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Review

Pasteurization of Food and Beverages by High Pressure Processing (HPP) at Room Temperature: Inactivation of *Staphylococcus aureus, Escherichia coli, Listeria monocytogenes, Salmonella,* and Other Microbial Pathogens

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Abstract: Vegetative pathogens actively grow in foods, metabolizing and dividing their cells. They have consequently become a focus of concern for the food industry, food regulators and food control agencies. Although much has been done by the food industry and food regulatory agencies, foodborne outbreaks are still reported globally, causing illnesses, hospitalizations, and in certain cases, deaths, together with product recalls and subsequent economic losses. Major bacterial infections from raw and processed foods are caused by *Escherichia coli* serotype O157:H7, *Salmonella enteritidis,* and *Listeria monocytogenes*. High pressure processing (HPP) (also referred to as high hydrostatic pressure, HHP) is a non-thermal pasteurization technology that relies on very high pressures (400–600 MPa) to inactivate pathogens, instead of heat, thus causing less negative impact in the food nutrients and quality. HPP can be used to preserve foods, instead of chemical food additives. In this study, a review of the effect of HPP treatments on major vegetative bacteria in specific foods was carried out. HPP at 600 MPa, commonly used by the food industry, can achieve the recommended 5–8-log reductions in *E. coli*, *S. enteritidis*, *L. monocytogenes*, and *Vibrio*. *Staphylococcus aureus* presented the highest resistance to HPP among the foodborne vegetative pathogens investigated, followed by *E. coli*. More susceptible *L. monocytogenes* and *Salmonella* spp. bacteria were reduced by 6 logs at pressures within 500–600 MPa. *Vibrio* spp. (e.g., raw oysters), *Campylobacter jejuni*, *Yersinia enterocolitica*, *Citrobacter freundii* and *Aeromonas hydrophila* generally required lower pressures (300–400 MPa) for inactivation. Bacterial species and strain, as well as the food itself, with a characteristic composition, affect the microbial inactivation. This review demonstrates that HPP is a safe pasteurization technology, which is able to achieve at least 5-log reduction in major food bacterial pathogens, without the application of heat.

Keywords: high hydrostatic pressure (HHP); HPP; cold pasteurization; pascalization; microbial inactivation; pathogen inactivation; non-thermal; vegetative; bacteria; strain; meat; milk; dairy

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1. Fundamentals of High-Pressure Processing Pasteurization of Food and Beverages

High pressure processing (HPP) is a commercial pasteurization technology employed to extend the shelf-life of both solid and liquid foods. It is an alternative to preservatives and additives to guarantee food safety (e.g., of sliced and cured ready-to-eat meat products). HPP at room temperature is not a sterilization technology, as microbial spores often survive the process, and consequently, HPP foods have a limited shelf-life, requiring refrigeration below 7 °C for distribution/storage, similar to thermal pasteurized foods (Silva and Gibbs, 2009; Silva et al., 2014; Evelyn and Silva, 2017; Silva and Evelyn, 2018) [1–4]. Depending on the food product, a shelf-life of several days up to several weeks under refrigeration is established. Exceptions are specific foods such as dry-cured meat products that were

reported to be stored at ambient temperatures for up to months (EFSA, 2022) [5]. HPP operates in batch, similar to canned foods in retort processing.

During HPP treatment, microorganisms naturally present in raw foods are inactivated with extremely high pressures in the range of 400 to 600 MPa, a thousand times higher than the atmospheric pressure of 0.1013 MPa, without the application of heat to the food. Thus, this process is classified as non-thermal, and HPP foods are referred to as cold-pasteurized foods, with demonstrated superiority in terms of overall flavor and higher contents of health-related food components (e.g., vitamins, antioxidants) (Sánchez-Moreno and de Ancos, 2018; Milani and Silva, 2016; Sulaiman et al., 2017; van Wyk et al., 2018; Lee and Oey, 2018) [6–10]. These are often thermolabile, similar to other food components associated with natural and fresh-like aroma and flavor sensory properties of raw unprocessed foods (Tříska, 2018; Houska et al., 2022; Silva et al., 2000) [11–13].

Briefly, vacuum-packed food in a flexible film/bottle is placed into a HPP treatment chamber, which is subsequently filled with water, as this is the medium used to transfer the pressure simultaneously and uniformly to all points of the food (isostatic pressure) during HPP treatment (Figure 1). This is a major advantage of HPP pasteurized foods compared to foods pasteurized with conventional thermal processes. Thus, there is no pressure profile inside the HPP food, and no need to determine the package cold point, as opposed to pre-packed sterilized foods. The technology is also named high hydrostatic pressure (HHP), as water (room temperature or pre-cooled) is used as the medium to transfer the pressure to the food. By analogy with thermal pasteurization treatments, the terminology used for the three stages of a HPP batch cycle is similar: pressure come-up time (CUT) or pressurization, pressure-holding time, and pressure come-down time or depressurization. Once the treatment chamber is filled with water, the pressurization (compression) raises the pressure up to 400–600 MPa, taking 30 s to 1–2 min depending on the set pressure and the food/beverage composition (Milani and Silva, 2016) [8]. For example, a beverage such as red wine took less than 2 min for 600 MPa with an increase in temperature up to 36 °C, and for a 200 MPa, the CUT was less than 40 s, and the temperature increase was lower (<30 °C) (van Wyk and Silva, 2017) [14,15]. A slight increase in food/beverage temperature is inevitable due to adiabatic heating with compression work, about 2–3 °C/100 MPa for beverages and high-moisture foods, and higher for foods with high fat content (e.g., meats, guacamole) 5–9 °C/100 MPa. As the industry wants to operate under non-thermal conditions (T < 45 °C), the food temperature before HPP (also known as pre-compression temperature) can be lowered to remain below this temperature. Then, in the second stage of the HPP cycle, the high pressure is kept for a period of seconds to a couple of minutes (holding time) depending on the food and microorganism used as the pasteurization target. The predefined time and pressure conditions during the constant pressure phase of the cycle characterize the HPP treatment. Quick depressurization with pressure release and reduction back to ambient pressure occurs during the last stage of the HPP cycle in less than 5 s of come-down time. This can also be referred to as the decompression stage, described by an almost instantaneous pressure drop.

Batch units of up to 525 L are available from equipment manufacturers for non-thermal pasteurization of pre-packed foods. The main disadvantage of HPP derives from its operation in "batch" mode. Therefore, each HPP cycle requires extra time for the following operations: pre-packaging of the food before the HPP treatment, loading/unloading of food and water in the HPP treatment chamber, pressurization/depressurization, and drying the packed product after HPP treatment. To overcome these issues, Hiperbaric introduced a piece of equipment that allows for HPP treatment of liquids before packaging ("In-Bulk"). The process begins by filling a huge flexible container inserted in the treatment chamber. After pressurisation, the HPP beverage fills the outlet tank through sterilized tubes and is aseptically packaged, similar to the aseptic processing used for thermal treatment (e.g., UHT, ultra-high temperature). Other disadvantages include the space required for this equipment, the downtime for maintenance/parts replacement, and the cost of the technology.

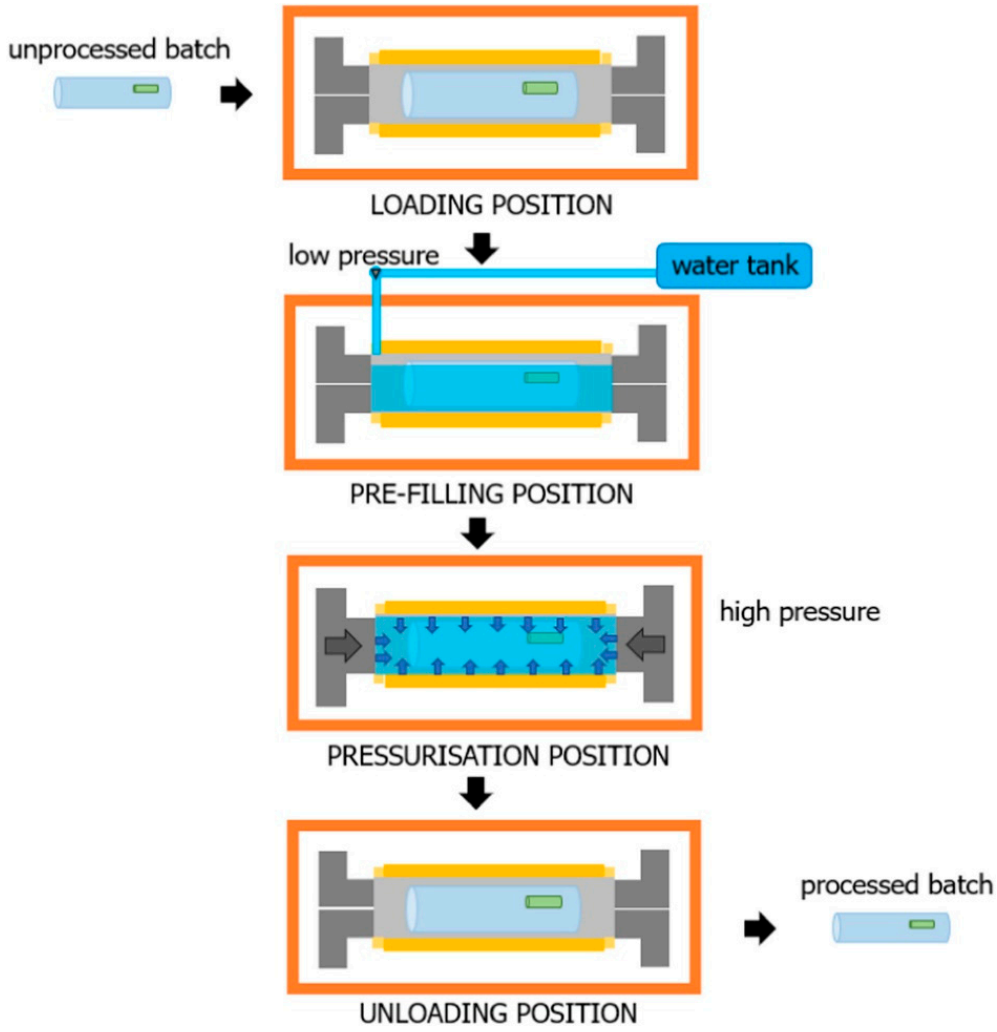


Figure 1. Diagram representing high-pressure processing (HPP) treatment of a pre-packed food (extracted from EFSA BIOHAZ Panel, European Food Safety Authority Panel on Biological Hazards, 2022) [5].

Commercial HPP products include (i) juices, vegetable and fruit products (e.g., purees), guacamole (Houska and Silva, 2018) [16]; (ii) meat and meat products, namely, ready-to-eat sliced deli meat, hot dogs, dry-cured meat products (EFSA, 2022) [5]; (iii) seafood products such as crustaceans, shellfish, molluscs; (iv) ready-to-eat meals, dips and salsas, wet salads and sandwich fillings, baby food purees, and dairy (Hyperbaric, 2022) [17]. HPP has also been used to speed up shell removal from bivalves and to extract molluscs' meat yield. Dairy HPP products and alternative HPP protein beverages are not so common nowadays, but this category of foods has potential to grow, with proper regulations and guidelines to safeguard consumers. Similar to thermal pasteurization, porous foods containing air (e.g., bread, cakes, whole fruits and vegetables), dried foods, and food/ingredient powders are not appropriate for HPP pasteurization.

The HPP process is sustainable, because: (i) it can speed up the process, requiring less energy than a conventional thermal treatment for an equivalent thermal pasteurization (e.g., beer pasteurization) (Milani and Silva, 2022) [18]; (ii) it increases food shelf-life and reduces food losses during distribution, and; (iii) it presents a good alternative to chemical preservatives, known to be harmful for human health.

2. Mechanisms and Factors Affecting the Inactivation of Vegetative Microorganisms in Foods

Alterations in the cellular structure or physiological functions of microorganisms with exposure to high pressure results in microbial cell death. This can be seen by observing the structural damage of the cell membrane and envelopes due to membrane phase transition and fluidity changes (Abe, 2013; Rozali et al., 2017) [19,20]. Microbial inactivation can occur due to protein denaturation and the disruption of cell membranes, with subsequent solute loss (Figure 2) (Silva and van Wyk, 2021) [21]. Research also suggests that microbial inactivation by HPP involves the perforation of the cell membrane, the formation of dimples and swelling, or the overall shrinkage of the volume of the cells (Norton and Sun, 2008; Rozali et al., 2017) [20,22].

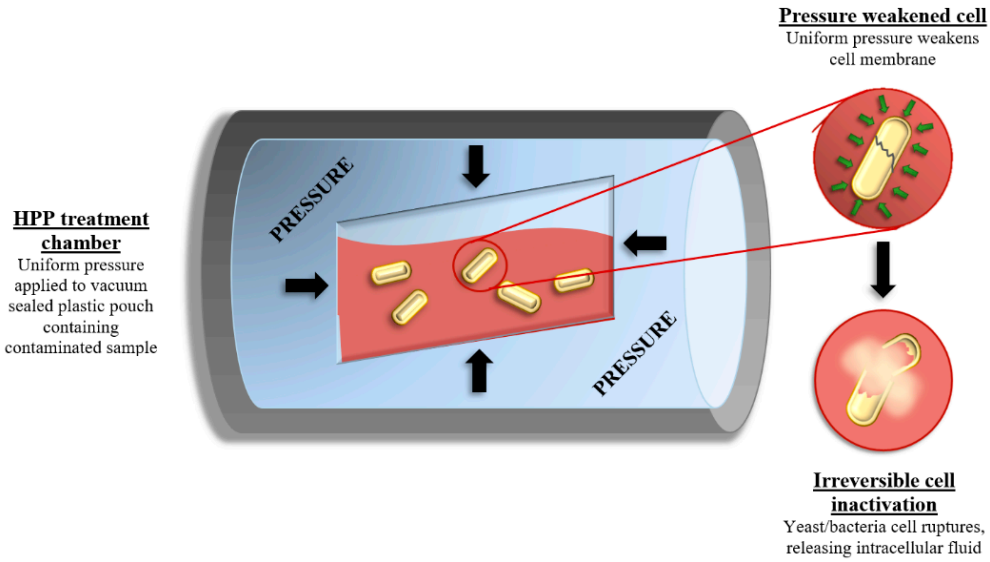


Figure 2. Diagram showing the high-pressure processing (HPP) inactivation of microorganisms in a beverage (extracted from Silva and van Wyk, 2021) [21].

The major factors affecting the inactivation of vegetative spoilage or pathogenic bacteria in foods and beverages are the HPP pressure and treatment time, in which higher pressure and/or time cause higher microbial inactivation (Evelyn and Silva, 2017; Silva and Evelyn, 2018) [3,4]. When the aim of treatment is the inactivation of spore forms of the microorganisms, the initial temperature of the food can be increased before the treatment. In heat-assisted HPP (also referred as high-pressure thermal processing, HPTP), the higher the temperature, the higher the inactivation (Evelyn and Silva, 2016; Uchida and Silva, 2017; Evelyn and Silva, 2018) [23–26]. HPP combined with heat has been the focus of many research studies but is not currently employed at commercial scale by the industry (EFSA, 2022) [5].

Other important aspects affecting the microbial inactivation are the type of microbe (bacteria, mold, yeast), the species and strain, and the composition of the food medium being treated. More complex vegetative cells of molds and yeasts (eukariotic) are more susceptible to inactivation than vegetative cells of bacteria (prokariotic), and parasites are usually inactivated at relatively low pressures (100–400 MPa) (Rendueles et al., 2011) [27].

With respect to water activity (a_w) Bover-Cid et al. (2015, 2017) [28,29] demonstrated that it was more difficult to inactivate pathogens with HPP (*Listeria monocytogenes*, *Salmonella enterica*) in dry-cured ham formulated with lower water activity (a_w). Regarding pH, although low pH (<4.6) prevents pathogens' growth, it seems not to have such an important role for HPP microbial inactivation (van Wyk and Silva, 2017) [14].

Counting Microorganisms and Assessing Microbial Reductions by HPP

The vegetative bacterium pathogen inactivation by HPP is well described by a first-order kinetics, in which a linear decrease in the logarithmic cell populations is

observed with treatment time. for a specific HPP pressure (Equation (1)). The decimal reduction time, or D_P-value, is the time in minutes at a certain pressure necessary to reduce microbial population to N/N_0 0.10, and it is calculated from the reciprocal of the slope of the following equation:

$$log\left(\frac{N}{N_0}\right) = \frac{-t}{D_P} \quad (1)$$

where N_0 is the initial number/concentration of a specific microorganism in the food, and N is the number/concentration of the microorganism after a certain treatment time (t) (time exposed to pressure P during the constant pressure phase of the cycle, not taking into account the pressurization and depressurization phases of HPP treatment). The pressure coefficient, or z_P-value (MPa), is the pressure increase that results in a 10-fold decrease in the D-value. This is estimated from the negative reciprocal of the slope of Equation (2):

$$log\left(\frac{D}{D_{Pref}}\right) = \frac{P_{ref} - P}{z_P} \quad (2)$$

D_{Pref} is the D-value at the reference pressure P_{ref} (and can be any reference pressure, MPa), and P is the pressure of the HPP isostatic treatment (MPa) during the holding phase of the HPP cycle.

3. Pasteurization Targets and Regulations

Foodborne outbreaks continue to be reported around the world, and more than 250 different foodborne diseases have been described (CDC 2022) [30]. In the US, 841 foodborne disease outbreaks were reported in 2017, resulting in 14,481 illnesses, 827 hospitalizations, 20 deaths, and 14 food product recalls (CDC, 2019) [31]. Foodborne bacterial infections from raw and heated foods include *Salmonella enteritidis* (poultry and eggs), *Escherichia coli* serotype O157:H7 (beef, cooked hamburgers, raw fruit juice, lettuce, game meat, cheese curd), *Listeria monocytogenes* (milk, soft cheese, ice cream, cold-smoked fish, chilled processed meat products, such as cooked poultry), *Vibrio parahaemolyticus* (improperly cooked, or cooked, re-contaminated fish and shellfish), *Vibrio cholerae* (water, ice, raw, or underprocessed seafood), and foodborne trematodes from fish and seafood produced by aquaculture (WHO, 2018; Silva et al., 2014; EFSA and ECDC, 2018) [2,32,33]. Pasteurized milk and dairy products may also be contaminated with *Brucella*, thermophilic *Streptococcus* spp., and *Mycobacterium avium* subsp. paratuberculosis (MAP) (Westhoff, 1978; Grant et al., 1996; Grant, 2003) [34–36], which can be infectious at low cell numbers, although they cannot grow at chill temperatures. *Coxiella burnetii*, the causative agent of 'Q-fever,' can also be a problem in milk (Cerf and Condron, 2006; Silva et al., 2014) [2,37].

Pathogenic bacteria are the main cause of foodborne outbreaks, although viruses and parasites can also be associated with problems. It is known that the acidity of high-acid foods (pH < 4.6) inhibits the growth of vegetative pathogens and the germination and growth of microbial spores (Silva et al., 2014) [2]. However, bacterial pathogens are a major food safety concern in low-acidic foods (pH > 4.6). Therefore, low-acid pasteurized foods should be stored and distributed under refrigeration below 7 °C (Silva and Gibbs, 2009) [1]. Among vegetative pathogens, *L. monocytogenes, Yersinia enterocolitica, Salmonella, V. parahaemolyticus,* and *Aeromonas hydrophila* are of great concern, because they are able to grow at refrigeration temperatures (D'Aoust, 1991; Penfield et al., 1990) [38,39] and can thus be a problem in HPP products, which are generally distributed and stored under refrigeration.

Vegetative pathogens actively grow, metabolize, and divide their cells in foods, and consequently, they are a focus of concern for the food industry, food regulators, and food control agencies. One of the main objectives of food pasteurization technologies, such as HPP, is to ensure a reduction in the numbers of these pathogenic microorganisms in foods to a safe level for consumption (Silva and Gibbs, 2009) [1]. As mentioned previously, foods

in which HPP is applied as a pathogen reduction step include vegetables and fruits (sauces, juices, dressings), meat (ready-to-eat meats and poultry), and seafood (shellfish and fish products) (EFSA, 2022) [5].

Regulatory Aspects of High Pressure Processed Foods

International food regulation agencies propose 5–8-$\log_{10}$ reductions ($log\left(\frac{N}{N_0}\right)$) in relevant microbial hazards for efficient pasteurization processes and the production of safe foods (EFSA, 2022) [5].

In 2011 the Food and Drug Administration (FDA) Food Safety Modernization Act was implemented, aiming the shift of the focus of federal regulators from responding to contamination to preventing it, thus ensuring the safety of the United States food supply (Public Law, 2011) [40]. With respect to HPP, FDA and Health Canada have established a regulatory frame specifically for this technology application (Koutchma and Warriner, 2018) [41]. There is a need to demonstrate that a new HPP treatment achieves a specific log reduction in the pathogen(s) of concern. On the contrary, HPP is not specifically regulated in Europe, where a precautionary approach designates HPP products as Novel Foods, with the need to demonstrate safety beyond pathogen reduction. Thus, in Europe, HPP foods are considered novel and subsequently require pre-market approval, in particular HPP products of animal origin.

The adoption of HPP in North America has been driven by a regulatory requirement for processors to apply a pathogen-reduction step in high-risk ready-to-eat (RTE) food production (Koutchma and Warriner, 2018) [41]. The pathogens of concern in RTE meats, fruits, and vegetable-based products are *Salmonella*, *L. monocytogenes*, and *E. coli* O157:H7. The FDA designated a 5-log cfu/mL reduction in food by the HPP process. With respect to processed meat, the United States Department of Agriculture (USDA) Food Safety and Inspection Service (FSIS) published a directive identifying HPP as an intervention to control *L. monocytogenes*, thereby fulfilling Alternative 1 or Alternative 2 within RTE meat production. HPP can also be applied to control *E. coli* O157:H7 on beef trim and *Salmonella* on poultry. When HPP processing is applied as a pathogen reduction step, there is a need to define the processing parameters and the product formulation.

4. *Staphylococcus aureus* Inactivation by HPP

Food poisoning outbreaks in pasteurized milk products (e.g., chocolate milk, milk) were reported due to the ingestion of foods containing staphylococcal enterotoxins (SEs) produced by *S. aureus* (Evenson et al., 1988; Asao et al., 2003; Schmid et al., 2009; Ostyn et al., 2010; Hennekinne et al., 2012) [42–46]. *S. aureus* infection symptoms begin with diarrhea, but vomiting, nausea, dizziness, and abdominal pain associated with moderate fever can also be registered (Hennekinne et al., 2012) [46]. At *S. aureus* concentrations of $\geq 10^5$ cells/g of food, detection of the enterotoxin in the contaminated food can confirm food poisoning by this bacterium (Hennekinne et al., 2012) [46].

Table 1 shows HPP inactivation studies carried out with different *S. aureus* strains and specific foods including milk, cheese slurry, poultry meat, pork slurry, and raw beef (Shigehisa et al., 1991, Zagorska et al., 2021, O'Reilly et al., 2000, Rocha-Pimienta et al., 2020, Patterson and Kilpatrick, 1998, Gervilla et al., 1999, Park et al., 2022, Jarzynka et al., 2021; Alpas and Bozoglu, 2000; Hugas et al., 2002) [47–56].

HPP at 600 MPa for 10–15 min achieved the minimum 5-log reductions recommended in milk and pork slurry. Cheese slurry required 20 min at 600 MPa for 4.5-log reductions in ATCC 6538 strain. Human milk required less stringent treatments of less time (4 min) at 600 MPa or 15 min at 450 MPa. ATCC 13565 *S. aureus* was more resistant in poultry meat than in milk, as only 4.0-log reductions in poultry meat vs. 5.5-log reductions in milk were obtained after a HPP treatment of 15 min at 600 MPa. Ovine milk subjected to 500 MPa for 15 min resulted in only 3.2-decimal reductions. Applying heat assisted HPP at a moderate temperature of 50 °C increased the *S. aureus* $\log_{10}$ reductions to 6.0 in poultry meat and >7.0 in ovine milk. Although not so realistic, studies can be

carried out using a cocktail of resistant strains to mimic the worst-case scenario in terms of inactivation. A HPP treatment of raw beef at 500 MPa for 7 min caused only 1.7-log reductions in a cocktail of 5 strains of *S. aureus* previously inoculated in raw beef. Similar to thermal pasteurization, dry-cured ham contains a high content of salt and presents low water activity, thus making it very difficult to inactivate microorganisms. Overall, for similar processing conditions, there are some differences in the *S. aureus* inactivation, depending on the food and the bacterial strain.

Table 1. Inactivation of *Staphylococcus aureus* in milks, cheese, and meat products by high pressure processing (HPP) and heat assisted HPP *.

Strain	Food Products	pH	Pressure (MPa)	Temperature (°C)	Time (min)	Log Reduction	Reference
ATCC 25923	Pork slurry	nr	600	RT	10	6.0	[47]
ATCC 25923	UHT milk 2% fat	nr	600	RT	15	4.7	[48]
ATCC 6538	Cheese slurry	5.2–5.4	600	RT	20	4.5	[49]
CECT 976 (ATCC 13565)	Human milk	nr	594	RT	4	5.8	[50]
NCTC 10652 (ATCC 13565)	Poultry meat	nr	600	RT 50 [a]	15 15	4.0 6.0	[51]
NCTC 10652 (ATCC 13565)	UHT milk	nr nr	600 500 500	RT RT 50 [a]	15 15 15	5.5 2.5 6.0	[51]
CECT 534 (NCTC 4163)	Ovine milk	6.7	500	RT 50 [b]	15 15	3.2 >7.0	[52]
Cocktail of 5 strains	Raw beef	5.8	500	RT	7	1.7	[53]
ATCC 33862	Human milk	nr	450	RT	15	≥6.8	[54]
485 765	Milk Milk	6.7	345	50 [a]	5 5	5.5 >8.0	[55]
Special Foods							
nr	Dry-cured ham Cooked ham Marinated beef	nr	600	RT	6 6 6	0.6 1.1 2.7	[56]

* RT = room temperature HPP; UHT = ultra-high temperature; nr—not reported. [a] Initial temperature before compression; [b] average temperature of holding phase of the HPP cycle.

5. *Escherichia coli* Inactivation by HPP

Outbreaks of *E. coli* serotype O157:H7, Shiga-like toxin-producing types, have been associated with a wide range of foods, including ground beef, packaged salads, leafy greens (e.g., lettuce, spinach), sprouts, fresh chopped salads, flour and cake mix, frozen falafel, and raw milk [57]. As this particular strain can survive and grow under very acidic conditions and at low temperatures (Weagant et al., 1994, Conner and Kotrola, 1995; Hsin-Yi and Chou, 2001) [58–60], outbreaks have been registered in high-acid foods as follows: fruit juices (CDC 2022; Cody et al., 1999) [61,62], apple cider (Miller and Kaspar, 1994) [63], mayonnaise (Weagant et al., 1994) [58], mustard and ketchup (Tsai and Ingham, 1997) [64], and yogurt (Morgan et al., 1993) [65]. Human foodborne infection symptoms by *E. coli* O157:H7 include diarrhea (in some cases, bloody diarrhea) and abdominal cramping (Ibrahim, 2015) [66]. Laboratory analysis of stool specimens (feces) can be used to diagnose the illness [67].

Table 2 presents the resume of *E. coli* HPP inactivation studies carried out with milk, non-cured cheese, meat products, coconut water, and acidic fruit beverages (Patterson and Kilpatrick, 1998, Zagorska et al., 2021, Stratakos et al., 2019, Raghubeer et al., 2020, Chien et al., 2017, Park et al., 2022, Capellas et al., 1996, Shigehisa et al., 1991, Linton et al., 1999, Hiremath and Ramaswamy, 2012, Jordan et al., 2001) [47,48,51,53,68–74]. Nine studies carried out with O157:H7 strains, ATCC 25922, and cocktails of several strains revealed ≥ 6.0-log reductions in the microorganism in UHT and raw milk, coconut water,

ground beef, fresh goat cheese, pork slurry, and several acidic juices (orange, apple, mango, tomato) after HPP treatments in the range of 500–600 MPa for a treatment time of 3 to 15 min, depending on the food and strains. Therefore, the minimum requirement of an inactivation of 5.0 was achieved in most of the studies carried out with this pathogen. The exception were two studies carried out with the specific strain NCTC 12079 in low-acidic foods, poultry meat, and UHT milk, in which only 1.5- and 0.5-log reductions were registered after 600 MPa-15 min treatment, respectively. The same authors, using heat-assisted HPP with an initial food temperature of 50 °C, could obtain 8.0-log reductions in both poultry meat and milk. Curiously, the same strain and much milder processing conditions (550 MPa-5 min) could achieve >7.0 in orange juice, indicating that it might be easier to inactivate *E. coli* in high-acidic fruit juices. Two other studies with orange, apple, mango, and tomato juices using ATCC 43894 and C9490 toxigenic strains and milder HPP treatment (500 MPa-5 min) could ensure more than 7-log reductions in these juices (Hiremath and Ramaswamy, 2012; Jordan et al., 2001) [73,74]. A few studies using cocktails of resistant strains also showed efficient inactivation of *E. coli* in raw milk, coconut water, ground beef, and raw beef. *E. coli* was more susceptible to HPP inactivation than *S. aureus*.

Table 2. Inactivation of *Escherichia coli* in milk, meat products, coconut water, and acidic fruit juices by high-pressure processing (HPP) *.

	Strain	Food Products	pH	Pressure (MPa)	Temperature (°C)	Time (min)	Log Reduction	Reference
O157:H7	NCTC 12079	Poultry meat	nr	600	RT 50 [a]	15 15	1.5 8.0	[51]
O157:H7	NCTC 12079	UHT milk	nr	600 500	RT 50 [a]	15 15	0.5 8.0	[51]
-	ATCC 25922	UHT milk 2% fat	nr	600	RT	15	≥7.0	[48]
-	Cocktail of 5 strains	Raw milk	nr	600	RT	5	6.8	[68]
O157:H7	Cocktail of 8 strains	Coconut water	5.2	593	RT	3	≥6.6	[69]
O157:H7	Cocktail of 3 strains	Ground beef (17% fat)	nr	500	RT	15	7.0	[70]
-	Cocktail of 5 strains	Raw beef	5.8	500	RT	7	4.4	[53]
-	CECT 405 (ATCC 10536)	Fresh goat cheese	6.5	450–500	RT	5	>8.5	[71]
-	ATCC 25922	Pork slurry	nr	400–500	RT	10	>6.0	[47]
Acidic juices								
O157:H7	NCTC 12079	Orange juice	3.4–4.5	550	RT	5	>7.0	[72]
O157:H7	ATCC 43894	Mango juice	4.5	550	RT	5	>8.0	[73]
O157:H7	C9490	Orange juice Apple juice Tomato juice	3.8 3.5 4.1	500	RT	5 5 5	>7.0 >7.0 >7.0	[74]

* RT = room temperature HPP; UHT = ultra-high temperature; nr—not reported. [a] Initial temperature before compression.

6. *Listeria monocytogenes* Inactivation by HPP

Listeriosis, the human infection caused by the *Listeria monocytogenes* bacterium, can be a great risk, particularly for vulnerable groups of people such as the elderly and pregnant women, as it is characterized by high morbidity, hospitalization, and mortality rate (Henriques and Fraqueza, 2015) [75]. A person with listeriosis presents symptoms similar to a flu or gastrointestinal illnesses, but also septicaemia, meningitis, and encephalitis (Gillespie et al., 2010) [76]. For pregnant women, the disease is confirmed by the isolation of the bacteria from blood, spinal fluid, or amniotic fluid or the placenta [77]. In the United

States, between 2018–2022, simultaneous food outbreaks caused by *L. monocytogenes* were registered in different states. These were linked to foods such as deli meat and cheese (e.g., sliced), fresh cheese, Brie and Camembert cheeses (outbreak in 2022), ice cream (outbreak in 2022), packaged fresh salads, mushrooms, hard-boiled eggs, pork products, and deli ham [78]. The EFSA reported public health risks posed by *L. monocytogenes* in specific ready-to-eat foods in the European Union (EFSA, 2018) [79]. Problems in frozen fruits and vegetables, including herbs, blanched during processing were also raised by the EFSA (EFSA, 2020) [80].

Table 3 presents *L. monocytogenes* inactivation studies in UHT and raw milk, goat cheese, meat products, and coconut water (Zagorska et al., 2021; Stratakos et al., 2019; Balamurugan et al., 2018; Raghubeer et al., 2020; Park et al., 2022; Gallot-Lavallée, 1998; Jarzynka et al., 2021; Bambace et al., 2021; Patterson et al., 1995) [48,53,54,68,69,81–84]. The studies demonstrated the efficiency of HPP pasteurization in the range of 450–600 MPa and times from 3 to 15 min, depending on the food and strain, for more than 5.6-decimal reductions in *Listeria*. A treatment of 375 MPa for 15 min was clearly not enough for pasteurizing milk and poultry meat (Patterson et al., 1995) [84]. The studies reviewed showed that the inactivation of *L. monocytogenes* required lower pressures (P) and/or lower holding times (t) than those P-t required for the inactivation of *E. coli* and *S. aureus*.

Table 3. Inactivation of *Listeria monocytogenes* in low-acid foods by high-pressure processing *.

Strain	Food Products	pH	Pressure (MPa)	Time (min)	Log Reduction	Reference
ATCC 7644	UHT milk 2% fat	nr	600	15	≥7.0	[48]
Cocktail of 5 strains	Raw milk	nr	600	5	5.9	[68]
Cocktail of 4 strains	Cooked pork sausage 28% fat	6.2	600	3	≥7.5	[81]
Cocktail of 7 strains	Coconut water	5.2	593	3	≥6.0	[69]
Cocktail of 5 strains	Raw beef	5.8	500	7	≥6.5	[53]
nr	Goat cheese	nr	500	5	>5.6	[82]
ATCC 7644	Human milk	nr	450	15	≥7.9	[54]
CECT 4032 (DSM 15675)	Apple cubes	nr	400	5	>5.0	[83]
NCTC 11994 (DSM 15675)	Milk Poultry meat	nr	375	15 15	0.5 2.0	[84]

* nr—not reported.

7. *Salmonella* inactivation by HPP

Salmonellosis, caused by *Salmonella*, is the most frequent foodborne disease reported worldwide. Outbreaks of *Salmonella enteritidis* and *Salmonella typhimurium* have been associated with several foods from animal origin as follows: shell eggs, ground beef, poultry (ground turkey meats, raw turkey products, chicken and chicken salad, raw frozen breaded stuffed chicken products), peanut butter (outbreak in 2022), fish Salami sticks, frozen cooked shrimp [85,86], although an increasing number of outbreaks was reported in contaminated green vegetables (Doyle and Erickson, 2008; Hanning et al., 2009) [87,88]. The most common clinical symptoms are diarrhea and abdominal cramps, with potential of fever of 38–39 °C (Giannella, 1996) [89]. Stool, blood, urine, or sometimes tissues can be used for the diagnosis of *Salmonella* bacteria (Behravesh et al., 2008) [90].

Table 4 presents HPP inactivation studies of single strains of *Salmonella enterica enteritidis* or *typhimurium* and also cocktails of resistant strains in cooked and peeled eggs, liquid

whole egg, chicken fillets and strained chicken, pork slurry, milk, coconut water, and Italian salamis (Stratakos et al., 2019; Raghubeer et al., 2020; Argyri et al., 2018; Shahbaz et al., 2018; Park et al., 2022; Ponce et al., 1999; Bari et al., 2008; Shigehisa et al., 1991; Metrick et al., 1989; Bonilauri et al., 2019) [47,53,68,69,91–96]. HPP treatments of 400–550 MPa for 5–10 min are enough for whole liquid and cooked and peeled egg products. With respect to chicken, though 500 MPa-10 min caused ≥7.0-log reductions in chicken fillets, 340 MPa-15 min was insufficient for strained chicken. Raw milk, raw beef, pork slurry, and coconut water were pasteurized with pressures between 400–600 MPa. Italian salamis are special dry foods consisting of cured sausage of fermented pork meat. Low water activities typically between 0.88 and 0.95 prevent microbial growth but also prevent microbial inactivation by thermal or non-thermal processes. In certain salamis, safe pasteurization was not achieved by HPP, as after being exposed for 5 min at 600 MPa, only 1.9- to 5-log reductions were obtained. Although not so common, HPP can be carried out at low temperatures. Boziaris et al. (2021) [97] conducted HPP at 250 MPa and −32 °C for 3 min and registered more than 3-log reductions in a cocktail of six strains of *Salmonella enteritidis* in frozen salmon fillets. *Salmonella* was less resistant than *E. coli* (and *S. aureus*) to HPP inactivation.

Table 4. Inactivation of *Salmonella* in foods by high-pressure processing (HPP) *.

Serovars	Strains	Food Products	pH	Pressure (MPa)	Time (min)	Log Reduction	Reference
-	Cocktail of 5 strains	Raw milk	nr	600	5	6.3	[68]
-	Cocktail of 9 strains	Coconut water	5.2	593	3	≥6.6	[69]
S. enterica enteritidis	Cocktail of 3 strains	Chicken fillets	nr	500	10	≥7.0	[91]
S. enterica enteritidis	nr	Eggs (hard-cooked and peeled)	nr	550	5	6.5	[92]
S. enterica	Cocktail of 5 strains	Raw beef	5.8	500	7	≥6.5	[53]
S. enterica enteritidis	nr	Liquid whole egg	8.0	450	15	5.1	[93]
S. enterica enteritidis	SE-4	Liquid whole egg	nr	400	10	6.0	[94]
S. enterica typhimurium	ATCC 14028	Pork slurry	nr	400	10	6.5	[47]
S. enterica typhimurium	ATCC 7136	Strained chicken baby food	nr	340	15	2.0	[95]
Special Foods							
S. enterica typhimurium	Cocktail of 3 strains	Ten Italian salamis a_w 0.88–0.95	5.1–6.1	600	5	1.9–5.0	[96]

* nr—not reported.

8. *Vibrio* Inactivation by HPP

Infections from non-cholera bacteria pathogens *Vibrio parahaemolyticus* and *Vibrio vulnificus* caused outbreaks associated with the consumption of raw oysters, fresh crab meat, raw shellfish, sushi and sashimi, and undercooked seafoods, since they are naturally distributed in water [98,99]. Outbreaks in the US in 2019 and 2018 had their origin in imported oysters from Mexico and imported fresh crab meat from Venezuela, respectively [99]. Large outbreaks of *V. parahaemolyticus* (O3:K6 serotype) occurred from 1997–1998 in Washington, Texas, New York, and on the West Coast of the United States (Daniels et al., 2000; DePaola et al., 2000) [100,101], whereas an outbreak of *V. vulnificus* occurred in coastal states from the Gulf of Mexico region (Shapiro et al., 1998) [102]. *Vibrio* bacteria can cause watery diarrhea, often accompanied by abdominal cramping, nausea, vomiting, fever, and chills, occurring within 24 h of ingestion and lasting for 3 days [99]. In 2011, *V. vulnificus*

was reported to have the highest mortality rate in the United States, and 35,000 foodborne infections were caused by *V. parahaemolyticus* (Scallan et al., 2011) [103].

The studies carried out with oysters and clam juice at lower pressures (275–300 MPa) for 2–3 min show the rapid inactivation of *V. vulnificus* and *V. parahaemolyticus* (>6.0-decimal reductions) (Table 5) (Ye et al., 2012; Cook, 2003) [104,105]. A flash treatment at 586 MPa without a holding phase was enough for oysters' pasteurization (Koo et al., 2006) [106], and a pressure as low as 170 MPa for 10 min could cause more than 5-log reductions in *V. parahaemolyticus* in clam juice (Styles et al., 1991) [107]. The studies reviewed showed much lower resistance to HPP inactivation of *V. vulnificus* and *V. parahaemolyticus* than major bacterial pathogens mentioned previously.

Table 5. Inactivation of *Vibrio* in oysters and clam juice by high-pressure processing (HPP) *.

Species	Strains	Food Products	pH	Pressure (MPa)	Time (min)	Log Reduction	Reference
Vibrio vulnificus	MO-624	Oyster	nr	586	0	>6.5	[106]
Vibrio parahaemolyticus	TX-2103, serotype O3:K6	Oyster	nr	586	0	>5.5	[106]
V. vulnificus	MLT 403	Oyster	nr	300	2	>7.0	[104]
V. parahaemolyticus	10 different strains	Homogenized oyster	nr	300	3	>6.0	[105]
V. parahaemolyticus	ATCC 43996	Oyster	nr	300	2	7.0	[104]
V. vulnificus	nr	Homogenized oyster	nr	275	3	>7.0	[105]
V. parahaemolyticus	T-3765-1	Clam juice	7.5	170	10	>5.0	[107]

* nr—not reported.

9. Inactivation of Other Vegetative Pathogens by HPP

Outbreaks of the following pathogenic vegetative bacteria associated with meat products can also pose a health risk to consumers: *Streptococcus faecalis, Campylobacter jejuni, Yersinia enterocolitica, Citrobacter freundii,* and *Aeromonas hydrophila* (Deming et al., 1987; Hussain et al., 1988; Tsai and Chen 1996; Gaibani et al., 2013; Grahek-Ogden et al., 2007) [108–112].

According to studies carried out with ground pork, pork slurry, chicken purée, milk, and soy drink, presented in Table 6, HPP treatments with pressures within 400–600 Mpa for 10 min ensured proper inactivation (>6-log reductions) of *Streptococcus faecalis,* Cronobacter sakazakii, Campylobacter jejuni, and *Yersinia enterocolitica* (Shigehisa et al., 1991; Jarzynka et al., 2021; Solomon and Hoover, 2004; Ellenberg and Hoover, 1999) [47,54,113,114]. *Citrobacter freundii* and *Aeromonas hydrophila* were more susceptible to HPP and required a lower pressure, i.e., 250–300 MPa (Carlez et al., 1993; Ellenberg and Hoover, 1999) [114,115].

Table 6. Inactivation of other pathogenic vegetative cells in meat products by high pressure processing (HPP) *.

Vegetative cells	Strain	Meat products	pH	Pressure (MPa)	Time (min)	Log Reduction	Reference
Streptococcus faecalis	nr	Pork slurry	nr	600	10	>6.0	[47]
Cronobacter sakazakii	ATCC 51329	Human milk	nr	450	15	≥5.9	[54]
Campylobacter jejuni	T1	Pork slurry	nr	400	10	>6.0	[47]
C. jejuni	ATCC 35921	Chicken purée Soy drink Milk	nr nr	400 400 375	10 10 10	≥8.0 ≥8.0 ≥8.0	[113]
Yersinia enterocolitica	nr	Pork slurry	nr	400	10	>6.0	[47]
Y. enterocolitica	9610	Ground pork	6.0	304	15	>7.0	[114]
Citrobacter freundii	nr	Minced beef	5.6–5.8	300	20	>6.0	[115]
Aeromonas hydrophila	ATCC 7965	Ground pork	6.0	253	15	>6.0	[114]

* nr—not reported.

10. Conclusions and Final Remarks

Major food outbreaks registered in the US from 2006–2022 were caused by *Escherichia coli*, *Salmonella* spp., and *Listeria monocytogenes*. This review has demonstrated that HPP at 600 MPa commonly used by the food industry can achieve the recommended 5–8-log reductions in *E. coli*, *Salmonella enterica*, *L. monocytogenes,* and *Vibrio*. *S. aureus* presented the highest resistance among the foodborne vegetative pathogens investigated. Though some strains were inactivated at room temperature at 600 MPa, some of the most resistant strains required heat assisted HPP, with an initial food temperature of 50 °C before compression, for safe food pasteurization. Following in resistance to HPP was *E. coli*, then *L. monocytogenes* and *Salmonella* spp., which were reduced by 6 logs by room temperature HPP within 500–600 MPa. *Vibrio* spp. and other vegetative pathogens, such as *C. jejuni*, *Y. enterocolitica*, *C. freundii*, and *A. hydrophila*, generally required lower pressures (300–400 MPa) for recommended inactivation. In addition to species and strain, the food itself, with a specific composition, also affects the microbial inactivation. HPP foods are distributed under refrigeration to control undesirable enzyme activity and the germination of resistant microbial spores. Therefore, *L. monocytogenes, Y. enterocolitica, Salmonella, V. parahaemolyticus,* and *A. hydrophila* are of extra concern, as they can grow at refrigerated temperatures used to distribute HPP foods. This review has demonstrated that HPP is a safe pasteurization technology, able to achieve at least 5-log reductions in major bacterial pathogens in foods. Nowadays, HPP is a commercial and sustainable alternative to conventional and emerging thermal pasteurization technologies due to negligible effects on health and flavor related components of the foods.

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References

1. Silva, F.V.M.; Gibbs, P.A. Principles of thermal processing: Pasteurization. In *Engineering Aspects of Thermal Food Processing*; Simpson, R., Ed.; CRC Press: Boca Raton, FL, USA, 2009; pp. 14–38.
2. Silva, F.V.M.; Gibbs, P.A.; Nunez, H.; Almonacid, S.; Simpson, R. Thermal processes: Pasteurization. In *Encyclopedia of Food Microbiology*; Batt, C.A., Tortorello, M.L., Eds.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 577–595.
3. Evelyn; Silva, F.V.M. *Inactivation of pathogenic microorganisms in foods by high-pressure processing. In Food Safety and Protection*; Rai, V.R., Bai, J.A., Eds.; CRC Press: Boca Raton, FL, USA, 2017; pp. 343–378.
4. Silva, F.V.M.; Evelyn. High pressure processing effect on microorganisms in fruit and vegetable products. In *High Pressure Processing of Fruit and Vegetable Juices*; Houška, M., Silva, F.V.M., Eds.; CRC Press: Boca Raton, FL, USA; London, UK; New York, NY, USA, 2018; pp. 3–37.
5. EFSA BIOHAZ Panel (EFSA Panel on Biological Hazards); Koutsoumanis, K.; Alvarez-Ordóñez, A.; Bolton, D.; Bover-Cid, S.; Chemaly, M.; Davies, R.; De Cesare, A.; Herman, L.; Hilbert, F.; et al. The efficacy and safety of high-pressure processing of food. *EFSA J.* **2022**, *20*, 7128.
6. Sulaiman, A.; Farid, M.; Silva, F.V.M. Strawberry puree processed by thermal, high pressure, or power ultrasound: Process energy requirements and quality modeling during storage. *Food Sci. Technol. Int.* **2017**, *23*, 293–309. [CrossRef]
7. Sánchez-Moreno, C.; de Ancos, B. High pressure processing effect on nutrients and their stability. In *High Pressure Processing of Fruit and Vegetable Juices*; Houška, M., Silva, F.V.M., Eds.; CRC Press: Boca Raton, FL, USA; London, UK; New York, NY, USA, 2018; pp. 85–103.
8. Milani, E.A.; Silva, F. Nonthermal pasteurization of beer by high pressure processing: Modelling the inactivation of *Saccharomyces cerevisiae* ascospores in different alcohol beers. *High Press. Res.* **2016**, *36*, 595–609. [CrossRef]

9. van Wyk, S.; Farid, M.M.; Silva, F.V. SO_2, high pressure processing and pulsed electric field treatments of red wine: Effect on sensory, Brettanomyces inactivation and other quality parameters during one year storage. *Innov. Food Sci. Emerg. Technol.* **2018**, *48*, 204–211. [CrossRef]
10. Lee, P.Y.; Oey, I. Sensory properties of high pressure treated fruit and vegetable juices. In *High Pressure Processing of Fruit and Vegetable Juices*; Houška, M., Silva, F.V.M., Eds.; CRC Press: Boca Raton, FL, USA; London, UK; New York, NY, USA, 2018; pp. 121–133.
11. Tříska, J. Health active components in fruit/vegetable juices treated by high pressure. In *High Pressure Processing of Fruit and Vegetable Juices*; Houška, M., Silva, F.V.M., Eds.; CRC Press: Boca Raton, FL, USA; London, UK; New York, NY, USA, 2018; pp. 105–119.
12. Houška, M.; Silva, F.V.M.; Evelyn; Buckow, R.; Terefe, N.S.; Tonello, C. High pressure processing applications in plant foods. *Foods* **2022**, *11*, 223. [CrossRef]
13. Silva, F.M.; Sims, C.; Balaban, M.O.; Silva, C.L.M.; O'Keefe, S. Kinetics of flavour and aroma changes in thermally processed cupuaçu (*Theobroma grandiflorum*) pulp. *J. Sci. Food Agric.* **2000**, *80*, 783–787. [CrossRef]
14. van Wyk, S.; Silva, F.V.M. High pressure processing inactivation of *Brettanomyces bruxellensis* in seven different table wines. *Food Contr.* **2017**, *81*, 1–8. [CrossRef]
15. van Wyk, S.; Silva, F.V.M. High pressure inactivation of *Brettanomyces bruxellensis* in red wine. *Food Microbiol.* **2017**, *63*, 199–204. [CrossRef]
16. Houska, M.; Silva, F.V.M. *High Pressure Processing of Fruit and Vegetable Products*; CRC Press Taylor and Francis Group: Boca Raton, FL, USA; London, UK; New York, NY, USA, 2018.
17. HPP Technology Applications. Available online: https://www.hiperbaric.com/en/hpp-technology/hpp-applications/ (accessed on 24 November 2022).
18. Milani, E.A.; Silva, F.V.M. Pasteurization of beer by non-thermal technologies. *Front. Food. Sci. Technol.* **2022**, *1*, 798676. [CrossRef]
19. Abe, F. Dynamic structural changes in microbial membranes in response to high hydrostatic pressure analyzed using time-resolved fluorescence anisotropy measurement. *Biophys. Chem.* **2013**, *183*, 3–8. [CrossRef]
20. Rozali, S.N.; Milani, E.A.; Deed, R.C.; Silva, F.V.M. Bacteria, mould and yeast spore inactivation studies by scanning electron microscope observations. *Int. J. Food Microbiol.* **2017**, *263*, 17–25. [CrossRef]
21. Silva, F.V.M.; van Wyk, S. Emerging non-thermal technologies as alternative to SO_2 for the production of wine. *Foods* **2021**, *10*, 2175. [CrossRef]
22. Norton, T.; Sun, D.-W. Recent advances in the use of high pressure as an effective processing technique in the food industry. *Food Bioprocess Technol.* **2007**, *1*, 2–34. [CrossRef]
23. Evelyn; Silva, F.V.M. High pressure thermal processing for the inactivation of *Clostridium perfringens* spores in beef slurry. *Innov. Food Sci. Emerg. Technol.* **2016**, *33*, 26–31. [CrossRef]
24. Evelyn; Silva, F.V.M. Modeling the inactivation of psychrotrophic *Bacillus cereus* spores in beef slurry by 600MPa HPP combined with 38–70 °C: Comparing with thermal processing and estimating the energy requirements. *Food Bioprod. Process.* **2016**, *99*, 179–187. [CrossRef]
25. Uchida, R.; Silva, F.V.M. *Alicyclobacillus acidoterrestris* spore inactivation by high pressure combined with mild heat: Modelling the effect of temperature and soluble solids. *Food Contr.* **2017**, *73*, 426–432. [CrossRef]
26. Evelyn; Silva, F.V.M. Heat assisted HPP for the inactivation of bacteria, molds and yeast spores in foods: Log reductions and mathematical models. *Trends Food Sci. Technol.* **2018**, *88*, 143–156. [CrossRef]
27. Rendueles, E.; Omer, M.K.; Alvseike, O.; Alonso-Calleja, C.; Capita, R.; Prieto, M. Microbiological food safety assessment of high hydrostatic pressure processing: A review. *LWT-Food Sci. Technol.* **2011**, *44*, 1251–1260. [CrossRef]
28. Bover-Cid, S.; Belletti, N.; Aymerich, T.; Garriga, M. Modeling the protective effect of aw and fat content on the high pressure resistance of *Listeria monocytogenes* in dry-cured ham. *Food Res. Int.* **2015**, *75*, 194–199. [CrossRef]
29. Bover-Cid, S.; Belletti, N.; Aymerich, T.; Garriga, M. Modelling the impact of water activity and fat content of dry-cured ham on the reduction of *Salmonella enterica* by high pressure processing. *Meat Sci.* **2017**, *123*, 120–125. [CrossRef]
30. Centers for Disease Control and Prevention (CDC). Foodborne Germs and Illnesses. Available online: http://www.cdc.gov/foodsafety/foodborne-germs.html (accessed on 24 November 2022).
31. Centers for Disease Control and Prevention (CDC). *Surveillance for Foodborne Disease Outbreaks, United States, 2017, Annual Report*; U.S. Department of Health and Human Services, CDC: Atlanta, GA, USA, 2019.
32. Centers for Disease Control and Prevention (CDC). Salmonella (Non-Typhoidal). Available online: https://www.who.int/en/news-room/fact-sheets/detail/salmonella-(non-typhoidal) (accessed on 24 November 2022).
33. European Food Safety Authority; European Centre for Disease Prevention and Control. Multi-country outbreak of Listeria monocytogenes serogroup IVb, multi-locus sequence type 6, infections linked to frozen corn and possibly to other frozen vegetables—First update. *EFSA Support. Publ.* **2018**, *15*, 1448E.
34. Westhoff, D.C. Heating milk for microbial destruction: A historical outline and update. *J. Food Prot.* **1978**, *41*, 122–130. [CrossRef]
35. Grant, I.R.; Ball, H.J.; Neill, S.D.; Rowe, M.T. Inactivation of *Mycobacterium paratuberculosis* in cows' milk at pasteurization temperatures. *Appl. Environ. Microbiol.* **1996**, *62*, 631–636. [CrossRef]
36. Grant, I.R. Mycobacterium paratuberculosis and milk. *Acta Vet Scand* **2003**, *44*, 261–266.
37. Cerf, O.; Condron, R. *Coxiella burnetii* and milk pasteurization: An early application of the precautionary principle? *Epidemiol. Infect.* **2006**, *134*, 946–951. [CrossRef]
38. D'Aoust, J. Psychrotrophy and foodborne *Salmonella*. *Int. J. Food Microbiol.* **1991**, *13*, 207–215. [CrossRef]
39. Penfield, M.P.; Campbell, A.M.; Penfield, M.P. *Experimental Food Science*; Academic Press: San Diego, CA, USA, 1990.

40. Implementation of the FDA Food Safety Modernization Act (FSMA, P.L. 111–353). Available online: https://www.govinfo.gov/content/pkg/PLAW-111publ353/pdf/PLAW-111publ353.pdf (accessed on 24 November 2022).
41. Koutchma, T.; Warriner, K. Regulatory aspects of high pressure processed foods in North America, Europe, Asia, New Zealand and Australia. In *High Pressure Processing of Fruit and Vegetable Juices*; Houška, M., Silva, F.V.M., Eds.; CRC Press: Boca Raton, FL, USA; London, UK; New York, NY, USA, 2018; pp. 155–168.
42. Evenson, M.L.; Hinds, M.W.; Bernstein, R.S.; Bergdoll, M.S. Estimation of human dose of staphylococcal enterotoxin A from a large outbreak of staphylococcal food poisoning involving chocolate milk. *Int. J. Food Microbiol.* **1988**, *7*, 311–316. [CrossRef]
43. Asao, T.; Kumeda, Y.; Kawai, T.; Shibata, T.; Oda, H.; Haruki, K.; Nakazawa, H.; Kozaki, S. An extensive outbreak of staphylococcal food poisoning due to low-fat milk in Japan: Estimation of enterotoxin A in the incriminated milk and powdered skim milk. *Epidemiol. Infect.* **2003**, *130*, 33–40. [CrossRef]
44. Schmid, D.; Fretz, R.; Winter, P.; Mann, M.; Höger, G.; Stöger, A.; Ruppitsch, W.; Ladstätter, J.; Mayer, N.; de Martin, A. Outbreak of staphylococcal food intoxication after consumption of pasteurized milk products, June 2007, Austria. Wien. *Klin. Wochenschr.* **2009**, *121*, 125–131. [CrossRef]
45. Ostyn, A.; De Buyser, M.L.; Guillier, F.; Groult, J.; Felix, B.; Salah, S.; Delmas, G.; Hennekinne, J.A. First evidence of a food poisoning outbreak due to staphylococcal enterotoxin type E, France, 2009. *Eurosurveillance* **2010**, *15*, 19528. [CrossRef]
46. Hennekinne, J.A.; De Buyser, M.L.; Dragacci, S. *Staphylococcus aureus* and its food poisoning toxins: Characterization and outbreak investigation. *FEMS Microbiol. Rev.* **2012**, *36*, 815–836. [CrossRef]
47. Shigehisa, T.; Ohmori, T.; Saito, A.; Taji, S.; Hayashi, R. Effects of high hydrostatic pressure on characteristics of pork slurries and inactivation of microorganisms associated with meat and meat products. *Int. J. Food Microbiol.* **1991**, *12*, 207–215. [CrossRef]
48. Zagorska, J.; Galoburda, R.; Raita, S.; Liepa, M. Inactivation and recovery of bacterial strains, individually and mixed, in milk after high pressure processing. *Int. Dairy J.* **2021**, *123*, 105147. [CrossRef]
49. O'Reilly, C.E.; O'Connor, P.M.; Kelly, A.L.; Beresford, T.P.; Murphy, P.M. Use of hydrostatic pressure for inactivation of microbial contaminants in cheese. *Appl. Environ. Microbiol.* **2000**, *66*, 4890–4896. [CrossRef]
50. Rocha-Pimienta, J.; Martillanes, S.; Ramírez, R.; Garcia-Parra, J.; Delgado-Adamez, J. *Bacillus cereus* spores and *Staphylococus aureus sub. aureus* vegetative cells inactivation in human milk by high-pressure processing. *Food Control* **2020**, *113*, 107212. [CrossRef]
51. Patterson, M.F.; Kilpatrick, D.J. The combined effect of high hydrostatic pressure and mild heat on inactivation of pathogens in milk and poultry. *J. Food Prot.* **1998**, *61*, 432–436. [CrossRef]
52. Gervilla, R.; Sendra, E.; Ferragut, V.; Guamis, B. Sensitivity of *Staphylococcus aureus* and *Lactobacillus helveticus* in ovine milk subjected to high hydrostatic pressure. *J. Dairy Sci.* **1999**, *82*, 1099–1107. [CrossRef]
53. Park, S.; Park, E.; Yoon, Y. Comparison of nonthermal decontamination methods to improve the safety for raw beef consumption. *J. Food Prot.* **2021**, *85*, 664–670. [CrossRef]
54. Jarzynka, S.; Strom, K.; Barbarska, O.; Pawlikowska, E.; Minkiewicz-Zochniak, A.; Rosiak, E.; Oledzka, G.; Wesolowska, A. Combination of high-pressure processing and freeze-drying as the most effective techniques in maintaining biological values and microbiological safety of donor milk. *Int. J. Environ. Res. Public Health* **2021**, *18*, 2147. [CrossRef]
55. Alpas, H.; Bozoglu, F. The combined effect of high hydrostatic pressure, heat and bacteriocins on inactivation of foodborne pathogens in milk and orange juice. *World J. Microbiol. Biotechnol.* **2000**, *16*, 387–392. [CrossRef]
56. Hugas, M.; Garriga, M.; Monfort, J.M. New mild technologies in meat processing: High pressure as a model technology. *Meat Sci.* **2002**, *62*, 359–371. [CrossRef] [PubMed]
57. Centers for Disease Control and Prevention (CDC). Reports of Selected *E. coli* Outbreak Investigations. Available online: http://www.cdc.gov/ecoli/outbreaks.html (accessed on 24 November 2022).
58. Weagant, S.D.; Bryant, J.L.; Bark, D.H. Survival of *Escherichia coli* O157:H7 in mayonnaise and mayonnaise-based sauces at room and refrigerated temperatures. *J. Food Prot.* **1994**, *57*, 629–631. [CrossRef] [PubMed]
59. Conner, D.E.; Kotrola, J.S. Growth and survival of *Escherichia coli* O157:H7 under acidic conditions. *Appl. Environ. Microbiol.* **1995**, *61*, 382–385. [CrossRef]
60. Hsin-Yi, C.; Chou, C. Acid adaptation and temperature effect on the survival of *E. coli* O157:H7 in acidic fruit juice and lactic fermented milk product. *Int. J. Food Microbiol.* **2001**, *70*, 189–195. [CrossRef] [PubMed]
61. Centers for Disease Control and Prevention (CDC). Outbreak of *Escherichia coli* O157:H7 infections associated with drinking unpasteurized commercial apple juice–British Columbia, California, Colorado, and Washington, October 1996. *MMWR Morb. Mortal. Wkly. Rep.* **1996**, *45*, 975.
62. Cody, S.H.; Glynn, M.K.; Farrar, J.A.; Cairns, K.L.; Griffin, P.M.; Kobayashi, J.; Fyfe, M.; Hoffman, R.; King, A.S.; Lewis, J.H. An outbreak of *Escherichia coli* O157:H7 infection from unpasteurized commercial apple juice. *Ann. Intern. Med.* **1999**, *130*, 202–209. [CrossRef]
63. Miller, L.G.; Kaspar, C.W. *Escherichia coli* O157:H7 acid tolerance and survival in apple cider. *J. Food Prot.* **1994**, *57*, 460–464. [CrossRef]
64. Tsai, Y.; Ingham, S.C. Survival of *Escherichia coli* O157:H7 and *Salmonella* spp. in acidic condiments. *J. Food Prot.* **1997**, *60*, 751–755. [CrossRef]
65. Morgan, D.; Newman, C.P.; Hutchinson, D.N.; Walker, A.M.; Rowe, B.; Majid, F. Verotoxin producing *Escherichia coli* O157 infections associated with the consumption of yoghurt. *Epidemiol. Infect.* **1993**, *111*, 181. [CrossRef]
66. Ibrahim, O.O. Food borne pathogen *Escherichia coli* O157: H7 History, sources of transmission, symptoms, detection and prevention. *EC Microbiol.* **2015**, *2*, 214–222.

67. Centers for Disease Control and Prevention (CDC). *E. coli* (*Escherichia coli*): General Information. Available online: http://www.cdc.gov/ecoli/general/ (accessed on 24 November 2022).
68. Stratakos, A.C.; Inguglia, E.S.; Linton, M.; Tollerton, J.; Murphy, L.; Corcionivoschi, N.; Koidis, A.; Tiwari, B.K. Effect of high pressure processing on the safety, shelf life and quality of raw milk. *Innov. Food Sci. Emerg. Technol.* **2019**, *52*, 325–333. [CrossRef]
69. Raghubeer, E.V.; Phan, B.N.; Onuoha, E.; Diggins, S.; Aguilar, V.; Swanson, S.; Lee, A. The use of high-pressure processing (HPP) to improve the safety and quality of raw coconut (*Cocos nucifera* L) water. *Int. J. Food Microbiol.* **2020**, *331*, 108697. [CrossRef] [PubMed]
70. Chien, S.Y.; Sheen, S.; Sommers, C.; Sheen, L.Y. Modeling the inactivation of *Escherichia coli* O157:H7 and uropathogenic *E. coli* in ground beef by high pressure processing and citral. *Food Control* **2017**, *73*, 672–680. [CrossRef]
71. Capellas, M.; Mor-Mur, M.; Sendra, E.; Pla, R.; Guamis, B. Populations of aerobic mesophils and inoculated *E. coli* during storage of fresh goat's milk cheese treated with high pressure. *J. Food Prot.* **1996**, *59*, 582–587. [CrossRef] [PubMed]
72. Linton, M.; McClements, J.M.J.; Patterson, M.F. Inactivation of *Escherichia coli* O157:H7 in orange juice using a combination of high pressure and mild heat. *J. Food Prot.* **1999**, *62*, 277–279. [CrossRef] [PubMed]
73. Hiremath, N.D.; Ramaswamy, H.S. High pressure destruction kinetics of spoilage and pathogenic microorganisms in mango juice. *J. Food Process. Pres.* **2012**, *36*, 113–125. [CrossRef]
74. Jordan, S.L.; Pascual, C.; Bracey, E.; Mackey, B.M. Inactivation and injury of pressure-resistant strains of *Escherichia coli* O157 and *Listeria monocytogenes* in fruit juices. *J. Appl. Microbiol.* **2001**, *91*, 463–469. [CrossRef]
75. Henriques, A.R.; Fraqueza, M.J. Listeria monocytogenes and ready-to-eat-meat-based food products: Incidence and control. In *Listeria Monocytogenes Incidence, Growth Behavior, and Control*; Vicario, T., Ed.; Nova Science Publishers Inc.: New York, NY, USA, 2015; pp. 71–103.
76. Gillespie, I.A.; Mook, P.; Little, C.L.; Grant, K.A.; McLauchlin, J. Human listeriosis in England, 2001–2007: Association with neighbourhood deprivation. *Eurosurveillance* **2010**, *15*, 7–16. [CrossRef]
77. CDC. Listeriosis: Diagnosis. Available online: http://www.cdc.gov/listeria/diagnosis.html (accessed on 24 November 2022).
78. CDC. Listeria Outbreaks. Available online: http://www.cdc.gov/listeria/outbreaks/ (accessed on 24 November 2022).
79. EFSA BIOHAZ Panel (EFSA Panel on Biological Hazards). Scientific Opinion on the *Listeria monocytogenes* contamination of ready-to-eat foods and the risk for human health in the EU. *EFSA J.* **2018**, *16*, 5134.
80. EFSA BIOHAZ Panel (EFSA Panel on Biological Hazards); Koutsoumanis, K.; Alvarez-Ordóñez, A.; Bolton, D.; Bover-Cid, S.; Chemaly, M.; Davies, R.; De Cesare, A.; Herman, L.; Hilbert, F.; et al. The public health risk posed by *Listeria monocytogenes* in frozen fruit and vegetables, including herbs, blanched during processing. *EFSA J.* **2020**, *18*, 6092.
81. Balamurugan, S.; Inmanee, P.; Souza, J.; Strange, P.; Pirak, T.; Barbut, S. Effects of high pressure processing and hot water pasteurization of cooked sausages on inactivation of inoculated *Listeria monocytogenes*, natural populations of lactic acid bacteria, *Pseudomonas* spp., and coliforms and their recovery during storage at 4 and 10 °C. *J. Food Prot.* **2018**, *81*, 1245–1251. [PubMed]
82. Gallot-Lavallee, T. Efficiency of high pressure treatment for destruction of *Listeria monocytogenes* in goat cheese from raw milk. *Sci. Aliment.* **1998**, *18*, 647–655.
83. Bambace, M.F.; Moreira, M.R.; Sánchez-Moreno, C.; De Ancos, B. Effects of combined application of high-pressure processing and active coatings on phenolic compounds and microbiological and physicochemical quality of apple cubes. *J. Sci. Food Agric.* **2021**, *101*, 4256–4265. [CrossRef]
84. Patterson, M.F.; Quinn, M.; Simpson, R.; Gilmour, A. Sensitivity of vegetative pathogens to high hydrostatic pressure treatment in phosphate-buffered saline and foods. *J. Food Prot.* **1995**, *58*, 524–529. [CrossRef] [PubMed]
85. Centers for Disease Control and Prevention (CDC). Reports of Selected Salmonella Outbreak Investigations. Available online: https://www.cdc.gov/salmonella/outbreaks.html (accessed on 24 November 2022).
86. Perales, I.; Audicana, A. The role of hens' eggs in outbreaks of salmonellosis in north Spain. *Int. J. Food Microbiol.* **1989**, *8*, 175–180. [CrossRef] [PubMed]
87. Doyle, M.P.; Erickson, M.C. Summer meeting 2007–the problems with fresh produce: An overview. *J. Appl. Microbiol.* **2008**, *105*, 317–330. [CrossRef]
88. Hanning, I.B.; Nutt, J.D.; Ricke, S.C. *Salmonellosis* outbreaks in the United States due to fresh produce: Sources and potential intervention measures. *Foodborne Pathog. Dis.* **2009**, *6*, 635–648. [CrossRef]
89. Giannella, R.A. Salmonella. In *Medical Microbiology*; Baron, S., Ed.; University of Texas Medical Branch: Galveston, TX, USA, 1996.
90. Behravesh, C.B.; Lynch, M.; Schlundt, J. *Salmonellosis, Control of Communicable Diseases Manual*; United Book Press: Baltimore, MD, USA, 2008.
91. Argyri, A.A.; Papadopoulou, O.S.; Nisiotou, A.; Tassou, C.C.; Chorianopoulos, N. Effect of high pressure processing on the survival of *Salmonella* Enteritidis and shelf-life of chicken fillets. *Food Microbiol.* **2018**, *70*, 55–64. [CrossRef]
92. Shahbaz, H.M.; Jeong, B.; Kim, J.U.; Ha, N.; Lee, H.; Ha, S.D.; Park, J. Application of high pressure processing for prevention of greenish-gray yolks and improvement of safety and shelf-life of hard-cooked peeled eggs. *Innov. Food Sci. Emerg. Technol.* **2018**, *45*, 10–17. [CrossRef]
93. Ponce, E.; Pla, R.; Sendra, E.; Guamis, B.; Mor-Mur, M. Destruction of *Salmonella* Enteritidis inoculated in liquid whole egg by high hydrostatic pressure: Comparative study in selective and non-selective media. *Food Microbiol.* **1999**, *16*, 357–365. [CrossRef]
94. Bari, M.L.; Ukuku, D.O.; Mori, M.; Kawamoto, S.; Yamamoto, K. Effect of hydrostatic pressure pulsing on the inactivation of *Salmonella* Enteritidis in liquid whole egg. *Foodborne Pathog. Dis.* **2008**, *5*, 175–182. [CrossRef] [PubMed]

95. Metrick, C.; Hoover, D.G.; Farkas, D.F. Effects of high hydrostatic pressure on heat resistant and heat sensitive strains of *Salmonella*. *J. Food Sci.* **1989**, *54*, 1547–1549. [CrossRef]
96. Bonilauri, P.; Grisenti, M.S.; Daminelli, P.; Merialdi, G.; Ramini, M.; Bardasi, L.; Taddei, R.; Cosciani-Cunico, E.; Dalzini, E.; Frustoli, M.A.; et al. Reduction of *Salmonella* spp. populations in Italian salami during production process and high pressure processing treatment: Validation of processes to export to the U.S. *Meat Sci.* **2019**, *157*, 107869. [CrossRef] [PubMed]
97. Boziaris, I.S.; Parlapani, F.F.; DeWitt, C.A.M. High pressure processing at ultra-low temperatures: Inactivation of foodborne bacterial pathogens and quality changes in frozen fish fillets. *Innov. Food Sci. Emerg. Technol.* **2021**, *74*, 102811. [CrossRef]
98. Jay, J.M. High-temperature food preservation and characteristics of thermophilic microorganisms. In *Modern Food Microbiology*; Springer: Berlin/Heidelberg, Germany, 2000; pp. 341–362.
99. Centers for Disease Control and Prevention (CDC). Vibrio Species Causing Vibriosis: Symptoms and Outbreaks. Available online: https://www.cdc.gov/vibrio/outbreaks.html (accessed on 24 November 2022).
100. Daniels, N.A.; Ray, B.; Easton, A.; Marano, N.; Kahn, E.; McShan, A.L., 2nd; Rosario, L.D.; Baldwin, T.; Kingsley, M.A.; Puhr, N.D.; et al. Emergence of a new *Vibrio parahaemolyticus* serotype in raw oysters: A prevention quandary. *JAMA* **2000**, *284*, 1541–1545. [CrossRef]
101. De Paola, A.; Kaysner, C.A.; Bowers, J.; Cook, D.W. Environmental investigations of *Vibrio parahaemolyticus* in oysters after outbreaks in Washington, Texas, and New York (1997 and 1998). *Appl. Environ. Microbiol.* **2000**, *66*, 4649–4654. [CrossRef]
102. Shapiro, R.L.; Altekruse, S.; Hutwagner, L.; Bishop, R.; Hammond, R.; Wilson, S.; Ray, B.; Thompson, S.; Tauxe, R.V.; Griffin, P.M. The role of Gulf Coast oysters harvested in warmer months in *Vibrio vulnificus* infections in the United States, 1988–1996. *J. Infect. Dis.* **1998**, *178*, 752–759. [CrossRef]
103. Scallan, E.; Hoekstra, R.M.; Angulo, F.J.; Tauxe, R.V.; Widdowson, M.; Roy, S.L.; Jones, J.L.; Griffin, P.M. Foodborne illness acquired in the United States—Major pathogens. *Emerg. Infect. Dis.* **2011**, *17*, 7–15. [CrossRef]
104. Ye, M.; Huang, Y.; Chen, H. Inactivation of *Vibrio parahaemolyticus* and *Vibrio vulnificus* in oysters by high-hydrostatic pressure and mild heat. *Food Microbiol.* **2012**, *32*, 179–184. [CrossRef]
105. Cook, D. Sensitivity of Vibrio species in phosphate-buffered saline and in oysters to high-pressure processing. *J. Food Prot.* **2003**, *66*, 2276–2282. [CrossRef]
106. Koo, J.; Jahncke, M.L.; Reno, P.W.; Hu, X.; Mallikarjunan, P. Inactivation of *Vibrio parahaemolyticus* and *Vibrio vulnificus* in phosphate-buffered saline and in inoculated whole oysters by high-pressure processing. *J. Food Prot.* **2006**, *69*, 596–601. [CrossRef] [PubMed]
107. Styles, M.F.; Hoover, D.G.; Farkas, D.F. Response of *Listeria monocytogenes* and *Vibrio parahaemolyticus* to high hydrostatic pressure. *J. Food Sci.* **1991**, *56*, 1404–1407. [CrossRef]
108. Deming, M.S.; Tauxe, R.V.; Blake, P.A.; Dixon, S.E.; Fowler, B.S.; Jones, T.S.; Lockamy, E.A.; Patton, C.M.; Sikes, R.O. *Campylobacter enteritis* at a university: Transmission from eating chicken and from cats. *Am. J. Epidemiol.* **1987**, *126*, 526–534. [CrossRef] [PubMed]
109. Hussain, Z.; Kuhn, M.; Lannigan, R.; Austin, T.W. Microbiological investigation of an outbreak of bacteraemia due to *Streptococcus faecalis* in an intensive care unit. *J. Hosp. Infect.* **1988**, *12*, 263–271. [CrossRef] [PubMed]
110. Tsai, G.; Chen, T. Incidence and toxigenicity of *Aeromonas hydrophila* in seafood. *Int. J. Food Microbiol.* **1996**, *31*, 121–131. [CrossRef] [PubMed]
111. Gaibani, P.; Ambretti, S.; Farruggia, P.; Bua, G.; Berlingeri, A.; Tamburini, M.V.; Cordovana, M.; Guerra, L.; Mazzetti, M.; Roncarati, G. Outbreak of *Citrobacter freundii* carrying VIM-1 in an Italian Hospital, identified during the carbapenemases screening actions, June 2012. *Int. J. Infect. Dis.* **2013**, *17*, e714–e717. [CrossRef] [PubMed]
112. Grahek-Ogden, D.; Schimmer, B.; Cudjoe, K.S.; Nygård, K.; Kapperud, G. Outbreak of *Yersinia enterocolitica* serogroup O:9 infection and processed pork, Norway. *Emerg. Infect. Dis.* **2007**, *13*, 754–756. [CrossRef] [PubMed]
113. Solomon, E.B.; Hoover, D.G. Inactivation of *Campylobacter jejuni* by high hydrostatic pressure. *Lett. Appl. Microbiol.* **2004**, *38*, 505–509. [CrossRef]
114. Ellenberg, L.; Hoover, D.G. Injury and survival of *Aeromonas hydrophila* 7965 and *Yersinia enterocolitica* 9610 from high hydrostatic pressure. *J. Food Saf.* **1999**, *19*, 263–276. [CrossRef]
115. Carlez, A.; Rosec, J.-P.; Richard, N.; Cheftel, J.-C. High pressure inactivation of *Citrobacter freundii*, *Pseudomonas fluorescens* and *Listeria innocua* in inoculated minced beef muscle. *LWT-Food Sci. Technol.* **1993**, *26*, 357–363. [CrossRef]

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