Nonthermal Decontamination of Raw and Processed Meat

Subjects: Others

Contributor: Ume Roobab, James S. Chacha, Afeera Abida, Sidra Rashid, Ghulam Muhammad Madni, Jose Manuel Lorenzo, Xin-An Zeng, Rana Muhammad Aadil

Meat may contain natural, spoilage, and pathogenic microorganisms based on the origin and characteristics of its dietary matrix. Several decontamination substances are used during or after meat processing, which include chlorine, organic acids, inorganic phosphates, benzoates, propionates, bacteriocins, or oxidizers. Unfortunately, traditional decontamination methods are often problematic because of their adverse impact on the quality of the raw carcass or processed meat. The extended shelf-life of foods is a response to the pandemic trend, whereby consumers are more likely to choose durable products that can be stored for a longer period between visits to food stores. This includes changing purchasing habits from “just in time” products “for now” to “just in case” products, a trend that will not fade away with the end of the pandemic.

Keywords: clean label foods ; ozone ; cold plasma

1. Introduction

Meat is high in protein, vitamins, and minerals, and it is one of the world’s most popular foods. Because of its intrinsic (nutrients, water availability, and pH) and extrinsic (transportation, processing, and storage) characteristics, meat is extremely susceptible to the development of pathogenic and spoilage microbes, for instance, *Campylobacter* spp., *Escherichia coli*, *Salmonella* spp., *Staphylococcus aureus*, lactic acid bacteria, and *Pseudomonas* spp. To guarantee food safety and conformity with quality requirements, all these microorganisms must be eliminated throughout industrial processing [1]. But in recent years, the safety of ready-to-eat (RTE) meats has been evaluated due to reported outbreaks that are associated with their consumption. During the repackaging of pasteurized meats, the core of the issue lies in post-process microbial contamination. Poultry and livestock producers can reduce the number of *Salmonella* (accounting for 31% of foodborne pathogenic deaths) that occur in animals before and during slaughter [2]. Besides, *Listeria* spp. grow during prolonged storage even at refrigeration temperatures (2–4 °C) [3]. This pathogen is sensitive to normal cooking, but it may contaminate the meat products after heating when exposed to the contaminated environment during cutting, slicing, and repackaging [4]. *L. monocytogenes* is of particular concern to meat and poultry products because it can grow in both raw and cooked meat [3]. This psychotropic Gram-positive pathogen causes a severe invasive disease called listeriosis. *L. monocytogenes* not only survive under a wide range of temperatures (1–45 °C) and pH (4.3–9.4), but it can also grow with water activity to a value of 0.92 and above. Furthermore, it can tolerate undesirable environmental conditions such as low-oxygen conditions, nitrite, and high salt content [3]. Food industries are putting efforts towards minimizing such post-process contamination and growth of pathogens by developing hurdle technologies [5]. Similarly, *S. aureus* can survive heat treatments and again can contaminate meat after cooking. Besides, the pre-and postslaughtering sources of *S. aureus* contamination include feed, feces, feathers, air, scald water and defeathering machines [6]. *S. aureus* has become a threat to public health because it can easily adapt to become methicillin-resistant *S. aureus* (MRSA), even during selective antimicrobial pressure, consequently causing staphylococcal foodborne illness that may lead to MRSA infection [7]. This opportunistic pathogen can grow in a wide range of temperatures, pH, and sodium chloride concentrations of up to 15% [8]. Raw and processed meat are the major food sources associated with food poisoning caused by *S. aureus*. The conventional techniques to evaluate the microbial safety of meat (i.e., culturing and biochemical testing) are time-consuming and labor-intensive [8].

Other thermal processing methods such as hot water and steam pasteurization [9], and chemical methods, for instance, lactic acid and sodium benzoate [10], trisodium phosphate and sodium hypochlorite [11], potassium sorbate [12], chlorine dioxide, and peroxyacetic acid [13], have been applied to reduce the bacterial counts in meat. For instance, Manzoor et al. [14] evaluated the effect of lactic acid spray (2–4%) on the microflora and shelf-life of buffalo meat displayed under modified atmospheric packaging. The aerobic plate count of sprayed carcasses and steaks was significantly lower than

the unsprayed controls. Similarly, the bactericidal activity of lactic acid, levulinic acid, and sodium dodecyl sulfate was determined individually and in combination against Shiga toxin-producing *E. coli* (STEC) in pure culture conditions [15]. Results showed that the use of 3% lactic acid for 2 min in pure cultures reduced *E. coli* O26: H11, O45: H2, O111: H8, O103: H2, O121: H2, O145: NM, and O157: H7 populations by 2.1, 0.4, 0.3, 1.4, 0.3, 2.1, and 1.7 log CFU/mL, respectively. While the treatments of 0.5% levulinic acid, plus 0.05% sodium dodecyl sulfate, for less than 1 min reduced the populations of all STEC strains to undetectable levels [15]. In general, lactic acid concentrations less than 5% have not proven to be effective against *Campylobacter* in the form of a spray wash [16][17], even though levels of just 2% produced significant *Salmonella* reduction compared to other treatments [18]. The increased levels of to up to 8% caused considerable deterioration of the appearance of the carcasses, although the use of high acid concentration was beneficial for reducing the numbers of *Campylobacter* [16]. Changes in the texture and nutritional components may occur in meat owing to such processes [19][20]. In addition, chemical residues on meat surfaces cause health problems [21]. In the past, the poultry industry utilized 0.5–1 ppm chlorine and ice with a circulation system to lower chicken carcass temperature and bacterial load in the gizzard and intestine during the chilling process. This approach, however, may create cross-contamination in chiller tanks due to cycled poultry water. Chlorine and organic materials may react to generate halogenated organic compounds like chloroform, which relates to bladder and rectal cancer in humans. While considering the limitations and health concerns of chemical antimicrobial agents, it is necessary to seek other disinfectants or nonthermal technologies, such as ozone [22], high-hydrostatic pressure (HHP) [23][24], and cold plasma (CP) [25], as alternatives. Ozone gas, for instance, is one of the most potent oxidants known (for its use as a bactericide) because it can attack the cellular membrane of bacterial cells, leading to the lysis of cell structure and damage of DNA and proteins [26]. On the other hand, HHP, as a food preservation technology used for short-term treatment under high pressure, replaced the utilization of chemical preservatives or high temperatures [27]. Similarly, CP had been identified as a potential source of nitrite and its application in the meat industry as plasma-activated water is a great and efficient way of meat curing [28].

2. Nonthermal Decontamination Technologies

2.1. Ozonation

In recent years, ozone (a naturally occurring water-soluble triatomic gas that can act as a strong oxidizing agent) has been of great interest to the processing industry. Bacterial inactivation through cell wall disruption, or lysis by ozone, is faster than other disinfectants that require time to invade the cell membrane [29]. It is, therefore, a very effective germicide against viruses, bacteria, and spores. The two mechanisms of inactivation include: (i) sulfhydryl group and amino acids of enzymes, proteins, and peptides oxidized to smaller peptides and (ii) polyunsaturated fatty acids oxidized to acid peroxides, resulting in cell death [30]. The effect of ozone treatment operating conditions on several microorganisms' reduction is presented in **Table 1**.

Table 1. Ozone applications to decontaminate meat and meat products.

Sample	Specification	Microbes	Highlights	Reference
Chicken legs	**2–10 mg/L for 1 h combined with vacuum packaging (polyamide/polyethylene bags) stored at 4 °C for 16 days.**	**TVC, *Pseudomonas* spp., LAB, Yeast-molds, & *Enterobacteriaceae***	**6-day shelf-life extension compared to vacuum packaging alone (4-day extension). Positively affected odor, texture, and taste retained an acceptable score for 14–16 days.**	**[29]**
Chicken meat (freeze-dried)	**0.6 ppm at 4 °C (90% RH) for 10 min.**	**TAMB, LAB, *E. coli*. & *Salmonella* spp.**	**1.1 log CFU/g was observed in TAMB and LAB. *E. coli*. and *Salmonella* spp. was not detected. Combination with MAP (20% CO_2, 80% N_2) improved the texture and sensory proprieties.**	**[30]**
Chicken meat (freeze-dried)	**0.4–0.7 ppm at 4 °C (90% RH) for 10–120 min.**	**LAB & TAMB**	**Reduced 4.77 and 6.8 log CFU/g, respectively. The combined use of ozone and lyophilization would be useful for extending shelf-life to 8 months.**	**[22]**

Sample	Specification	Microbes	Highlights	Reference
Chicken breast meat	10×10^{-6} kg $O_3/m^3/h$ for 3 days.	Coliform, aerobic, and anaerobic bacteria	Aerobic: 2.96 log CFU/g (untreated = 5.35 log CFU/g) Anaerobic: 2.18 log CFU/g (untreated = 4.63 log CFU/g) Coliform: 1.74 log CFU/g (untreated = 3.35 log CFU/g)	[31]
Duck breast meat			Aerobic: 2.52 log CFU/g (untreated = 4.11 log CFU/g) Anaerobic: 3.46 log CFU/g (untreated = 3.95 log CFU/g) Coliform: 1.39 (untreated = 3.28)	
Turkey breast meat	1×10^{-2} kg/m^3 at 22 °C (21.6% RH) for 8 h.	TAMB, *Enterobacteriaceae* & yeast-mold	Reduced 2.9, 2.3 and 1.9 log CFU/g, respectively.	[32]
Beef (sliced)	218–286 mg/m^3, 5–20 pulses for 2–40 min with intervals of 30 min.	Heterotrophic microflora & *L. monocytogenes*	Decreased 1.5 log CFU/g heterotrophic counts. Decreased inoculated *L. monocytogenes* counts by more than 1 log CFU/g. Exposure times of more than 10 min negatively affected red color and rancidity.	[33]

The significant oxidative properties of ozone justify its use as a decontaminating agent as an alternative to conventional agents (50% more effective than chlorine) [34]. It is highly efficient in killing viruses, bacteria, and protozoa within a short contact time. **Figure 1** shows the action mechanism of ozone imparting decontamination activity. Ozone has an oxidative potential of 2.07 V, which is nearly double the oxidizing potential of chlorine (1.36) and greater than the efficacy of peroxyacetic acid (1.81) [34]. The exclusion of heat generation during ozone treatment makes it adaptable for heat-sensitive foods [35]. The threshold limit of ozone exposure has usually been calculated as 8 h/day at 0.1 ppm (0.2 mg/m^3). However, its oxidizing power may prove toxic for humans depending upon the exposure length and level of concentration (0.1–0.3 ppm) [29]. Since all the consumer demands are fulfilled by ozone treatment, it can therefore be regarded as a "greener" additive. Furthermore, no specific guidelines for foodstuff related to the dosage of ozone are given, and it can thus be used in compliance with current industry standards of good manufacturing practice [36].

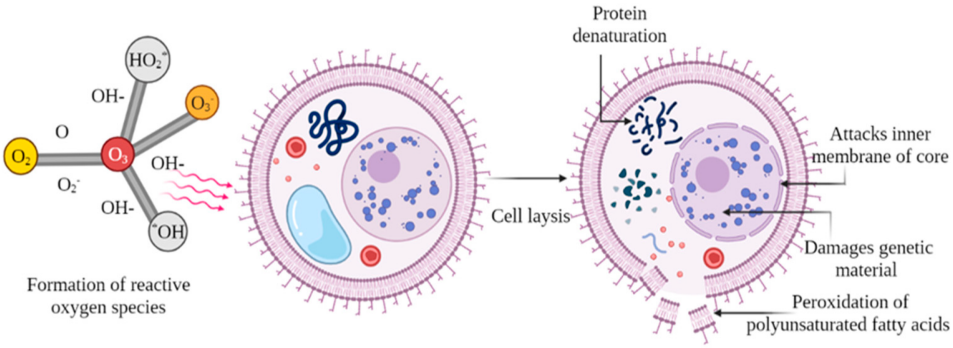

Figure 1. Schematic presentation of decontamination using ozone.

Commercially, ozone is applied for industrial waste deodorization and drinking water disinfection. However, its food application has increased since 1997, when the Food and Drug Administration (FDA) designated it as generally recognized as safe (GRAS). In December 2001, the USDA's Food Safety Inspection Service (FSIS) approved ozone as a suitable and safe ingredient used for the treatment of ready-to-eat (RTE) meat and poultry products just before packaging [37]. Ozonation safely oxidized the contaminants without affecting their quality and left no residues behind [38]. It is an ecofriendly approach to disinfecting a wide range of materials and replacing other chemical disinfectants, such as chlorine, salts, and acids [33]. Although many researchers have proposed that ozonized water effectively improved the chemical properties and safety of meat, there are, however, no specific guidelines for its usage [32].

Gaseous ozone provides an advantage over aqueous ozone by invading pathogens residing in inaccessible places [39]. According to Giménez et al. [33], the gaseous ozone pulses (duration ranging between 5 and 10 min) effectively control microbial flora in beef every 30 min for 5 h using 280 mg/m^3, whereby these treatments enacted the reduction (of >1 log) of LAB, mesophilic, and Enterobacteriaceae. Furthermore, this reduced the inoculated *L. monocytogenes* (102 CFU g/tissue) to below the detection limit and restricted its growth for 16 days at 4 °C. However, ozone treatment intensities of >58.66 mg/min in beef samples with a concentration of 286 mg/m^3 are harmful concerning lipid oxidation and surface

discoloration. Similarly, more than 10 min of exposure results in rancidity and color loss. In addition, ozone is a nonradical derivative of ROS (reactive oxygen species), which initiates oxidation reaction in foods. The production of free radicals is closely coupled to myoglobin oxidation. Similar results were previously demonstrated by Muhlisin et al. [31].

In chicken and duck breast, gaseous ozone (10×10^{-6} kg $O_3/m^3/h$) suppressed coliforms, aerobic, and anaerobic bacteria effectively. However, oxidation by ozone action led to the irreversible damage of cellular proteins and fatty acids in the cell membrane [31]. In addition, continuous exposure to ozone gas might increase oxygen generation due to ozone degradation. Chicken breast meat showed acceptable thiobarbituric acid reactive substances (TBARS) values until up to 3 days, while duck meat TBARS values increased with undesirable browning. According to the authors, ozone and other ROS are powerful oxidants that induce myoglobin and lipid oxidation. Metmyoglobin is produced as a result of myoglobin oxidation, which leads to meat discoloration, i.e., lower redness. Furthermore, ozone oxidizing activity increases rancidity and modifies surface color, affecting red meat quality [31]. Ozone can decontaminate and protect meat surfaces against microbial spoilage. For instance, turkey breast meat treated with ozone (1×10^{-2} kg/m^3, for up to 8 h) reduced 2.9, 2.3 and 1.9 log CFU/g of total aerobic mesophilic bacteria, *Enterobacteriaceae*, and yeast and mold, respectively [32]. Furthermore, the increased ozone treatment time enhanced the number of carbonyls, as well as the cooking yield and water-holding capacity, of turkey samples. It can be assumed that after ozonation, structural changes of protein increased both of these properties owing to the amount of water stored in both cooked and raw meat, as this is closely related to the proteinaceous substances in tissues. Probably, a thin layer forms on the meat surface with this restricting water loss due to the protein denaturation caused by pH reduction. In addition, a partially denatured protein film layer (rich in connective tissue) could result in lighter colors on meat surfaces. Recent trends in packaging showed a delay in meat spoilage that involves the combination of nonthermal treatment with vacuum or modified atmospheric packaging using the plastic materials alone or in combination. Gertzou et al. [29] used 2–10 mg/L ozone to treat fresh vacuum packaged chicken legs for 16 days at 4 °C. According to the authors, the lower concentration of ozone (5 or 10 mg/L) for 1 h resulted in a 0.5–1.0 log reduction of *Pseudomonas* and a total viable count when combined with vacuum packaging, whereas an increase in the intensity of gaseous ozone up to 10 mg/L resulted in >1.0 log cycles to the population of *Enterobacteriaceae*, lactic acid bacteria, and yeast and molds. Moreover, the shelf-life of vacuum-packaged ozonated chicken legs was extended to 6 days in comparison to single vacuum packaging. However, the physicochemical parameters noticeably varied depending on the intensity of the ozonation and storage period. In contrast, Zouaghi et al. [30] investigated that 0.6 ppm for 10 min was the best ozonation condition for maintaining the acceptable color, texture, and sensory quality of dried chicken breast fillets stored in modified atmosphere packaging with 80% N_2 and 20% CO_2 gas combination at room temperature.

Cantalejo et al. [22] used the hurdle approach to preserve raw meat products by combining ozone and freeze-drying. However, the microorganisms' growth ceased for a longer period in a well-lyophilized product due to lower water activity and residual humidity (<10%). Ozone treatment (0.6 ppm for 10 min) combined with lyophilization reduced total aerobic mesophilic bacteria (6.8 log CFU/g) and lactic acid bacteria counts (4.77 log CFU/g) with an extended shelf life of 8 months. Nevertheless, increasing ozone treatment intensity (concentration and time) decreased the aerobic mesophilic counts significantly. In contrast, four-month shelf-life stability was obtained for the lyophilized samples (alone). Furthermore, 0.4 ppm ozonation showed a negative effect on the chicken meat sample by increasing both chewiness and hardness, while lyophilized samples were susceptible to oxidation when stored in undesirable conditions, producing unwanted organoleptic characteristics [22]. These findings introduced the need for a suitable packaging hurdle for ozonated freeze-dried samples.

The innovative nonthermal ozonation method is beneficial as it is cost-effective, chemical-free, and eco-friendly, as well as easy to use. However, ozone application in the meat industry is challenging because of its strong oxidative power, which might cause damage to the meat's cellular proteins and fatty acids. Moreover, ozone is quite unstable, with even exposure to light potentially degrading it; hence, it cannot be stored [40]. Furthermore, ozone requires on-site generation, thus cutting the cost of control of chemical production. Ozone is water-insoluble; special mixers are therefore required to solubilize it, which also limits ozone application for the surface disinfection of fresh fruit and packaged food compared to microbial inactivation within the food samples. Furthermore, in comparison to other disinfection processes, the installation of ozone technology is highly complicated and demands a large capital investment. All these disadvantages limit ozone application in food industries. For that reason, further research is needed to overcome these limitations, as well as expand ozone technology utilization in the food industry.

2.2. High Hydrostatic Pressure (HHP)

HHP is a major trend in the food industry nowadays in terms of clean label technology. It is the most modern method of increasing the shelf stability of food products [41][42]. HHP is a response to the challenges faced by the industry and provides a competitive advantage, which is undoubtedly worth implementing sooner rather than later. According to Lee et

al. [43], global revenues from the high-pressure food protection (i.e., HHP) market amounted to USD 1055 million in 2019 and will reach USD 2123 million in 2025, with a compound annual growth rate of 12.34% from 2021–2025. HHP can achieve food safety, inactivate pathogens, such as *Salmonella*, *Listeria*, and *E. coli*, and prevent recontamination, seeing as the packed product is virtually impossible to recontaminate. HHP reduces microorganisms or eliminates them and/or reduces chemical preservatives. **Table 2** summarizes the range of parameters used in HHP to decontaminate meat and meat products. In general, HHP (a single step at 86,000 psi for 3 min) as a clean label (no preservatives) technology was able to effectively double the shelf-life of meat products, with the control product lasting for about 30 days compared to 60 days for the HHP product, concerning pathogen control.

Table 2. HHP applications to decontaminate meat and meat products.

Meat Type	Treatment Conditions	Storage Conditions	Findings	Reference
Chicken fillets	500 MPa for 10 min.	4 and 12 °C	HHP resulted in the reduction of the pathogen population below the detection limit of the enumeration method (0.48 log CFU/g), irrespective of the inoculum. HHP extended the shelf life of chicken fillets by 6 and 2 days, at 4 and 12 °C, respectively.	[44]
Frozen chicken breast	500 MPa for 1 min and 400 MPa for 5 min.	–	HHP showed inactivation of *Salmonella* at 400 MPa for 5 min and 500 MPa for 1 min.	[45]
Ground chicken meat	350 MPa for 10 min + 0.75% carvacrol.		HHP with 0.60% carvacrol treatment resulted in a >5-log pathogen reduction.	[46]
Ground beef	400 MPa for 15 min at 25, 35, and 45 °C.	4 and −20 °C for up to 5 days	At 25 °C, 5 log reduction in *E. coli* O157:H7 was observed further low-temperature storage serves as the hurdle in its survival and recovery after treatment. HHP showed no effect on the chromatic profile of grounded beef.	[47]
Vacuum-packed ground beef	200 and 400 MPa for 5 min at 25 °C.	–	*L. sakei* is good pressure-resistant lactic acid bacteria used in combination with HHP at 400 MPa and is efficient in controlling pathogenic *E. coli* strains.	[48]
Uncooked ground beef patties	300, 400, and 500 MPa for 5 min.	4 °C for 10 days	HHP combine with *Lactobacillus acidophilus* showed less total aerobic count (3.35 log CFU/g) than untreated (6.74 log CFU/g) beef patties with 0.80 log CFU/mL yeast and mold count. The combined treatment showed a delayed decrease in pH value, inhibited lipid oxidation with better color retention and the highest sensory score.	[49]
Beef patty	400 and 600 MPa for 5 min.	Refrigerated storage for 18 h	An amount of 2 and 4 log CF/mL reductions after 400 and 600 MPa in Shiga toxin-producing *E. coli* O157:H7, respectively. Variations in fat concentration of 10 and 20% did not affect. In contrast, 1% NaCl evident more reduction than 2%, indicating bar protective effect of salt.	[50]
Vacuum-pack ripened mutton patties	200 and 400 MPa for 10 min.	4 °C for 28 days	Significant reduction in total plate count after HHP at both levels, with a significant increase in lightness (L*). Redness (a*), yellowness (b*); hardness, gumminess, and chewiness of patties reduced significantly.	[51]
Beef steak	450 MPa, 600 MPa 1, 3, 6, 10, 15 min.	–	HHP have the potential to allow the production of a convenient and safe product by achieving 5 log definition of pasteurization of beef steak inoculated with *E. coli* 0157:H7.	[52]
Beef slurry	600 MPa for 20 min at 75 °C.	–	Best inactivation of spores of *Clostridium perfringens* in beef slurry was a 2.2 log reduction.	[53]
Beef slurry	600 MPa for 20 min at 75 °C.	–	After HHP, a greater reduction (2.2 log) in *C. perfringens* spores was observed as compared to thermal treatment (no reduction) after 20 min.	[54]

Meat Type	Treatment Conditions	Storage Conditions	Findings	Reference
Beef slurry	600 MPa at 70 °C for 20 min.	–	A 4.9 log reduction in *Bacillus cereus* spores after treatment at 70 °C but same temperature thermal processing led to 0.5 log reduction in spore. Increasing HHP temperature from 38 to 70 °C increases the spore inactivation for up to 3 logs.	[55]
Marinated beef (*Longissimus lumborum*)	300, 400, and 600 MPa for 5 min.	Refrigerated storage for 14 days	HHP was proven to provide safe meat along with a sodium reduction in it. Meat marinated with salt and citric acid has no sufficient inactivation of *L. innocua* and *Enterococcus faecium*, while when combine with HHP, a 6 log cycle reduction was observed.	[56]
Beef burgers	300 MPa for 10 min at 9.9 °C and 600 MPa 10 min, 10.2 °C.	–	Mesophilic and psychotropic count remain at the detection limit after HHP at 600 MPa, with no effect on lipid oxidation for at least 6 days.	[57]
Raw meatballs (beef, veal, beef + veal + pork)	400 and 600 MPa for 0 and 18 min.	4 and −12 °C for 18 h	No difference in the extent of inactivation in different species of meat used for meatballs preparation in refrigerated storage (0.9 to 2.9 log CFU/g) as compared to frozen samples (1.0 to 3.0 log CFU/g). A total of 600 MPa requires 1–3 min and 400 MPa requires 9 min for a ≥2.0 log CFU/g reduction.	[58]
Emulsified beef sausages	100–400 MPa for 15 min at 10 °C.	–	HHP proved to be an effective technique to produce microbial safe beef sausages (reduce total viable count equivalent to the sausages having higher salt concentration) with lower salt concentration.	[59]
Dry fermented sausages	600 MPa for 3 min.	4 °C for 4 weeks	Inactivation of *E. coli* O157:H7 in dried fermented sausages was observed to be affected by a_w. At $a_w \leq 0.90$, or moisture protein ratio in the range of 1.9–2.3, led to 6.4 log reduction. Further drying reduced to 2.2 log reduction. Recovery of *E. coli* O157:H7 was observed for 1 week of storage but in 2-, 3-, and 4-week storage, no further recovery was observed.	[60]
Pork cooked sausages	600 MPa for 3 min.	4 and 10 °C for 35 days	Cooking of sausages leads to a >6 log reduction in inoculated *L. monocytogenes*. During storage at 4 °C, no significant growth was observed after HHP. But at 10 °C storage, growth remains below the detection limit up to 21 days after the 4.5 log CFU/mL increase in population was observed. No lactic acid bacterial growth was observed till the end of storage.	[61]
Italian salami	600 MPa for 300 s.	–	HHP related microbial inactivation depicts an inverse relation with a_w. All 20 salami samples showed a 5 log reduction in *Salmonella* after treatment.	[62]
Italian salami	600 MPa for 300 s.	–	An amount of 0.34–4.32 log CFU/g reduction during processing in *L. innocua* was observed which was reduced to 0.48–3.4 log CFU/g after HHP. The efficacy of HHP was associated with a_w and higher pH after acidification, drying and seasoning phase.	[63]
Nitrite-free emulsion-type sausage	0.1, 500 MPa for 12 min + 0, 1, 2% vinegar	4 °C for two weeks followed by at 20 °C for three weeks	HHP (500 MPa; four cycles and each for 3 min) + vinegar (1%) reduced vegetative cells and spores of *C. perfringens* by 4.8 and 2.8 log CFU/g, respectively.	[64].
Traditional Portuguese ready-to-eat meat sausage (*Chouriço de carne*)	300 MPa for 5 min at 10 °C + lactic acid bacteria (Pediococcus acidilactici, HA-6111-2) and its bacteriocin (bacHA-6111-2).	Refregrated storage for 60 days.	The hurdle technology (bacteriocin and pressurization) showed a 0.5 log CFU/g decrease in *L. innocua* cells compared to non-treated cells.	[65]

Meat Type	Treatment Conditions	Storage Conditions	Findings	Reference
Dry-cured ham	**450 MPa for 10 min and 600 MPa for 5 min.**	**4 °C for 30 days**	**The efficacy of HHP against *L. monocytogenes* was reduced by low a_w values. The changes in HHP-surviving bacteria gene transcription patterns were strain-dependent.**	**[66]**
Cooked ham	**400 MPa for 10 min at 17 °C + alginate films containing enterocins.**	**1 or 6 °C for 2 months**	**Both antimicrobial packaging and pressurization delayed the growth of *L. monocytogenes* levels below the detection limit (day 90) during 6 °C storage.**	**[67]**

Although the microbiological quality of poultry meat depends on several critical factors such as the physiological status of an animal, temperature, and other conditions during slaughter, HPP (for 10 min at 500 MPa) inhibited *Salmonella* ser. *Enteritidis* during 12 °C storage (0.48 log CFU/g) and extended the shelf-life of the chicken meat by 6 to 12 days [44]. Moreover, the population of *Salmonella* ser. *Enteritidis* remained below or near the detection limit during storage at 4 °C. According to the authors, the inactivation of *Salmonella* in HHP-treated samples was highly related to the product (raw material), as well as to the strains of *Salmonella* being inoculated. As compared to the control samples, HHP-treated samples showed unpredictable changes in the distribution and survival of the *Salmonella* strains at different inoculum levels and storage temperatures [44]. These results highlighted a potential mechanism involving the ecological modification of the food microbiota via different treatment conditions, which is crucial for designing and applying a new or different technology in the food industry.

HHP (applied for 5 min at 400 MPa and 1 min at 500 MPa) not only lowered *Salmonella* spp. (>3 log units) populations in frozen fillets of chicken but also improved the color and texture profile, as compared to the control samples [45]. However, HHP at increased pressure (600 MPa) flattened and deformed the cells while increasing the holding times (5 min) and elongating the cellular tissues. Although changes in the textural profile of meat depend on the protein system, rigor state, and processing parameters (i.e., temperature, pressure level, and time), researchers have observed an increase in firmness and work area for the HHP-treated cooked chicken breast fillets, as compared to the control [45]. Additionally, no significant differences were found between *Salmonella* spp. counts for pressurized samples treated for 1 and 3 min and among the treatments of 5, 7 and 9 min, which indicated the fact that HHP treatments quickly destroy sensitive cells, while the remaining cells produce stress adaptation and higher resistance [45].

References

1. Cerveny, J.; Meyer, J.D.; Hall, P.A. Compendium of the Microbiological Spoilage of Foods and Beverages. Compend. Microbiol. Spoilage Foods Beverages 2009, 69–86.
2. Alum, E.A.; Urom, S.M.O.C.; Ben, C.M.A. Microbiological Contamination of Food the Mechanisms Impacts and Prevention. Int. J. Sci. Technol. Res. 2015, 4, 65–78.
3. Yousefi, M.; Khorshidian, N.; Hosseini, H. Potential Application of Essential Oils for Mitigation of Listeria Monocytogenes in Meat and Poultry Products. Front. Nutr. 2020, 7, 255.
4. Stoica, M.; Stoean, S.; Alexe, P. Overview of Biological Hazards Associated with the Consumption of the Meat Products. J. Agroaliment. Process. Technol. 2014, 20, 192–197.
5. ur Rahman, U.; Sahar, A.; Ishaq, A.; Aadil, R.M.; Zahoor, T.; Ahmad, M.H. Advanced Meat Preservation Methods: A Mini Review. J. Food Saf. 2018, 38, e12467.
6. Khalafalla, F.A.; Ali, H.M.; El-Fouley, A. Microbiological Evaluation of Chicken Meat Products. J. Vet. Med. Res. 2019, 26, 151–163.
7. Ribeiro, C.M.; Stefani, L.M.; Lucheis, S.B.; Okano, W.; Cruz, J.C.M.; Souza, G.V.; Casagrande, T.A.C.; Bastos, P.A.S.; Pinheiro, R.R.; Arruda, M.M.; et al. Methicillin-Resistant Staphylococcus Aureus in Poultry and Poultry Meat: A Meta-Analysis. J. Food Prot. 2018, 81, 1055–1062.
8. Hu, K.L.; Yu, X.Q.; Chen, J.; Tang, J.N.; Wang, L.Z.; Li, Y.M.; Tang, C. Production of Characteristic Volatile Markers and Their Relation to Staphylococcus Aureus Growth Status in Pork. Meat Sci. 2020, 160, 107956.
9. Whyte, P.; McGill, K.; Collins, J.D. An Assessment of Steam Pasteurization and Hot Water Immersion Treatments for the Microbiological Decontamination of Broiler Carcasses. Food Microbiol. 2003, 20, 111–117.

10. Gu, J.-G.; Park, J.-M.; Yoon, S.-J.; Ahn, B.-K.; Kang, C.-W.; Song, J.-C.; Kim, J.-M. Assessment of Dipping Treatment with Various Lactic Acid or Sodium Benzoate Concentrations to Extend the Shelf-Life of Spent Hen Breast Meats. Korean J. Food Sci. Anim. Resour. 2011, 31, 428–435.
11. Sarjit, A.; Dykes, G.A. Trisodium Phosphate and Sodium Hypochlorite Are More Effective as Antimicrobials against Campylobacter and Salmonella on Duck as Compared to Chicken Meat. Int. J. Food Microbiol. 2015, 203, 63–69.
12. Juneja, V.K.; Valenzuela-Melendres, M.; Heperkan, D.; Bautista, D.; Anderson, D.; Hwang, C.A.; Peña-Ramos, A.; Camou, J.P.; Torrentera-Olivera, N. Development of a Predictive Model for Salmonella Spp. Reduction in Meat Jerky Product with Temperature, Potassium Sorbate, PH, and Water Activity as Controlling Factors. Int. J. Food Microbiol. 2016, 236, 1–8.
13. Kocharunchitt, C.; Mellefont, L.; Bowman, J.P.; Ross, T. Application of Chlorine Dioxide and Peroxyacetic Acid during Spray Chilling as a Potential Antimicrobial Intervention for Beef Carcasses. Food Microbiol. 2020, 87, 103355.
14. Manzoor, A.; Jaspal, M.H.; Yaqub, T.; Haq, A.U.; Nasir, J.; Avais, M.; Asghar, B.; Badar, I.H.; Ahmad, S.; Yar, M.K. Effect of Lactic Acid Spray on Microbial and Quality Parameters of Buffalo Meat. Meat Sci. 2020, 159, 107923.
15. Zhao, T.; Zhao, P.; Chen, D.; Jadeja, R.; Hung, Y.C.; Doyle, M.P. Reductions of Shiga Toxin–Producing Escherichia Coli and Salmonella Typhimurium on Beef Trim by Lactic Acid, Levulinic Acid, and Sodium Dodecyl Sulfate Treatments. J. Food Prot. 2014, 77, 528–537.
16. Burfoot, D.; Allen, V.; Mulvey, E.; Jewell, K.; Harrison, D.; Morris, V. Reducing Campylobacter Numbers on Chicken Carcasses Using Lactic Acid in Processing Plants. Int. J. Food Sci. Technol. 2015, 50, 2451–2457.
17. Hansson, I.; Sandberg, M.; Habib, I.; Lowman, R.; Engvall, E.O. Knowledge Gaps in Control of Campylobacter for Prevention of Campylobacteriosis. Transbound. Emerg. Dis. 2018, 65, 30–48.
18. Killinger, K.M.; Kannan, A.; Bary, A.I.; Cogger, C.G. Validation of a 2 Percent Lactic Acid Antimicrobial Rinse for Mobile Poultry Slaughter Operations. J. Food Prot. 2010, 73, 2079–2083.
19. Yoon, K.S. Effect of Gamma Irradiation on the Texture and Microstructure of Chicken Breast Meat. Meat Sci. 2003, 63, 273–277.
20. Anang, D.M.; Rusul, G.; Bakar, J.; Ling, F.H. Effects of Lactic Acid and Lauricidin on the Survival of Listeria Monocytogenes, Salmonella Enteritidis and Escherichia Coli O157:H7 in Chicken Breast Stored at 4 °C. Food Control 2007, 18, 961–969.
21. Ko, J.-K.; Ma, Y.-H.; Song, K.-B. Effect of Chlorine Dioxide Treatment on Microbial Growth and Qualities of Chicken Breast. Prev. Nutr. Food Sci. 2005, 10, 122–129.
22. Cantalejo, M.J.; Zouaghi, F.; Pérez-Arnedo, I. Combined Effects of Ozone and Freeze-Drying on the Shelf-Life of Broiler Chicken Meat. LWT 2016, 68, 400–407.
23. Nabi, B.G.; Mukhtar, K.; Arshad, R.N.; Radicetti, E.; Tedeschi, P.; Shahbaz, M.U.; Walayat, N.; Nawaz, A.; Inam-Ur-raheem, M.; Aadil, R.M. High-Pressure Processing for Sustainable Food Supply. Sustainability 2021, 13, 13908.
24. Roobab, U.; Fidalgo, L.G.; Arshad, R.N.; Khan, A.W.; Zeng, X.A.; Bhat, Z.F.; Bekhit, A.E.D.A.; Batool, Z.; Aadil, R.M. High-Pressure Processing of Fish and Shellfish Products: Safety, Quality, and Research Prospects. Compr. Rev. Food Sci. Food Saf. 2022, 1–29.
25. Umair, M.; Jabbar, S.; Ayub, Z.; Muhammad Aadil, R.; Abid, M.; Zhang, J.; Liqing, Z. Recent Advances in Plasma Technology: Influence of Atmospheric Cold Plasma on Spore Inactivation. Food Rev. Int. 2021.
26. Gonçalves, A.A.; Lira Santos, T.C. Improving Quality and Shelf-Life of Whole Chilled Pacific White Shrimp (Litopenaeus Vannamei) by Ozone Technology Combined with Modified Atmosphere Packaging. LWT 2019, 99, 568–575.
27. Roobab, U.; Afzal, R.; Ranjha, M.M.A.N.; Zeng, X.A.; Ahmed, Z.; Aadil, R.M. High Pressure-Based Hurdle Interventions for Raw and Processed Meat: A Clean-Label Prospective. Int. J. Food Sci. Technol. 2022, 57, 816–826.
28. Gök, V.; Aktop, S.; Özkan, M.; Tomar, O. The Effects of Atmospheric Cold Plasma on Inactivation of Listeria Monocytogenes and Staphylococcus Aureus and Some Quality Characteristics of Pastırma—A Dry-Cured Beef Product. Innov. Food Sci. Emerg. Technol. 2019, 56, 102188.
29. Gertzou, I.N.; Karabagias, I.K.; Drosos, P.E.; Riganakos, K.A. Effect of Combination of Ozonation and Vacuum Packaging on Shelf Life Extension of Fresh Chicken Legs during Storage under Refrigeration. J. Food Eng. 2017, 213, 18–26.
30. Zouaghi, F.; Cantalejo, M.J. Study of Modified Atmosphere Packaging on the Quality of Ozonated Freeze-Dried Chicken Meat. Meat Sci. 2016, 119, 123–131.
31. Muhlisin, M.; Utama, D.T.; Lee, J.H.; Choi, J.H.; Lee, S.K. Effects of Gaseous Ozone Exposure on Bacterial Counts and Oxidative Properties in Chicken and Duck Breast Meat. Korean J. Food Sci. Anim. Resour. 2016, 36, 405–411.

32. Ayranci, U.G.; Ozunlu, O.; Ergezer, H.; Karaca, H. Effects of Ozone Treatment on Microbiological Quality and Physicochemical Properties of Turkey Breast Meat. Ozone Sci. Eng. 2020, 42, 95–103.
33. Giménez, B.; Graiver, N.; Giannuzzi, L.; Zaritzky, N. Treatment of Beef with Gaseous Ozone: Physicochemical Aspects and Antimicrobial Effects on Heterotrophic Microflora and Listeria Monocytogenes. Food Control 2021, 121, 1–9.
34. Cooke, E.M. Principles and Practice of Disinfection, Preservation and Sterilization. J. Clin. Pathol. 1983, 36, 364.
35. Kaavya, R.; Pandiselvam, R.; Abdullah, S.; Sruthi, N.U.; Jayanath, Y.; Ashokkumar, C.; Chandra Khanashyam, A.; Kothakota, A.; Ramesh, S.V. Emerging Non-Thermal Technologies for Decontamination of Salmonella in Food. Trends Food Sci. Technol. 2021, 112, 400–418.
36. USDA-FSIS. Safe and Suitable Ingredients Used in the Production of Meat and Poultry, and Egg Products; USDA-FSIS: Washington, DC, USA, 2016. Available online: https://www.google.com/search?q=USDA-FSIS.+Safe+and+Suitable+Ingredients+Used+in+the+Production+of+Meat+and+Poultry%2C+and+Egg+Products%3B+USDA-FSIS%3A+Washington%2C+DC%2C+USA%2C+2016&oq=USDA-FSIS.+Safe+and+Suitable+Ingredients+Used+in+the+Production+of+M (accessed on 16 May 2022).
37. USDA-FSIS USDA FSIS, 2001, Letter from Robert C. Post (FSIS, Washington, DC) to Mark D. Dopp (Am. Meat Institute, Arlington, VA) Dated 21 December 2001. Available online: https://www.fsis.usda.gov/ (accessed on 16 May 2022).
38. Pandiselvam, R.; Subhashini, S.; Banuu Priya, E.P.; Kothakota, A.; Ramesh, S.V.; Shahir, S. Ozone Based Food Preservation: A Promising Green Technology for Enhanced Food Safety. Ozone Sci. Eng. 2019, 41, 17–34.
39. Shynkaryk, M.V.; Pyatkovskyy, T.; Mohamed, H.M.; Yousef, A.E.; Sastry, S.K. Physics of Fresh Produce Safety: Role of Diffusion and Tissue Reaction in Sanitization of Leafy Green Vegetables with Liquid and Gaseous Ozone-Based Sanitizers. J. Food Prot. 2015, 78, 2108–2116.
40. Pandiselvam, R.; Kaavya, R.; Jayanath, Y.; Veenuttranon, K.; Lueprasitsakul, P.; Divya, V.; Kothakota, A.; Ramesh, S.V. Ozone as a Novel Emerging Technology for the Dissipation of Pesticide Residues in Foods—A Review. Trends Food Sci. Technol. 2020, 97, 38–54.
41. Roobab, U.; Khan, A.W.; Lorenzo, J.M.; Arshad, R.N.; Chen, B.R.; Zeng, X.A.; Bekhit, A.E.D.; Suleman, R.; Aadil, R.M. A Systematic Review of Clean-Label Alternatives to Synthetic Additives in Raw and Processed Meat with a Special Emphasis on High-Pressure Processing (2018–2021). Food Res. Int. 2021, 150, 110792.
42. Roobab, U.; Inam-Ur-Raheem, M.; Khan, A.W.; Arshad, R.N.; Zeng, X.; Aadil, R.M. Innovations in High-Pressure Technologies for the Development of Clean Label Dairy Products: A Review. Food Rev. Int. 2021, 1–22.
43. Global High Pressure Processing (HPP) Food Market—Analysis by Product Type, Distribution Channel, by Region, by Country (2020 Edition): Market Insights, Outlook Post COVID-19 Pandemic (2020–2025); Research and Markets: Dublin, Ireland, 2020.
44. 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.
45. Cap, M.; Paredes, P.F.; Fernández, D.; Mozgovoj, M.; Vaudagna, S.R.; Rodriguez, A. Effect of High Hydrostatic Pressure on Salmonella Spp Inactivation and Meat-Quality of Frozen Chicken Breast. LWT 2020, 118, 108873.
46. Chuang, S.; Sheen, S.; Sommers, C.H.; Zhou, S.; Sheen, L.Y. Survival Evaluation of Salmonella and Listeria Monocytogenes on Selective and Nonselective Media in Ground Chicken Meat Subjected to High Hydrostatic Pressure and Carvacrol. J. Food Prot. 2020, 83, 37–44.
47. Zhou, Y.; Karwe, M.V.; Matthews, K.R. Differences in Inactivation of Escherichia Coli O157: H7 Strains in Ground Beef Following Repeated High Pressure Processing Treatments and Cold Storage. Food Microbiol. 2016, 58, 7–12.
48. Wang, L.; Kong, X.; Jiang, Y. Recovery of High Pressure Processing (HPP) Induced Injured Escherichia Coli O157:H7 Inhibited by Lactobacillus Sakei on Vacuum-Packed Ground Beef. Food Biosci. 2021, 41, 100928.
49. Lee, H.; Shahbaz, H.M.; Yang, J.; Jo, M.H.; Kim, J.U.; Yoo, S.; Kim, S.H.; Lee, D.U.; Park, J. Effect of High Pressure Processing Combined with Lactic Acid Bacteria on the Microbial Counts and Physicochemical Properties of Uncooked Beef Patties during Refrigerated Storage. J. Food Process. Preserv. 2021, 45, e15345.
50. Eccoña Sota, A.; Cap, M.; Rodriguez, A.; Szerman, N.; Speroni, F.; Vaudagna, S.R. Effects of High Hydrostatic Pressure and Beef Patty Formulations on the Inactivation of Native Strains of Shiga Toxin-Producing Escherichia Coli O157:H7. Food Bioprocess Technol. 2021, 14, 1194–1198.
51. Banerjee, R.; Jayathilakan, K.; Chauhan, O.P.; Naveena, B.M.; Devatkal, S.; Kulkarni, V.V. Vacuum Packaged Mutton Patties: Comparative Effects of High Pressure Processing and Irradiation. J. Food Process. Preserv. 2017, 41, e12880.

52. Sun, S.; Sullivan, G.; Stratton, J.; Bower, C.; Cavender, G. Effect of HPP Treatment on the Safety and Quality of Beef Steak Intended for Sous Vide Cooking. LWT-Food Sci. Technol. 2017, 86, 185–192.
53. Evelyn; Milani, E.; Silva, F.V.M. Comparing High Pressure Thermal Processing and Thermosonication with Thermal Processing for the Inactivation of Bacteria, Moulds, and Yeasts Spores in Foods. J. Food Eng. 2017, 214, 90–96.
54. 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.
55. Evelyn; Silva, F.V.M. Modeling the Inactivation of Psychrotrophic Bacillus Cereus Spores in Beef Slurry by 600 MPa HPP Combined with 38–70 °C: Comparing with Thermal Processing and Estimating the Energy Requirements. Food Bioprod. Process. 2016, 99, 179–187.
56. Rodrigues, I.; Trindade, M.A.; Caramit, F.R.; Candoğan, K.; Pokhrel, P.R.; Barbosa-Cánovas, G.V. Effect of High Pressure Processing on Physicochemical and Microbiological Properties of Marinated Beef with Reduced Sodium Content. Innov. Food Sci. Emerg. Technol. 2016, 38, 328–333.
57. Mizi, L.; Cofrades, S.; Bou, R.; Pintado, T.; López-Caballero, M.E.; Zaidi, F.; Jiménez-Colmenero, F. Antimicrobial and Antioxidant Effects of Combined High Pressure Processing and Sage in Beef Burgers during Prolonged Chilled Storage. Innov. Food Sci. Emerg. Technol. 2019, 51, 32–40.
58. Porto-fett, A.C.S.; Jackson-davis, A.; Kassama, L.S.; Daniel, M.; Oliver, M.; Jung, Y.; Luchansky, J.B. Inactivation of Shiga Toxin-Producing Escherichia Coli in Refrigerated and Frozen Meatballs Using High Pressure Processing. Microorganisms 2020, 8, 360.
59. Zhu, Y.; Yan, Y.; Yu, Z.; Wu, T.; Bennett, L.E. Effects of High Pressure Processing on Microbial, Textural and Sensory Properties of Low-Salt Emulsified Beef Sausage. Food Control 2022, 133, 108596.
60. Balamurugan, S.; Gemmell, C.; Lau, A.T.Y.; Arvaj, L.; Strange, P.; Gao, A.; Barbut, S. High Pressure Processing during Drying of Fermented Sausages Can Enhance Safety and Reduce Time Required to Produce a Dry Fermented Product. Food Control 2020, 113, 107224.
61. Balamurugan, S.; Inmanee, P.; De Souza, J.E.; 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 A. J. Food Prot. 2018, 81, 1245–1251.
62. 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.
63. Bonilauri, P.; Merialdi, G.; Ramini, M.; Bardasi, L.; Taddei, R.; Grisenti, M.S.; Daminelli, P.; Cosciani-Cunico, E.; Dalzini, E.; Frustoli, M.A.; et al. Modeling the Behavior of Listeria Innocua in Italian Salami during the Production and High-Pressure Validation of Processes for Exportation to the U.S. Meat Sci. 2021, 172, 108315.
64. Lee, S.H.; Choe, J.; Shin, D.J.; Yong, H.I.; Choi, Y.; Yoon, Y.; Jo, C. Combined Effect of High Pressure and Vinegar Addition on the Control of Clostridium Perfringens and Quality in Nitrite-Free Emulsion-Type Sausage. Innov. Food Sci. Emerg. Technol. 2019, 52, 429–437.
65. Castro, S.M.; Kolomeytseva, M.; Casquete, R.; Silva, J.; Teixeira, P.; Castro, S.M.; Queirós, R.; Saraiva, J.A. Biopreservation Strategies in Combination with Mild High Pressure Treatments in Traditional Portuguese Ready-to-Eat Meat Sausage. Food Biosci. 2017, 19, 65–72.
66. Pérez-Baltar, A.; Alía, A.; Rodríguez, A.; Córdoba, J.J.; Medina, M.; Montiel, R. Impact of Water Activity on the Inactivation and Gene Expression of Listeria Monocytogenes during Refrigerated Storage of Pressurized Dry-Cured Ham. Foods 2020, 9, 1092.
67. Marcos, B.; Aymerich, T.; Monfort, J.M.; Garriga, M. High-Pressure Processing and Antimicrobial Biodegradable Packaging to Control Listeria Monocytogenes during Storage of Cooked Ham. Food Microbiol. 2008, 25, 177–182.