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The use of soluble gas stabilization technology on food – A review

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ABSTRACT

Background: Increasing the shelf life of perishable food products contributes to lower food waste and the possibility of widening distribution outreach in the food value chain. Soluble gas stabilization (SGS) technology is a pre-step process of dissolving carbon dioxide (CO2) into the product before packaging. This technology shows promising results on the lab-scale to limit microbial growth and other deteriorating mechanisms in food products.
Scope and approach: This review aims to gather available research results on the effects of combining SGS technology or dissolved CO2 with thermal and non-thermal processing technologies. The effects are structured according to the microbiological shelf life and safety as well as food quality parameters such as texture, color, drip loss, lipid oxidation, and adenosine triphosphate (ATP) degradation. This paper reviews the SGS effects alone and in combination with conventional food treatments on the parameters mentioned above.
Key findings and conclusions: Improving thermal and non-thermal technologies efficacy meets the demand for better food quality while being more economically feasible. Combining dissolved CO2 with these treatments, as hurdle technology, considerably enhances the bacteriostatic effect of the treatments, mostly without compromising the product quality. However, it is highly dependent on the product kind, treatment method, experiment protocol, and composition and concentration of the product microbiota. Moreover, the extent of positive synergistic effects could be promoted by addressing specific problems such as gas layer formation during sous vide treatment. This paper provides a better understanding of the SGS effectiveness, performing beside conventional food processing technologies, for the full-scale implementation of the technology.

1. Introduction

Food industries are showing a continuous interest in developing technologies to extend the shelf life of products while maintaining nutritional quality and ensuring safety. The prolongation of product shelf life can be achieved by utilizing several different thermal and non-thermal processing technologies. However, each technology alone has its limitations, and since the consumer demand for minimally processed foods is rising (Erkmen & Bozoglu, 2016), promoting their effectiveness is highly demanded by industries.

Thermal processing is a well-established treatment used extensively for food preservation and preparation. This preservative effect is mainly due to the denaturation of proteins, which destroys enzyme activity and enzyme-controlled metabolism in microorganisms (Fellows, 2009). However, thermal technologies tend to reduce product freshness and sensory quality, to some extent, as the price for extended shelf life (Ohlsson & Bengtsson, 2002).

Non-thermal technologies are processing methods for achieving microbial inactivation without exposing foods to the adverse effects of heat. However, these physical methods are hardly effective sufficiently on their own without reducing the sensory and nutritional quality (Ohlsson & Bengtsson, 2002). In addition, some bacteria are reported as becoming more resistant under stress (e.g., psychrotolerant lactobacilli), lowering the effectiveness of non-thermal technologies (Tsironi, Houhoula, & Taoukis, 2020).

Summary of the positive and negative traits of different thermal and non-thermal technologies discussed in this paper is shown in Fig. 1. There is a high demand for reducing the severity of these treatments, thus lowering the adverse effects on nutritional and/or sensory quality. This demand could be satisfied by hurdle technology with comparative

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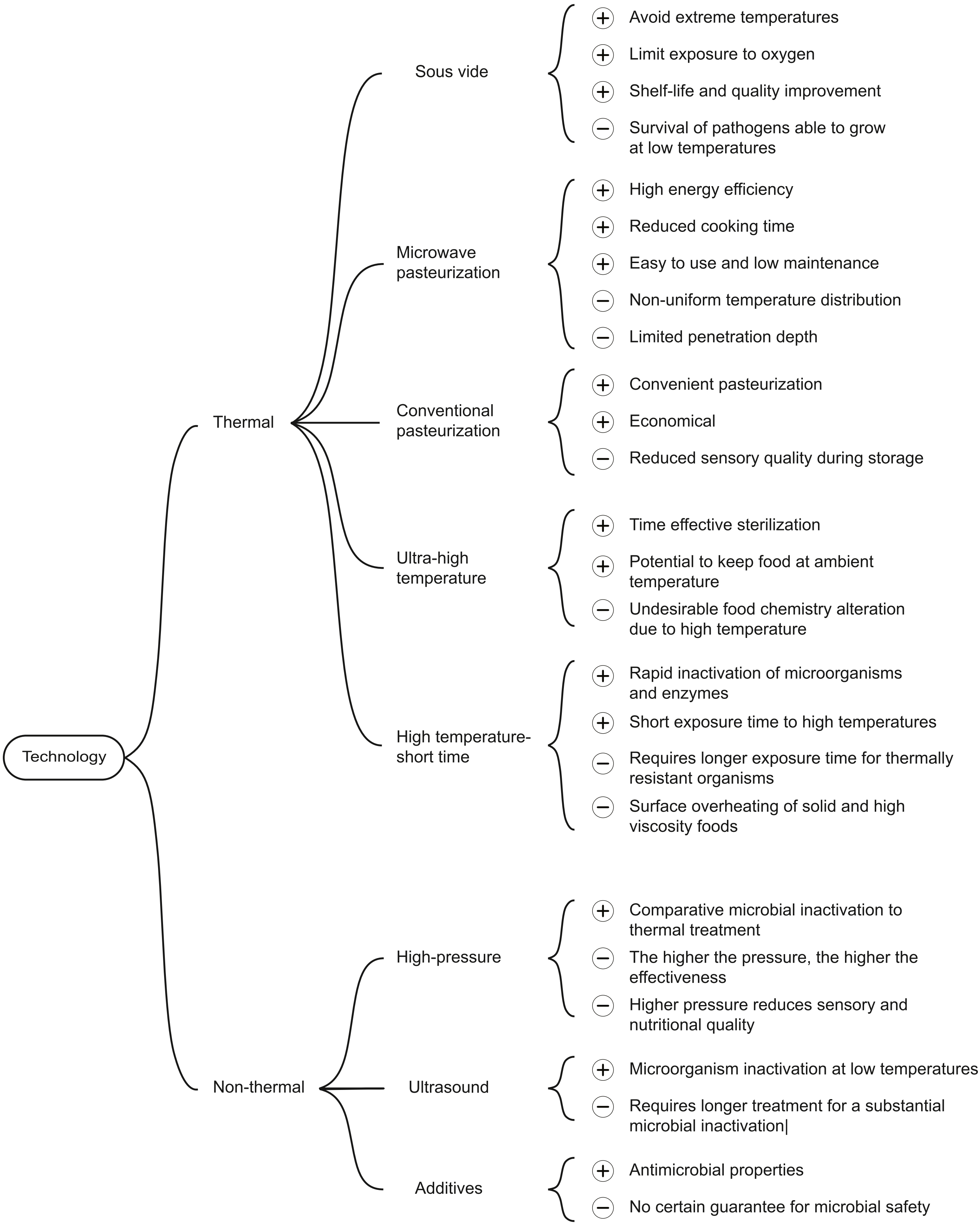

Fig. 1. Summary of the positive (+) and negative (-) traits of the discussed thermal and non-thermal technologies.

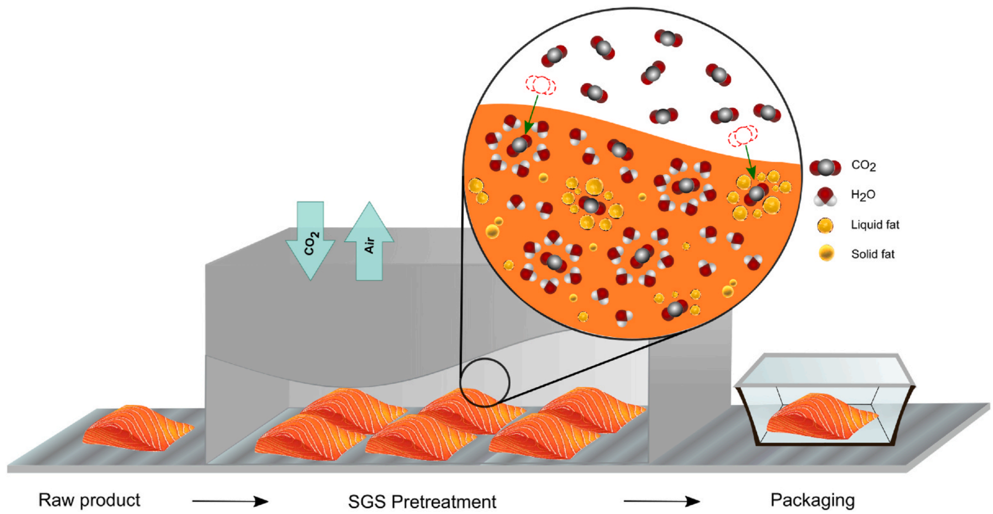

Fig. 2. SGS pretreatment procedure and dissolution of CO_2 into the liquid phase, water and liquid fat of salmon product with approximate pH of 6.1–6.3. For the SGS pretreatment, the atmosphere inside the chamber is evacuated and instead filled with almost 100% food-grade CO_2.

microbial inactivation (Raso & Barbosa-Cánovas, 2003; Tsironi et al., 2020). Intelligent use of hurdle technology combines existing and novel preservation techniques (called hurdles) in order to get maximum lethality against microorganisms and at the same time keep the damage to the sensory and nutritional quality at the minimum (Leistner, 2000).

Soluble gas stabilization (SGS) has been introduced by Sivertsvik (2000) as a novel preservation technology. SGS technology is a pre-step process of dissolving carbon dioxide (CO_2) into the product before packaging (Sivertsvik & Jensen, 2005). This technology relies on the bacteriostatic effect of CO_2, limiting microbial growth and other deteriorating mechanisms in food products (Sivertsvik & Rotabakk, 2012). The bacteriostatic effect of CO_2 is proportional to the concentration of dissolved CO_2 in the food matrix (Devlieghere, Debevere, & Van Impe, 1998). CO_2 is highly soluble in the liquid phase, either in water or liquid fat, depending on the product (Abel, Rotabakk, Rustad, & Lerfall, 2018; Devlieghere et al., 1998). The dissolution of CO_2 in water leads to the formation of carbonic acid, which with its dissociation to bicarbonate and hydrogen ions, causes pH reduction (Chaix, Guillaume, & Guillard, 2014; Daniels, Krishnamurthi, & Rizvi, 1985). However, the dissociation of carbonic acid depends on the hydrogen ion concentration of the solution or the product pH. For the pH lower than 5, CO_2 in solution exists mostly in the form of aqueous CO_2 and, to a small extent as carbonic acid. Between the pH of 8 and 9.5, the carbonic acid dissociates to form the bicarbonate and hydrogen ions (Daniels et al., 1985). The SGS pretreatment procedure and CO_2 dissolution into the aqueous phase of salmon product are illustrated in Fig. 2. Since CO_2 solubility increases at lower temperatures and higher pressures (Sivertsvik, Jeksrud, Vågane, & Rosnes, 2004), a sufficient amount of CO_2 can be dissolved into the product during 1–2 h in pure CO_2 (Rotabakk, Birkeland, Jeksrud, & Sivertsvik, 2006). It has been shown under laboratory conditions that SGS technology is beneficial for improving microbial shelf life and preserving food quality for an extended period, mostly without influencing taste and visual impression (Mendes & Gonçalves, 2008; Rotabakk et al., 2006, 2008). Longer shelf life fulfills the need to transport fresh products over long distances and enables the related industries to reach new future markets. It also contributes to reducing food loss in the food supply chain and providing a secure food supply. Safe, sufficient, and secure food supply is one of the world's leading challenges due to the ever-growing population and the increased need for food globally.

SGS additionally improves modified atmosphere (MA) packaging by providing a higher possible degree of filling (DF), i.e., smaller packages. The problem with MA packaging alone with a high DF is that it requires higher CO_2 partial pressure for an equal amount of dissolved CO_2. Hence, more gas volume reduction and package collapse would occur. SGS by dissolving CO_2 into the product before packaging prevents this compromise between chosen DF and CO_2 partial pressure in MA packaging (Sivertsvik & Birkeland, 2006; Sivertsvik & Rotabakk, 2012). Consequently, SGS can enhance packaging efficiency, reduce distribution costs, and decrease the amount of plastic materials used for packaging. All the aforementioned advantages are intrinsically SGS implications that comply with sustainable food production. So, having SGS technology as an option to combine with conventional treatments for reducing their severity would also be a sustainability-inducing choice.

Several papers have been published dealing with SGS or dissolved CO_2 in combination with thermal treatments (Abel, Rotabakk, & Lerfall, 2019; Abel, Rotabakk, Rustad, Ahlsen, & Lerfall, 2019; Dang, Rode, & Skipnes, 2020; Lerfall et al., 2018; Loss & Hotchkiss, 2002; Vianna et al., 2012) and non-thermal treatments (Abel, Rotabakk, & Lerfall, 2020; Al-Nehlawi, Guri, Guamis, & Saldo, 2014; Birkeland & Rotabakk, 2014; Corwin & Shellhammer, 2002; Dang et al., 2020; Elliott, Tomlins, & Gray, 1985; Ferrentino & Spilimbergo, 2016; Gomez-Gomez, Brito-de la Fuente, Gallegos, Garcia-Perez, & Benedito, 2020; Marchesini et al., 2012; Paniagua-Martínez et al., 2016, 2018; Park, Park, & Park, 2003; Rode, Hovda, & Rotabakk, 2015; Wang, Pan, Xie, Yang, & Lin, 2010; Xu, Azam, Wang, Zhang, & Bhandari, 2019), as a hurdle technology. However, to the best of our knowledge, this is the first review that creates a collection of these studies. In addition, this paper can pave the road for the concept development of SGS as a new technology to be used beside conventional treatments during full-scale implementation. The synergistic effects of SGS in combination with other food treatments on food quality parameters, microbial shelf life, and safety are highlighted.

2. The effect of SGS and dissolved CO_2 on food quality and shelf life

Food quality and shelf life vary according to several parameters such as texture, color, drip loss, lipid oxidation, adenosine triphosphate (ATP) degradation, and microbiological load and composition. Therefore, it is not easy to draw a general conclusion concerning the SGS effects on the quality parameters and shelf life. Furthermore, it depends on the product kind, treatment method, experiment protocol, composition, and concentration of the product microbiota. The mentioned SGS effects discussed as follows may not be valid for all the products or different conditions as various influencers contribute.

2.1. Texture

Some studies have shown a negative correlation between pH and firmness for fish muscle and pre-cooked chicken breast (Dang et al., 2020; Hyldig & Nielsen, 2001). In addition, pH reduction due to CO_2 dissolution has been reported for different products such as fresh red meats and farmed cod (Jakobsen & Bertelsen, 2001; Sivertsvik, 2007). Consequently, an implicit effect of dissolved CO_2 on texture can be inferred. According to Sivertsvik, Jeksrud, and Rosnes (2002), the dissolution of CO_2 in the aqueous phase of fish muscle lowers the pH of muscle proteins and induces a more significant loss of the water-holding capacity (WHC) and consequently loss of succulence. However, studies have found that SGS does not significantly affect the product texture (Mendes & Gonçalves, 2008; Sivertsvik & Birkeland, 2006). One possible explanation is that even if a pH change can occur at the product surface, the carbonic acid does not diffuse to the interior of the muscle, or else diffusion is insufficient to change the overall muscle pH (Mendes & Gonçalves, 2008).

2.2. Color

A high concentration of CO_2 can induce darkening in meat products, which is interpreted based upon the primary formation of metmyoglobin. The accumulation of metmyoglobin at the meat surface is the primary factor leading to meat discoloration during aging (Hur, Jin, Park, Jung, & Lyu, 2013). The CO_2-induced darkening is also reported for Atlantic salmon (*Salmo salar* L.) fillets, which had a darker, more reddish, and yellowish color than vacuum packaged samples (Chan et al., 2021). This darkening effect of CO_2 is more noticeable in red meat than in white meat (Narasimha Rao & Sachindra, 2002). However, the effect of high CO_2 concentration on the color varies depending on the product kind and packaging conditions. For example, some studies reported no effect of CO_2 concentration on the color of low-grade beef and retail meat (Hur et al., 2013; Sørheim, Aune, & Nesbakken, 1997), while some studies found high CO_2 concentration as a color deterioration for meat (Jeremiah, 2001; Viana, Gomide, & Vanetti, 2005).

2.3. Drip loss

O'Keeffe et al. (1981) reported that CO_2 increased the drip loss of fresh beef as it caused a pH reduction in the product. The pH reduction resulted in isoelectric precipitation of some of the sarcoplasmic proteins with a consequent decrease in WHC. Increased CO_2 amount is also found to increase the liquid loss for Atlantic cod (*Gadus morhua*) fillets (Sivertsvik, 2007) and filleted Atlantic salmon (Randell et al., 1999). Increased drip loss could additionally result from snug down, the volume reduction of package headspace. The snug down occurs when the CO_2 in MA packages dissolves into the product, resulting in the volume contraction of the flexible package, which squeezes the product and causes drip loss (Rotabakk et al., 2006). SGS as a pretreatment would counteract this effect by dissolving CO_2 in the product before the packaging (Rotabakk, Birkeland, Lekang, & Sivertsvik, 2008). That agrees with the studies performed by Rotabakk et al. (2008) and Sivertsvik and Birkeland (2006) that reported a drip loss reduction for SGS treated halibut and ready-to-eat shrimp, respectively. WHC is also affected by microbial quality (Jay, 1965), meaning SGS could change the drip loss by influencing the microbial load in the product.

2.4. Lipid oxidation

pH is a contributing factor that affects lipid oxidation as decreased pH can promote the oxidation of deoxymyoglobin to metmyoglobin and increase lipid oxidation. Increased lipid oxidation could also be related to the higher iron solubility at low pH and that heme-protein oxidation is favored at reduced pH. However, all the compounds produced during the lipid oxidation process are not affected by the reduced pH. For instance, the prooxidant effect of ferryl heme-protein is independent of pH (Baron & Andersen, 2002). Accordingly, SGS may increase lipid oxidation by lowering pH. On the other hand, high oxygen levels lead to an increased susceptibility of muscle to lipid oxidation as oxygen plays a key role during this process (Domínguez et al., 2019). So, SGS, on the contrary, could lower lipid oxidation by reducing oxygen accessibility to the product.

2.5. ATP degradation

Postmortem degradation of ATP goes through the intermediate products of adenosine diphosphate (ADP), adenosine monophosphate (AMP), Inosine monophosphate (IMP), Inosine (HxR), and hypoxanthine (Hx). Endogenous enzymes essentially cause ATP degradation. However, the hydrolysis of HxR and formation of Hx may also result from bacterial enzymes (Surette, Gill, & LeBlanc, 1988). Warthesen, Waletzko, and Busta (1980) reported a lower concentration of Hx in fish samples stored in 100% CO_2 than those stored at lower CO_2 concentrations. Hx is responsible for the progressive loss of desirable flavors in stored muscle products (Hong, Regenstein, & Luo, 2015). Özogul, Taylor, Quantick, and Özogul (2000) also showed a lower accumulation of Hx in herring samples held under CO_2 (60%) compared to the herrings kept in ice. Similar results are shown for hybrid striped bass strips packaged in MA with 60% CO_2 (Handumrongkul & Silva, 1994) and deepwater pink shrimp packaged in MA with 40% and 45% CO_2 (Gonçalves, López-Caballero, & Nunes, 2003), which had lower Hx production than those packed in air. Lower Hx content means lower IMP degradation to Hx. That enhances desirable tastes as IMP is associated with pleasant flavors (Hong et al., 2015). Since the Hx formation is also due to microbial activity, lower accumulation of Hx in the presence of CO_2 can be related to the bacteriostatic effect of CO_2 (Gonçalves et al., 2003). On the contrary, López-Gálvez, De La Hoz, Blanco, and Ordóñez (1998) showed no effect of different CO_2 percentages of 20 and 40 on the ATP breakdown products for sole fillets. It demonstrates the product-specificity of the CO_2 effect on ATP degradation.

2.6. Product microbiota

The overall CO_2 effect on product microbiota increases both the lag phase and the generation time of spoilage and pathogenic microorganisms (Daniels et al., 1985) and postpones their recovery from injury (Rode et al., 2015). Devlieghere and Debevere (2000) found a linear relationship between the concentration of dissolved CO_2 in the food matrix and the maximum specific growth rates (μ_{max}) for Gram-negative spoilage bacteria. Growth parameters (μ_{max} and lag phase) of Gram-negative bacteria were more influenced by dissolved CO_2 than Gram-positive bacteria. Nevertheless, inhibition of Gram-positive bacteria such as *Brochothrix thermosphacta* was observed. Due to inter- and intraspecies variation in CO_2-tolerance, the application of SGS or MA packaging will reshape the initial microbiota (Kolbeck, Ludwig, Meng, Hilgarth, & Vogel, 2020). Although many studies have been conducting the bacteriostatic action of CO_2, less is known about the involved mechanisms. Several mechanisms of action have been proposed, such as the replacement of O_2 by CO_2, intracellular pH reduction by dissociation of formed carbonic acid (Daniels et al., 1985), changes in membrane fluidity (Sears & Eisenberg, 1961), and membrane lipid composition (Kolbeck, Kienberger, Kleigrewe, Hilgarth, & Vogel, 2021), direct inhibition of metabolic pathways including decarboxylation reactions and DNA replication (Dixon & Kell, 1989), and loss of intracellular enzyme function (Daniels et al., 1985). Accordingly, SGS would lower the growth of bacteria by increasing CO_2 concentration in the product (Sivertsvik & Birkeland, 2006; Sivertsvik & Rotabakk, 2012). On the other hand, one concern related to the use of CO_2 for food preservation is the regulatory induction of metabolic enzymes by CO_2 or bicarbonate reported for specific pathogens such as *Helicobacter pylori* and *Citrobacter rodentium,* resulting in virulence and toxin production (Park, Ko, & Lee, 2011; Yang et al., 2009).

3. SGS in combination with thermal technologies

3.1. Sous vide processing

Sous vide is a cooking method performed in vacuumed plastic pouches at precisely controlled temperature and time. This method controls the causes of adverse changes in quality, such as exposure to oxygen and extreme temperatures, improving the shelf-life and quality (Zavadlav et al., 2020). Though food can be pasteurized and made safe at low temperatures, the risk of survival and growth of some pathogens, able to grow at low temperatures such as *Listeria monocytogenes* and *non-proteolytic Clostridium botulinum*, is a particular risk in sous vide processing (Ohlsson & Bengtsson, 2002). Consequently, keeping the product safe and durable without compromising the food quality necessitates combining this technique with other innovative technologies (Zavadlav et al., 2020).

Abel, Rotabakk, and Lerfall (2019) found that SGS does not significantly influence the texture and color of sous vide processed Atlantic salmon loins packaged in MA. It was also shown for the combination of SGS and heat treatment at 40 °C, 50 °C, and 60 °C; the higher the temperature, the higher the concentrations of IMP and the lower concentrations of HxR and Hx, at the end of storage. Moreover, SGS did not affect the drip loss. At the same time, it is expected to reduce the drip loss in MA packaging by dissolving CO_2 before the packaging (Rotabakk et al., 2008). The reason could be related to the myosin denaturation during heat treatment, which increased the cook loss, limiting the drip loss later at the storage period (Abel, Rotabakk, Rustad, et al., 2019).

Furthermore, Houteghem et al. (2008) showed that the combination of mild heat treatment and preservation in a CO_2-rich atmosphere extends the lag phase of *L. monocytogenes*. Since the pH reduction can increase the thermal sensitivity of microorganisms and extend the lag phase (Jay, Loessner, & Golden, 2005), the reason may back to the pH reduction due to CO_2 dissolution, which causes an adverse condition for bacterial growth. The synergistic effect of CO_2 and thermal treatment gives SGS the privilege to inhibit bacteria more than MA packaging within the same D-values. Abel, Rotabakk, and Lerfall (2019) showed for fish patties of silver smelt *(Argentina silus)* that the growth of *B. thermosphacta* and *Listeria innocua* was lower in the SGS samples than MA packaged samples at the end of 16 days of storage for applied D-values of 3.5 and 4.5. Similar results were also shown for Atlantic salmon loins (Abel, Rotabakk, Rustad, et al., 2019), where SGS had better inhibition of ingenious microbiota and *L. innocua* at the end of storage compared to MA packaged samples treated with the same temperatures of 40 °C and 50 °C. However, SGS bacteria inhibition is not just limited to this level. Abel, Rotabakk, and Lerfall (2019) also showed for the salmon loins that *Listeria* inhibition of SGS samples heated at 40 °C was comparable to that of MA packaged samples heated at 50 °C, at the end of 24 days of storage. It implies that SGS applies a lower level of thermal treatment with a comparable bacteria inhibition to MA packaging, which is highly demanded concerning fresh and lightly processed foods (Ohlsson & Bengtsson, 2002).

However, during sous vide cooking, a gas layer can be formed surrounding the sample inside the vacuum pouch due to CO_2 desorption at increased temperatures. In other words, the solubility of CO_2 is highly temperature-dependent (Sivertsvik, Rosnes, & Jeksrud, 2004), and heating at high temperatures for prolonged periods decreasing CO_2 solubility, resulting in an isolating gas layer around the sample which reduces heat transfer from the water bath to the product (Abel, Rotabakk, Rustad, et al., 2019). This problem can be highlighted depending on the applied temperature, the exposure time, and bacterial species. For instance, for the fish patties heated with different D-values of 3.5 and 4.5, there was no significant difference in bacteria count during storage time when SGS was used as a pretreatment (Abel, Rotabakk, & Lerfall, 2019). Therefore, it can be inferred that SGS decreases bacteria count at the same level regardless of D-value used for the heat treatment. However, in the other study for the salmon loins, the SGS effect on bacteria inhibition significantly changed in different temperatures (Abel, Rotabakk, Rustad, et al., 2019). Hence, the reason may not be just related to the kind of product or bacteria. One possible explanation could be related to the applied domain of temperature at the exposed time. To be more specific, to assess *L. innocua* growth, for the fish patties, the experiments were applied at temperatures of 60 °C and 64 °C for 15 and 5 min, respectively (Abel, Rotabakk, & Lerfall, 2019). While for the salmon loins, these amounts were 45 °C and 55 °C for 15 and 18 min, respectively (Abel, Rotabakk, Rustad, et al., 2019). Accordingly, maybe the applied degrees of temperature at the exposure times for the fish patties study caused considerable CO_2 desorption as a layer in a way that heat treatment could not be as effective as expected. Ultimately there was no significant difference between the bacteria count of SGS samples treated with different D-values during storage.

Regarding the bacteria that can survive in CO_2 and without O_2 but are sensitive to the temperature, heat transfer during thermal treatment has a key role in the bacterial inhibition. For instance, the ingenious microbiota of salmon loins mainly consists of lactic acid bacteria (LAB), which can survive in an environment with elevated CO_2 concentration (Stiles, 1996). Though Abel, Rotabakk, and Lerfall (2019) showed that the SGS treated salmon loins had a lower count of ingenious microbiota compared to MA packaged samples when both heated at the same temperatures of 40 °C and 50 °C, MA packaging with 50 °C was more effective than SGS with 40 °C to inhibit the growth of this bacteria at the end of storage. When the same temperature is applied during the heat treatment for both MA packaged, and SGS treated samples, the increase in heat sensitivity of the bacteria induced by CO_2 reinforces heat inactivation of ingenious microbiota for SGS samples. Thus, more inhibition resulted even with the presence of a gas layer around the sample. However, this increase in heat sensitivity due to CO_2 dissolution can be surpassed by raising the temperature during the heat treatment of samples packaged in MA, increasing heat transfer directly to the product, and consequently inactivating more of the ingenious microbiota present. Overall, solving the problem concerning the formation of the gas layer during heat treatment offers the advantage of lowering the applied temperature during heat treatment with the potential organoleptic quality improvements. The solution could be applied by increasing the imposed pressure on the product as a counter pressure.

3.2. Microwave volumetric heating (MVH)

Microwave heating is an efficient technique that has attracted much interest from both research and industry in food processing due to its high energy efficiency, reduced cooking time, enhanced product properties, ease of use, and low maintenance. Microwave heating is caused by molecular friction generated by the dipolar rotation of polar solvents like water and the conductive migration of dissolved ions during exposure to electromagnetic radiation. Unlike convection or conduction heating, microwave radiation penetrates directly into the material and generates heat throughout the volume. Therefore, it is called volumetric microwave heating (MVH) (Chandrasekaran, Ramanathan, & Basak, 2013). However, non-uniform temperature distribution and a limited penetration depth are the major drawbacks concerning microwave use for food processing. The efficacy of microwaves to uniformly heat foods depends on the type, size, shape, and temperature of the food and frequency of the microwave (Oliveira & Franca, 2002). By introducing counter pressure during heat treatment, a new lab-scale microwave oven is developed to avoid such limitations (Rosnes & Skipnes, 2017).

Lerfall et al. (2018) found SGS did not negatively affect the firmness and drip loss during storage for pasteurized Atlantic salmon loins packaged with vacuum. These results agree with Dang et al. (2020), which found no significant difference in texture between MVH-SGS and MVH pre-cooked chicken breasts, either right after processing or during storage. There was also no significant difference in drip loss between these two groups right after processing. However, the drip loss of MVH samples slightly increased over the storage time, while those treated by SGS had a stable low drip loss. The squeezing effect of vacuum packaging causing increased drip loss (Payne, Durham, Scott, & Devine, 1998), can explain the slightly increased drip loss in MVH chicken breasts. In addition, more differentiation in drip loss was observed in the MVH samples, showing more muscle structure changes in the product. Finally, both MVH-SGS and MVH chicken breasts shared a comparative pH during storage.

Moreover, Lerfall et al. (2018) found no significant difference in color in terms of $L^*a^*b^*$ between the MVH-SGS and MVH salmon loins. Even though the Duncan comparison test did range MVH samples to be more reddish (higher a^*-value) than MVH-SGS ones, the use of CO_2 affected the reflection properties and, in turn, the visual perception of the salmon loins to a more reddish hue. Consumers perceive the more reddish salmon as fresher, with better flavor, higher quality, and higher price (Anderson, 2000). Dang et al. (2020) also showed that SGS did not negatively affect the color in terms of $L^*a^*b^*$ for the precooked chicken breasts. However, SGS lowered the lightness of samples at day 0 due to CO_2-induced darkening. Nonetheless, no significant difference was observed at the end of storage as the lightness of MVH-SGS samples significantly increased while that of MVH samples decreased. The MVH-SGS pre-cooked chickens were found to be less reddish (lower a^*-value) at the end of storage. The reason can be related to the negative interrelation found between lipid oxidation and a^*-value for pre-cooked chicken. This negative interrelationship between lipid oxidation and redness is also reported for chevon cuts and restructured meats, suggesting that pigment oxidation can catalyze lipid oxidation and vice versa (Akamittath, Brekke, & Schanus, 1990; Kannan, Kouakou, & Gelaye, 2001). The lipid oxidation of MVH-SGS precooked chickens increased more during storage compared to that of MVH ones. According to Dang et al. (2020), it is due to the CO_2 gas stabilization, which generated compounds that temporarily reacted with precooking-induced oxidative products. However, these oxidative products were released gradually, combined with newly generated Malondialdehyde (MDA), showing higher values of mg MDA/kg sample during storage. MDA is one of the most important secondary compounds derived from lipid oxidation process. It has the largest contribution to volatile flavors in meat even at low amounts (Domínguez et al., 2019). Concerning sensory quality, there was no significant difference in the overall acceptability of the judges between MVH and MVH-SGS salmon loins after 12 days of storage. However, the judges did score MVH samples (5.0/9) slightly higher than those pretreated with SGS (4.9/9). The observed taste of CO_2 (tingling) was almost ignorable for MVH-SGS samples.

Regarding the SGS effect on product microbiota, Lerfall et al. (2018) found that SGS has a considerable potential to inhibit the bacteria in MVH salmon loins. The growth of bacteria analyzed by aerobic plate counts (APC), psychotropic aerobic plate counts (PC), and lactic acid bacteria (LAB) counts was significantly lower in MVH-SGS salmon loins than MVH samples during 24 days of storage time. Although the microbial inhibition of MVH was not negligible for the short storage period of 6 days, the bacteriostatic effect of SGS acted in a conspicuously significant way for the rest of the storage time of 24 days. Moreover, the maximum specific growth rate of APC, PC, and LAB in the MVH-SGS samples was almost half of that in the MVH ones. Even though there was no significant difference in maximum population density between the samples, it was reached much sooner in MVH salmon loins (at day 19) than in MVH-SGS samples (at day 24). In MVH samples, several potential spoilage organisms, namely sulfite-reducing bacterial spores, Enterobacteriaceae, *Pseudomonas* spp., and *B. thermosphacta*, were detected. In the MVH-SGS samples, these were inactivated. In total, the combination of MVH and SGS enhanced the microbiological shelf life of salmon loins compared to MVH alone. Dang et al. (2020) also showed for precooked chicken that SGS improved LAB inhibition of MVH. However, the synergetic effects on microbial quality were insignificant during storage. High bacterial load variation in SGS treated samples and unequally CO_2 absorption throughout the chicken samples (Dang et al., 2020) could cause this insignificant synergistic effect, impeding bacteriostatic effect of SGS.

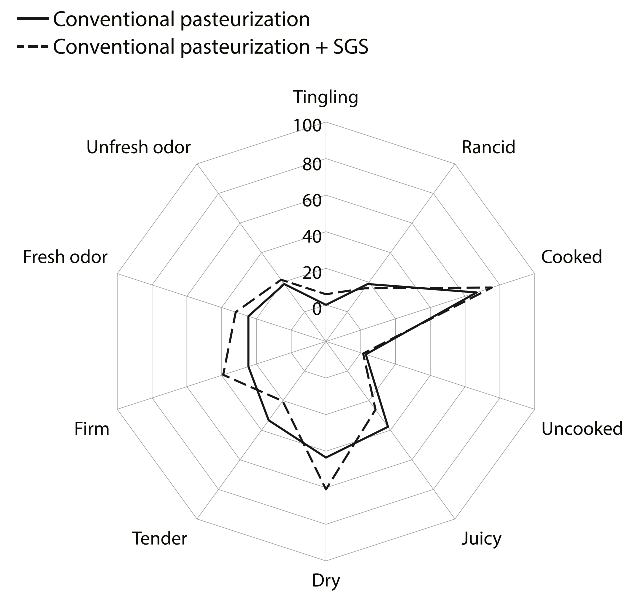

Fig. 3. Spider plot showing the mean score (%) of respondents (n = 69) for sensory characteristics of conventional pasteurized Atlantic salmon loin pretreated with or without SGS, after 12 days of storage time.*significant levels with $p < 0.05$. (Adapted from (Lerfall et al., 2018)).

3.3. Conventional pasteurization

From the industrial perspective, conventional pasteurization with an autoclave is an economical processing technology and an easy way for pasteurization. During heat treatment without an autoclave, low pressure may produce a dead space between the food and the package that will insulate the food. Autoclave provides a counter-pressure and a temperature distribution that are much better at low temperatures (<90 °C) compared to other alternative technologies for thermal treatment (Skipnes, 2014). The induced counter pressure is significant for heat transfer when the SGS step is used before heating (Rosnes & Skipnes, 2017).

Lerfall et al. (2018) found SGS not to influence the firmness and drip loss of pasteurized Atlantic salmon loin packaged with vacuum. Furthermore, no significant difference in color in terms of $L^*a^*b^*$ was shown between SGS and non-SGS samples. However, the Duncan comparison test ranged the SGS samples to be less reddish (lower a^*-value) than those packaged in vacuum only. Nonetheless, by analyzing the reflection on the pasteurized samples, it was demonstrated that the use of CO_2 affects the visual perception to a more reddish hue, which is more acceptable for consumers. SGS was also found to reduce the fillet juiciness and tenderness in a consumer study (Fig. 3), which is not consistent with consumer preferences regarding meat quality (Font-i-Furnols & Guerrero, 2014). The reason could be related to the pH reduction due to CO_2 dissolution into the product during SGS pretreatment, which causes fish meat to be firm, dry, and harsher (Hyldig & Nielsen, 2001). In total, judges scored non-SGS pasteurized samples (4.7/9) higher overall acceptability than those pretreated with SGS (4.4/9), which shows a weak effect of SGS on this characteristic. In addition, the tingling taste of CO_2 was almost ignorable to the judges. Concerning the microbiota inhibition, SGS caused too much stress on *Aeromonas* spp. to recover and regain viability in the salmon loins.

Table 1
Effects of SGS or dissolved CO2 on quality parameters of food products treated with thermal treatments. The overview contains product kind, thermal treatment type, and different food quality parameters. Positive and negative effects are designated by + and - signs, respectively. If there was no effect, the symbol _ is used. If the parameter was not investigated, it is left blank.

Product	Treatment	Quality parameters					Reference
		Lipid oxidation	Texture	Color ($L^*a^*b^*$)	Drip loss	Sensory properties	
Atlantic salmon (*Salmo salar* L.) loin	Sous vide		_	_	_		Abel, Rotabakk, Rustad, et al. (2019)
	Microwave pasteurization		_	_	_	_	Lerfall et al. (2018)
	Conventional pasteurization		_	_	_	$\downarrow^{-}$	Lerfall et al. (2018)
Precooked chicken breast	Microwave pasteurization	$\uparrow^{-}$	_	_	$\downarrow^{+}$		Dang et al. (2020)
Milk	Ultra-high temperature					$\uparrow^{+}$	Vianna et al. (2012)
	High temperature-short time					$\uparrow^{+}$	Loss and Hotchkiss (2002)

3.4. Ultra-high temperature processing (UHT)

The ultra-high temperature (UHT) treatment for a short time can effectively sterilize the product, causing a bacteriologically stable product at ambient temperature when packaged aseptically (Datta & Deeth, 2001). The high quality of UHT foods is on par with chilled and frozen foods, besides its advantage of a shelf life of at least six months without refrigeration. However, the high temperature during UHT may cause undesirable changes to the chemistry of some foods (Fellows, 2009).

Vianna et al. (2012) found a reduction in pH during storage for both UHT milk and UHT milk treated by CO_2, with no significant difference between them. The pH reduction, in general, backs to the produced acids by the Maillard reaction, breakdown of lactose, the dephosphorylation of casein, and proteolysis (Gaucher, Mollé, Gagnaire, & Gaucheron, 2008). A lower rancid flavor and bitter taste were also shown for UHT milk treated by CO_2 than UHT milk alone (Vianna et al., 2012). Since the sensory defects in UHT milk occur due to bacterial activation (Datta & Deeth, 2001), CO_2 microbial inhibition improves the product quality. Furthermore, as UHT's quality is directly related to the raw product quality (Vianna et al., 2012), enhancing product quality before UHT processing can offer a final product with much better quality. In conclusion, adding CO_2 to a product before the UHT processing could alleviate the compromised quality resulted from the heat treatment.

Even though UHT can inactivate microorganisms and enzymes to some extent, it cannot destroy the more heat-resistant species, which may limit product shelf life (Fellows, 2009). However, treatment with CO_2 is suggested by several studies to control the growth of psychrotrophic bacteria (PB), which is the producer of heat-resistant extracellular enzymes such as proteases in milk (Ma, Barbano, & Santos, 2003; Martin, Werner, & Hotchkiss, 2003). Heat-stable protease can lead to proteolysis, which causes age gelation in milk and reduces the quality and shelf life (Datta & Deeth, 2001). Vianna et al. (2012) showed that UHT heated milk without CO_2 treatment had a high microbial protease activity during the storage time, which caused a significant increase in proteolysis compared to the treated UHT milk with CO_2. In other words, CO_2 could benefit the physicochemical quality of UHT-treated products by inhibiting microorganisms and enzymes, which limit the shelf life. On top of that, an increase in temperature can enhance the antimicrobial effects of CO_2 (Erkmen, 2000). Together, a synergistic effect against microorganisms has been observed.

3.5. High temperature-short time (HTST) pasteurization

High temperature-short time (HTST) pasteurization can overcome or minimize undesirable quality changes resulting from thermal treatment by rapid inactivation of microorganisms and enzymes with higher temperatures within a short time duration (Ohlsson & Bengtsson, 2002). However, HTST and holding times are often increased beyond that required by legal pasteurization in an attempt to reduce the number of spoilage organisms, especially thermally resistant kinds (Loss & Hotchkiss, 2002). Moreover, HTST is not efficient for all kinds of

Table 2
Studies reporting combinations of SGS or dissolved CO2 with different thermal treatments and its effects on food product's microbial load and quality parameters. The overview contains thermal treatment type, product kind, and main findings. SGS= Soluble gas stabilization, WHC = water holding capacity, MVH = microwave volumetric heating, UHT = ultra-high temperature.

Thermal Treatment	Product	Main Findings	Reference
Sous vide	Fish mince patties of silver smelt (*Argentina silus*)	SGS combined with sous vide significantly increased the bacterial inhibition, decreased the growth of both *Brochothrix thermosphacta* and *Listeria innocua*, extended their lag phase, fulfilling the consumers' demand for fresh, lightly processed seafood with a prolonged shelf life	Abel, Rotabakk, and Lerfall (2019)
	Atlantic salmon (*Salmo salar* L.) loin	SGS increased product shelf life significantly, decreased the growth rate of *Listeria innocua* and endogenous microbiota, and prolonged their lag phase without having any negative effect on the quality parameters of WHC, drip loss, surface color, and texture	Abel, Rotabakk, Rustad, et al. (2019)
Microwave pasteurization	Atlantic salmon (*Salmo salar* L.) loin	SGS increased product shelf life without negatively affecting the liquid loss, texture, color, and sensory properties as compared to samples heated in microwave alone in vacuum-packages	Lerfall et al. (2018)
	Precooked chicken breast	The synergetic effects of SGS with MVH on microbial and physicochemical quality were insignificant. MVH-SGS samples had higher lipid oxidation compared to MVH ones during storage	Dang et al. (2020)
Conventional pasteurization	Atlantic salmon (*Salmo salar* L.) loin	SGS increased product shelf life without negatively affecting the liquid loss, texture, and color. However, in a consumer study, SGS samples were judged less juicy and tender while firmer and drier compared to non-SGS ones	Lerfall et al. (2018)
Ultra-high temperature	Milk	The addition of CO_2 to raw milk benefited the microbial and physicochemical quality, resulting in a product with less proteolysis and possibly longer shelf life, which is usually limited by the age gelation of UHT milk	Vianna et al. (2012)
High temperature-short time	Milk	The addition of CO_2 to milk could be used as a processing aid to enhance microbial inactivation during pasteurization	Loss and Hotchkiss (2002)

products such as solid and high viscosity foods due to surface overheating, which can counterbalance the HTST advantages (Ohlsson & Bengtsson, 2002).

The heat resistance of microorganisms tends to increase as the incubation temperature increases, which is especially true for spore formers (Jay et al., 2005). So, it does not seem rational and financially effective to increase the temperature until reaching the required bacterial inhibition level. Thus, the survival of a significant number of spore-forming PB during pasteurization can limit the shelf life of HTST treated milk products (Meer, Baker, Bodyfelt, & Griffiths, 1991). Loss et al. (2002) showed for CO_2 treated milk a decrease in thermal survival rates (D-values) for *Pseudomonas fluorescens* R1-232, a reprehensive of one of the most common spoilage organisms in milk, and *Bacillus cereus* ATCC 14579 spores, a thermal resistant organism. This decrease was also positively correlated with CO_2 concentrations. Besides, a significant reduction in the number of surviving standard plate count (SPC) organisms was found in the milk heated over the range of 67–93 °C and treated with different concentrations of CO_2 ranging from 44 to 58 mM. These results suggest that CO_2 could be used as a processing aid to increase the thermal sensitivity of microorganisms, enhancing microbial inactivation during pasteurization.

Table 1 summarizes the SGS or dissolved CO_2 effects on different quality parameters of products treated with thermal treatments. In addition, the summary of reviewed papers for the combination of SGS or dissolved CO_2 with different thermal treatments is presented in Table 2.

4. SGS in combination with non-thermal technologies

4.1. High-pressure processing (HPP)

High-pressure processing (HPP) is one of the most promising non-thermal processing technologies in which foods will be subjected to high pressures ranging from 100 to 1000 MPa at low or ambient temperatures. This process is directed to inactivate microorganisms and enzymes without the degradation in flavor and nutrients associated with traditional thermal processing. Nonetheless, this technology, on its own, is more effective at intensities that may affect the sensory and nutritional quality (Kruk et al., 2011). In this sense, the barotolerance of bacteria is an important parameter for pressure treatment, and it varies largely depending on the species and treatment conditions (Alpas et al., 1999). Consequently, to improve HPP efficacy, it is necessary to reduce the operating pressure or dwell time and, in turn, the processing costs (Wang et al., 2010).

Dang et al. (2020) found no significant difference in the texture of HPP and HPP-SGS precooked chicken breasts after processing and during storage. Moreover, a low amount and stable drip loss during storage were observed for HPP and HPP-SGS samples. The reason may go back to the cooking before the treatments, which caused the most water loss (Dang et al., 2020). Kong, Tang, Lin, and Rasco (2008) also reported for chicken breast that most cook loss during heating at 121 °C occurred during the first 20 min (26.2%), and more prolonged cooking did not significantly change the cook loss. Consequently, combining SGS with HPP would not make any difference in drip loss of precooked chicken products during storage. As for the drip loss, HPP and HPP-SGS samples shared a relatively comparable pH during storage time. Therefore, neither of the HPP-SGS and HPP treatments did affect the pH of precooked chickens during the storage period. However, Rode et al. (2015) showed that HPP treatment alone increased pH in fish soup compared to untreated samples, which was directly proportional to the introduced pressure. A significant increase in pH was also seen for HPP-SGS fish soup samples after storage, probably due to the bacterial growth reduction.

Regarding the color, Dang et al. (2020) found SGS to reduce the lightness of precooked chickens considerably at day 0 due to CO_2-induced darkening. However, this sensitivity of lightness to SGS was prolonged just for a short storage time (14 days), and there was no significant difference in color in terms of $L^*a^*b^*$ between the HPP and HPP-SGS samples at the end of storage (119 days). As another quality parameter, lipid oxidation increased substantially for both HPP and HPP-SGS precooked chickens over the storage time. However, HPP treated samples oxidized least. Thus, although SGS suppressed MDA right after processing, it promoted a greater development rate of MDA during refrigerated storage. According to Dang et al. (2020), the possible explanation for instant MDA suppression in SGS samples could be related to the almost absence of oxygen during SGS pretreatment. It stopped primary oxidative products (e.g., hydroperoxides) from reacting with oxygen to form secondary oxidative products (e.g., MDA). In addition, the CO_2 gas stabilization generated compounds that temporarily reacted with precooking induced oxidative products, making mg MDA/kg low at day 0. The oxidative products were nevertheless released gradually, combined with newly generated MDA showing higher values during storage time.

HPP is known to induce injury and inactivate bacteria, depending on the level of pressure. The higher pressure used during exposure, the more bacterial inactivation effect irrespective of pre-treatment, packaging, and storage time (Rode et al., 2015). Combining dissolved CO_2 with HPP provides this opportunity to have comparable microbial inhibition in lower pressures (Al-Nehlawi et al., 2014). In this combination, bacteria death and membrane damage correlate with the CO_2 enrichment and penetration of the membrane under pressure (Park et al., 2003; Wang et al., 2010). Enrichment of CO_2 on the cell surface promotes pressure-induced cell membrane permeabilization and can result in membrane damage and cell death. Scanning electron microscopy (SEM) images also showed seriously deformed microbial cells in broth cultures after synergistic treatment of HPP and CO_2, while the cells treated with HPP alone had a relatively smooth surface with invaginations (Wang et al., 2010).

Furthermore, reduced pH due to CO_2 dissolution may alter enzyme conformations and membrane permeability, increasing the susceptibility of bacteria to high pressures (Koseki & Yamamoto, 2006). This synergistic effect can inhibit the microorganisms with a high level of barotolerance under pressure alone, making HPP treatment more economically feasible (Wang et al., 2010). In addition, several studies have reported recovery of damaged bacteria within hours to several weeks after treatment with HPP (Bull, Hayman, Stewart, Szabo, & Knabel, 2005; Koseki, Mizuno, & Yamamoto, 2007). Rode et al. (2015) showed that with CO_2 present, the surviving and injured *L. innocua* in fish soup will have more difficulties growing and repairing.

Additionally, an increase in pressure enhances the antimicrobial effects of CO_2 (Erkmen, 2000). To be more specific, when high pressure is applied, the cell membrane is damaged, and consequently, a higher amount of CO_2 can penetrate the cell, causing more lethal effect on microorganisms (Al-Nehlawi et al., 2014; Park et al., 2003). So, this synergistic effect can be used as a leverage point to inhibit the bacteria, especially those that can survive in the presence of CO_2. For instance, Erkmen (2000) showed a combination of CO_2 at relatively low pressures (<6 MPa) affects reducing *L. monocytogenes*. Several studies have also assessed this synergistic inhibition effect on different bacterial species. For instance, Rode et al. (2015) showed for fish soup that SGS without HPP did not give any additional bacterial inhibition compared to other untreated samples packaged by vacuum or MA. While SGS in combination with pressure significantly restrained the growth of *L. innocua* during storage. Al-Nehlawi et al. (2014) also showed that the poultry sausages packaged in the CO_2 atmosphere and treated with HPP had considerably better bacterial inhibition during storage time than samples packaged with CO_2 alone. In addition to this synergistic effect, pressure can reinforce the interaction between SGS and MA packaging, which improves the SGS inhibitory effect as there would be a higher amount of dissolved CO_2 in the product (Rode et al., 2015). Rode et al. (2015) found no interaction between SGS and MA packaging for untreated fish soup, while a significant interaction was shown with pressure, which decreased considerably the number of *L. innocua* in the samples during storage.

Depending on the bacteria, product type, and the experiment protocol, the synergetic inhibition effects of SGS with HPP on microorganisms can be insignificant. For instance, this observation is reported for TVC and LAB in pre-cooked chicken breast (Dang et al., 2020), *Salmonella enteritidis,* a CO_2 resistant bacteria*,* and *Campylobacter jejuni*, a high-pressure sensitive bacteria, in poultry sausage (Al-Nehlawi et al., 2014), *Escherichia coli* in the culture of trypticase soy broth (Corwin & Shellhammer, 2002), and *Bacillus subtilis*, a spore-forming bacteria, in broth culture (Park et al., 2003). In addition, SGS may not cause any additional microbiostatic effect to HPP during high-pressure processing. For example, Rode et al. (2015) showed for fish soup that applying SGS had no significant additional effect on the microbial inhibition during HPP treatment as there was no considerable difference in the number of survived *L. innocua* at day 0 between SGS-HPP and HPP samples. Nonetheless, the synergetic effect of SGS and HPP was significant over the storage time.

4.2. Ultrasound

Ultrasound is an innovative technology that has attracted much attention in the food industry due to its ability to inactivate microorganisms and enzymes at low temperatures without changing the sensory and nutritional quality. Ultrasound generates acoustic cavitation in a liquid medium, which involves the formation, growth, and rapid collapse of microscopic bubbles (Rastogi, 2011). This cavitation phenomenon can change physical properties, catalyze chemical reactions, improve mass transfer processes (Rastogi, 2011), promote the freezing process (Xu et al., 2019), and cause mechanical damage for microbial inactivation (Piyasena, Mohareb, & McKellar, 2003) in food products. However, despite all the advantages that ultrasound can offer, an extended treatment would be needed for a substantial microbial inactivation (Piyasena et al., 2003).

Ultrasound effectively promotes the freezing process for liquid and solid foods. A higher freezing rate forms much smaller ice crystals, reducing damages to the food tissue with better preservation of the original quality. This ultrasound function results from the violent collapse of bubbles, reinforcing instantaneous nucleation. Moreover, turbulence flow caused by the movement of the cavitation bubbles can also act as a driving force for the commencement of nucleation (Kiani, Zhang, Delgado, & Sun, 2011). Infused CO_2 significantly decreases the freezing time and ice crystal size of the nucleation initiated by ultrasound due to the high solubility of CO_2 in water (Xu et al., 2019). Xu et al. (2019) showed the synergistic effect on the nucleation when the infused CO_2 and ultrasound were applied on gelatin gel samples simultaneously. The pre-existing CO_2 bubbles in the gelatin gel samples facilitated nucleation, suggesting that the infused CO_2 treatment favors ultrasound-initiated nucleation. So, the synergistic effect of combined CO_2 with ultrasound can improve the freezing rate and minimize the ice crystal size by ultrasound treatment, offering a frozen product with much better final quality. The ultrasound technology can also be used to improve milk sanitization and shelf life (Piyasena et al., 2003). However, treating milk with ultrasound leads to specific changes in the composition and quality, namely significant increases in oxidation, free fatty acid levels, and burnt off-flavor. The addition of CO_2 significantly reduces the disruptive effect of ultrasound by lowering the intensity and duration of the ultrasound treatment. Dissolved CO_2 decreases the burnt off-flavor and the formation of lipid oxidation products in milk, whereas the sour flavor can be increased (Marchesini et al., 2012).

Ultrasound has also shown a significant potential to inactivate microorganisms in food products, particularly liquid foods. However, this technology is not very effective alone (Piyasena et al., 2003), and a prolonged treatment would be needed for a substantial microbial inactivation, which can compromise the food quality. Using lethal effects of CO_2 on bacteria could be a solution to this problem. Moreover, the violent collapse of microbubbles in the succeeding compression cycles of a propagated sonic wave results in localized high temperatures, pressures, and significant shearing effects (Paniagua-Martínez, Mulet, García-Alvarado, & Benedito, 2018). Thus, high-power ultrasound, ultrasound of low frequency and high intensity can synergistically improve the inactivation mechanisms of supercritical CO_2 (Ortuño, Martínez-Pastor, Mulet, & Benedito, 2013). Supercritical CO_2 has a density close to liquid CO_2 and similar diffusivity and solubility to those of a gas, resulting in an improved dissolving capacity and transport properties (Paniagua-Martínez et al., 2018). So, with the combination of supercritical CO_2 and high-power ultrasound, an increase is produced both in the solubilization rate of supercritical CO_2 in the liquid and the mass transfer due to the vigorous stirring produced by the ultrasonic field (Paniagua-Martínez et al., 2016). Thereby, a quick CO_2 saturation in the medium is achieved, intensifying the inactivation mechanisms.

Furthermore, cavitation and agitation produced by the high-power ultrasound can cause cell wall damage, increasing the supercritical CO_2 penetration, the intracellular compound extraction, and the death of microbial cells (Paniagua-Martínez et al., 2018). Paniagua-Martínez et al. (2018) showed the effectiveness of this combination for microbial inactivation in orange juice. Complete inactivation was obtained for *E. coli* and total aerobic mesophilic bacteria, and a 99.7% reduction for *Saccharomyces cerevisiae*. In another study, a high capacity of the combination was also demonstrated to inactivate *S. cerevisiae* in apple juice (Paniagua-Martínez et al., 2016). Consequently, combined supercritical CO_2 and high-power ultrasound synergistic effect offers effective microbial pasteurization, improving food safety and quality by providing mild process conditions. Several studies have also reported the synergistic effects of this combination on microbial shelf life and safety for different products, such as cooked ham and soybean oil-in-water emulsions (Ferrentino & Spilimbergo, 2016; Gomez-Gomez et al., 2020).

4.3. Additives

Additives are the compounds added to food products to protect against food quality deterioration due to their antimicrobial properties. These compounds include traditional additives either alone or in combination, namely sodium chloride (NaCl), organic acids (acetic and citric acid), salts of organic acids (citrates, acetates, diacetates, lactates, sorbates, phosphates, pyrophosphates), sodium benzoate, and ethylenedinitrilotetraacetic acid (EDTA) (Fletcher, 2012). NaCl, commonly known as salt, is a widely used additive in the food industry due to its preservation and antimicrobial properties provided by its ability to reduce water activity. However, it does not ensure microbial safety on its own (Kim, Cho, & Rhee, 2017). CO_2 solubility in aqueous salt solutions usually decreases when the salt concentration increases (Schumpe, Quicker, & Deckwer, 1982), ascribed to changes in the water fraction caused by the increased electrolyte concentration (Chaix et al., 2014). For SGS treated Atlantic salmon injected with brine, Abel et al. (2020) showed that the increased NaCl concentration raises the product's water content, making ground for the higher solubility of CO_2.

Nonetheless, as the increased amount of water is bound and not free (Ruusunen & Puolanne, 2005), it was no longer available for CO_2 uptake. This effect, however, was only perceptible over more extended periods of storage (Abel et al., 2020). Furthermore, the SGS effect of increasing CO_2 concentration outnumbered the negative effect of NaCl, giving potentially better microbial inhibition and thereby longer shelf life due to the combined effect of NaCl and CO_2. This agrees with the study of Birkeland and Rotabakk (2014) regarding Atlantic cod mince packaged in MA where SGS-NaCl samples had a significantly lower load of PC and APC than those treated with NaCl only. Moreover, with adding sodium lactate (NaL) premix to the samples, both NaL and SGS had a bacteriostatic effect on APC and PC, but no interaction was observed. So, SGS pretreatment before packaging in MA could successfully be used as an alternative to adding NaL to increase microbiological shelf life without compromising food quality. Elliott et al. (1985) also found that combining potassium sorbate up to 2.5% with 100% CO_2, even at the

Table 3
Effects of SGS or dissolved CO2 on quality parameters of food products treated with non-thermal treatments. The overview contains product kind, non-thermal treatment type, and different food quality parameters. Positive and negative effects are designated by + and - signs, respectively. If there was no effect, the symbol _ is used. If the parameter was not investigated, it is left blank.

Product	Non-thermal treatment	Quality parameters						Reference
		Lipid oxidation	Texture	Color ($L^*a^*b^*$)	Drip loss	Sensory properties	Ice crystal size	
Precooked chicken breast	High-pressure processing	$\uparrow^{-}$	_	_	_			Dang et al. (2020)
Milk	Ultrasound	$\downarrow^{+}$				$\uparrow^{+}$		Marchesini et al. (2012)
Gelatin gel	Ultrasound						$\downarrow^{+}$	Xu et al. (2019)

Table 4
Studies report a combination of SGS or dissolved CO2 with non-thermal treatments and its effects on microbial load and quality parameters or medium microbial load. The overview contains non-thermal treatment type, product kind, and main findings. SGS= Soluble gas stabilization, PME = pectin methylesterase, PPO = polyphenol oxidase, HPP = high-pressure processing, MDA = Malondialdehyde, NaCl = sodium chloride, PC = psychrotrophic counts, APC = aerobic plate counts.

Non-thermal Treatment	Product/Medium	Main Findings	Reference
High-pressure processing	Broth culture	CO_2 and HPP had a significant interaction when inactivating PME, PPO, and *lactobacillus plantarum* bacteria. However, no significant effect on *Escherichia coli* survivors was observed with CO_2 addition	Corwin and Shellhammer (2002)
	Broth culture	Combined CO_2 treatment and HPP had a synergistic inactivation effect on *Staphylococcus aureus, Fusarium oxysporum,* and *Fusarium sporotrichioides* microorganisms while *Bacillus subtilis* was not completely inactivated after the combined treatment	Park et al. (2003)
	Broth culture	The combined treatment of dissolved CO_2 and HPP had a strong bactericidal effect on *Staphylococcus aureus* and *Escherichia coli* microorganisms, which usually have high levels of barotolerance under pressure alone. This synergistic effect promoted pressure-induced cell membrane permeabilization greatly	Wang et al. (2010)
	Poultry sausages	Combined CO_2 treatment and HPP had a synergistic effect against *Leuconostoc carnosum*, and *Brochothrix thermosphacta* microorganisms except in *Salmonella enteritidis* and *Campylobacter jejuni*. This combination making HPP more economically feasible as the pressure could be lowered without compromising the reduction of microbial counts	Al-Nehlawi et al. (2014)
	Fish soup	SGS showed a significant interaction with pressure. This combination significantly inhibited the growth of *Listeria innocua* compared to non-SGS samples during storage	Rode et al. (2015)
	Precooked chicken breast	The synergetic effects of SGS with HPP on microbial and physicochemical quality were insignificant. SGS-HPP and HPP shared relatively comparable color, texture, pH, and drip loss. SGS instantly suppressed MDA at day 0 but higher lipid oxidation was shown for SGS samples compared to non-SGS ones during storage	Dang et al. (2020)
Ultrasound	Milk	The addition of CO_2 significantly reduced the disruptive effect of ultrasound, the formation of oxidation products, and the detection of the burnt off-flavor	Marchesini et al. (2012)
	Orange juice	Combined supercritical CO_2 and high-power ultrasound technology was effective for microbial pasteurization. The mild process conditions used could lead to an increase in the juice quality. The synergistic effect of this combination caused a complete inactivation for *Escherichia coli* and total aerobic mesophilic bacteria, and 99.7% reduction for *Saccharomyces cerevisiae*	Paniagua-Martínez et al. (2018)
	Apple juice	The combination of supercritical CO_2 and high-power ultrasound technology showed great potential for microbial inactivation in apple juice under mild process conditions. A high capacity of the combination was reported to inactivate *Saccharomyces cerevisiae* in the product	Paniagua-Martínez et al. (2016)
	Gelatin gel	The synergistic effect of combined CO_2 with ultrasound facilitated nucleation to occur in gelatin gel samples, showing the potential to minimize the ice crystal size and improving the product quality	Xu et al. (2019)
	Cooked ham	CO_2 and high-power ultrasound combination induced a synergistic effect on the inactivation of the natural microbiota (mesophilic microorganisms, lactic acid bacteria, yeasts, and molds) in cooked ham. This synergistic effect demonstrated the potential of this combination for the microbial stabilization of ready-to-eat meats	Ferrentino and Spilimbergo (2016)
	Soybean oil-in-water emulsions	Combined supercritical CO_2 and high-power ultrasound intensified the inactivation capacity of supercritical CO_2 against *Escherichia coli* and *Brevundimonas* in the lipid emulsion. The synergistic effect led to a mild process condition, reducing the process cost and improving product quality	Gomez-Gomez et al. (2020)
Additives	Atlantic cod (*Gadus morhua*) mince	SGS-NaCl samples had a significantly lower load of PC, and APC compared to those treated with NaCl only. SGS treatment before packaging in MA can successfully be used as an alternative to adding NaL with respect to microbiological product quality and without compromising quality characteristics	Birkeland and Rotabakk (2014)
	Chicken thigh	Combining potassium sorbate up to 2.5% with 100% CO_2, even at the abuse temperature of 10 °C, resulted in doubling the shelf life of chicken thighs compared to those treated with agent alone	Elliott et al. (1985)
	Atlantic salmon (*Salmo salar* L.)	The effect of SGS outnumbered the negative effect of NaCl on reducing CO_2 dissolution, thus making the use of both NaCl and CO_2 possible without losing the effect of either. Consequently, a better microbial inhibition and longer shelf life will be observed	Abel et al. (2020)

abuse temperature of 10 °C, doubled the shelf life of chicken thighs compared to the effect of the agent used alone.

Table 3 summarizes the effect of SGS or dissolved CO_2 on different quality parameters of products treated with non-thermal treatments. The summary of reviewed papers for the combination of SGS or dissolved CO_2 with non-thermal treatments and its effects on the food microbial load and quality or medium microbial load is also presented in Table 4.

5. Conclusion and future trends

Food security and safety, along with sustainable food production, demand attention. Future generations are threatened by the growing global population combined with the loss of nutritious food resources along the whole food value chain. SGS as a new technology aligns with sustainable goals by enhancing packaging efficiency, reducing distribution costs, lowering amount of plastic materials used for packaging, prolonging food shelf life, decreasing food loss, and opening new opportunities for the related industries.

This review provided an overview of combined dissolved CO_2 with different food treatments, thermal and non-thermal technologies, and its effects on the microbial shelf life and safety and food quality parameters. Improving thermal and non-thermal technologies efficacy and reducing their severity meets the demand for better food quality while being more economically feasible. Combining SGS or dissolved CO_2 with these treatments considerably enhances the bactericidal effect of the treatments, mostly without compromising the product quality. However, it is highly dependent on the product kind, treatment method, experiment protocol, and composition and concentration of the product microbiota. For instance, SGS combined with HPP and MVH showed insignificant synergetic effects on both microbial and physicochemical qualities for pre-cooked chicken breast. The reason could be related to the unequally absorption of CO_2 throughout the samples, impeding bacteriostatic effect of SGS. Another reason may lie in the precooking step, as SGS has shown promising results concerning non-precooked products. However, more research regarding the effects of SGS combined with other technologies on various precooked products is required to conclude. In addition, solving the problem concerning the formation of the gas layer during sous vide treatment offers the advantage of lowering the applied temperature during heat treatment with the potential organoleptic quality improvements. The solution could be applied by increasing the imposed pressure on the product as a counter pressure.

As SGS is executed only in the laboratories so far, recently a project has been funded by the Research Council of Norway to develop the full-scale implementation of this technology. The current paper can pave the road for developing SGS concept through the industrial implementation, operating beside conventional treatments. Although several studies have been conducted in the area of combined SGS with other processing technologies, they are limited. More research is needed to understand the SGS effects with different technologies to find the most effective combinations applicable to specific foods.

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References

Abel, N., Rotabakk, B. T., & Lerfall, J. (2019). Effect of heat treatment and packaging technology on the microbial load of lightly processed seafood. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 101*(7491), 123–129. https://doi.org/10.1016/j.lwt.2018.11.025

Abel, N., Rotabakk, B. T., & Lerfall, J. (2020). Effect of salt on CO_2 solubility in salmon (*Salmo salar* L) stored in modified atmosphere. *Journal of Food Engineering, 278*. https://doi.org/10.1016/j.jfoodeng.2020.109946

Abel, N., Rotabakk, B. T., Rustad, T., Ahlsen, V. B., & Lerfall, J. (2019). Physiochemical and microbiological quality of lightly processed salmon (*Salmo salar* L.) stored under modified atmosphere. *Journal of Food Science, 84*(12), 3364–3372. https://doi.org/10.1111/1750-3841.14852

Abel, N., Rotabakk, B. T., Rustad, T., & Lerfall, J. (2018). The influence of lipid composition, storage temperature, and modified atmospheric gas combinations on the solubility of CO_2 in a seafood model product. *Journal of Food Engineering, 216*, 151–158. https://doi.org/10.1016/j.jfoodeng.2017.08.020

Akamittath, J. G., Brekke, C. J., & Schanus, E. G. (1990). Lipid oxidation and color stability in restructured meat systems during frozen storage. *Journal of Food Science, 55*(6), 1513–1517. https://doi.org/10.1111/j.1365-2621.1990.tb03557.x

Al-Nehlawi, A., Guri, S., Guamis, B., & Saldo, J. (2014). Synergistic effect of carbon dioxide atmospheres and high hydrostatic pressure to reduce spoilage bacteria on poultry sausages. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 58*(2), 404–411. https://doi.org/10.1016/j.lwt.2014.03.041

Alpas, H., Kalchayanand, N., Bozoglu, F., Sikes, A., Dunne, C. P., & Ray, B. (1999). Variation in resistance to hydrostatic pressure among strains of food-borne pathogens. *Applied and Environmental Microbiology, 65*(9), 4248–4251. https://doi.org/10.1128/aem.65.9.4248-4251.1999

Anderson, S. (2000). Salmon color and the consumer. In A. L. Shriver, & R. S. Johnston (Eds.), *IIFET 2000 proceedings* (p. 3).

Baron, C. P., & Andersen, H. J. (2002). Myoglobin-induced lipid oxidation. A review. *Journal of Agricultural and Food Chemistry, 50*(14), 3887–3897. https://doi.org/10.1021/jf011394w

Birkeland, S., & Rotabakk, B. T. (2014). Effects of additives and packaging method on quality and microbiological characteristics in mild thermal processed fish mince. *Journal of Aquatic Food Product Technology, 23*(4), 368–384. https://doi.org/10.1080/10498850.2012.720004

Bull, M. K., Hayman, M. M., Stewart, C. M., Szabo, E. A., & Knabel, S. J. (2005). Effect of prior growth temperature, type of enrichment medium, and temperature and time of storage on recovery of *Listeria monocytogenes* following high pressure processing of milk. *International Journal of Food Microbiology, 101*(1), 53–61. https://doi.org/10.1016/j.ijfoodmicro.2004.10.045

Chaix, E., Guillaume, C., & Guillard, V. (2014). Oxygen and carbon dioxide solubility and diffusivity in solid food matrices: A review of past and current knowledge. *Comprehensive Reviews in Food Science and Food Safety, 13*(3), 261–286. https://doi.org/10.1111/1541-4337.12058

Chandrasekaran, S., Ramanathan, S., & Basak, T. (2013). Microwave food processing-A review. *Food Research International, 52*(1), 243–261. https://doi.org/10.1016/j.foodres.2013.02.033

Chan, S. S., Skare, M., Rotabakk, B. T., Sivertsvik, M., Lerfall, J., Løvdal, T., et al. (2021). Evaluation of physical and instrumentally determined sensory attributes of Atlantic salmon portions packaged in modified atmosphere and vacuum skin. *Lebensmittel-Wissenschaft & Technologie, 146*. https://doi.org/10.1016/j.lwt.2021.111404. December 2020), 0–7.

Corwin, H., & Shellhammer, T. H. (2002). Combined carbon dioxide and high pressure inactivation of pectin methylesterase, polyphenol oxidase, *lactobacillus plantarum* and *escherichia coli*. *Journal of Food Science, 67*(2), 697–701. https://doi.org/10.1111/j.1365-2621.2002.tb10661.x

Dang, T. T., Rode, T. M., & Skipnes, D. (2020). Independent and combined effects of high pressure, microwave, soluble gas stabilization, modified atmosphere and vacuum packaging on microbiological and physicochemical shelf life of precooked chicken breast slices. *Journal of Food Engineering, 292*. https://doi.org/10.1016/j.jfoodeng.2020.110352

Daniels, J. A., Krishnamurthi, R., & Rizvi, S. S. H. (1985). A review of effects of carbon dioxide on microbial growth and food quality. *Journal of Food Protection, 48*(6), 532–537. https://doi.org/10.4315/0362-028x-48.6.532

Datta, N., & Deeth, H. C. (2001). Age gelation of UHT milk - a review. *Food and Bioproducts Processing: Transactions of the Institution of of Chemical Engineers, Part C, 79*(4), 197–210. https://doi.org/10.1205/096030801753252261

Devlieghere, F., & Debevere, J. (2000). Influence of dissolved carbon dioxide on the growth of spoilage bacteria. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 33*(8), 531–537. https://doi.org/10.1006/fstl.2000.0705

Devlieghere, F., Debevere, J., & Van Impe, J. (1998). Concentration of carbon dioxide in the water-phase as a parameter to model the effect of a modified atmosphere on microorganisms. *International Journal of Food Microbiology, 43*, 105–113. https://doi.org/10.1016/S0168-1605(98)00101-9

Dixon, N. M., & Kell, D. B. (1989). The inhibition by CO_2 of the growth and metabolism of micro-organisms. *Journal of Applied Bacteriology, 67*(2), 109–136. https://doi.org/10.1111/j.1365-2672.1989.tb03387.x

Domínguez, R., Pateiro, M., Gagaoua, M., Barba, F. J., Zhang, W., & Lorenzo, J. M. (2019). A comprehensive review on lipid oxidation in meat and meat products. *Antioxidants, 8*(10), 429. https://doi.org/10.3390/antiox8100429

Elliott, P. H., Tomlins, R. I., & Gray, R. J. H. (1985). Control of microbial spoilage on fresh poultry using a combination potassium sorbate/carbon dioxide packaging system. *Journal of Food Science, 50*(5), 1360–1363. https://doi.org/10.1111/j.1365-2621.1985.tb10477.x

Erkmen, O. (2000). Effect of carbon dioxide pressure on *Listeria monocytogenes* in physiological saline and foods. *Food Microbiology, 17*(6), 589–596. https://doi.org/10.1006/fmic.2000.0361

Erkmen, O., & Bozoglu, T. F. (2016). In *Food Microbiology: Principles into practice*. John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119237860.ch35.

Fellows, P. J. (2009). In *Food processing technology: Principles and practice* (4th ed.). Woodhead Publishing.

Ferrentino, G., & Spilimbergo, S. (2016). A combined high pressure carbon dioxide and high power ultrasound treatment for the microbial stabilization of cooked ham. *Journal of Food Engineering, 174*, 47–55. https://doi.org/10.1016/j.jfoodeng.2015.11.013

Fletcher, G. C. (2012). Advances in vacuum and modified atmosphere packaging of fish and crustaceans. In J. P. Kerry (Ed.), *Advances in meat, poultry and seafood packaging* (pp. 261–283). Woodhead Publishing Limited.

Font-i-Furnols, M., & Guerrero, L. (2014). Consumer preference, behavior and perception about meat and meat products: An overview. *Meat Science, 98*(3), 361–371. https://doi.org/10.1016/j.meatsci.2014.06.025

Gaucher, I., Mollé, D., Gagnaire, V., & Gaucheron, F. (2008). Effects of storage temperature on physico-chemical characteristics of semi-skimmed UHT milk. *Food Hydrocolloids, 22*(1), 130–143. https://doi.org/10.1016/j.foodhyd.2007.04.007

Gomez-Gomez, A., Brito-de la Fuente, E., Gallegos, C., Garcia-Perez, J. V., & Benedito, J. (2020). Non-thermal pasteurization of lipid emulsions by combined supercritical carbon dioxide and high-power ultrasound treatment. *Ultrasonics Sonochemistry, 67*, Article 105138. https://doi.org/10.1016/j.ultsonch.2020.105138

Gonçalves, A. C., López-Caballero, M. E., & Nunes, M. L. (2003). Quality changes of deepwater pink shrimp (*Parapenaeus longirostris*) packed in modified atmosphere.

Journal of Food Science, 68(8), 2586–2590. https://doi.org/10.1111/j.1365-2621.2003.tb07065.x

Handumrongkul, C., & Silva, J. L. (1994). Aerobic counts, color and adenine nucleotide changes in CO_2 packed refrigerated striped bass strips. *Journal of Food Science, 59*(1), 67–69. https://doi.org/10.1111/j.1365-2621.1994.tb06899.x

Hong, H., Regenstein, J. M., & Luo, Y. (2015). The importance of ATP-related compounds for the freshness and flavor of post-mortem fish and shellfish muscle: A review. *Critical Reviews in Food Science and Nutrition, 57*(9). https://doi.org/10.1080/10408398.2014.1001489, 00–00.

Houteghem, N. V., Devlieghere, F., Rajkovic, A., Gómez, S. M. O., Uyttendaele, M., & Debevere, J. (2008). Effects of CO_2 on the resuscitation of *Listeria monocytogenes* injured by various bactericidal treatments. *International Journal of Food Microbiology, 123*(1–2), 67–73. https://doi.org/10.1016/j.ijfoodmicro.2007.12.002

Hur, S. J., Jin, S. K., Park, J. H., Jung, S. W., & Lyu, H. J. (2013). Effect of modified atmosphere packaging and vacuum packaging on quality characteristics of low grade beef during cold storage. *Asian-Australasian Journal of Animal Sciences, 26*(12), 1781–1789. https://doi.org/10.5713/ajas.2013.13225

Hyldig, G., & Nielsen, D. (2001). A review of sensory and instrumental methods used to evaluate the texture of fish muscle. *Journal of Texture Studies, 32*, 219–242.

Jakobsen, M., & Bertelsen, G. (2001). *The use of CO_2 in packaging of fresh red meats and its effect on chemical quality changes in the meat. A Review, 13*, 143–168, 2002.

Jay, J. M. (1965). Relationship between water-holding capacity of meats and microbial. *Applied Microbiology, 13*(1), 120–121. https://doi.org/10.1128/aem.13.1.120-121.1965

Jay, J. M., Loessner, M. J., & Golden, D. A. (2005). *Modern Food Microbiology* (7th ed.). Springer. https://doi.org/10.1007/978-94-011-6480-1

Jeremiah, L. E. (2001). Packaging alternatives to deliver fresh meats using short- or long-term distribution. *Food Research International, 34*(9), 749–772. https://doi.org/10.1016/S0963-9969(01)00096-5

Kannan, G., Kouakou, B., & Gelaye, S. (2001). Color changes reflecting myoglobin and lipid oxidation in chevon cuts during refrigerated display. *Small Ruminant Research, 42*(1), 67–74. https://doi.org/10.1016/S0921-4488(01)00232-2

Kiani, H., Zhang, Z., Delgado, A., & Sun, D. W. (2011). Ultrasound assisted nucleation of some liquid and solid model foods during freezing. *Food Research International, 44*(9), 2915–2921. https://doi.org/10.1016/j.foodres.2011.06.051

Kim, N. H., Cho, T. J., & Rhee, M. S. (2017). Sodium chloride does not ensure microbiological safety of foods: Cases and solutions. *Advances in Applied Microbiology, 101*, 1–47. https://doi.org/10.1016/bs.aambs.2017.05.001

Kolbeck, S., Kienberger, H., Kleigrewe, K., Hilgarth, M., & Vogel, R. F. (2021). Effect of high levels of CO_2 and O_2 on membrane fatty acid profile and membrane physiology of meat spoilage bacteria. *European Food Research and Technology, 247*(4), 999–1011. https://doi.org/10.1007/s00217-020-03681-y

Kolbeck, S., Ludwig, C., Meng, C., Hilgarth, M., & Vogel, R. F. (2020). Comparative proteomics of meat spoilage bacteria predicts drivers for their coexistence on modified atmosphere packaged meat. *Frontiers in Microbiology, 11*, 1–15. https://doi.org/10.3389/fmicb.2020.00209

Kong, F., Tang, J., Lin, M., & Rasco, B. (2008). Thermal effects on chicken and salmon muscles: Tenderness, cook loss, area shrinkage, collagen solubility and microstructure. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 41*(7), 1210–1222. https://doi.org/10.1016/j.lwt.2007.07.020

Koseki, S., Mizuno, Y., & Yamamoto, K. (2007). Predictive modelling of the recovery of *Listeria monocytogenes* on sliced cooked ham after high pressure processing. *International Journal of Food Microbiology, 119*(3), 300–307. https://doi.org/10.1016/j.ijfoodmicro.2007.08.025

Koseki, S., & Yamamoto, K. (2006). pH and solute concentration of suspension media affect the outcome of high hydrostatic pressure treatment of *Listeria monocytogenes*. *International Journal of Food Microbiology, 111*(2), 175–179. https://doi.org/10.1016/j.ijfoodmicro.2006.05.008

Kruk, Z. A., Yun, H., Rutley, D. L., Lee, E. J., Kim, Y. J., & Jo, C. (2011). The effect of high pressure on microbial population, meat quality and sensory characteristics of chicken breast fillet. *Food Control, 22*(1), 6–12. https://doi.org/10.1016/j.foodcont.2010.06.003

Leistner, L. (2000). Basic aspects of food preservation by hurdle technology. *International Journal of Food Microbiology, 55*(1–3), 181–186. https://doi.org/10.1016/S0168-1605(00)00161-6

Lerfall, J., Jakobsen, A. N., Skipnes, D., Waldenstrøm, L., Hoel, S., & Rotabakk, B. T. (2018). Comparative evaluation on the quality and shelf life of Atlantic Salmon (*Salmo salar* L.) filets using microwave and conventional pasteurization in combination with novel packaging methods. *Journal of Food Science, 83*(12), 3099–3109. https://doi.org/10.1111/1750-3841.14384

López-Gálvez, D. E., De La Hoz, L., Blanco, M., & Ordóñez, J. A. (1998). Refrigerated storage (2 °C) of sole (*Solea solea*) fillets under CO_2-enriched atmospheres. *Journal of Agricultural and Food Chemistry, 46*(3), 1143–1149. https://doi.org/10.1021/jf9706383

Loss, C. R., & Hotchkiss, J. H. (2002). Effect of dissolved carbon dioxide on thermal inactivation of microorganisms in milk. *Journal of Food Protection, 65*(Issue 12). http://meridian.allenpress.com/jfp/article-pdf/65/12/1924/1674881/0362-028x-65_12_1924.pdf.

Ma, Y., Barbano, D. M., & Santos, M. (2003). Effect of CO_2 addition to raw milk on proteolysis and lipolysis at 4°C. *Journal of Dairy Science, 86*(5), 1616–1631. https://doi.org/10.3168/jds.S0022-0302(03)73747-3

Marchesini, G., Balzan, S., Montemurro, F., Fasolato, L., Andrighetto, I., Segato, S., et al. (2012). Effect of ultrasound alone or ultrasound coupled with CO_2 on the chemical composition, cheese-making properties and sensory traits of raw milk. *Innovative Food Science & Emerging Technologies, 16*, 391–397. https://doi.org/10.1016/j.ifset.2012.09.003

Martin, J. D., Werner, B. G., & Hotchkiss, J. H. (2003). Effects of carbon dioxide on bacterial growth parameters in milk as measured by conductivity. *Journal of Dairy Science, 86*(6), 1932–1940. https://doi.org/10.3168/jds.S0022-0302(03)73780-1

Meer, R. R., Baker, J., Bodyfelt, F. W., & Griffiths, M. W. (1991). Psychrotrophic *Bacillus spp.* in fluid milk products: A review. *Journal of Food Protection, 54*(12), 969–979. https://doi.org/10.4315/0362-028X-54.12.969

Mendes, R., & Gonçalves, A. (2008). Effect of soluble CO_2 stabilization on the quality of fillets from farmed gilthead sea bream (*Sparus aurata*) and European sea bass (*Dicentrarchus labrax*). *Journal of Aquatic Food Product Technology, 17*(4), 342–366. https://doi.org/10.1080/10498850802369187

Narasimha Rao, D., & Sachindra, N. M. (2002). Modified atmosphere and vacuum packaging of meat and poultry products. *Food Reviews International, 18*(4), 263–293. https://doi.org/10.1081/FRI-120016206

Ohlsson, T., & Bengtsson, N. (2002). *Minimal Processing Technologies in the Food Industry*. Woodhead Publishing. https://doi.org/10.1533/9781855736795

O'Keeffe, M., & Hood, D. E. (1981). Anoxic storage of fresh beef. 2: Colour stability and weight loss. *Meat Science, 5*(4), 267–281. https://doi.org/10.1016/0309-1740(81)90017-6

Oliveira, M. E. C., & Franca, A. S. (2002). Microwave heating of foodstuffs. *Journal of Food Engineering, 53*(4), 347–359. https://doi.org/10.1016/S0260-8774(01)00176-5

Ortuño, C., Martínez-Pastor, M. T., Mulet, A., & Benedito, J. (2013). Application of high power ultrasound in the supercritical carbon dioxide inactivation of *Saccharomyces cerevisiae*. *Food Research International, 51*(2), 474–481. https://doi.org/10.1016/j.foodres.2013.01.041

Özogul, F., Taylor, K. D. A., Quantick, P. C., & Özogul, Y. (2000). A rapid HPLC-determination of ATP-related compounds and its application to herring stored under modified atmosphere. *International Journal of Food Science and Technology, 35*(6), 549–554. https://doi.org/10.1111/j.1365-2621.2000.00405.x

Paniagua-Martínez, I., Mulet, A., García-Alvarado, M. A., & Benedito, J. (2016). Ultrasound-assisted supercritical CO_2 treatment in continuous regime: Application in Saccharomyces cerevisiae inactivation. *Journal of Food Engineering, 181*, 42–49. https://doi.org/10.1016/j.jfoodeng.2016.02.024

Paniagua-Martínez, I., Mulet, A., García-Alvarado, M. A., & Benedito, J. (2018). Orange juice processing using a continuous flow ultrasound-assisted supercritical CO_2 system: Microbiota inactivation and product quality. *Innovative Food Science & Emerging Technologies, 47*, 362–370. https://doi.org/10.1016/j.ifset.2018.03.024

Park, S. A., Ko, A., & Lee, N. G. (2011). Stimulation of growth of the human gastric pathogen *Helicobacter pylori* by atmospheric level of oxygen under high carbon dioxide tension. *BMC Microbiology, 11*. https://doi.org/10.1186/1471-2180-11-96

Park, S. J., Park, H. W., & Park, J. (2003). Inactivation kinetics of food poisoning microorganisms by carbon dioxide and high hydrostatic pressure. *Journal of Food Science, 68*(3), 976–981. https://doi.org/10.1111/j.1365-2621.2003.tb08273.x

Payne, S. R., Durham, C. J., Scott, S. M., & Devine, C. E. (1998). The effects of non-vacuum packaging systems on drip loss from chilled beef. *Meat Science, 49*(3), 277–287. https://doi.org/10.1016/S0309-1740(97)00135-6

Piyasena, P., Mohareb, E., & McKellar, R. C. (2003). Inactivation of microbes using ultrasound: A review. *International Journal of Food Microbiology, 87*(3), 207–216. https://doi.org/10.1016/S0168-1605(03)00075-8

Randell, K., Hattula, T., Skyttä, E., Sivertsvik, M., Bergslien, H., & Ahvenainen, R. (1999). Quality of filleted salmon in various retail packages. *Journal of Food Quality, 22*(5), 483–497. https://doi.org/10.1111/j.1745-4557.1999.tb00180.x

Raso, J., & Barbosa-Cánovas, G. V. (2003). Nonthermal preservation of foods using combined processing techniques. *Critical Reviews in Food Science and Nutrition, 43*(3), 265–285. https://doi.org/10.1080/10408690390826527

Rastogi, N. K. (2011). Opportunities and challenges in application of ultrasound in food processing. *Critical Reviews in Food Science and Nutrition, 51*(8), 705–722. https://doi.org/10.1080/10408391003770583

Rode, T. M., Hovda, M. B., & Rotabakk, B. T. (2015). Favourable effects of soluble gas stabilisation and modified atmosphere for supressing regrowth of high pressure treated Listeria innocua. *Food Control, 51*, 108–113. https://doi.org/10.1016/j.foodcont.2014.11.006

Rosnes, J. T., & Skipnes, D. (2017). Minimal Heat processing applied in fish processing. In *Trends in fish processing technologies* (pp. 28–57).

Rotabakk, B. T., Birkeland, S., Jeksrud, W. K., & Sivertsvik, M. (2006). Effect of modified atmosphere packaging and soluble gas stabilization on the shelf life of skinless chicken breast fillets. *Journal of Food Science, 71*(2), S124–S131. https://doi.org/10.1111/j.1365-2621.2006.tb08915.x

Rotabakk, B. T., Birkeland, S., Lekang, O. I., & Sivertsvik, M. (2008). Enhancement of modified atmosphere packaged farmed atlantic Halibut (*Hippoglossus Hippoglossus*) fillet quality by soluble gas stabilization. *Food Science and Technology International, 14*(2), 179–186. https://doi.org/10.1177/1082013208092051

Schumpe, A., Quicker, G., & Deckwer, W. D. (1982). Gas solubilities in microbial culture media. *Reaction Engineering*, 1–38.

Sears, D. F., & Eisenberg, R. M. (1961). A model representing a physiological role of CO_2 at the cell membrane. *The Journal of General Physiology, 44*(5), 869–887. https://doi.org/10.1085/jgp.44.5.869

Sivertsvik, M. (2000). Use of soluble gas stabilisation to extend shelf-life of fish. In S. A. Georgakis (Ed.), *Proceedings of 29th WEFTA-Meeting* (pp. 79–91), 1999 October 10–14.

Sivertsvik, M. (2007). The optimized modified atmosphere for packaging of pre-rigor filleted farmed cod (*Gadus morhua*) is 63 ml/100 ml oxygen and 37 ml/100 ml carbon dioxide. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 40*(3), 430–438. https://doi.org/10.1016/j.lwt.2005.12.010

Sivertsvik, M., & Birkeland, S. (2006). Effects of soluble gas stabilisation, modified atmosphere, gas to product volume ratio and storage on the microbiological and sensory characteristics of ready-to-eat shrimp (*pandalus borealis*). *Food Science and*

Technology International, 12(5), 446–454. https://doi.org/10.1177/1082013206070171
Sivertsvik, M., Jeksrud, W. K., & Rosnes, J. T. (2002). A review of modified atmosphere packaging of fish and fishery products - significance of microbial growth, activities and safety. *International Journal of Food Science and Technology, 37*(2), 107–127. https://doi.org/10.1046/j.1365-2621.2002.00548.x
Sivertsvik, M., Jeksrud, W. K., Vågane, Å., & Rosnes, J. T. (2004). Solubility and absorption rate of carbon dioxide into non-respiring foods: Part 1: Development and validation of experimental apparatus using a manometric method. *Journal of Food Engineering, 61*(3), 449–458. https://doi.org/10.1016/S0260-8774(03)00167-5
Sivertsvik, M., & Jensen, J. S. (2005). Solubility and absorption rate of carbon dioxide into non-respiring foods. Part 3: Cooked meat products. *Journal of Food Engineering, 70*(4), 499–505. https://doi.org/10.1016/j.jfoodeng.2004.10.005
Sivertsvik, M., Rosnes, J. T., & Jeksrud, W. K. (2004). Solubility and absorption rate of carbon dioxide into non-respiring foods. Part 2: Raw fish fillets. *Journal of Food Engineering, 63*(4), 451–458. https://doi.org/10.1016/j.jfoodeng.2003.09.004
Sivertsvik, M., & Rotabakk, B. T. (2012). Solubility of carbon dioxide in muscle foods and its use to extend the shelf life of packaged products. In J. P. Kerry (Ed.), *Advances in meat, poultry and seafood packaging* (pp. 314–330). Woodhead Publishing.
Skipnes, D. (2014). Heat processing of fish. In I. S. Boziaris (Ed.), *Seafood processing* (pp. 61–81). https://doi.org/10.1201/9781420027396
Sørheim, O., Aune, T., & Nesbakken, T. (1997). Technological, hygienic and toxicological aspects of carbon monoxide used in modified-atmosphere packaging of meat. *Trends in Food Science & Technology, 8*(9), 307–312. https://doi.org/10.1016/S0924-2244(97)01062-5
Stiles, M. E. (1996). Biopreservation by lactic acid bacteria. *Antonie van Leeuwenhoek. International Journal of General and Molecular Microbiology, 70*, 331–345. https://doi.org/10.1007/BF00395940
Surette, M. E., Gill, T. A., & LeBlanc, P. J. (1988). Biochemical basis of postmortem nucleotide catabolism in cod (*Gadus morhua*) and its relationship to spoilage. *Journal of Agricultural and Food Chemistry, 36*(1), 19–22. https://doi.org/10.1021/jf00079a005
Tsironi, T., Houhoula, D., & Taoukis, P. (2020). Hurdle technology for fish preservation. *Aquaculture and Fisheries, 5*(2), 65–71. https://doi.org/10.1016/j.aaf.2020.02.001
Viana, E. S., Gomide, L. A. M., & Vanetti, M. C. D. (2005). Effect of modified atmospheres on microbiological, color and sensory properties of refrigerated pork. *Meat Science, 71*(4), 696–705. https://doi.org/10.1016/j.meatsci.2005.05.013
Vianna, P. C. B., Walter, E. H. M., Dias, M. E. F., Faria, J. A. F., Netto, F. M., & Gigante, M. L. (2012). Effect of addition of CO_2 to raw milk on quality of UHT-treated milk. *Journal of Dairy Science, 95*(8), 4256–4262. https://doi.org/10.3168/jds.2012-5387
Wang, L., Pan, J., Xie, H., Yang, Y., & Lin, C. (2010). Inactivation of *Staphylococcus aureus* and *Escherichia coli* by the synergistic action of high hydrostatic pressure and dissolved CO_2. *International Journal of Food Microbiology, 144*(1), 118–125. https://doi.org/10.1016/j.ijfoodmicro.2010.09.006
Warthesen, J. J., Waletzko, P. T., & Busta, F. F. (1980). High-pressure liquid chromatographic determination of hypoxanthine in refrigerated fish. *Journal of Agricultural and Food Chemistry, 28*(6), 1308–1309. https://doi.org/10.1021/jf60232a046
Xu, B., Azam, R. S. M., Wang, B., Zhang, M., & Bhandari, B. (2019). Effect of infused CO_2 in a model solid food on the ice nucleation during ultrasound-assisted immersion freezing. *International Journal of Refrigeration, 108*, 53–59. https://doi.org/10.1016/j.ijrefrig.2019.09.005
Yang, J., Dogovski, C., Hocking, D., Tauschek, M., Perugini, M., & Robins-Browne, R. M. (2009). Bicarbonate-mediated stimulation of RegA, the global virulence regulator from *Citrobacter rodentium*. *Journal of Molecular Biology, 394*(4), 591–599. https://doi.org/10.1016/j.jmb.2009.10.033
Zavadlav, S., Blažić, M., Van de Velde, F., Vignatti, C., Fenoglio, C., Piagentini, A. M., et al. (2020). Sous-vide as a technique for preparing healthy and high-quality vegetable and seafood products. *Foods, 9*(11), 1537. https://doi.org/10.3390/foods9111537