having the strongest germicidal properties (Bintsis et al., 2000). The energy released during UV treatment causes the formation of DNA photoproducts, most importantly pyrimidine dimers (Lee et al., 2015). This covalent cross-link between two pyrimidines of the same DNA strand can cause interruption to both transcription and translation leading to loss of function and death of the cell (Regan et al., 1968; Sharma, 2010).

PL, also known as high-intensity, broad-spectrum pulsed light (Roberts & Hope, 2003), high-intensity pulsed UV light (Ngadi et al., 2012), intense light pulses (Gómez-López et al., 2005), intense pulsed light (Choi et al., 2010), pulsed UV light (Sharma & Demirci, 2003), or pulsed white light (Marquenie et al., 2003), uses short pulses of intense, broad-spectrum light to inactivate microorganisms. PL processing uses light between 200 and 1100 nm, thus including UV, visible, and some infrared light. The germicidal effect of PL is mainly ascribed to the effect of UV-C, as described above (Gómez-López et al., 2007).

Both methods are considered efficient for decontaminations and have been used for microbial inactivation of foods, food contact materials, air, and water (Kramer et al., 2017; Oms-Oliu et al., 2010). Cheigh et al. (2013) compared continuous UV-C and PL treatment for the inactivation of *L. monocytogenes* in solid medium. They found PL for up to 350 s resulted in more than a 6-log CFU/g reduction, similar to MacGregor et al. (1998) and Rowan et al. (1999). However, the penetration depth is poor for liquid media (*D*-value of 93 ± 5 s), but a thin-profile treatment can be considered (Pollock et al., 2017). Comparably, treatment using continuous UV-C treatment for up to 1000 s resulted in a 4-log CFU/g reduction. Furthermore, the significantly longer treatment time resulted in increased sample temperature. Conversely, the same PL treatment used for *L. monocytogenes*-inoculated shrimps, Atlantic salmon, and flatfish (*Paralichthys olivaceus*) fillets resulted in approximately 2.2-, 1.9-, and 1.7-log CFU/g reduction, respectively, whereas UV-C treatment gave no significant reduction (Cheigh et al., 2013). This highlights one of the main disadvantages of using UV and PL treatment for food processing—the penetration depth. Although the penetration depth is higher for PL than continuous UV-C treatment (Oms-Oliu et al., 2010), the uneven surface of food products can harbor microorganisms that will not be affected by the treatment. Similarly, if there is a high microorganism population density, they will be shadowing each other, hindering effective disinfection (Cheigh et al., 2013). Despite this, the use of continuous UV or PL treatment has shown promising results for multiple seafood products, which includes the inactivation of *E. coli* O157:H7 and *L. monocytogenes* by UV-light, on inoculated raw salmon fillets (Ozer & Demirci, 2006), improved shelf life of vacuum packaged *Colossoma macropomum* × *Piaractus mesopotamicus*, and pirarucu (*Arapaima gigas*) fillets (Bottino et al., 2016; de Souza Lira Santos et al., 2018), improved microbiological stability and sensory quality of dried seafood (Lee et al., 2015), and no negative sensory changes in UV-C-treated (50 mJ/cm^2) cold smoked salmon (Holck et al., 2018). However, for raw salmon fillets, doses higher than 200.0 mJ/cm^2 introduce unwanted organoleptic characteristics (Pedrós-Garrido et al., 2018).

The main concern regarding the use of UV-C light for food processing is that it is known to be a potent prooxidant agent (Mendes de Souza et al., 2013). Nevertheless, experiments on both lean and fatty fish species have shown that the prooxidative effect is neglectable when using mild treatment dosages (Monteiro et al., 2017; Rodrigues et al., 2016). Furthermore, only applying treatment in short pulses as in PL has shown significantly decreased oxidation rates (Heinrich et al., 2016). UV-based treatments have been shown to cause discoloration to food products, especially dark meat, fruit, and vegetables (Heinrich et al., 2016). In contrast, little or no changes in color have been reported for Nile tilapia (*Oreochromis niloticus*) (Monteiro et al., 2017), sea bass (Molina et al., 2014), Atlantic salmon, flatfish, shrimps (Cheigh et al., 2013), and dried squid (*Todarodes pacificus*) (Lee et al., 2015).

UV treatment, continuous or pulsed, has gained popularity because it does not use chemicals or leave residues, the heat is minimal, it is fast and economical, and it occupies very little space. It has been used for decontamination of air, water, and equipment for long, and applications for food products are growing. However, there is still limited research regarding seafood products, as the low penetration depth of UV radiation and absorption of energy by food constituents limit the efficiency.

3.2.5 | Cold plasma

The term "plasma" refers to the fourth state of matter first discovered in 1928 (Saklani et al., 2019). It is a partially ionized gas that can be generated in two ways: (1) by heating gas to extreme temperatures (approximately 1000–10,000 K), leading to the formation of thermal plasma. The high temperature of this method renders it unsuitable for food processing (Samal, 2017). (2) Alternatively, gas is passed through a high-energy electric field, which disrupts and breaks down the gas's equilibrium state by the formation of ions and electrons. The latter is known as nonthermal or cold plasma (CP) (Kulawik & Tiwari, 2019). As the name indicates, temperatures of CP are close to ambient temperatures; hence, it does not heat the treated product (Misra et al., 2015), making the methods suitable for mild processing. There are two forms of CP, low-pressure plasma systems and atmosphere condition plasma, the latter of which is the most used due to the more accessible and cheaper utilization (Misra et al., 2011).

When gases, typically O_2, nitrogen (N_2), argon (Ar), atmospheric air, or a mixture hereof, are electrified, an assortment of ions, electrons, and free radical species is generated (Olatunde & Benjakul, 2018). These molecules are responsible for microbial inactivation. The exact working mechanism of CP microbial inactivation is not fully understood, but four different suggestions have been made: (1) the production of reactive molecules, (2) UV radiation, (3) the production of charged particles, and (4) the production of ozone (Guo et al., 2015). The overall effect is probably due to a combination of two or more. A common feature for all these reactions is that they cause oxidative degradation of microbial components, including the membrane leading to microbial injury or death (Kulawik & Tiwari, 2019). This highlights the benefit of O_2 in the atmosphere when working with plasma. Eto et al. (2008) and Patil et al. (2014) found that addition of O_2 to the atmosphere increased the efficiency of CP decontamination. Besides gas atmosphere composition, the efficiency of CP depends on the type of plasma generation unit (dielectric barrier discharge and atmospheric pressure plasma jet are the most commonly used), the product (composition, size, and surface), CP generation parameters (voltage, frequency, and time), exposure mode (indirect or direct contact), and microorganisms present (Liao et al., 2017).

The use of CP for food processing or food packaging decontamination is relatively new, and up until recently, the application has been focusing on fresh produce (Critzer et al., 2007; Fernandez-Gutierrez et al., 2010; Perni et al., 2008). The main parts of research regarding CP processing of seafood only date back to the last couple of years (Kulawik & Tiwari, 2019). Despite promising results from fresh produce, the findings from fresh seafood samples have been discouraging. Kulawik et al. (2018) reported no significant reduction in microbial load after CP treatment of sushi at up to 80 kW, 50 kHz for 5 min. Similar reports have been made for other fish products (Albertos et al., 2017; Albertos et al., 2019; Chiper et al., 2011). Considering dried and semidried seafood products, the findings are highly different. For example, CP has been reported to cause inhibition of an array of different microorganisms, including bacteria (Choi et al., 2016, 2017; Puligundla et al., 2018), yeast, and molds (Park & Ha, 2015; Puligundla et al., 2018). A summary of the findings is presented in Kulawik and Tiwari (2019). Although reports have not been made from seafood products, CP has been shown to inactive bacterial spores in culture samples (Tseng et al., 2011).

The main disadvantage to the use of CP, and why fresh seafood has often been considered unsuitable for CP treatment, is the possibility of increased oxidation rate. As stated above, CP works by causing oxidative stress to the microorganisms; however, a similar effect has been suggested to the seafood product itself. All identified studies that investigated oxidation levels of CP-treated fresh or dried seafood reported an increase in oxidation rates (Albertos et al., 2017; Albertos et al., 2019; Choi et al., 2016, 2017; Kulawik et al., 2018; Park & Ha, 2015; Puligundla et al., 2018). The oxidation level depends on the CP treatment conditions showing increased oxidation rates due to higher voltage and holding times. A high-voltage treatment (e.g., 80 kV) will give an excellent inhibitory effect on microbial counts but also increase oxidation rates. However, lower voltage (e.g., 70 kV) and shorter treatment times (<5 min) will reduce the number of oxidation products such as peroxides and dienes (Albertos et al., 2017; Albertos et al., 2019). Similarly, replication of the same studies reported a significant decrease in moisture content following CP treatments and significant color changes, including a reduction in lightness. On the other hand, no adverse changes in sensory parameters were reported (Choi et al., 2016, 2017; Kim et al., 2015). One study even reported improved appearance, color, and overall acceptance scores following CP treatment of semidried Pacific saury (*Cololabis saira*) at 20 kV, 58 kHz for up to 10 min (Puligundla et al., 2018).

CP is a method of gaining interest from research groups worldwide because it is a cost-effective, environmentally friendly method that can eliminate microorganisms, including spores. However, applications in the food industry, especially seafood, are still scarce.

3.3 | Mild inhibition methods

Most of the above technologies aim to inactivate or kill microorganisms, whereas others rely on inhibiting the microorganisms by reducing growth and propagation without eliminating the microorganisms present. The most used example of the latter is the application of carbon dioxide (CO_2) in food processing and packaging (Figure 2).

CO_2 has long been known for its bacteriostatic and antifungal effect and it has been demonstrated that CO_2 can extend the growth lag phase and reduce the growth rate during the logarithmic growth phase of several bacteria (Church, 1994). Hence, CO_2 is extensively used for atmosphere modification of multiple food products, including seafood.

Although the antifungal and antimicrobial effect has been demonstrated in multiple experiments (DeWitt & Oliveira, 2016; Sivertsvik et al., 2002; Stammen et al., 1990), the mechanism is not fully understood. In the beginning, it was believed that the bacteriostatic effect of CO_2 was solely due to the replacement of O_2. However, this theory was rejected when experiments showed markedly improved bacterial inhibition when using 100% CO_2 compared to 100% N_2 (Daniels et al., 1985). CO_2 is easily absorbed in most food products due to its high solubility in water and liquid lipids (Abel et al., 2018). The dissolvement of CO_2 facilitates a drop in surface pH due to carbonic acid formation (Knoche, 1980). Although bacteriostatic, the pH drop cannot account for the entire bacterial inhibition observed from CO_2 processing (Coyne, 1933). Today there is a consensus that the effect of CO_2 is due to intracellular accumulation causing disruption of the normal physiological equilibrium, and four mechanisms have been identified: (1) alteration of cell membrane functions including cellular uptake and release, (2) inhibition of bacterial enzymes, (3) intracellular pH changes,

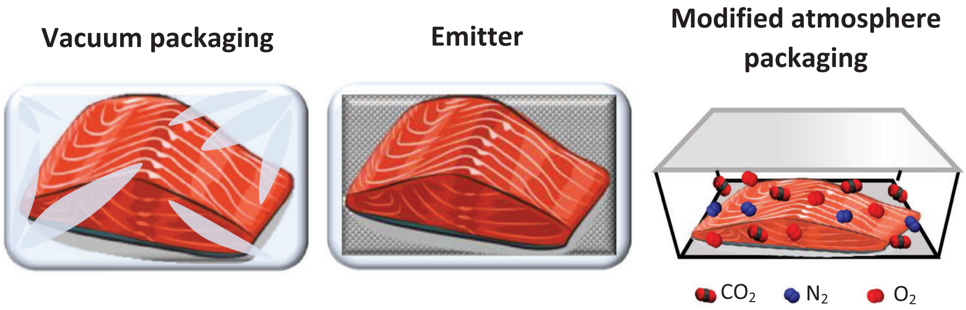

FIGURE 2 Various forms atmosphere modification, vacuum packaging, emitter, and modified atmosphere packaging. All of these can be applied in combination with soluble gas stabilization

or (4) immediate changes in physicochemical properties of proteins (Sivertsvik et al., 2002). The bacteriostatic effect is probably a combination of all the mentioned mechanisms. The mechanisms described highlight the importance of CO_2 concentration in the product, as demonstrated by Devlieghere et al. (1998a, 1998b), who found the growth inhibition of microorganisms in modified atmosphere (MA) to be determined by, and proportional to, the concentration of dissolved CO_2 in the product.

3.3.1 | Soluble gas stabilization

Due to the solubility of CO_2 in the water and liquid lipids (Abel et al., 2018; Gill, 1988), absorption of CO_2 by the product in an MA packaging system results in either a pressure reduction, volume reduction, or both, depending on the packaging material (Sivertsvik et al., 2002). This volume reduction can lead to package collapse, one of the main disadvantages of CO_2 in MA packaging. In order to overcome this issue, a filler gas can be introduced, reducing the percentage of CO_2, thereby lessening the volume change, but also reducing the bacteriostatic effect of the CO_2. Alternatively, a higher gas-to-product volume (g/p) ratio can be applied, typically in the range of 3:1–4:1, implicating a packages size four to five times the actual size of the product (Sivertsvik et al., 2004). The consequence is lower packaging efficiency, increased distribution costs, and an increased amount of plastic materials and waste produced. An alternative for reducing the packaging size is dissolving the CO_2 into the product before packaging, a method known as soluble gas stabilization (Sivertsvik, 2000, 2003). SGS has been shown to prevent package collapse, even when low g/p ratios are applied (Birkeland & Rotabakk, 2014; Rotabakk et al., 2006; Rotabakk et al., 2008; Sivertsvik & Birkeland, 2006). SGS treatment is effectuated at low temperature and pressure equal to or above 1 atm. Because the solubility of CO_2 increases at lower temperature and higher partial and/or total pressure, a sufficient amount of CO_2 can be dissolved into the product during 1–2 h in pure CO_2 (Sivertsvik et al., 2004). Despite being designated as such, SGS is not a packaging technology by definition. Hence, SGS pretreatment is followed by repackaging after ended treatment, either in vacuum or MA packaging (Birkeland & Rotabakk, 2014). Mendes and Gonçalves (2008a) compared SGS pretreatment followed by vacuum packaging with pure vacuum-packaged sea bream and sea bass and found SGS to delay the growth of naturally present bacteria, in agreement with Mendes et al. (2011) for octopus (*Octopus* vulgaris). Furthermore, SGS pretreatment maintained the initial sensory characteristics and quality longer, resulting in a 2–3 days extension of shelf life than pure vacuum-packaged samples (Mendes & Gonçalves, 2008a). Most literature reporting the use of SGS does so in combination with MA packaging, as it is believed to be necessary to repack in MA after SGS treatment to maintain the effect of the dissolved CO_2 (Birkeland & Rotabakk, 2014). Abel, Rotabakk, Rustad, et al. (2019) found MA packaging of SGS-pretreated,pasteurized Atlantic salmon loins to significantly reduced the growth of *Listeria innocua* by extending the lag phase and reducing the growth rate, which was in agreement with the findings of Abel, Rotabakk, and Lerfall (2019). Reduction in bacterial growth by SGS followed by MA packaging has also been observed for shrimps (*Pandalus borealis*) (Sivertsvik & Birkeland, 2006), Atlantic halibut (*Hippoglossus hippoglossus*) (Rotabakk et al., 2008), Atlantic cod mince (Birkeland & Rotabakk, 2014), and Atlantic salmon fillets (Sivertsvik, 2003).

The relationship between measured bacterial growth and perceived quality and shelf life is not straightforward. Despite the positive effect on bacterial inhibition observed from SGS treatment, multiple experiments have shown that SGS does not provide the ability to prolong shelf life when evaluated based on sensory scores. They report no beneficial or adverse effect of the SGS treatment (Abel, Rotabakk, Rustad, et al., 2019; Birkeland & Rotabakk, 2014; Mendes & Gonçalves, 2008b; Mendes et al., 2011; Rotabakk et al., 2008). However, the studies who has reported an increase in sensory shelf life, ranging from 4 to more than 9 days, were primarily based on off-odor evaluations (Mendes & Gonçalves, 2008a; Rotabakk et al., 2006; Sivertsvik & Birkeland, 2006). The effect of SGS is often ascribed to inhibition of the specific spoilage organisms and inhibition of oxidative rancidity. It has been shown that an increased percentage of CO_2 in the headspace can induce increased drip loss (DL) as a result of pH changes causing confrontational changes to the proteins (Davis, 1998). No such effect was observed in any of the experiments analyzing DL after using SGS (Abel, Rotabakk, Rustad, et al., 2019; Al-Nehlawi et al., 2013); some even reported a reduction in DL (Rotabakk et al., 2008; Sivertsvik & Birkeland, 2006). All the mentioned studies make a comparison between SGS-treated samples and regular MA packaging, hence all samples containing some level of CO_2. This might explain the lack of difference.

3.3.2 | Gaseous packaging methods

Packaging might not be considered a processing method, as processing often is thought of as something that aims to alter the product, whereas traditionally, packaging is mostly applied to maintain the product as it is. However, development within the field of food packaging has made it just as important as any other processing, especially within the field of mildly processed foods. Particular focus has been on MA packaging and active packaging (Yildirim et al., 2018).

The term modified atmosphere is often perceived as a synonym for modified atmosphere packaging, a postprocessing packaging step in which a mixture of different gases instantly replaces the air within a package at the time of sealing (Stammen et al., 1990). In reality, the term is much broader. Multiple methods exist for modifying the atmosphere within food packages, including vacuum packaging, emitters, SGS, and of course, MA packaging. Another storage principle is the controlled atmosphere storage (CAS), aiming to obtain the initial atmosphere in the storage system through storage (Yahia et al., 2019). CAS is widely used in the packaging of fruit and vegetables (Mditshwa et al., 2018; de Siqueira Oliveira et al., 2020) but is less used for seafood. However, an industrial application of SGS will need a prestep of CAS to obtain stable conditions before repacking in either MA or vacuum. Most of the SGS research has been performed in lab-scale experiments using the MAP principle to dissolve CO_2 into the product. However, an ongoing project funded by the Research Council of Norway (RCN) aims to develop a full-scale SGS technology concept for seafood (RCN, project number 294641).

The functional principle is the same regardless of the method chosen: the headspace within food packages is altered to remove unwanted gases or introduce wanted ones. The main gases of importance are O_2, N_2, and CO_2, whereas other constituents have been investigated and used (Sivertsvik et al., 2002). For most fish and seafood products, packaging aims at eliminating the presence of O_2, as O_2 in most cases has deleterious effects on the quality of stored seafood products (Bouletis et al., 2017; Korpf & Mancini, 2014). As mentioned, bacterial spoilage of fish and seafood is often ascribed to the presence and growth of aerobic or facultative anaerobic bacteria (Gram & Huss, 1996) or lipid oxidation and development of rancidity (Mariutti & Bragagnolo, 2017). Hence, elimination of O_2 will provide extended shelf life by slowing bacterial spoilage and lipid oxidation. On the other hand, species with high trimethylamine oxide (TMAO) content often suffer from the removal of O_2, as O_2-depleted bacteria degrades TMAO to trimethylamine, causing formation of the characteristic "fishy" odor of spoiled seafood (Ashie et al., 1996). The removal of O_2 is the main purpose of vacuum packaging. Vacuum packaging was the first commercially developed MA packaging method. It consisted of packaging in low O_2 permeable materials after the evacuation of air, which under good vacuum conditions should reduce the O_2 concentration below 1% (DeWitt & Oliveira, 2016). Alternatively, flushing with N_2 is used to replace O_2 in packages as a measure for delaying spoilage. However, for the most part, N_2 is only used as a filler in MA packaging gas mixtures due to its solubility properties (Church & Parsons, 1995).

The most common application of gaseous packaging of fish and seafood is MA packaging. However, experimental findings vary significantly; mostly an extension in the range of 30%–60% of shelf life for fresh seafood is obtained when using an atmosphere with elevated CO_2 levels (Sivertsvik et al., 2002).

The use of high CO_2 in packaging headspace can change the composition of the microbiota of the product by favoring anaerobic or facultatively anaerobic species (Koutsoumanis et al., 2000; Noseda et al., 2012; Silbande et al., 2016). *Brochothrix thermospacta* is a potent spoilage bacterium that is considered the predominant spoilage organism of MA-packaged seafood products. Abel, Rotabakk, and Lerfall (2019) found MA packaging to reduce the growth of *B. thermospacta* compared to vacuum packaging. This agrees with Noseda et al.'s (2012) findings for pangasius fillets (*Pangasius hypophthalmus*). Rotabakk et al. (2008) found *B. thermospacta* not to be affected by increased CO_2 concentration. Moreover, Parlapani et al. (2014) reported MA packaging to favor the growth of *B. thermospacta* due to reduced competition. Differences in initial gas mixtures, g/p-ratio, or product characteristics could all be part of explaining these differences, although the exact reason is unknown. This shows the difficulty in comparing studies and hence estimating the effect of MA packaging (Sivertsvik et al., 2002).

Reduced-O_2 atmosphere may inhibit the growth of aerobic spoilage bacteria, but the same environment may be beneficial for strict or facultatively anaerobes such as *Listeria* spp. High CO_2 levels have been shown to reduce the growth of *Listeria* spp. when used in MA packaging (Mejlholm & Dalgaard, 2007) by prolonging the lag phase as well as the growth rate (Abel, Rotabakk, & Lerfall, 2019; Pothuri et al., 1996; Provincial et al., 2013; Rutherford et al., 2007). However, it is essential to point out that these studies found MA packaging to cause a delay or slowdown of *Listeria* growth, not a complete inhibition. This is underlined by the predictive model developed by Mejlholm and Dalgaard (2007) showing that even an already preserved product as cold smoked Atlantic salmon needed a near 100% equilibrium dissolved CO_2 concentration to prevent the growth of *L. monocytogenes*.

Another concern regarding *L. monocytogenes* is the ability to form biofilms, a complex community of microorganisms attached to surfaces of food processing equipment. It has been shown that *L. monocytogenes* can form bacterial biofilms to survive on food processing surfaces under anaerobic conditions (Qian et al., 2020). Qian et al. (2020) investigated the influence of MA on *L. monocytogenes* biofilms during storage. They found that anaerobiosis significantly reduced the prevalence and thickness of biofilms formed compared to aerobic conditions.

Multiple methods have been used to evaluate the product quality of MA-packaged seafood. One of these is the evaluation of WHC or DL. It has been reported that increased CO_2 amount will alter WHC and hence increase DL (Davis, 1998; Masniyom et al., 2002; Randell et al., 1999; Rotabakk et al., 2008). However, when using SGS pretreatment or addition of CO_2 emitters in combination with MA packaging, no effect (Abel, Rotabakk, Rustad, et al., 2019) or even reduced DL (Hansen et al., 2007, 2009; Hansen, Mørkøre, Rudi, Rødbotten, et al., 2009; Rotabakk et al., 2008; Sivertsvik & Birkeland, 2006) was seen. A suggested explanation is an effect on the reduction in headspace volume, which occurs due to solubilization of CO_2 (Rotabakk et al., 2008).

Bouletis et al. (2014) evaluated color, appearance, odor, structure, flavor, and overall impression of squid on a five-grade scale and found high CO_2 content to increase the period with quality above the acceptable limit. Similar findings were made in almost all studies reporting sensory evaluation, with a tendency toward higher CO_2 concentration resulting in shelf life extension (Hansen et al., 2016; Nikzade et al., 2019; Provincial et al., 2010).

The optimal use of CO_2 MA packaging is limited by the solubility of CO_2 causing volume changes and potentially packaging collapse when applied in flexible or semirigid packages. A suggested solution is the use of CO_2 emitters. Although SGS and MA packaging rely on changing the atmosphere before sealing the packages, CO_2 emitters aim to obtain a CAS system by producing CO_2 inside the packages through chemical reactions (Sivertsvik, 2003), hence classifying CO_2 emitters as a form of active packaging (Yildirim et al., 2018). Other types of active packaging include oxygen scavengers, moisture scavengers, and antioxidant releaser (Yildirim et al., 2018).

Hansen et al. (2016) compared packaging of Atlantic cod in vacuum or MA packaging, with or without a CO_2 emitter, and found that inclusion of the emitter significantly decreased bacterial growth and prolonged sensory shelf life from 7 to 13 days. This agrees with Hansen et al. (2007), Hansen, Mørkøre, Rudi, Rødbotten, et al. (2009), and Tsironi et al. (2019). More importantly, the latter studies obtained increased shelf life, despite lowering the g/p ratio considerably, from 4:1 to 1.3:1 and 3:1 to 1:1, respectively (Hansen et al., 2007; Hansen, Mørkøre, Rudi, Rødbotten, et al., 2009). This means that less volume is needed for packaging, thus increasing transport and storage efficiency. Hansen et al. (2007, 2009) reported bulging of the top web as a result of the increased amount of CO_2 produced by the CO_2 emitter, which is one of the main disadvantages of emitter use. Relying on a chemical reaction within the packages makes it hard to control the CO_2 volume, especially as the facilitator, DL, varies significantly from sample to sample even within the same species.

3.3.3 | Superchilling

A different approach to the mild inhibition methods and one of the most widely applied hurdles in the food industry is cold storage. In the industrial world, it has become so common that most of the time, it is not even considered an option but a necessity. Lowering the storage temperature has proven one of the most critical parameters affecting the growth of microorganisms. Similarly, reduced product temperature tends to slow enzymatic and other biochemical deterioration: the lower the temperature, the slower the deterioration (Kaale et al., 2011). The most used methods for fish and seafood are refrigerated ice storage (usually 0–4°C) or frozen storage (−18 to −40°C) (Gallart-Jornet et al., 2007). Conventional freezing is often not preferred for high-quality products, as it may induce undesirable changes such as protein denaturation, reduced WHC, and increased DL on thawing (Kaale et al., 2011). The detrimental effect of freezing is triggered by the slow temperature decrease of conventional freezers, causing large ice crystals to form within the product. Large intracellular and extracellular ice crystals lead to rupture of cellular membranes and denaturation of cell components (Kaale & Eikevik, 2016; Kaale et al., 2011; Magnussen et al., 2008). Superchilling may act as an attractive compromise between conventional chilling and freezing (Duun & Rustad, 2008).

Superchilling, also known as partial freezing, implies temperatures in the borderline between chilling and freezing. During superchilling, the temperature of the food product is lowered 1–2°C below the initial freezing point of the product. This causes partial freezing of the product's water content (Kaale et al., 2011). The conversion of water into ice makes it less available for deteriorative processes. Furthermore, superchilling temperatures reduce microbial activity and prevent the growth of most bacteria (Kaale et al., 2011).

Use of superchilling has been reported for multiple fish and seafood products, including Atlantic salmon (*Salmo salar* L.) (Fernández et al., 2009; Sivertsvik et al., 2003), Atlantic cod (Eliasson et al., 2019; Sørensen et al., 2020), and crustaceans (Sun et al., 2017; Zeng et al., 2005). The general conclusion has been that superchilling results in an extension of the shelf life of stored food by 1.5 to four times compared to conventional chilling (Kaale et al., 2011; Magnussen et al., 2008).

The formation of ice crystals within the product can cause microstructural changes to the food. One potential effect of these changes is increased DL (Kaale et al., 2011), as reported by Bahuaud et al. (2008) and Liu et al. (2013). On the other hand, Sivertsvik et al. (2003) found no significant increase in DL, nor any other adverse effects on tested quality traits of superchilled Atlantic salmon. Similar reports were made by Duy Bao et al. (2007) for Arctic charr (*Salvelinus alpinus*). Chan et al. (2020), Cropotova et al. (2019), and Duun and Rustad (2007) even reported superchilling to decrease DL compared to traditional chilled or iced storage. Other potential negative effects of superchilling include degradation of texture and adverse sensory changes, as is reviewed by Banerjee and Maheswarappa (2019), Kaale et al. (2011), Magnussen et al. (2008), and Wu et al. (2014).

A downside to superchilling is the difficulty in maintaining appropriate storage temperatures with traditional consumer equipment such as refrigerators and freezers. A stable temperature is necessary to prevent ice melting and recrystallization, which may result in quality deterioration. These issues are easily overcome with industrial equipment, making superchilling a highly relevant application for commercial use. Furthermore, the ice formed on the surface of the products during superchilling will act as an internal ice reservoir, eliminating the need for external ice during transportation or short period storage. Ice usually makes up 20%–30% of the transported weight for ice-storage seafood (Magnussen et al., 2008); thus, superchilling could significantly increase transportation efficiency (Kaale et al., 2011).

A novel technology to preserve food is acidic electrolyzed water (AEW) ice (Ekonomou & Boziaris, 2021). AEW is produced in an electrolyzed water generator using water-added sodium chloride (NaCl) and voltage and current values of 9—10 V and 8—10 A, respectively. For the preservation of seafood, the AEW is normally frozen before use, and the term AEW ice is often used. AWE ice has been shown beneficial to improve the quality, shelf life, and food safety of several kinds of seafood, including shrimps (Lin et al., 2013; Wang et al., 2014; Zhang et al., 2015; Zhao et al., 2018) and squid (Xuan et al., 2017). Wang et al. (2014) suggested a primary mechanism improving the quality and safety of shrimps. Compared to traditional tap water ice, they reported AEW ice to limit the pH change, shrinkage of muscle fibers, and bacterial growth, whereas no adverse effects were reported on sarcoplasmic proteins. Moreover, they reported cathepsin B and polyphenol oxidase to be partly inhibited by the treatment. The working mechanisms causing the improved quality are not fully understood. However, it is known that chlorine and reactive oxygen can affect cell membranes and cause oxygen damage to DNA (Liao et al., 2018) and that factors such as pH (Park et al., 2004) and the oxidation–reduction potential (Liao et al., 2007) could be of significance. Most likely, there is a combination of mentioned reactions that inhibit bacterial growth and prevent product quality deterioration (Ekonomou & Boziaris, 2021).

4 | HURDLE TECHNOLOGY

When applied individually, most of the aforementioned technologies are not sufficient to ensure food safety and shelf life. Hence, two or more technologies are often combined, either simultaneously or sequentially (Leistner & Gorris, 1995). The utilization of this approach is known as hurdle technology, barrier technology, or combination technology. "Hurdle technology" visualizes those technologies, or hurdles, that individually are to week to hamper spoilage alone. However, it might slow it down and if combined in sufficient numbers and correct height, it will be efficient in inhibiting microbial growth (Ashie et al., 1996). Hurdle technology is often applied to reduce the severity of the individual hurdles, thus lowering the adverse effect on nutritional and/or sensory quality (Tsironi et al., 2020).

The application of multiple technologies in one operation can act in one of three ways: (1) additively, (2) synergistic, or (3) antagonistic (Leistner & Gorris, 1995; Raso & Barbosa-Cánovas, 2003). Ates et al. (2016) found combined HP processing and mild heat treatment and showed a synergistic effect on the inactivation of *L. monocytogenes* as they obtained 6.62-log CFU/g reduction in inoculated fish soup after treatment using 500 MPa at 44°C compared

TABLE 1 Examples of researched hurdle technology combinations for fish products (black), other food products (red), or bacterial samples (blue)

	Modified atmosphere	PEF	Curing	High-pressure processing	UV and pulsed light	Cold plasma	Ohmic heating	Microwave	Mild heat
Superchilling	Hansen et al. (2009); Sivertsvik et al. (2003); Sørensen et al. (2020); Wang et al. (2008)	–	Beaufort et al. (2009); Chan et al. (2020); Lauzon et al. (2009); Midelet-Bourdin et al. (2008)	–	–	–	–	–	–
Mild heat/sous vide	Abel, Rotabakk, and Lerfall (2019); Abel, Rotabakk, Rustad, et al. (2019); Mohan et al. (2017)	Aouir et al. (2015)	Gedela et al. (2007)	Ates et al. (2016); Okozaki et al. (2000); Reddy et al. (1999); Reineke et al. (2011)	Gaýan et al. (2012); Kaya et al. (2015); Walkling-Ribeiro et al. (2008); Bradley et al. (2012); Marquenie et al. (2003)	–		Murashita et al. (2017); Park et al. (2013)	–
Microwave	Lerfall et al. (2018)	–	–		Maktabi et al. (2011)	Kim et al. (2017); Kim et al. (2019)	Choi et al. (2011)		
Ohmic heating	–	–	–	Min et al. (2016); Park et al. (2013)	–	–			
Cold plasma	Olatunde et al. (2020); Yadav et al. (2020)	–	–	–	Colejo et al. (2018); Feizollahi et al. (2021)				
UV and pulsed light	Monteiro et al. (2020); Rodrigues et al. (2016); Hinojosa et al. (2015)	–	Heir et al. (2019); Holck et al. (2018)	Monteiro et al. (2018); Monteiro et al. (2019)					
High-pressure processing	Amanatidou et al. (2000); López-Caballero, Pérez-Mateos, Bonderías, et al. (2000); Rode et al. (2015)	Gudmundsson & Hafsteinsson (2001)	Ekonomou et al. (2020); Erkan et al. (2011); Gómez-Estaca et al. (2007); Gudbjørnsdottir et al. (2010); Montero et al. (2007)						

(Continues)

TABLE 1 (Continued)

	Modified atmosphere	PEF	Curing	High-pressure processing	UV and pulsed light	Cold plasma	Ohmic heating	Microwave	Mild heat
Curing	Goktepe and Moody (1998); Mejlholm and Dalgaard (2007); Muratore and Licciardello (2005); Nilsson et al. (1997); Tsogas et al. (2019)	Cropotova, Tappi, Genovese, Rocculi, Laghi, et al. (2021); Cropotova, Tappi, Genovese, Rocculi, Dalla Rosa, et al. (2021)							
PEF	Chotphruethipong et al. (2019)								

to 2.64-log CFU/g reduction when using same pressure but lower (16°C) temperature, both for 5 min. A similar synergistic effect was reported for combined HP processing and MA packaging of Atlantic salmon (Amanatidou et al., 2000). On the contrary, Heinz and Knorr (2000) demonstrated that the lethality of PEF treatment applied in combination with sublethal HP processing on *Bacillus subtilis* vegetative cells was lower than the lethality of PEF treatment applied alone, thus indicating that HP treatment had a stabilizing effect.

Furthermore, combining processing technologies may facilitate the use of technologies that alone have been found infeasible for seafood, as is the case for ultrasound treatment. With ultrasonication, long processing times are needed to achieve sufficient bacterial inactivation, often resulting in adverse effects on the product (Lee et al., 2009; Sango et al., 2014). However, when combined with heat treatment (<53°C), a process known as thermoultrasonication, it was found to be an efficient processing method for shrimps, increasing the bacterial reduction from 0.6 to up to 4 log CFU/g, as well as reducing the processing time needed (Wang et al., 2013).

MA or other forms of CO_2 are often one of the most used methods in combinations. On the other hand, combinations of SGS with other processing methods are relatively new and have recently been reviewed by Esmaeilian et al. (2021). Rode et al. (2015) showed that use of SGS before HP processing reduced the average amount of *L. innocua* in fish soup by 1.5 log CFU/g, resulting in significantly lower content during storage. Furthermore, Abel, Rotabakk, and Lerfall (2019) showed pretreatment with SGS to cause a significant increase in heat inactivation of *B. thermospacta* compared to sous vide treated samples without SGS. Abel, Rotabakk, Rustad, et al. (2019) investigated the influence of a low-temperature treatment (40, 50, or 60°C) combined with various packaging technologies (MA or SGS) on both the microbial growth and the product quality in general. The study reported improved inhibition of *L. innocua* and highlighted the potential to obtain safe products even at low temperature sous vide treatments such as 40 and 50°C. This is in agreement with findings from milk samples (Loss & Hotchkiss, 2002). Combining MA packaging with superchilling increased shelf life of Atlantic cod from 13 days on ice storage to more than 32 days superchilled in MA packaging (13, 17, 23, and <32 days for iced air, iced MA, superchilled air, and superchilled MA, respectively), highlighting the synergistic nature of the hurdle combination (Sørensen et al., 2020).

An overview of some of the researched hurdle technology combinations in fish and seafood is presented in Table 1. When no research was found regarding fish or seafood, research on other food products or bacterial cultures was included. The addition of natural or artificial preservatives or competitive microbiota is another hurdle often used in combinations. The table shows that multiple knowledge gaps exist regarding combination processing, especially for fish and seafood products. Some combinations are to be considered infeasible solely based on their different working mechanisms. For instance, CP relies on O_2 to produce ozone and other reactive species, which in turn causes the decontamination effect (Patil et al., 2014). On the other hand, MA packaging and SGS rely on the presence of CO_2 and the removal of O_2 to inhibit bacterial growth (Sivertsvik, 2000). Thus, a combination of these methods will probably prove inefficient if applied simultaneously. Other combinations have been proven efficient for other product types, such as pressure-ohmic thawing of beef and meat products (Min et al., 2016), but have not been tested for fish or seafood products.

Application of pressure-ohmic thawing showed a significantly improved quality of the meat compared to other thawing methods, based on texture, DL, and color, and significantly reduced thawing time (Min et al., 2016). Traditional freezing and thawing of seafood products are linked to quality deterioration. Hence, applying pressure-ohmic thawing could help improve the quality and offer an opportunity for long-distance transportation or storage.

Carbon dioxide to limit microbial growth is widely used, and Table 1 shows that effort has been taken to combine the bacteriostatic effect of CO_2 with other mild technologies (Abel, Rotabakk, & Lerfall, 2019; Abel, Rotabakk, Rustad, et al., 2019; Lerfall et al., 2018; Rode et al., 2015). The combination of SGS with other technologies was recently reviewed by Esmaeilian et al. (2021). One of the key findings was that combining dissolved CO_2 with other preservation technologies, as a hurdle technology, considerably enhanced the bacteriostatic effect of the treatments, mostly without compromising the product quality. Moreover, an industrial full-scale SGS concept is under development and will hopefully be available for the industry within a few years (Esmaeilian et al., 2021).

Other trending technologies in the food sector are PEF (Ekonomou & Boziaris, 2021) and HP processing (Ekonomou et al., 2020; Ekonomou & Boziaris, 2021; Shynkaryk et al., 2020). HP processing shows a comparative microbial inactivation to thermal processing, especially at higher pressures. A limitation is that too high pressures reduce the products' sensory and nutritional quality (Esmaeilian et al., 2021). However, as part of a hurdle approach, for example, in combination with CO_2, a considerable potential for the seafood industry exists. The combined effect of PEF with other technologies is attractive due to its potential to inhibit microorganisms and alter structural properties. Table 1 shows several gaps of potential combinations of PEF with other thermal and nonthermal technologies of high interest for further research and industrial applications.

5 | CONCLUSIVE REMARKS AND FURTHER OPPORTUNITIES

The general consumer's demand for minimally processed food is accompanied by shelf life and food safety challenges. Many mild processing technologies based on a variety of different working mechanisms have been developed to meet these challenges. This review on the current status of mild processing technologies and their effect on seafood safety, shelf life, and sensory quality shows that only a few of these technologies have been thoroughly studied and optimized for seafood products. Even fewer have been commercialized in the seafood processing industry. The reason is complex and consists of factors ranging from health, safety, and environmental issues on the processing plant (e.g., SGS) to high operating costs (HP processing), poor penetration depth (PL and UV), challenges due to unwanted color changes (HP processing), and increased product rancidity (CP). However, these challenges could be solved by developing novel technological concepts and/or using mild processing conditions in combination (Table 1). Most mild processing technologies are not sufficient alone to ensure food safety and proper shelf life. Hence more technologies are often combined to meet consumer's expectations and the food safety criteria set by national and international food authorities.

The present review has created an insight into and an overview of combinations of mild processing technologies with potential applications in the seafood industry. However, just as important as showing what is known, it visualizes the knowledge gaps and the potential for new technology developments in the sector (Table 1). Some methods, or combinations thereof, have shown great potential for non-seafood products, yet data are missing for fish and seafood. Table 1 highlights several of these gaps, which include, for example, the combination of mild heating (e.g., sous vide or MW) with more novel technologies such as PEF, PL, SGS, CP, or OH. However, before industrial applications are possible, more research is needed.

With the consumers' growing interest in mildly processed, fresh, and natural seafood options, there could be knowledge and profit from exploring these gaps, both for the academic sector and the industry.

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AUTHOR CONTRIBUTIONS

Nanna Abel performed investigation and wrote the original draft. Bjørn Tore Rotabakk and Jørgen Lerfall supervised the study, and were responsible for editing the manuscript through the first and second revision. All authors conceptualized the idea of the study and reviewed and edited the original manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Nanna Abel https://orcid.org/0000-0002-6102-7915
Jørgen Lerfall https://orcid.org/0000-0001-6243-0880

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