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High-pressure pasteurization of low-acid chilled ready-to-eat food

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Abstract: The working population growth have created greater consumer demand for ready-to-eat (RTE) foods. Pasteurization is one of the most common preservation methods for commercial production of low-acid RTE cold-chain products. Proper selection of a pasteurization method plays an important role not only in ensuring microbial safety but also in maintaining food quality during storage. Better retention of flavor, color, appearance, and nutritional value of RTE products is one of the reasons for the food industry to adopt novel technologies such as high-pressure processing (HPP) as a substitute or complementary technology for thermal pasteurization. HPP has been used industrially for the pasteurization of high-acid RTE products. Yet, this method is not commonly used for pasteurization of low-acid RTE food products, due primarily to the need of additional heating to thermally inactivate spores, coupled with relatively long treatment times resulting in high processing costs.

KEYWORDS
pasteurization, high-pressure processing, food safety, *Clostridium botulinum*, *Listeria monocytogenes*, ready-to-eat (RTE)

Practical Application: Food companies would like to adopt novel technologies such as HPP instead of using conventional thermal processes, yet there is a lack of information on spoilage and the shelf-life of pasteurized low-acid RTE foods (by different novel pasteurization methods including HPP) in cold storage. This article provides an overview of the microbial concerns and related regulatory guidelines for the pasteurization of low-acid RTE foods and summarizes the effects of HPP in terms of microbiology (both pathogens and spoilage microorganisms), quality, and shelf-life on low-acid RTE foods. This review also includes the most recent research articles regarding a comparison between HPP pasteurization and thermal pasteurization treatments and the limitations of HPP for low-acid chilled RTE foods.

1 | INTRODUCTION

The food industry has developed multiple strategies to meet the increasing demand for convenient meals that require a minimum time to prepare at home (Jabs & Devine, 2006) including canned, frozen, and chilled meals. However, today's consumers choose food more carefully, they read the information on packages to learn about ingredients and demand fresh-like, nutritious, minimally processed food products (Meijer et al., 2021). According to the 2020 Food & Health Survey (conducted by the International Food Information Council), the eating and food preparation habits of consumers have recently changed during the COVID-19 pandemic. Since cooking at home during COVID-19 has left consumers feeling fatigued, more consumption of canned or frozen foods is expected in the coming years (Food Trends to Watch in 2021, 2021). Chilled ready-to-eat (RTE) meals are also a possible alternative to meet consumer demand for convenient meals.

Commercially prepared meals are ordinarily supplied to consumers in frozen or chilled forms (Stratakos & Koidis, 2015). Some frozen meals containing undercooked ingredients are called not-ready-to-eat meals, which must be properly cooked by consumers at home before consumption. To avoid the risk of pathogens such as *Salmonell*a and *Listeria monocytogenes*, food companies provide product-specific cooking instructions for frozen not-ready-to-eat meals (Rounds et al., 2013). However, consumers may or may not follow cooking instructions on the packages. Other frozen meals that contain fully cooked ingredients may still be contaminated before or during packaging in food plants (Lambertz et al., 2012). Reheating frozen meals without following proper instructions on the food packages is a serious food safety concern since *L. monocytogenes* can survive at freezing temperatures (Tang et al., 2018; Todd, 2006).

Chilled RTE meals refer to completely precooked and pasteurized meals that do not require cooking before consumption (Tang et al., 2018). Cooking instructions are not required for chilled RTE meals which may be warmed to increase palatability. Thus, in-package pasteurization with a combination of chilled distribution and storage ensures that the RTE meals are free of microbial pathogens (Daelman et al., 2013).

The commercial methods for pasteurization of prepacked foods can be divided into two groups; (1) thermal processing such as conventional, microwave, and ohmic heating and (2) nonthermal processing such as high-pressure processing (HPP) (Öztürk & Nilüfer-Erdil, 2015). Even though the RTE meal sector has shown significant growth in sales, most RTE meals are produced by conventional methods (such as steam or hot-water heating), which have proven to be effective in inactivating harmful microorganisms and enzymes (Torres & Velazquez, 2005). Novel methods such as HPP could be a good candidate to replace the conventional well-established preservation processes for the production of high-quality foods (Khan et al., 2017). It is the case that there is no review article on the benefits and limitations of HPP for low-acid (pH > 4.6) RTE foods.

This article presents an overview of the microbial concerns associated with pasteurization and how they relate to the United States and European Union regulations. The microbial concerns for pasteurization are discussed in two sections: the pathogenic bacteria concerning microbial safety issues and spoilage bacteria regarding the shelf-life of RTE products under chilled storage conditions. The topics covered include HPP as a pasteurization method for low-acid foods, its effects on microbial activity and enzyme inactivation, and quality changes of the products in HPP treatments and storage. Attention is paid to a comparison between HPP pasteurization and thermal pasteurization treatments and consider the limitations of HPP for low-acid chilled RTE products.

2 | PASTEURIZATION

The original definition of pasteurization was used to encompass only heat treatments, but later the definition was modified to accommodate the novel technologies in which heat is not the main stress factor for the inactivation of microorganisms (Peng et al., 2017). The National Advisory Committee on Microbiological Criteria for Foods (NACMCF) in the United States recently revised its definition of pasteurization as; "any process, treatment, or combination thereof that is applied to food to reduce the most resistant microorganism(s) of public health significance to a level that is not likely to present a public health risk under normal conditions of distribution and storage." The novel processes and treatments mentioned in NACMCF's report include high pressure, microwave processing, ohmic heating, UV irradiation, and ultrasound (NACMCF, 2006).

2.1 | Pasteurization of foods and regulations

Food matrix characteristics such as pH, water activity (a_w), and food constituents play a significant role in the development of pasteurization processes. The pH of the food is also an important factor in determining the storage conditions after a pasteurization treatment. Pasteurized low-acid foods must be stored under chilled conditions because pasteurization does not inactivate all microorganisms,

particularly some bacterial spores, of public health concern. However, pasteurization of high-acid foods (pH < 4.6) can provide shelf-stable products because the acidic environment inhibits the germination and outgrowth of bacterial spores during storage (NACMCF, 2006). Thus, high-acid foods can be stored at room temperature or refrigerated to obtain a higher quality (Silva & Gibbs, 2010). Spoilage and pathogenic psychrophiles and mesophiles are the organisms of public health concern related to chilled meals. Psychotropic bacteria can grow at refrigeration temperatures, and mesophilic bacteria can survive at refrigeration temperatures and grow in the case of temperature abuse, which might occur during transportation or storage (Petruzzi et al., 2017).

The regulatory guidelines imposed by the Food Safety Modernization Act (Implementation of the FDA Food Safety Modernization Act (FSMA, P.L. 111–353)) play a vital role in ensuring that food products manufactured or marketed in the United States are safe to consume (Keener et al., 2014). In the United States, there are pasteurization guidelines for milk, juices, seafood, and eggs. For instance, the United States Food and Drug Administration (FDA) considers a 6-$\log_{10}$ reduction of *Clostridium botulinum* (nonproteolytic [np] types B, E, and F) for pasteurization of seafood, and the United States Department of Agriculture's Food Safety and Inspection Service (USDA-FSIS) provides specific regulation for *Salmonella Enteritis* reduction (5-$\log_{10}$) in shell eggs (Peng et al., 2017). There are no specific regulations or standards for commercial pasteurization of vegetables and other products due to wide variations in food characteristics such as pH, a_w, and salt concentration (Peng et al., 2017). However, the foods in this category may be subject to the regulatory requirements imposed by the Acidified and Low Acid Canned Foods Regulations of the United States FDA (21CFR108; 21CFR113; 21CFR114) depending on their formulation, packaging, and mode of distribution. Thermal pasteurization guidelines for heat-treated refrigerated RTE meals have been provided by the European Chilled Food Federation (ECFF), and their recommendation is a 6-$\log_{10}$ reduction of either *L. monocytogenes* after treatment at 70°C for 2 min (minimum pasteurization value, $P_{70°C} = 2$ min) for a product with a shelf-life of ≤ 10 days < 5°C or np *C. botulinum* spores after treatment at 90°C for 10 min (minimum pasteurization value, $P_{90°C} = 10$ min) for a product shelf-life of ≤ 6 weeks at < 5°C, respectively (ECFF, 2006).

The equivalent lethal time of a thermal pasteurization process, known as the pasteurization value (*p*-value, min), can be calculated using the equation:

$$P^{z}_{Tref} = \int_0^t 10^{\frac{(T_t)-(T_{ref})}{z}} dt, \quad (1)$$

where T_t is the temperature measured at the cold spot (the area that receives the lowest thermal energy) at the time (t) during the process, T_{ref} is the reference temperature (usually selected as 70°C or 90°C), and z characterizes the sensitivity of the thermal resistance of the target bacteria to temperature changes (Silva & Gibbs, 2010). The calculated equivalent lethal time divided by the D value of the target bacterium at the reference temperature gives the number (N) of $\log_{10}$ reduction:

$$\frac{P^{z}_{Tref}}{D_{Tref}} = N\log_{10}\text{reduction}. \quad (2)$$

A pasteurization treatment with an equivalent lethal time of 2 min at 70°C ($P^{7.5}_{70} = 2$) results in more than 6-$\log_{10}$ reduction of *L. monocytogenes* (a typical $D_{70°C}$ value of 0.3 min and z value of 7.5°C) and $P^{9.8}_{90} = 10$ gives a 6-$\log_{10}$ reduction of np *C. botulinum* with a typical $D_{90°C}$ value of 1.5 min (ECFF, 2006) and suggested z value of 9.8°C (Gaze & Brown, 1990). For instance, the D (at 90°C) and z values of np *C. botulinum* type B and E in cod were 1.1 min and 0.8 min and 8.6°C and 8.3°C, respectively. For carrot, the D (at 90°C) and z values of np *C. botulinum* type B and E were 0.4 and 0.5 min and 9.8°C for both types, respectively (Betts & Gaze, 1995; Gaze & Brown, 1990).

2.2 | Microorganisms of concern for pasteurization

Several factors, including the identification of the most resistant pathogen(s) of public health concern and the efficacy of the specific technology to reduce the pathogen(s) of concern, must be considered in the development of pasteurization processes (NACMCF, 2006). In the design of a pasteurization process, the most heat-/pressure-resistant microorganisms in the food products are selected as targets to ensure the microbial safety of the products. High pH (> 4.6), high a_w, and a salt concentration of < 3.5% are the main concerns for controlling microbial safety in most refrigerated processed foods (Silva & Gibbs, 2010). Under those conditions, *L. monocytogenes* or *C. botulinum* (np strains) is commonly selected as a target bacterium for thermal pasteurization in the commercial production of RTE chilled meals (Figure 1).

Another goal of pasteurization is the shelf-life extension. The presence of heat-resistant endospores might result in spoilage, which impairs the quality and safety of pasteurized foods during storage (Guinebretiere et al., 2001). In this regard, postprocessing storage conditions should be considered to extend the shelf-life (Gaze, 2006). Freezing and refrigeration can be utilized in addition

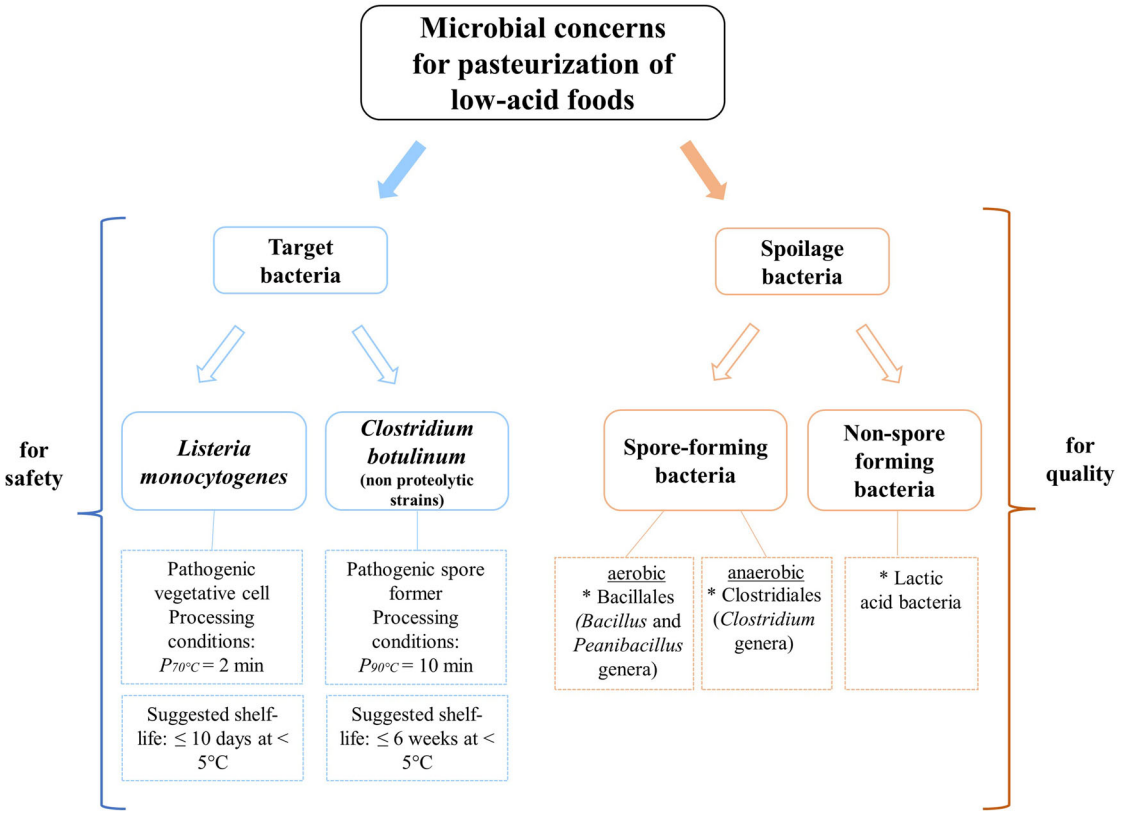

FIGURE 1 Microbial concerns for pasteurization of low-acid chilled ready-to-eat products

TABLE 1 Growth and survival limits of *Listeria monocytogenes*

Environmental factor	Minimum for multiplication	Maximum for multiplication	Optimal for multiplication	Survival without multiplication
Temperature (°C)	−1.5 to 3	45	30–37	−18
pH	4.2–4.3	9.4–9.5	7.0	3.3–4.2
Water activity	0.90–0.93	> 0.99	0.97	< 0.90
Salt (%)	< 0.5	12–16	N/A	≥ 20

Source: Todd (2006).

to pasteurization to prevent spoilage throughout the shelf-life of products (NACMCF, 2006).

2.2.1 | Foodborne pathogens

L. monocytogenes

L. monocytogenes can multiply at temperatures between −1.5°C to 3°C and also survive at lower temperatures as low as −18°C, as shown in Table 1 (Todd, 2006). The composition of some chilled foods, in terms of pH, a_w, and low salt content provides excellent growth conditions for *Listeria* spp. In addition, *L. monocytogenes*, a facultative anaerobe, can tolerate vacuum packaging (Melo et al., 2015). *L. monocytogenes* can multiply during storage at refrigerated temperatures (Wernars et al., 1991) and is the most heat resistant vegetative pathogen in low-acid foods, which makes *L. monocytogenes* a serious concern for chilled low-acid RTE foods (Peck, 1997). The RTE product-associated outbreaks of listeriosis have been attributed to contamination during processing and subsequent storage conditions. The USDA-FSIS recommends that the storage temperature of RTE foods should be 4.4°C or below to control the growth of *L. monocytogenes* (Pal et al., 2008). Shelf-life determination is crucial for the consumption of RTE foods since *L. monocytogenes* can grow during a long shelf-life (more than 10 days) (Lambertz et al., 2012). It is noticeable that the United States regulations do not establish a detection level for *L. monocytogenes* in RTE foods and hence its mere presence in such foods is a violation of the Federal Food Drug and Cosmetic Act (Pal, 2007).

Multiple listeriosis outbreaks have been linked to the consumption of not-ready-to-eat food products (Francis et al., 1999). No regulatory limits for *L. monocytogenes* apply to frozen not-ready-to-eat products due to the assumption that consumers will fully cook the product before consumption (Zoellner et al., 2019). However, frozen vegetables, such as peas, are consumed without cooking, which can be used for smoothies and dips (Zoellner et al., 2019) or added to salad after thawing although they are not considered to be RTE (Magdovitz et al., 2020). Therefore, many global recalls and outbreaks of listeriosis have been associated with frozen foods including vegetables such as corn, spinach, and green beans although food products after freezing do not support the growth of *L. monocytogenes* (European Food Safety Authority & European Centre for Disease Prevention and Control, 2018). Recently, the United States Centers for Disease Control and Prevention reported that frozen, fully cooked chicken products were recalled due to the outbreak of listeriosis (Center for Disease Control and Prevention, 2022). The main factors contributing to the outbreak of *L. monocytogenes* are moist and cold conditions in frozen food production environments and improper storage temperatures (Luber et al., 2011).

The USDA-FSIS established the zero-tolerance policy for *L. monocytogenes* in RTE foods (USDA-FSIS, 1989) because multiple studies have linked outbreaks of listeriosis with the consumption of RTE products including meat, poultry, seafood products, dairy products, and vegetables (Gombas et al., 2003; Malley et al., 2015; Sant'Ana et al., 2012). The pathogenic nature of *L. monocytogenes* and its ability to grow in RTE foods during refrigerated storage has led to the development of this policy (Archer, 2018). The "zero-tolerance" policy assumes that all strains of *L. monocytogenes* are pathogenic (Gombas et al., 2003). The minimum detectable level of this microorganism with the current analytical methods is 0.04 CFU/g sample (Klontz et al., 2008).

L. monocytogenes can endure longer than most other nonspore-forming food pathogens under several adverse conditions including freezing, drying, mild heat, and anaerobic conditions. However, *L. monocytogenes* can be effectively inactivated by pasteurization (with adequate processing conditions) (Sauders & Wiedmann, 2007). The internal temperature of food held at 70°C for a minimum of 2 min is regarded as adequate thermal pasteurization conditions to ensure the inactivation of *L. monocytogenes* (Mackey & Bratchell, 1989). After treatment at 70°C for 2 min, *L. monocytogenes* was not detected in several RTE foods such as chicken drumsticks, chicken mousse, turkey breasts (Nyati, 2000), homogenates of chicken, beef steak, and carrot (Gaze et al., 1989), oyster (Lekjing et al. et al., 2017), and chicken breast (Murphy et al., 2002).

Nonproteolytic C. botulinum

C. botulinum is an anaerobic spore-forming bacterium that produces the most potent neurotoxin and causes botulism. *C. botulinum* produces endospores under unfavorable growth conditions. The spore enables the bacteria to survive for extended periods until conditions become more favorable (Schneider et al., 2005). *C. botulinum* is classified as groups I (proteolytic) and II (nonproteolytic) (Table 2). Group I produces toxin of either types A, B, and F, and group II produces toxin of either types B, E, or F. While group II strains tend to be less heat resistant than group I, strains from both groups may survive pasteurization at 70°C for 2 min (Silva, 2019; Sun, 2014). Typically, the proteolytic strains of *C. botulinum* are not an organism of concern in refrigerated foods because refrigeration temperatures are not favorable conditions for growth. However, the np strains of *C. botulinum* are psychotropic and capable of growth at temperatures as low as 3.3°C (Wachnicka et al., 2016). Therefore, np *C. botulinum strains* are of concern for chilled RTE foods held in anaerobic packaging (Betts & Gaze, 1995).

Anaerobic conditions, low-acid, and low-salt environments are favorable for the growth and toxin production by np strains of *C. botulinum* (Sobel et al., 2004). Refrigeration is required to reduce or at least retard toxin production by np *C. botulinum* (Peck, 2006). No growth and neurotoxin production of np *C. botulinum* was observed in low-acid RTE foods stored at 2.5°C or below for 12 weeks (Peck, 2009). Peck and Stringer (2005) reported growth and toxin formation in that category of foods by np *C. botulinum* in low-acid foods after 5–7 weeks at 3.0–3.3°C. For crabmeat homogenates, no toxin production was observed for 55 days at 4.4°C for the strains of ATCC 17786 and Beluga and 58 days for the strain of 070, 22 days at 8°C, and 8 days at 10°C for all three strains (Cockey & Tatro, 1974). Toxin production of np *C. botulinum* was observed in 3 weeks of storage at 8°C in low-acid RTE products (Conner et al., 1989), in 10 days of storage at 10°C in hot-fill soups (Rodgers, 2002), after 7 days at 15°C in sous-vide-cooked cod and chicken (Brown et al., 1991), after 14 days at a storage temperature of 15°C in sous-vide spaghetti and meat sauce (Simpson et al., 1995). The results of these various studies emphasize the need for temperature control during storage for the microbial safety of low-acid pasteurized products. Maier et al. (2018) have suggested that storage temperatures below 3°C can be considered (for low-acid chilled storage products) as a safety limitation for chilled meals.

The combination of heat treatment with other preservation factors such as reduced pH and higher concentration of salt (Graham et al., 1996), low a_w, and antimicrobial preservatives such as sodium nitrite, and salt (Roberts & Ingram, 1973) inhibit the growth and toxin production of

TABLE 2 Characteristics of *Clostridium botulinum* strains, which form botulinum neurotoxin

Characteristic	*C. botulinum* group I (proteolytic, mesophilic)	*C. botulinum* group II (nonproteolytic, psychrotrophic)
Toxins formed	A, B, F	B, E, F
Minimum growth temp (°C)	10	3
Optimum growth temp (°C)	35–37	26–30
Growth limiting pH	4.6	5
Growth limiting NaCl	10%	5%
Minimum growth a_w	0.94	0.97
Heat resistance of spores	High ($D_{100°C} > 15$ min)	Moderate ($D_{100°C} < 0.1$ min)
Potential food problems	Canned foods	Minimally heated, chilled foods
Similar non-toxigenic organism	*C. sporogenes*	No specific name given

Source: Modified from Peck and Stringer (2005), Lindstrom and Korkeala (2006), and Peck et al. (2006).

np *C. botulinum*. However, the limited use of salt and preservatives in RTE meals (to satisfy consumer demand) may pose a risk of np *C. botulinum*. Since *C. botulinum* is an obligate anaerobe, toxin formation by np *C. botulinum* can be rapid in anaerobically packaged foods. Post et al. (1985) reported that vacuum packaging, N_2, CO_2, and mixed gas flushed packages might extend shelf-life, but not enough to provide the safety required for extended storage of fish filets against the risk of outgrowth and toxin production by *C. botulinum* type E.

In the endospore form, np *C. botulinum* can survive under severe environmental conditions such as starvation, drying, and extreme temperatures (Lindström et al., 2006). However, the use of a heat treatment at 90°C for 10 min or other treatment conditions (such as 85°C for 36 min) with equivalent lethality results in a 6-$\log_{10}$ reduction in the count of np *C. botulinum* spores in RTE foods (Betts & Gaze, 1995; Wachnicka et al., 2016). Among the np *C. botulinum* strains, types E and B are the most heat resistant (Eklund et al., 1988; Wachnicka et al., 2016). A 6-$\log_{10}$ reduction of np *C. botulinum* spores (types B and E) was observed in cod and carrot homogenate (Gaze & Brown, 1990) and turkey slurry (Juneja et al., 1995) after heat treatment at 90°C for 6.6 min and 4.8 min, respectively.

2.2.2 | Spoilage-causing microorganisms

Food spoilage can be defined as a process in which a food product becomes undesirable or unacceptable in color, flavor, taste, texture, or nutritional value for human consumption (Rawat, 2015). Spoilage-associated microorganisms may multiply during storage and cause foods to be undesirable for human consumption; therefore, they limit the shelf-life of pasteurized foods, which is between a few days to a few months at refrigerated temperatures depending on the process intensity (Guinebretiere et al., 2001).

Pasteurization inactivates many nonpathogenic bacteria, which normally restrict the growth of pathogens through competition. When nonpathogenic bacteria are eliminated by pasteurization conditions, pathogenic bacteria may grow faster (Francis et al., 1999); therefore, pasteurized products must be protected against recontamination (Muir, 2011). Pasteurization significantly reduces nonpathogenic microorganisms, yet it is not enough to inactivate heat- or pressure-resistant spores. Spores normally remain dormant and highly resistant to heat, radiation, desiccation, pH extremes, and toxic chemicals. However, spores return to active metabolism when they receive proper conditions such as high pressures (50–400 MPa) (Moerman, 2005; Smelt, 1998) and mild temperatures (e.g., 70°C/30 min) (Smelt et al., 2008). After pasteurization, surviving spores may germinate to become vegetative cells which will multiply if conditions such as storage temperature, pH, a_w, and food components are favorable (Lorenzo et al., 2018; Silva & Gibbs, 2010). Therefore, chilled storage is essential to delay quality loss due to spoilage. The conditions of vacuum packaging may allow a delay but do not prevent spoilage because spore-formers could be both aerobic and anaerobic (Helmond et al., 2017).

Spoilage-causing microorganisms may be either nonspore-forming or spore-forming bacteria (Figure 1). Table 3 presents the dominant spoilage microorganisms during storage in various RTE foods treated by thermal treatments and HPP. The predominant nonspore-forming bacteria associated with spoilage are *Brochothrix thermosphacta*, lactic acid bacteria (LAB) (*Lactobacillus* spp., *Lactococcus* spp., *Leuconostoc* spp., *Pediococcus* spp., *Streptococcus* spp.), and *Weisella* spp. (Table 3). These bacteria become predominant spoilage bacteria under low oxygen, low temperature, and acidic and low acidic conditions (Rawat, 2015). In addition to LAB, *Pseudomonas* species such as *Pseudomonas fluorescens*, *Pseudomonas putida*, and *Pseudomonas fragi* are well-known food spoilers

TABLE 3 The dominant spoilage microorganisms during storage in various ready-to-eat (RTE) foods pasteurized by thermal processing or high-pressure processing (HPP)

Spoilage organisms	Product (pH)	Pasteurization conditions	Storage temperature	Significant findings	Reference
LAB	Sliced cooked ham	200–400 MPa for 5–20 min	2°C	The LAB counts in samples treated at 200 and 400 MPa (5 min) increased to 6–7-log CFU/g after 21 and 35 days storage. Treatment at 400 MPa for 20 min provides 35 days of shelf-life at 2°C.	López-Caballero et al. (1999)
	Spaghetti and meat sauce (4.5–6)	Process 1: 65°C/71–105 min (sous-vide) Process 2: 75°C/37–40 min (sous-vide)	5°C and 15°C	After 14 and 21 days of storage at 15°C, packages treated by processes 1 (71 min) and 2 (37 min) were swollen, respectively. Longer treatment time resulted in 35 days of storage at 5°C and 15°C.	Simpson et al. (1994)
	Vegetable sausages (6.4)	82°C	< 8°C	The LAB count reached 8.8-log CFU/g in 21 days of storage and according to sensorial quality, sausages were unacceptable. The spoilage was related to postcooking contamination.	Vihavainen et al. (2008)
LAB and *Pseudomonas*	RTE meals (18 products)	70°C/2 min or 90°C/5 min	3°C and 8°C	Eight out of 18 products spoiled after 2 weeks of storage at 8°C. LAB reached ≥ 7-log CFU/g for some RTE meals after 3 weeks at 8°C. *Pseudomonas* number increased after 5 weeks at 3°C and 8°C for different meals.	Nyati (2000)
Lactobacilli and *Brochothrix*	RTE lacón (6.1)	500 MP, 600 MPa/5 min	4°C	*Lactobacilli* and *Brochothrix* did not exceed 7-log CFU/g during 120 and 60 days at 4°C, respectively.	Del Olmo et al. (2014)
LAB and *Enterobacteriaceae*	Cooked ham (6.3)	600 MPa/6 min/31°C	4°C	*Enterobacteriaceae* was below the detection limit during 120 days at 4°C in HPP-treated samples. However, LAB counts exceeded 7-log CFU/g at day 120.	Garriga et al. (2004)
		400 MPa/10 min/30°C	2°C,7°C, and 12°C	In 56 days, LAB in pressurized samples reached 7-log CFU/g during storage at 7°C and 12°C.	Ruiz-Capillas et al. (2007)
B. thermosphacta	Chicken fillet (6.0)	500 MPa/10 min	4°C and 12°C	After 14 days of storage, *B. thermosphacta* reached 7-log CFU/g. *Bacillus thermosphacta* was the main spoilage microorganism.	Argyri et al. (2018)
B. cereus and *Bacillus pumilus*	Cream, bechamel sauce, vegetable soup (5.5–6.7)	70°C–80°C–90°C/10 min	7°C and 10°C	Treatment of 80–90°C for 10 min provided prevention of outgrowth over 34 days at 7°C. When pH was close to 7, the outgrowth of *B. cereus* and *B. pumilus* occurred earlier than at lower pH values.	Samapundo et al. (2014)

(Continues)

TABLE 3 (Continued)

Spoilage organisms	Product (pH)	Pasteurization conditions	Storage temperature	Significant findings	Reference
B. cereus	Vegetable purees	80°C/10–20 min	4°C and 10°C	Most of the samples were tested positive after 20 days at 10°C, yet no detection in samples stored at 4°C was observed.	Choma et al. (2000)
Bacillus spp.	Vegetable purees (6.0–6.5)	80°C/30 min	4°C,10°C, and 25°C	All samples spoiled when they were stored at 25°C. The count of *Bacillus* spp. increased to 6–8-log CFU/g after 45 days of storage at 4°C.	Carlin et al. (2000)
B. cereus, *B. subtilis or Paenibacillus amylolyticus*	Rice	400 MPa and 600 MPa/10 min400 MPa and 600 MPa/10 min then cooking (100°C for 10 min)	25°C	Only HPP and cooked samples spoiled after 1 and 3 days of storage at 25°C, respectively. 400 MPa and cooking resulted in no detection of bacterial counts for 56 days at 25°C.	Yu et al. (2018)
Paenibacillus spp.	RTE meals (6.3)	85°C for 5 min	2°C, 4°C, 7°C, and 22°C	The number of spoilage microorganisms increased after 30 days of storage at 4°C. During storage of 14 days at 2°C, the number of spoilage microorganisms did not significantly change.	Helmond et al. (2017)
Bacillus and *Clostridium*	Mashed potato (5.7)	80°C for 10 min	8°C and 25°C	Growth of *Clostridium* and *Bacillus* strains increased after 13 and 39 days at 8°C, respectively.	Thomas et al. (2002)

Abbreviation: LAB, lactic acid bacteria.

under aerobic refrigerated conditions in low acidic foods (pH > 5.8) (Bevilacqua et al., 2016).

Psychrotolerant spore-forming bacteria cause spoilage and therefore limit the shelf-life of pasteurized foods (Doll et al., 2017). Two major groups of psychrotolerant spore-forming bacteria, the aerobic or facultative anaerobic *Bacillus* genera, and the strictly anaerobic *Clostridium* genera may pose spoilage risks in chilled packaged foods. *Bacillus cereus* and *C. botulinum* in these two genera are known foodborne pathogens (André et al., 2017). The spoilage of RTE foods is associated with aerobic endospore formers (*Bacillus* and *Paenibacillus* species) and anaerobic spore formers (such as np *C. botulinum* and *Clostridium estertheticum*) (Table 3). Many *Bacillus* and *Paenibacillus* species can grow under anaerobic conditions; thus, vacuum packaging does not prevent their growth. These microorganisms are mostly observed when products undergo unintentional temperature abuse. A temperature shift from 4°C to 10°C enhanced the growth of *Bacillus* and *Paenibacillus* species. *Paenibacillus* is a significant spoilage-causing, endospore-forming bacterium for pasteurized, refrigerated foods at the end of storage at refrigeration temperatures below 8–10°C. *Paenibacillus* have been isolated from a variety of environments including soil, water, plants, animals, and feed (Grady et al., 2016).

3 | HIGH-PRESSURE PROCESS PASTEURIZATION

Although thermal processing is one of the most common conventional methods for pasteurization of food products, high temperatures may introduce undesirable changes in appearance, texture, flavor, and color due to slow heat penetration in conductive heating (Torres & Velazquez, 2005). In this regard, the food industry is interested in developing nonthermal pasteurization methods to produce fully cooked RTE meals with a variety of nutritious snacks and meals, and ethnic dishes to meet the consumer demand for safe, nutritious, and good sensorial quality (Stratakos & Koidis, 2015). Among novel nonthermal pasteurization methods, HPP is one of the best options at the industrial level (Bello et al., 2014). Additionally, the FDA and USDA FSIS have recognized that HPP could be utilized as a post-packaging pasteurization method for low-acid foods when spores are not the target microorganisms (Chakraborty et al., 2014).

The effect of high pressure on food has been known for more than a century (Patterson et al., 2006). In 1899, Bert Hite used high pressure for the pasteurization of milk in the United States and in 1914 developed hydrostatic pressure for the inactivation of some microorganisms to preserve fruits and vegetables (Rivalain et al., 2010). However, several difficulties, including the high equipment cost, the technical limitations to fabricating pressure vessels to stand the high pressures needed for meaningful inactivation levels, lack of packaging materials, prevented any commercial benefit from this technique for almost 80 years. Therefore, HPP was not considered feasible for the food processing industries until the late 1980s (Rastogi et al., 2007). Still, between the 1940s and 1980s, scientists investigated the pressure resistance of bacteria, the germination of spores, and the effect of high pressures on enzymes for food processing applications (Rivalain et al., 2010). The food companies that pioneered the use of HPP starting from the early 1990s are given in Table 4. To date, companies in several countries including Japan, France, Canada, Spain, China, Peru, Greece, Italy, Australia, Mexico, and the United States have been producing a wide range of high-pressure pasteurized products (Tao et al., 2014). Examples of the commercially available high-pressure pasteurized products in the United States are juices, smoothies, guacamole, deli meat slices, ready meal components, poultry, dairy products, oysters, ham, and salsa (Balasubramaniam et al., 2016).

Over the past two decades, HPP has increasingly been acknowledged as an alternative to thermal pasteurization. HPP treatment at ambient temperatures is utilized to inactivate vegetative microorganisms to extend the shelf-life of low-acid foods at refrigeration conditions or produce shelf-stable high-acid foods. The high-pressure pasteurization is usually conducted under the pressure between 400 MPa and 600 MPa for 1–15 min at chilled or mild temperatures (< 45°C) (Mor-Mur et al., 2014). During a pressure build-up, the temperature of products is slightly elevated due to compression heating (Tao et al., 2014). The magnitude of temperature increase is dependent on the target pressure, pressurizing medium and food composition. The temperature rise is typically 2–3°C per 100 MPa for aqueous materials and 6–9°C for oil-based materials (when the food contains a high amount of fat such as butter) and the product temperature returns close to its initial temperature after decompression (Rastogi et al., 2007).

Two scientific principles are crucial for understanding the mechanism of HPP in food processing. The first principle is Le Chatelier's principle, which states that when a system at equilibrium is disturbed, the system tends to minimize the disturbance. During HPP, phase transition, molecular configuration change, and chemical reaction associated with a volume decrease are enhanced by the application of pressure, and vice-versa (Tao et al., 2014). The second one is the isostatic principle, also known as the Pascal principle, which states that pressure is distributed uniformly and simultaneously throughout

TABLE 4 Food companies that pioneer the use of high-pressure processing (HPP)

Year	Company (country)	Product	Processing conditions
Early 1990s	Meidi-Ya (Japan)	Fruit jams	400 MPa for 20 min
1994	Pampryl formerly Ulti (France)	Freshly squeezed juices	400 MPa
1997	Megamex formerly Avomex (United States)	Avocado products	690 MPa
1998	Espuña (Spain)	RTE meat products	400 MPa for 10 min
1998	Groupe Danone (France)	Fruit-based preparations	800 MPa for 6 min at 20°C

Abbreviation: RTE, ready-to-eat.
Source: Leadley (2008), Rovere (2001), and Balasubramaniam et al. (2016), Tonello (2011).

the entire sample of homogenous soft solids and liquids independently of the product size and geometry (Knorr, 1993; Nair et al., 2016).

3.1 | High-pressure inactivation of microorganisms

The inactivation of microorganisms under high pressure may depend on the intrinsic properties of foods. The a_w (Hayman et al., 2008; Sevenich et al., 2015) and acidity (Roberts & Hoover, 1996) of foods have an impact on the pressure sensitivity of vegetative cells and bacterial spores. Baroprotective effect on microorganisms can be enhanced by reducing a_w. A treatment of 400 MPa at 25°C for 15 min resulted in no inactivation in *Rhodotorula rubra* at a_w below 0.91, yet a 7-$\log_{10}$ reduction was observed at a_w of 0.96 (Oxen & Knorr, 1993). Morales et al. (2006) reported that the decrease from 0.98 to 0.90 in the a_w of fresh Hispánico-type cheese had a baroprotective effect on the inactivation of *L. monocytogenes*. Xu et al. (2021) reported less reduction of *B. cereus* spores with a decrease of a_w (from 0.99 to 0.80) of buffer solutions at different pH values (3.8–7.3). Reduction of pH from 6.5 to 4.8 during HPP at 550–650 MPa and 55−75°C enhanced microbial inactivation of *Clostridium* spores (Paredes-Sabja et al., 2007). Due to inherent food matrices, vegetative cells and bacterial spores could be protected by food constituents such as fat, sugars, salt, and spices (Sevenich, 2016). For instance, a decrease in fat content in milk exerted a baroprotective effect on *Escherichia coli*, *L. monocytogenes*, and *Staphylococcus aureus* (Gervilla et al., 2000), while the fat content of tuna and sardine resulted in the protection of spores against HPP inactivation (Sevenich et al., 2013). Additionally, antimicrobial compounds such as nisin (Lebow et al., 2017; Pokhrel et al., 2019), reutericyclin (Hofstetter et al., 2013), and potassium lactate (Fulladosa et al., 2012) have been utilized to enhance microbial inactivation during HPP. Several other antimicrobial compounds and their effect under HPP conditions have been discussed in De Oliveira et al. (2015).

3.1.1 | Inactivation of vegetative cells

Large molecules (such as protein) are denatured under high pressure, which explains the mechanisms of the inactivation of microorganisms (Stute et al., 1996). The response of microorganisms under compression depends upon process parameters such as pressure, temperature, and time (Jofré et al., 2010). The minimum pressure level should be 300 MPa to achieve microbial inactivation regardless of the process time (NACMCF, 2006). High-pressure treatments up to 600 MPa at ambient or moderate temperatures can inactivate both pathogenic and spoilage vegetative bacteria cells (Patterson et al., 2006). The FDA recommends a minimum pressure of 580 MPa for pasteurization of low-acid foods to inactivate pathogenic bacteria such as *Listeria* spp. and *Salmonella* spp. (FDA, 2010). Resistance of living cells to high pressure depends on several factors related to the gram type, physiological state, and strain particularities (Jofré et al., 2010). In general, vegetative bacteria at the exponential growth phase are more pressure sensitive than that at the stationary phase and Gram-negative bacteria have less tolerance to high pressure than Gram-positive bacteria due to the inherent thicker peptidoglycan layer of Gram-positive bacteria (Dumay et al., 2010).

Listeria monocytogenes and *S. aureus* are the most pressure-resistant nonspore-forming Gram-positive bacteria (Farkas & Hoover, 2000). Hugas et al. (2002) reported more than 3-$\log_{10}$ reduction of *S. aureus* in marinated beef and cooked ham processed at 600 MPa, 31°C, 6 min. The pressure resistance of certain strains of *E. coli* O157:H7 is relatively high although they are classified as Gram-negative bacteria (Patterson et al., 2006). Zhou et al. (2016) reported that HPP at 400 MPa, 25°C at five pressure cycles of 3 min each led to a 5-$\log_{10}$ reduction of *E. coli* O157:H7 cocktail in ground beef. Some *Salmonella* strains such as *Salmonella enterica* are sensitive to pressure compared to *L. monocytogenes* and *E. coli* O157:H7 (González-Angulo et al., 2021), while some strains such as *Salmonella* Enteritidis FDA and *Salmonella* Typhimurium E21274 showed higher resistance to pressure compared to

E. coli O157:H7 (Alpas et al., 2000). The pressure sensitivity varies among the different strains, which plays a significant role in establishing processing parameters to ensure the safety of pressure-pasteurized foods (Alpas et al., 1999). For instance, 275, 350, and 450 MPa for 15 min in phosphate buffer (pH 7.0) are required to obtain 5-$\log_{10}$ reductions of *Yersinia enterocolitica*, *S.* Typhimurium, *S.* Enteritidis, respectively. *Escherichia coli* O157:H7 and *S. aureus* require 700 MPa for 15 min for a similar reduction (Patterson et al., 1995). High-pressure treatment at 600 MPa for 18 min resulted in a 1.7-$\log_{10}$ reduction of *Salmonella* in peanut butter (D'Souza et al., 2014).

3.1.2 | Inactivation of spores

Bacterial spores are extremely resistant to various stresses including pressure due to the structure and thickness of the spore coat (Reddy et al., 2006). However, the inactivation of spores by high pressure can happen in two steps: germinating spores and then inactivating the spores in germinated form. Treatment of a few hundred MPa leads to spore germination, yet insufficient to inactivate these germinated forms (Balci & Wilbey, 1999). High pressure alone is not effective for the inactivation of spore-forming bacteria (Hogan et al., 2005; Hugas et al., 2002). In the food industry, HPP is inapplicable to low-acid foods due to the endurance of bacterial spores during pressure treatment up to 800 MPa at an ambient temperature (Farkas & Hoover, 2000; Serment-Moreno et al., 2014). The limited efficacy of HPP against spore formers requires elevated temperature, in addition to high pressure to inactivate bacterial spores, this process is known as pressure-assisted thermal sterilization (PATS) (Ahmed & Ramaswamy, 2006; Reddy et al., 2006), yet sterilization is not the scope of this review.

Clostridium (*C. botulinum* (type A, B, E, and F), *Clostridium sporogenes*, and *Clostridium perfringens*) and *Bacillus* (*Bacillus cereus*, *Bacillus coagulans*, and *Bacillus subtilis*) spores are highly resistant to pressure (Georget et al., 2015; Margosch et al., 2004). The presence of toxigenic *C. botulinum* and *B. subtilis* and their ability to germinate plays a crucial role in the microbial safety of low-acid foods. *C. botulinum* and *B. subtilis* cannot be completely inactivated by the pressure up to 1000 MPa at ambient temperature. However, 600 MPa at 80°C for 10 min resulted in a 4-$\log_{10}$ reduction of *C. botulinum* ATCC 19397 in the mashed carrots (Margosch et al., 2004). Several studies have examined the inactivation of bacterial spores, such as *B. coagulans*, and *B. cereus*, under combined pressure (400–600 MPa) and thermal treatment (50–85°C) conditions (Daryaei & Balasubramaniam, 2013; Daryaei et al., 2013). Processes of 600 MPa at 50°C and 600 MPa at 60°C after 15 min of treatment time, the reductions were 3.1-$\log_{10}$ and 5.7-$\log_{10}$ reductions in *B. coagulans* spores in tomato pulp, respectively (Zimmermann et al., 2013).

Many studies reported the inactivation of np and proteolytic *C. botulinum* spores at a minimum pressure level of 600 MPa and an initial temperature of 60°C (will increase to 90–120°C during treatment), these treatments were already mentioned as PATS (Barbosa-Cánovas & Juliano, 2008). However, there is relatively little information on the inactivation of np *C. botulinum* spores under high pressure with elevated temperatures as a pasteurization method. Reddy et al. (1999) reported that HPP at 827 MPa for 5 min at 55–60°C induced more than 5-$\log_{10}$ reduction of np *C. botulinum* type E spores in phosphate buffer (pH 7.0). Therefore, Knockaert et al. (2011) extrapolated the above data of Reddy et al. (1999) and assumed that the conditions of 600 MPa for 20 min at 45°C might result in a 6-$\log_{10}$ reduction of np *C. botulinum* spores. However, no microbiological study has been reported to validate these processing conditions due to the lack of suitable surrogates for *C. botulinum* np types B, E, and F. Table 5 shows the inactivation of *L. monocytogenes* and np *C. botulinum* for processing of low-acid foods and different substrates exposed to HPP treatments at different pressure-time-temperature combinations.

3.1.3 | Inactivation of viruses

The virus can be divided into two groups: enveloped and nonenveloped viruses. The enveloped viruses (influenza viruses) are usually more sensitive than the nonenveloped ones (norovirus, poliovirus) to pressure. The nonenveloped viruses lack a lipid envelope and therefore are more resistant to stresses such as heat and pressure (Kishida et al., 2013; Tao et al., 2014). The major foodborne viruses, including the hepatitis A virus (HAV), human norovirus (HuNoV), human adenovirus (HuAdV), and Aichi virus (AiV), are from the nonenveloped group (Govaris & Pexara, 2021). Among the most important foodborne viruses, noroviruses are considered to be the leading cause of foodborne illnesses and are responsible for approximately 9.2 million cases/year, followed by HAV with 12,600 foodborne cases/year in the United States. These viruses cause foodborne illnesses from the consumption of particularly shellfish such as oysters, clams, and mussels and other foods such as green onion (Shearer et al., 2016).

Viruses show a wide range of sensitivity to high pressure. Human viruses appear to be more pressure sensitive than tobacco mosaic virus, which requires 920 MPa for the inactivation (Farkas & Hoover, 2000; Grove et al., 2006) or 800 MPa for 45 min (Basset et al., 1938). A treatment

TABLE 5 High-pressure processing conditions to inactivate target microorganisms for processing of low-acid foods and different buffer solutions

Product (pH)	Processing conditionspressure, time, and temperature	Target microorganism	Inactivation level	Reference
Model soup (6.1)	600 MPa, 5 min, 25°C or 525 MPa, 5 min, 40°C	*L. monocytogenes*	> 6-log	Ates et al. (2016)
Brain heart infusion broth (6.7)	600 MPa, 10 min, 25°C	*L. monocytogenes*	6-log	Dogan and Erkmen (2004)
Broth	345 MPa, 10 min, 35°C	*L. monocytogenes*	5-log	Alpas et al. (2000)
Thai coconut water (5.2)	550 MPa, 3 min, 10°C	*C. botulinum* type E	0-log	González-Angulo et al. (2020)
Phosphate buffer (7.0)	827 MPa, 10 min, 40°C	*C. botulinum* type E	5-log	Reddy et al. (1999)
Phosphate buffer (7.0)	827 MPa, 5 min, 60–70°C	*C. botulinum* type E	> 5-log	Reddy et al. (2000)
Phosphate buffer (7.0)	600 MPa, 4-5 min, 100°C	*C. botulinum* type E	6-log	Maier et al. (2018)
ACES buffer (7.0)	600 MPa, 18–54 min, 80°C	*C. botulinum* types B and F	6-log	Skinner et al. (2014)
ACES buffer (7.0)	600 MPa, 15 min, 90°C	*C. botulinum* type F	6-log	Skinner et al. (2018)
Emulsion model systems (n.d.)	750 MPa, 10 min, 75°C	*C. botulinum* type E	< 3.5-log	Schnabel et al. (2015)
Phosphate buffer (7.0)	620 MPa, 10 min, 100°C	*C. botulinum* type B	5.5-log	Reddy et al. (2006)
Crabmeat blend (7.2–7.4)	827 MPa, 20 min, 75°C	*C. botulinum* type B	5–6-log	Reddy et al. (2006)
Phosphate buffer (7.0)	827 MPa, 20–30 min, 75°C	*C. botulinum* type B	> 6-log	Reddy et al. (2006)
Minced chicken (6.7)	600 MPa, 2 min, 20°C	*C. botulinum* types B and E	< 1-log	Linton et al. (2014)
Mashed carrot (5.2)	600 MPa, 1 s, 80°C	*C. botulinum* type B	> 5.5-log	Margosch et al. (2004)

Abbreviation: n.d., not described.

of 600 MPa for 10 min resulted in more than 5-$\log_{10}$ and 3-$\log_{10}$ reduction in feline calicivirus (FCV) (a surrogate for norovirus) and HAV, respectively (Grove et al., 2008). Sharma et al. (2008) reported 3.3-$\log_{10}$ and 1.1-$\log_{10}$ reduction of HAV in water and sausages under HPP conditions of 500 MPa at 4°C for 5 min, respectively. Kingsley et al. (2005) observed a 4.8-$\log_{10}$ reduction of HAV in sliced green onion after 5 min of exposure to HPP at 375 MPa. Treatments of 200 MPa for 15 min, 400 MPa for 15 min, and 600 MPa for 15 and 60 min showed no significant inactivation of poliovirus, while treatments at 400 and 600 MPa for 15 min resulted in complete inactivation of HuAdV (Wilkinson et al., 2001). Kingsley et al. (2004) observed no reduction in AiV under HPP conditions of 600 MPa at 21°C for 5 min. However, Kingsley et al. (2004) reported a 7-$\log_{10}$ reduction of FCV (nonenveloped) at a lower pressure level of 275 MPa at 22°C for 5 min.

Food matrices or composition and pH could affect the HPP inactivation of viruses (Shearer et al., 2016). Kingsley and Chen (2008) reported that pressure inactivation of FCV was higher at pH ≤ 5.2 compared to a pH range between 5.2 and 8. Low pH (3 and 4) also significantly enhanced pressure inactivation of HAV compared to pH 5.2, 6, and 7 (Kingsley & Chen, 2009). However, a pressure treatment of 400 MPa at 4°C and 20°C for 2 min resulted in more inactivation of HuNoV at pH 7 than at pH 4 in a strawberry puree (DiCaprio et al., 2019). Salt concentrations higher than 1% provided a significant protective effect for HAV against pressure, a significant log reduction of HAV was observed in salt concentrations lower than 1% (Kingsley & Chen, 2009). Lower a_w with increased concentrations of sucrose and salt generally resulted in lower inactivation of FCV by pressure (Kingsley & Chen, 2008).

Low temperature promotes the denaturation of proteins and viruses under HPP conditions (Shearer et al., 2016). Huang et al. (2016) observed a 2.5-$\log_{10}$ reduction of HuNoV GI.1 in strawberry puree after an HPP treatment of 550 MPa at 0°C for 2 min. An increase in temperature from 0°C to 4°C and 20°C resulted in 2.2-$\log_{10}$ and 1.0-$\log_{10}$ reductions of HuNoV GI.1, respectively (Huang et al., 2016). The HPP treatments of 500 MPa and 300 MPa at 1°C for 2 min resulted in more than 3-$\log_{10}$ reduction of HuNoV GII.4 in green onions (pH 5.1) and salsa (pH ~ 4), respectively (Sido et al., 2017). Reducing the initial sample temperature from 10°C to 1°C increased the inactivation of murine norovirus (MNV-1), a common surrogate for HuNoV, in green onions (Sido et al., 2017).

HPP has become the most promising method for oyster shucking in the United States which has tested positive for norovirus (DePaola et al., 2010). For oyster shucking and inactivation of *Vibrio* spp., the process conditions of 400 MPa at 21°C for between 1 to 5 min are currently

used (López-Caballero et al., 2000). But these same processing parameters are reported to be inadequate for the norovirus inactivation (Agarwal, 2015). However, HPP at 400 MPa for 1 min at 4°C and 21°C resulted in a decrease in MNV-1 in oysters (Agarwal, 2015). Agarwal (2015) has also reported that decreasing the initial temperature of oysters from 21°C to 4°C increases the reduction of MNV-1 from 1-$\log_{10}$ to 4-$\log_{10}$. The HPP conditions (600 MPa, 6°C, 5 min) could completely inactivate HuNoV GI.1 strain in inoculated oysters, but not for lower HPP conditions (400 MPa, 6°C, 5 min) (Leon et al., 2011).

3.1.4 | Inactivation of fungi

Fungi consist of two groups: yeasts and molds (Tao et al., 2014) which are known to be low pH resistant. Inactivation of these microorganisms in acidic foods (pH < 4) is difficult, and therefore, they are mostly the target microorganisms for acidic foods (Smelt, 1998). Even though fungi are not targeted microorganisms for low-acid foods, they may lead to spoilage and deterioration in some low-acid RTE foods such as tofu, tortillas, cheese, and minimally processed vegetables due to the growth of these organisms (Bello et al., 2014). Vegetative forms of yeasts and molds are relatively sensitive to pressure and can be inactivated at pressures ranging from 300 MPa to 400 MPa in a few minutes of exposure time and at a temperature of 25°C. For example, HPP at 200–400 MPa at 5°C for 30 min resulted in a 2−4-$\log_{10}$ reduction of yeast and mold in lettuce, tomato, asparagus, onions, cauliflower, and spinach (Arroyo et al., 1999). Inactivation of ascospores requires higher levels of pressure than that for vegetative yeasts and molds. For example, the treatment conditions of 600 MPa at 60°C within 60 min destroy most of the ascospores of *Byssochlamys nivea*. It has been reported that the ascopores of *B. nivea*, a heat-resistant mold, require 700 MPa at 70°C for 60 min for complete inactivation in sodium salt solution ($a_w = 0.89$) (Butz et al., 1996). Ascospore suspensions of *Talaromyces macrosporus* can survive at 1000 MPa up to 5 min (Dijksterhuis & Teunissen, 2004). The higher-pressure resistance of the ascospores of *Zygosaccharomyces bailii* compared to vegetative cells was attributed to the thicker ascospore wall (Raso et al., 1998).

3.2 | Quality of high-pressure processed foods

The effect of pressure on primary and covalent bonds is negligible under the levels used in the food processing (Neetoo & Chen, 2014). Thus, molecules with low molecular weights that contribute to the color, flavor, or nutritional quality of food remain intact during high-pressure treatments (Patterson et al., 2006). Additionally, uniform compression heating and expansion cooling help to prevent the detrimental effect of high temperature (thermal degradation) and preserve the nutritional value (Park et al., 2014). On the other hand, high pressure can irreversibly affect noncovalent bonds (hydrogen, ionic, and hydrophobic bonds), resulting in changes in some compounds particularly protein, lipid, and starch. Therefore, HPP processes may change perceived quality when the organoleptic attributes of food depend on the structural or functional macromolecules (Balasubramaniam et al., 2016; Govaris & Pexara, 2021).

3.2.1 | Enzyme inhibition by HPP

Since enzymes are proteins, enzymatic reactions are affected by high pressure that results in changes in the quality attributes of many foods including meats, fruits, and vegetables (Patterson et al., 2006). Inhibition of enzyme activity is highly desirable for HPP-treated foods to prevent quality degradation during subsequent storage (Chakraborty et al., 2014). Enzymes can be inactivated by pressure, but the level of pressure required for inactivation varies greatly, due to their relative sensitivity to the pressure (Aertsen et al., 2009). The baroresistance of some enzymes such as peroxidase (POD), polyphenol oxidase (PPO), and pectin methylesterase (PME) is relatively high, those enzymes are only partially inactivated at commercially feasible processing conditions (up to 600 MPa). On the other hand, polygalacturonase and lipoxygenase (LOX) display low baroresistance, and commercial processing conditions are sufficient for their complete inactivation (Terefe et al., 2014). Significantly, some baroresistant enzymes require higher pressure combined with elevated temperatures to achieve high levels of inactivation (Serment-Moreno et al., 2014). Thus, the challenge of enzyme degradation by HPP can be solved by combining high pressure with mild heat (Crelier et al., 2001).

One of the most pressure-resistant vegetable enzymes is POD. This highly heat-stable enzyme is frequently used to determine the efficiency of blanching processes. POD causes negative flavor changes in vegetables. A high-pressure treatment at 900 MPa for 10 min inactivated 88% of POD in green peas and the residual activity of POD was found to be identical to water-blanched beans (Quaglia et al., 1996). A 90% residual activity of POD was also observed after treatment of 600 MPa at 60°C for 30 min by Seyderhelm et al. (1996). The influence of the residual POD on the quality of the HPP-treated produce differs among vegetables. For example, the incomplete

inactivation of POD in pressure-treated cauliflower at 100–400 MPa at 5°C for 30 min induced browning at high pressures, while many other vegetables including asparagus, spinach, and tomato displayed no change in sensory properties, as reported in Arroyo et al. (1997).

PPO, another pressure-resistant enzyme, causes undesirable color changes such as enzymatic browning (Weemaes et al., 1999). Gomes and Ledward (1996) highlighted that it is difficult to completely inactivate PPO when using high pressure alone. Eshtiaghi et al. (1994) reported that 900 MPa for 30 min at 45°C is required for the complete inactivation of PPO. Changes in the color of avocado pulp and guacamole after HPP treatments and during subsequent storage were attributed to partial disruption of cellular organelles releasing enzymes such as PPO. An HPP treatment at 689 MPa for 20 min resulted in 22% of the residual activity of the PPO (Palou et al., 2000). Inactivation of PPO increased when the pH of the immersion medium was decreased by the addition of citric acid during high-pressure treatments (Eshtiaghi & Knorr, 1993).

HPP treatment at a pressure less than 700 MPa is insufficient for inhibition of PME, another pressure stable enzyme that impacts texture because of its ability to break down pectin. Heated tomato puree (90°C) treated by HPP at 700 MPa for 30 s resulted in complete inactivation of the PME (Krebbers et al., 2003). Polydera et al. (2004) observed 95% of PME inhibition in orange juice after treatment of 800 MPa at 60°C for 4 min.

The activity of LOX in diced Roma tomatoes markedly decreased with the application of 600 MPa at 45°C in 3 min, or pressure dwell time should be increased to 5 min at 25°C (Shook et al., 2001). Rodrigo et al. (2007) reported complete inactivation of LOX in tomato juice at pressures higher than 550 MPa at 20°C for 12 min. In the treatment of 689 MPa at 21°C, LOX activity in the guacamole samples was completely inactivated at times higher than 15 min (Palou et al., 2000).

3.2.2 | Changes in quality attributes by HPP

At ambient temperatures, HPP has a limited effect on color pigments in vegetables such as chlorophyll, carotenoids, antioxidants because of their covalent structure (Butz et al., 2002; Van Loey et al., 1998). For example, no significant green color change in broccoli juice was observed under pressure treatments up to 800 MPa at temperature ranges of 30–40°C, yet treatments at higher temperatures (50–60°C) for 50 min accelerate the degradation of color in broccoli juice (Weemaes et al., 1999). Van Loey et al. (1998) found significant reductions in the chlorophyll of broccoli extract when HPP treatment was combined with temperatures above 50°C.

HPP treatment can increase lipid oxidation and induce color changes in red meat, resulting in a cooked appearance (Yagiz et al., 2009). Loss of color in meat could be due to certain enzymes such as oxygen utilizing enzymes or denaturation of globin proteins in a high pressure (Pandrangi & Balasubramaniam, 2005). Color change in meat typically occurs above 150 MPa, representing a similar color to cooked meat (Hugas et al., 2002). High-pressure treatments of pork, beef, and tuna have a detrimental impact on its red color (although the processes are at 5–10°C) since the sensitivity of the muscle structure and protein constituents to pressure is high (Cheftel & Culioli, 1997). A pressure range of 250–350 MPa on minced beef meat resulted in a significant increase in the L^* values (color turned into pink) and a decrease in a^* values with a cooked aspect (becoming brownish), which is undesirable for RTE meats (Carlez et al., 1995; Cheftel & Culioli, 1997). Two distinct phenomena are attributed to the discoloration of meat under pressure treatments; (1) whitening occurs due to globin denaturation and/or heme displacement or release, and (2) oxidation of ferrous myoglobin to ferric metmyoglobin (Carlez et al., 1995).

Pressure treatments above 200 MPa (room temperature/5–60 min) resulted in softening due to the breakdown of cellular membranes in several fruits and vegetables including apple, pear, orange, pineapple, carrot, celery, green pepper, red pepper, and cherry tomatoes (Basak & Ramaswamy, 1998). Various vegetables show different resistance to pressure due to different vegetable cell structures. For instance, pressure treatment of 600 MPa, 25°C, 5 min resulted in textural degradation in carrot samples, whereas textural improvement occurred in red radish and jicama samples (Nguyen et al., 2010). HPP has the potential to prevent texture degradation since β-eliminative pectin solubilization and depolymerization minimally occur, especially at lower processing temperatures (De Roeck et al., 2009; De Roeck et al., 2008). Foods containing air voids might be affected more by pressure due to shrinkage, for instance, the structure of strawberries collapsed after HPP treatment at 400 MPa and 10°C (Duvetter et al., 2005).

HPP can affect and retard enzymatic and chemical reactions, in which flavor components are involved. HPP may indirectly alter the content of some flavor compounds and disturb the whole balance of flavor composition in fruits and vegetables, consequently causing undesirable changes in flavor (Castro & Saraiva, 2014). HPP has been found to result in the rancid taste often reported in tomato-related products (Rodrigo et al., 2007), sour and rancid flavors in avocado paste after treatment conditions of 600 MPa, 23°C, 3 min (Jacobo-Velázquez & Hernández-Brenes, 2010), fried odor in onions under conditions of 300 MPa, 25°C, 30 min (Butz et al., 2002). When HPP was combined with elevated

temperatures, undesired odor and flavor were observed in tomato puree (treated at 800 MPa, 20–60°C, 10 min) (Viljanen et al., 2011). Flavor changes in HPP-treated foods might occur during subsequent storage due to the residual activity of enzymes.

Micronutrients, low-molecular-weight compounds, are composed of covalent bonds. Therefore, HPP at ambient temperature could preserve or minimally affect micronutrients. Water-soluble vitamins such as B and C are more pressure sensitive than fat-soluble vitamins including A, D, E, and K (Castro & Saraiva, 2014). Among them, vitamin C has been used as a quality indicator because of its pressure sensitivity. Mild pressures up to 400 MPa combined with mild temperatures between 30°C and 60°C or pressure levels of 400–600 MPa at ambient temperature can preserve vitamin C content (Castro & Saraiva, 2014). No significant effect on vitamin C of green beans was observed after HPP (500 MPa, 1 min) compared to raw beans (Krebbers et al., 2002). Sánchez-Moreno et al. (2006) found a 30% loss in vitamin C in tomato puree after HPP treatment (400 MPa, 25°C, 15 min). In general, HPP preserves vitamin C content at low pressure for a short treatment time.

Table 6 summarizes the key findings in terms of microbial safety and quality attributes, storage temperature, and packaging materials of low-acid RTE meals processed using different HPP treatments. As shown in the table, most RTE products are treated by HPP as a second step after cooking (such as 100°C for 10 min). Such products can be considered RTE meals that do not require precise instructions for proper cooking prior to consumption.

3.3 | Comparison of food quality changes after HPP and thermal processing

Thermal processing has been widely used for many decades as a pasteurization method by the food industry. Thermal processes are also known to have a negative effect on food quality attributes due to the application of intense heat during the thermal processing (Lemmens et al., 2013). After the advent of HPP, many studies compared the impact of two pasteurization methods on microbial safety and the quality attributes of pasteurized foods. HPP pasteurization generally has the advantage of limited adverse effects on quality attributes compared to thermally pasteurized foods. Fewer quality changes in nutritional value, flavor, taste, texture, and color of HPP-treated foods can be attributed to less exposure to heat and the minimal effects of HPP on small molecules like nutrients and flavors (Vervoort et al., 2012). Table 7 presents comparison studies, in terms of quality attributes, of low-acid foods treated by HPP and of similar food processed using thermal treatments.

In the literature, inappropriate comparisons between HPP and thermal methods have been reported which may lead to a biased perception of HPP. Trejo Araya et al. (2009) compared HPP pasteurization (600 MPa, 2 min) with a thermal cooking process (20 min in boiling water) for carrots in terms of quality and sensory attributes, which is not relevant due to the different aims of these processing conditions. For a fair comparison between the two pasteurization methods in terms of their impact on quality attributes, the processing conditions should be selected to achieve a similar level of reduction of the target pathogens, as microbial safety is the main concern when selecting pasteurization processing conditions. Other factors may also be considered as secondary criteria for the comparison of different pasteurization methods. For instance, the same level of enzyme inactivation by processing can be targeted for comparative studies when enzymatic deterioration plays a more significant role in a particular product (Vervoort et al., 2012).

Pasteurization using microbiologically equivalent processing conditions of HPP at 600 MPa for 10 min and thermal pasteurization at 70°C for 2 min had a similar impact on color, total carotenoid content, and hardness in carrots (Vervoort et al., 2012). Inanoglu et al. (2021) reported a similar color degradation and retention in firmness in green beans treated by both HPP (600 MPa/10 min) and short-time microwave-assisted thermal pasteurization (MAPS) (70°C/2 min). This study reported more vitamin C degradation in HPP-treated green beans compared to MAPS-treated ones. Microbiologically equivalent processing conditions of HPP (700 MPa at 38°C for 5 min) and thermal processing (90°C for 10 min) of carrots resulted in a similar color degradation, yet HPP treatment conditions preserve the hardness of carrots better than the applied thermal processing conditions (Vervoort et al., 2012). Similar results were obtained in green beans under HPP (600 MPa/45°C/20 min) and microwave-assisted thermal pasteurization (90°C/10 min) by Inanoglu et al. (2022). In another study, Vervoort et al. (2012) observed more peroxidase inactivation after thermal treatments compared to HPP treatments under the above-mentioned conditions.

3.4 | Limitations

The pH of foods influences the inactivation of bacteria by high pressure. If the pH of the food is optimal for the growth of particular bacteria species, the inactivation of those species during HPP might be challenging, particularly for high-pressure resistant spores (Norton & Sun, 2008). As mentioned in Section 2.2.1, low-acid foods provide excellent growth conditions for *L. monocytogenes* and np *C. botulinum* spores. Several studies reported that *L.*

TABLE 6 Low-acid ready-to-eat (RTE) meals processed by high-pressure processing (HPP)

Pasteurization conditions	Product (pH)	Storage temperature and shelf-life	Packaging	Key findings	Reference
Soup, pasta, and vegetable-based meals					
600 MPa/20–50°C/5 min	Model soup (6.1)	4°C and 8°C/21 days	Polyethylene film, vacuum packaged	HPP treatment at 600 MPa/25°C/5 min resulted in more than 6-log reduction of *L. monocytogenes*. No bacterial regrowth in the soup during 3 weeks at 4°C and 8°C was observed after pressurization at 600 MPa above 45°C for 5 min.	Ates et al. (2016)
650 MPa/55–65°C/10 min	Model soup (6.1)	–	Trays with a 90 μm PA/PP film layer, vacuum packaged	HPP treatments resulted in up to 4.5-log reduction of *Bacillus subtilis* spores.	Ates et al. (2016)
500 MPa or 600 MPa/18°C,1 min (after cooking)	Lasagna (5.5)	4°C and 12°C/56 days	Polyethylene/poly film, vacuum packaged	HPP treatments at 500 and 600 MPa/1 min resulted in a significant reduction in TAC, LAB, and *Pseudomonas* counts and prolong the shelf-life of lasagna. The recovery of *L. monocytogenes* was observed in lasagna treated by HPP at 600 MPa after 7 days of storage at 8°C. The quality attributes of HPP-treated lasagna were stable during storage.	Stratakos et al. (2015)
300, 400, 500, 600, and 680 MPa/5-7°C/5 min and 8 min (after cooking)	Spanish potato omelette (6.7)	6°C/15 days	Vacuum packaged with polyethylene-polyamide plastic film	Treatments of at least 680 MPa for 8 min should be recommended to reduce the concentration of intact *Salmonella* cells.	Toledo et al. (2012)
400 MPa or 600 MPa/10°C/1 min and 5 min (after cooking at 100°C for 10 min for meal A and at 70°C for 45 min)	Meal A: pumpkin and broccoli (5.8). Meal B: eggplant, zucchini, chard, and spinach (5.4)	4°C/20 days	Polypropylene film	400 MPa was not effective enough to reduce the initial microbial loads of the meals, whereas 600 MPa/5 min effectively maintained microbial safety. HPP at 600 MPa reduced the antioxidant activity of meal B and increased the antioxidant activity of meal A.	Masegosa et al. (2014)

(Continues)

TABLE 6 (Continued)

Pasteurization conditions	Product (pH)	Storage temperature and shelf-life	Packaging	Key findings	Reference
600 MPa/25°C/10 min	Green beans with brine	2°C/36 days and 10°C/20 days	Vacuum packaged with laminate multilayer polymer film	HPP treatment resulted in a 3.7-log CFU/g reduction in *L. innocua* ATCC 51742. The green color significantly changed after 8 and 6 days at 2°C and 10°C, respectively. The vitamin C content of green beans were completely degraded in 8 and 2 days at 2°C and 10°C, respectively.	Inanoglu et al. (2021)
600 MPa/45°C/20 min (after preheating at 45°C)	Green beans with brine	2°C/14 weel and 7°C/7 week	Vacuum packaged with laminate multilayer polymer film	Swelling was observed in HPP-treated pouches after 3 weeks of storage at 7°C. Growth of *Clostridium beijerinckii* and *Peanibacillus* spp. was detected in green beans during storage at 7°C. For the shelf life of HPP-treated green beans, 6 and 2 weeks were suggested when stored at 2°C or less, and at 7°C, respectively.	Inanoglu et al. (2022)
Chicken-based meals					
500 MPa/4°C/1 min (after cooking)	RTE chicken breast (6.1)	4°C and 8°C/60 days	Vacuum packaged with the polyethylene-polyamide film	The counts of *L. monocytogenes* in HPP-treated samples were below the detection limit during 60 days at 4°C. The incorporation of active packaging in the treatments was able to better preserve the color of meat.	Stratakos et al. (2015)
500 MPa/−10°C, 5°C, 20°C and 50°C/30 min and 60 min	Minced chicken thighs (6.3)	4°C/9 day	Vacuum packaged with plastic film	HPP treatments resulted in significant color changes. HPP treatment at 20°C and 50°C caused the palest color in chicken thighs compared to other HPP treatments.	Beltran et al. (2004)

(Continues)

TABLE 6 (Continued)

Pasteurization conditions	Product (pH)	Storage temperature and shelf-life	Packaging	Key findings	Reference
Beef-based meals					
600 MPa/ambient temperature/3 min (after cooking at 80°C until internal temperature reached 72°C)	Sausages (6.2)	4°C and 10°C/35 days	Vacuum packaged	Pressures < 450 MPa are generally ineffective in inactivating *L. monocytogenes* in foods. HPP and hot water pasteurization could be used to successfully enhance the safety and shelf-life of cooked sausages and hot-water pasteurization (75°C) was more effective than HPP (600 MPa) to control *L. monocytogenes*.	Balamurugan et al. (2018)
200, 300, 400, or 500 MPa/20°C/20 min/20	Beef-based RTE meals	–	Vacuum packaged with polyamide polyethylene film	This research investigated the effects of HPP on consumer acceptance in terms of tenderness, juiciness, flavor, and purchase intent. Note that 200 MPa was acceptable for most consumers. A higher pressure level might negatively affect the majority of consumers.	Sorenson et al. (2011)
349–600 MPa/18°C/0–12.5 min (after fermentation and drying at 23°C)	Spanish chorizo sausage (4.8–5.3)	–	Polyamide/polyet plastic film	Pressures equal to or below 400 MPa did not lead to significant inactivation levels of *L. monocytogenes*. HPP treatment at 550 MPa for 12.3 min might result in 4-log reductions when a_w was set at 0.86.	Rubio et al. (2018)
Seafood-based meals					
250 MPa and 350 MPa/27°C/10 min	Hilsa fillets	4°C/25 days	Vacuum packaged with LDPE film	The most effective HPP treatment was a pressure level of 350 MPa for 10 min. During storage days L^* and ΔE^* values of 350 MPa and thermal treatment were almost the same.	Chouhan et al. (2015)

(Continues)

TABLE 6 (Continued)

Pasteurization conditions	Product (pH)	Storage temperature and shelf-life	Packaging	Key findings	Reference
550 MPa/25°C/5 min	Wine-marinated shrimp (6.1)	4°C and 25°C/90 days	Vacuum packaged with nylon/polyethylene retort pouch	The TPC in the HPP-treated samples increased significantly after 30 days of storage compared to the initial TPC count. HPP-treated shrimp showed better quality attributes such as color, hardness, and springiness than their thermally treated counterparts.	Yi et al. (2013)
250 MPa/7°C/15 min.	Salmon carpaccio (6.5–6.6)	5°C/11 days	Flexible film, vacuum packaged	HPP with hurdle barriers (gelatin–chitosan edible film) retarded the growth of spoilage microorganisms. The combined treatment extended shelf-life and a "fresh-like" (minimally processed) product.	Gómez-Estaca et al. (2018)
150, 300, or 450 MPa/20°C/5 min	Cod and salmon fillet (6.8, 6.2)	4°C/14 days	Vacuum packaged with PA/PE film	The processing condition of 450 MPa was the most effective for microbial growth. HPP provided 14 days of shelf-life at 4°C with minimal changes in protein denaturation, hardness, and color.	Arnaud et al. (2018)
300 or 600 MPa/5°C/5 min (after cooking at 65°C for 46 min)	Seabream (4.2–4.9) with sauce (4.8–5.6)	2°C/62 days	Vacuum packaged with the polyamide-polypropylene film	HPP conditions did not completely eliminate the total viable counts, yet HPP conditions were enough to ensure microbial safety during storage. No pro-oxidant effect was observed with HPP treatments. Enhanced textural attributes and a high degree of sensory quality were obtained at 600 MPa compared to the treatment at 300 MPa.	Espinosa et al. (2015)

Abbreviations: LDPE, low density polyethylene; PA/PP, polyamide/polyethylene; TAC, total aerobic counts; TPC, total plate count.

TABLE 7 Comparison of thermal and high-pressure processing (HPP) treatments for different low-acid food products

Food product	Processing conditions		Comparison	Reference
	Thermal	HPP		
Green and red bell pepper	70°C, 80°C, and 98°C for 1 and 2.5 min (blanching)	100 and 200 MPa for 10 and 20 min	HPP treatments lead to more reduction in ascorbic acid of green pepper compared to blanching at 70°C and 80°C for 1 min. But HPP treatments showed more retention of ascorbic acid in red pepper compared to blanching at 80 and 98°C and even the unprocessed peppers. Enzyme inactivation (PPO) was similar for both treatments.	Castro et al. (2008)
Carrot, red radish, and jicama	105°C for 5 min	600 MPa, 25°C for 5 min	HPP provided a better color and firmness retention compared to thermal treatment. Thermal treatment had the smallest crunchiness values.	Nguyen et al. (2010)
Beetroot	90°C for 7 min (blanching)	650 MPa for 3, 7, 15, and 30 min	Blanching had a stronger effect on enzyme inactivation and color preservation than HPP treatments. No significant change was observed in total phenolics except HPP treatment for 30 min (increased). Betanin, ascorbic acid content, and hardness were significantly higher in HPP-treated beetroot.	Paciulli et al. (2016)
Tomato puree	72°C for 4 min	500 MPa, 20°C for 2 min 700 MPa, 20°C for 1×2 min	Enzymes (PG and PME) were partially inactivated by HPP. Lycopene retention was significantly higher in HPP-treated puree than thermally treated puree. Slightly more retention in color was observed in the thermally treated puree.	Krebbers et al. (2003)
Carrot and spinach	Parboiled for 7 min (carrot) and 5 min (spinach)	100, 300, and 500 MPa, 20°C for 20 min, respectively	Ascorbic acid content was not significantly different for the carrot at all pressure conditions and spinach at 500 MPa. Carotenoids were significantly higher at all pressure levels than those thermally treated. HPP resulted in better color retention for carrot and spinach and less enzyme inactivation compared to the thermal treatment.	Jung et al. (2013)
Tomato and carrot puree	70°C for 2 min	400–600 MPa/20°C for 15 min	Carrot: Thermal treatment causes an increment in total carotenoids more than at pressures of 400 MPa and 500 MPa, yet 600 MPa showed the highest. No significant change was observed in color. Total phenols decreased by thermal treatment and increased after HPP treatment at 400 MPa and 500 MPa. Tomato: Thermal treatment causes less ascorbic acid degradation than HPP treatments at 400 MPa and 500 MPa, but 600 MPa resulted in more ascorbic acid degradation than thermally treated ones. No significant change was observed in color. Total phenols of HPP-treated samples were higher than thermally treated ones.	Patras et al. (2009)
Spinach sauce	70°C for 10 min	400, 500, and 650 MPa for 5 and 10 min at 20°C	HPP treatments retained significantly higher ascorbic acid, chlorophyll, and greenness, yet less enzyme activity was observed. Chlorophyll degradation followed a similar trend during 16 days of storage at 4°C.	Medina-Meza et al. (2015)

(Continues)

TABLE 7 (Continued)

Food product	Processing conditions		Comparison	Reference
	Thermal	HPP		
Cucumber juice	110°C for 8.6 s	500 MPa for 5 min	HPP resulted in less color change after treatment and during 20 days of refrigerated storage compared to thermal treatment. The clarity, brix, and titratable acidity of juice did not significantly change for HPP and thermal treatment.	Liu et al. (2016)
Carrot juice	80°C for 7 min	600 MPa for 5 min	Thermal treatment retained color in juice more than HPP treatment. HPP provided better sensorial quality in terms of fresh taste. Both treatments showed similar nutritional quality attributes (carotene content).	Picouet et al. (2015)
Asparagus juice	121°C for 3 min	200–600 MPa for 10–20 min	Ascorbic acid and total phenolic contents of HPP-treated juice were significantly higher at all pressure levels. Total antioxidant activity was higher in thermally treated juice. HPP treatments maintained higher volatile compounds than thermal treatments.	Chen et al. (2015)
Watermelon juice	60°C for 5, 20, 40, and 60 min	300, 600, and 900 MPa for 5, 20, 40, and 60 min at 60°C	Enzyme (PME) inactivation was significantly higher at 900 MPa for 40 and 60 min compared to all the thermal treatments used in this study. The color of juice treated by HPP at 600 MPa was close to the untreated one.	Zhang et al. (2011)
Vegetable beverage (tomato, green pepper, green celery, onion, carrot, lemon, and olive oil)	90–98°C for 15 and 21 s	100, 200, 300, and 400 MPa for 120–540 s	Less color change was observed in HPP-treated juices compared to thermally treated ones. No significant difference in ascorbic acid of beverages was reported for both treatments. Longer treatment time for HPP cause more ascorbic acid degradation.	Barba et al. (2010)

Abbreviations: PG, polygalacturonase; PME, pectin methylesterase; PPO, polyphenol oxidase.

monocytogenes can be inactivated in low-acid foods under HPP conditions (Table 5). Although strains of *Listeria innocua* have been used as a surrogate for *L. monocytogenes* in thermal processing, there is no published study to show that *L. monocytogenes* and *L. innocua* behave similarly under nonthermal conditions (Mohan et al., 2019). Ates et al. (2016) and Dogan and Erkmen (2004) reported a 6.0-$\log_{10}$ reduction of *L. monocytogenes* in soup (pH 6.1) and brain heart infusion broth (pH 6.7) under HPP conditions of 600 MPa/5–10 min. However, Inanoglu et al. (2021) reported less than 4-$\log_{10}$ reduction of *L. innocua* ATCC 51742 in green beans (pH 5.8) after 600 MPa/10 min.

Np *C. botulinum* spores are resistant to pressure, presenting a significant food safety challenge to the food industry in pasteurization of low-acid foods (Smelt, 1998; Torres & Velazquez, 2005) and also presenting a major concern in refrigerated ready-to-drink low-acid beverages (González-Angulo et al., 2020). Raghubeer et al. (2020) observed less than 1-log reduction of np *C. botulinum* spores in coconut water (pH 5.4) after HPP treatment at 593 MPa for 3 min. Total counts of np *C. botulinum* remained constant in coconut water (pH 5.2) after HPP intervention at 550 MPa for 3 min (González-Angulo et al., 2020). High-pressure treatment can be combined with heat for the inactivation of spores, yet no suitable nontoxigenic surrogate has been reported for np *C. botulinum* spores, posing another challenge to validating the efficacy of HPP (Clauwers et al., 2016). When pasteurization conditions were selected as 600 MPa/45°C/20 min for HPP and 90°C/10 min for microwave-assisted thermal pasteurization, the microbial equivalency of these methods could not be validated due to the lack of a surrogate for np *C. botulinum* spores (Inanoglu et al., 2022).

Physical compression occurs due to pressure application, correspondingly heat is generated within the food and other compressible materials. Inevitable temperature changes within the material differ according to different food compressibility values. The compression heating of gases is the fastest, followed then by liquids and solids. The differences in temperature changes in food

substances caused by compression might be related to molecular structure and properties of the phase transition (Rasanayagam et al., 2003) as mentioned in Section 3. Rapid compression causes the temperature of a material to increase due to the conversion of mechanical energy to thermal energy. The change in the temperature depends on the compressibility and the specific heat of the material. For example, when both meat and water at 20°C were compressed to 600 MPa, their temperature increased to 42°C and 35°C, respectively (Rastogi et al., 2007). Thus, the difference in the compression heating properties of food constituents and the pressurizing medium may cause nonuniform heating. In addition, the compression heating properties of a material are temperature dependent. For instance, compression heating of water increases from 3°C/100 MPa to 4.4°C/100 MPa when the temperature increases from room temperature to 80°C. During an HPP treatment, the temperature of both food and pressurizing fluid may rise 20–40°C, yet compression heating of metal pressure vessel does not change significantly (Ting et al., 2002), thus causing a loss of thermal energy to the pressure vessel. Therefore, pressure holding time is typically selected as low as 3 min for commercial HPP treatments to reduce subsequent heat loss to the surroundings (Rasanayagam et al., 2003). This nonuniform temperature distribution may lead to differences in enzyme inactivation and variation in the microbial destruction (Denys et al., 2000; Reyns et al., 2000). The temperature difference has a minimal impact when the process is carried out at room temperature and microorganisms can be inactivated by pressure alone. However, a high temperature is needed for the inactivation of spores, which is the primary concern for processing low-acid foods (Khurana & Karwe, 2013). Thus, monitoring temperature changes during treatment are crucial for optimization and designing industrial processes (Rastogi et al., 2007). Although the HPP equipment features temperature sensors within the pressure chamber, those sensors can only measure the temperature of pressurizing fluid in the vicinity of food. Therefore, detecting the temperature of food while it is under HPP conditions is a need for the food industry to better understand the effect of the temperature (Grauwet et al., 2011).

The temperature distribution in HPP vessels has been studied to counter potential heat losses during HPP. Knoerzer et al. (2007) inserted a polytetrafluoroethylene carrier into the vessel, and the inside of the carrier showed thermal uniformity and a uniform level of sterilization. Salvi et al. (2017) added insulation to the horizontal HPP vessel, yet the authors did not observe any improvement in the uniformity of temperature and microbial inactivation for the vessel with insulation compared to the vessel without insulation. However, the authors suggested adding water for compression at the same temperature as the initial temperature of the process resulting in a more uniform temperature and more uniform *C. botulinum* spore inactivation compared to adding water at the initial temperature. Knoerzer et al. (2010) reported that using a packaging material with compression heating properties similar to the pressurizing fluid and/or packed food products may provide a more uniform temperature distribution.

Only liquids and high-moisture content solid foods are appropriate for HPP processing. By comparison, solid foods with entrained air such as bread, cake, and low-moisture foods such as spices, and peanut butter are not compatible with the application of HPP treatments (Balasubramaniam et al., 2008; Stratakos & Koidis, 2015). HPP treatment at 600 MPa and 45°C for 5 min led to less than 1-$\log_{10}$ reduction of *S.* Typhimurium in creamy peanut butter and peanut-based model systems (Grasso et al., 2010). D'Souza et al. (2014) reported that HPP alone or formulation modification (including nisin incorporation) is not a suitable technology for microbial safety of *Salmonella*-contaminated peanut butter. An increase in the inactivation level of *Salmonella* from 1.7-$\log_{10}$ CFU/g to below the detection limit was achieved when peanut butter was modified to a_w of 0.96, yet the modified product is different from the original peanut butter. HPP treatment can be utilized as a final step in a multiple-hurdle approach to ensure the microbial safety of peanut butter.

HPP as a pasteurization method relies on the fact that regardless of the size or shape of the food, isostatic pressure applies uniformly to food during processing, which is true for liquids and homogeneous solids (Nair et al., 2016) as long as there are no significant temperature changes. However, pressure nonuniformity might occur during HPP pasteurization for solid foods with hard inclusions such as meat with bones (Maldonado Ugaz, 2015; Nair et al., 2016). Minerich and Labuza (2003) used a copper powder tablet during HPP to measure pressure and inserted the tablet at the center of a large ham piece. The authors reported that the center of the ham piece received 9 MPa less pressure than the pressurizing medium. Some physicochemical properties of food constituents such as water change under HPP conditions (Mathys & Knorr, 2009). However, the determination of food properties (e.g., density, thermal conductivity, and specific heat) under high pressure is complicated. Reliable data on the physical and chemical properties of food under pressure are necessary for a better understanding of the interaction between high pressure and food constituents (Rastogi et al., 2007). On the other hand, Khan et al. (2013) studied the effect of high pressure on some physicochemical properties of sweet potato protein (extracted from sweet potatoes) such as hydrophobicity, enthalpy of denaturation, and solubility. The authors reported that hydrophobicity, enthalpy

of denaturation, and solubility significantly changed after HPP treatment at 200, 400, and 600 MPa for 15 min at 25°C and suggested that HPP can be used to modify the physicochemical and emulsifying properties of sweet potato proteins.

Another limiting aspect of the commercialization of novel technologies is the cost of the specialized equipment (Jermann et al., 2015). The cost of HPP industrial-size equipment (ranging from 600,000 to 4 million US dollars) is significantly higher than the cost of equipment used for thermal treatments. Installing new systems requires a significant capital investment, increasing the price per package of the finished products (Balasubramaniam et al., 2016; Koutchma, 2014). The total cost (energy consumption, capital cost, and labor) of HPP pasteurization of orange juice was estimated to be 10.7 ¢/L and sevenfold higher than that for thermal processing (1.5 ¢/L) (Sampedro et al., 2014). Bermúdez-Aguirre and Barbosa-Cánovas (2011) and Koutchma (2014) highlighted that the treatment cost has dropped, making it suitable for premium quality value-added products where the equipment and operation costs are offset by the processed product price, as a result of the increased availability and throughput of the equipment (e.g., Avure, Hyperbaric).

Another downside of HPP is that products are processed in batch or semi-continuous mode, thus limiting the production throughput (Palou et al., 2002; Stratakos & Koidis, 2015). However, a few companies such as Hiperbaric and Avure Technologies provide a throughput of 3000 and 3960 kg/h, respectively, with a vessel volume of 525 L (Koutchma, 2014). Most HPP-treated foods (90%) in the industry are packaged prior to treatments in the batch systems (Lambert et al., 2000). The selection of packaging materials plays a significant role since it impacts the efficacy of HPP. Packaging materials made of paper, metal, and glass are not appropriate to use for HPP treatments (Júnior et al., 2019; Tao et al., 2014). Packages should accommodate a 15% reduction in volume during pressurizing and equal expansion during depressurizing to prevent loss of seal integrity or barrier properties (Tao et al., 2014). Suitable packaging material for HPP requires good sealing and barrier properties, withstanding pressure, and flexibility (Lambert et al., 2000). Enough flexibility of package to allow reversible deformation for packaging material is a crucial requirement to process appropriate treatment. In this regard, polypropylene (PP), polyester tubes, polyethylene (PE) pouches, and nylon-cast polypropylene pouches are used to transmit the pressure without structural damage in the food (Muntean et al., 2016). Additionally, the space (headspace) in the package must be minimized to control the deformation of packaging materials and ensure efficient use of the space in the pressure vessel (Rastogi et al., 2007). Al-Ghamdi et al. (2019) highlighted the importance of package headspace on package integrity to avoid physical damage such as white spots and delamination to the packaging material under HPP conditions. Vacuum packaging is necessarily desired for HPP treatments since it has been utilized for reducing headspace and air in a product (Júnior et al., 2019; Singh, 2017).

4 | FINAL REMARKS

HPP as a processing technology provides an excellent opportunity to preserve the fresh taste and other desirable organoleptic attributes and simultaneously extend the shelf-life of RTE products. HPP has been successfully applied, for many years, to acidic or acidified foods for the destruction of microorganisms and inactivation of enzymes at low or moderate temperatures with minimal impact on the initial quality of value-added foods maintained at refrigerated temperatures. However, the desired reduction, for public health protection, of some relevant spores in a low-acid food, while maintaining nonthermal processing conditions, is not possible at present. Therefore, HPP products are either acidic or acidified to prevent the outgrowth of bacterial spores. Further improvement on spore inactivation by pressure (alone) is required before the full potential of HPP in low-acid food pasteurization can be realized.

Currently, using HPP singly does not guarantee the complete elimination of viruses due to the broad range of sensitivities of viruses to high pressure. The lack of appropriate surrogates for validating spore (such as np *C. botulinum*) inactivation in HPP treatmments and the high cost of the HPP equipment limit its application for pasteurization of low-acid RTE foods. HPP can be utilized as a processing step or a pretreatment combined with thermal treatments to obviate these limitations.PP. As HPP technology develops, the high cost of equipment and other noted impediments will likely be overcome. These further developments are seen as making this preservation technique more accessible and attractive to produce pasteurized RTE products.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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