Review Article

Principles and Applications of Non-thermal Technologies for Meat Decontamination

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Abstract

Meat contains high-value protein compounds that might degrade as a result of oxidation and microbial contamination. Additionally, various pathogenic and spoilage microorganisms can grow in meat. Moreover, contamination with pathogenic microorganisms above the infectious dose has caused foodborne illness outbreaks. To decrease the microbial population, traditional meat preservation methods such as thermal treatment and chemical disinfectants are used, but it may have limitations for the maintenance of meat quality or the consumers acceptance. Thus, non-thermal technologies (e.g., high-pressure processing, pulsed electric field, non-thermal plasma, pulsed light, supercritical carbon dioxide technology, ozone, irradiation, ultraviolet light, and ultrasound) have emerged to improve the shelf life and meat safety. Non-thermal technologies are becoming increasingly important because of their advantages in maintaining low temperature, meat nutrition, and short processing time. Especially, pulsed light and pulsed electric field treatment induce few sensory and physiological changes in high fat and protein meat products, making them suitable for the application. Many research results showed that these non-thermal technologies may keep meat fresh and maintain heat-sensitive elements in meat products.

Keyword

Non-thermal technology, decontamination, meat

Introduction

As meat provides essential nutrients such as proteins, lipids, and fatty acids, meat can be a nutritious food source for humans. Meat is an especially perishable food with an A_w greater than 0.90 and is sensitive to microbial contamination; however, the deterioration of meat products due to the contamination with pathogens may causes public health threats (Turantaş *et al*., 2015).

The predominant bacteria related with meat deterioration are Enterobacteriaceae, *Pseudomonas* spp., *Shigella* spp., *Carnobacterium* spp., *Lactobacillus* spp., *Brochothrix thermosphacta, Leuconostoc* spp., *Clostridioides difficile, Aeromonas* spp., and *Shewanella putrefaciens* (Turantaş *et al*., 2015). Foodborne pathogens associated with meat products, such as *Bacillus cereus, Clostridium perfringens, Escherichia coli, Listeria monocytogenes, Staphylococcus aureus, Yersinia enterocolitica, Campylobacter jejuni,* and *Salmonella* Enteritidis are also detected (Bhandare *et al*., 2007). Foodborne illness can result from the presence and proliferation of pathogenic bacteria in response to infectious doses of meat products. Furthermore, some pathogens such as enterohemorrhagic *E. coli* can persist for more than 180 days in frozen beef products (Ziuzina and Misra, 2016).

To preserve the microbial safety and stability of meat products, food preservation techniques are essential. Since meat is commonly distributed raw, heat processing is not encouraged due to the impact on meat quality. The conventional decontamination of meat products involves refrigerated storage, vacuum packaging, chemical preservatives, and thermal processing. However, heat may change the organoleptic properties and nutrients in meat, and chemically treated products are unacceptable because of excessive residual deposition (Wang *et al*., 2016; Jadhav *et al*., 2021). Hence, non-thermal procedures are developed as alternatives to standard pasteurization to inactivate spoilage bacteria and pathogens in meat products at room temperature with minimizing changes in their organoleptic qualities of meat products

(Huang and Wang, 2009; Jaeger *et al*., 2010). According to Data Bridge Market Research, the specific non-thermal processing market grew to $1.43 billion in 2021, and it is expected to reach $5.87 billion by 2029 at a compound annual growth rate (CAGR) of 19.3% during the forecast period (Bridge, 2021). Non-thermal technologies are appropriate to enhance the shelf-life and improve food safety while minimizing changes in the quality of processed foods such as chicken nuggets and fresh-cut fruits (Bridge, 2021).

Therefore, the mechanisms, merits, limitations, and applications of recent non-thermal technologies in meat products are reviewed.

1. High-pressure processing

High-pressure processing (HPP) is a non-thermal food preservation technique using pressures ranging from 100 to 1,000 MPa in an aqueous solution at room temperature (Guyon *et al*., 2016). An HPP is composed of a pressure chamber, where food is stored, and water is added. The water is then used to pressurize the food (González-Cebrino *et al*., 2013). Because of the absence of high temperatures and chemical additions, HPP-treated foods are characteristically fresher. When pressure is applied to the cell membrane, substances are transported from the inside to the outside of the cell, membrane permeability increases, and the osmotic condition is lost (Rosario *et al*., 2021). Furthermore, organelle breakdown and an inability to maintain homeostasis occurs (Hugas *et al*., 2002; Campus, 2010). Moreover, cellular processes (e.g., protein synthesis, enzyme activity, and cellular components such as ribosomes) are inhibited or altered (Rendueles *et al*., 2011).

HPP is blocking DNA synthesis, denaturing proteins, inactivating enzymes, and destroying cellular membranes and organelles by inactivating bacteria, yeast, and mold (Deng *et al*., 2020). The microbial inactivation mechanism depends on several factors, including treatment pressure and temperature, treatment time, moisture content, pH, A_w and acidity of meat products,

sensitivity of the microbial strain, and the equilibrium constant (Rifna *et al*., 2019; Slavov *et al*., 2019).

HPP treatment had minimal effects on the nutritional and sensory properties of meat (Table 1). HPP treatment with 500 MPa for 7 min for raw beef reduced the cell counts of *S. aureus, E. coli, Salmonella,* and *L. monocytogenes* by 1.7–6.7 Log CFU/g depending on the bacteria (Park *et al*., 2022). Treatment with 400–500 MPa for 1–7 min reduced *Salmonella* cell counts to below the detection limit in chickens (Cap *et al*., 2020). Also, HPP treatment (600 MPa, 5 min) at 10℃ for pork burgers reduced the cell counts of lactic acid bacteria, psychrotrophic bacteria, and mesophilic bacteria by 4.8, 6.7, and 7.0 Log CFU/g, respectively (Amaro-Blanco *et al*., 2018). HPP treatment (300 MPa, 5 min) in the beef fillets reduced the cell counts of total coliforms, mesophilic bacteria, and lactic acid bacteria by 2.2 Log CFU/mL, 1.5 Log CFU/g, and 2.9 Log CFU/mL, respectively (Giménez *et al*., 2015). Additionally, the same treatment in chicken breast fillet products reduced the cell counts of *E. coli, S.* Typhimurium, and *L. monocytogenes* by 1.7, 0.6, and 3.2 Log CFU/g, respectively (Kruk *et al*., 2011). When the poultry products were treated with HPP, the cell counts of mesophilic bacteria, psychrotrophic bacteria, *B. thermosphacta, C. jejuni, Leuconostoc carnosum, Listeria innocua,* and *S.* Enteritidis were reduced by 1.5, 2.4, 3.5, 6.0, 0.5, 0.5, and 3.5 Log CFU/g, respectively (Al-Nehlawi *et al*., 2014; Canto *et al*., 2015; Jackowska-Tracz and Tracz, 2015). Similarly, Clariana *et al*. (2011) reported that utilizing higher pressures of up to 600 MPa for 6 min at 15℃ reduced the growth of microorganisms with preserving the color features of dry-cured ham.

HPP has several benefits such as nutrient preservation, lower heat damage, and quicker processing time (Qiu *et al*., 2019). Thus, HPP technology is considered one of the best non-thermal decontamination technologies for improving the microbial safety of food and is used in Europe as a pasteurization technology for sliced ham (Norton and Sun, 2008). Recently,

HPP processing machines that can process bulk size of food have been developed and commercialized and are used in various food processing applications (Food processing, 2020). However, protein denaturation caused by high-pressure causes unfavorable alterations in the sensory and physicochemical aspects of protein-rich meat products (Rosario *et al*., 2021). Also, HPP processing causes lipid oxidation and thus, it may not be suitable for high-fat meat (Medina-Meza *et al.,* 2014). There is a limitation of HPP in that the high pressure produces adiabatic heating, causing the temperature of water to rise 3℃ every 100 MPa (Morales *et al*., 2019). However, pressure levels of 100–800 MPa are typically applied for food preservation for short time applications (a few sec to several min) at mild temperatures (4–20℃); thus, they do not significantly disrupt the sensory sensitivity of food (Heinz *et al*., 2010).

2. Supercritical carbon dioxide technology

Supercritical carbon dioxide (SC-CO_2) modifies cell membranes through CO_2 diffusion, decreases the cytoplasmic pH, and extracts essential components from microbial cells (Guerrero *et al*., 2017). The inactivation mechanism of SC-CO_2 in meat products occurs in a series of steps that include the solubilization of CO_2 in free water, diffusion through cell membranes, intracellular solubilization, and a rapid drop in intracellular pH. As a result, a number of enzymatic processes required for cellular metabolism are broken down (Dillow *et al*., 1999; Spilimbergo and Bertucco, 2003; Damar and Balaban, 2006; Garcia-Gonzalez *et al*., 2007; Giulitti *et al*., 2011). In addition, the integrity of the cell membrane is damaged by permeabilization of the cell membrane (Spilimbergo *et al*., 2009). The yield and extraction process of this technology depends on treatment temperature, treatment pressure, treatment time, CO_2/meat sample ratio, surface area, shape of meat samples, variance in moisture content, fluid flow rate, and extraction time (Allai *et al*., 2022). The solubility of CO_2 in the meat products is the crucial element for the success of SC-CO_2 technology.

With SC-CO_2 treatment, 1.3 Log CFU/g of *E. coli* and 1.4 Log CFU/g of *Listeria innocua* were reduced in fresh chicken breast meat (Santi *et al.*, 2023). Morbiato *et al.* (2019) reduced 2.5 Logs of mesophilic microorganisms in chicken breast samples treated for 15 min in an SC-CO_2 drying frame at 100 bar and 40℃, and all were not detected after 90 min. Ferrentino *et al*. (2013) observed a 3 Log CFU/g reduction of *L. monocytogenes* in dry-cured ham, and Cappelletti *et al*. (2015) reported a reduction of 1–3 Log CFU/g in overall mesophilic bacteria in raw pork. Additionally, cell counts of the total mesophilic bacteria and *Salmonella* in ground pork decreased by 1.7 and 2.2 Log CFU/g, respectively (Bae *et al*., 2010). Furthermore, several studies have reported synergistic effects when combining SC-CO_2 with other treatments. The combined treatment of SC-CO_2 with high-intensity ultrasound reduced the cell counts of *Salmonella enterica* in raw chicken breast and *L. monocytogenes* in cured ham (Spilimbergo *et al*., 2014; Morbiato *et al*., 2019). In fresh pork, additives such as lactic or acetic acid have been used with SC-CO_2 to inactivate bacteria more effectively than when SC-CO_2 was used alone (Choi *et al*., 2009). Huang *et al*. (2017) reported that combining SC-CO_2 with rosemary powder significantly reduced total bacterial counts in raw pork during storage.

The advantages of SC-CO_2 include ease of process implementation due to the low critical point (31℃ and 73.9 bar), low pressure allowing effective process control, and low investment costs (Ferrentino and Spilimbergo, 2011). Additionally, it provides low viscosity, which makes it easier to penetrate the solid matrix such as meat products during the extraction process (Cunha et al., 2018). However, SC-CO_2 technology requires a relatively long processing time to inactivation microorganisms (Silva et al., 2020). Moreover, this technology is more successful for liquid foods than for solid foods such as meat products, and previous studies showed that the decrease in microbial cell counts in vegetable or fruit juice with this technology (Sunil et al., 2018).

3. Non-thermal plasma

Plasma is the fourth state of matter and is a partially or fully ionized gas such as light or UV photons. They are composed of a variety of species, including free radicals, electrons, positive and negative ions, gas atoms, molecules in ground or excited states, visible electromagnetic radiation, and neutral particles. Thermal equilibrium [e.g., high-temperature (thermal equilibrium state: 10^6–10^8 *K*) and low-temperature plasma] and pressure conditions can be used to identify the plasma. Low-temperature plasma is further classified as non-thermal plasma (NTP, non-equilibrium state: 300–1,000 *K*) and thermal plasma (local thermal equilibrium state: 4,000–20,000 *K*) (Nehra *et al*., 2008; Lee *et al*., 2017; Pankaj *et al*., 2018). NTP is also referred to cold plasma, low-temperature plasma, and atmospheric pressure plasma (Qiu *et al*., 2019). In NTP technology, a quasi-neutral ionized gas devoid of thermodynamic equilibrium is utilized to generate atoms, excited molecules, ions, electrons, free radicals, photons, and other reactive species (RS) (Barroug *et al*., 2021). The ionized gases include oxygen, nitrogen, or mixtures of specific ratios of noble gases such as neon, argon, or helium. These components effectively inactivate bacteria, fungi, viruses, spores, and biofilms (Bahrami *et al*., 2020). Cells surface etching by RS produced during plasma generation causes cell viability loss, morphological alterations, nucleic acid damage, protein oxidation, and erosion in microbial cells (Ulbin-Figlewicz *et al*., 2015; Qiu *et al*., 2019).

NTP decontamination is effective on meat products. Cold plasma treatment (24 kV for 3 min) in chicken products reduced the counts of mesophilic bacteria and *Salmonella* by 0.7 and 1.5 Log CFU/g, respectively, improving microbial safety (Lee *et al.*, 2020). Another study reported that 100 kV for 5 min cold plasma treatment reduced 2 Log CFU/g of natural microflora in chicken (Moutiq *et al.*, 2020). Additionally, 10 min of plasma exposure in chicken breast decreased the counts of *S.* Typhymurium, *L. monocytogenes,* and *E. coli* O157:H7 by 2.7, 2.1, and 2.7 Log CFU/g, respectively (Lee *et al*., 2016). The total number of

193 microorganisms, yeasts, molds, and psychrotrophic microorganisms was reduced by 1.1–1.5
194 Log CFU/cm^2 in pork and 1.0–2.1 Log CFU/cm^2 in beef after cold plasma treatment at 20 kPa
195 for 10 min (Ulbin-Figlewicz *et al*., 2015). Several studies have reported the antimicrobial
196 effects of combined treatment of cold plasma with natural compounds. Thyme oil/silk fibroin
197 nanofibers treated with cold plasma exhibited antimicrobial effects against *S.* Typhimurium in
198 chicken and duck meat (Lin *et al*., 2019). Breast chicken fillets inoculated with *S. aureus* and
199 *E. coli* showed significant microbial reductions (3–4 Log CFU/g) after cold plasma treatment
200 at 32 kHz for 10 min and essential oil (marinade solutions) treatment (Sahebkar *et al*., 2020).
201 The antimicrobial effectiveness of the NTP is affected by the electrode type, gas
202 composition, applied voltage, relative humidity, treatment time and temperature, and bacterial
203 strain (Bahrami *et al*., 2020). However, NTP treatment is not suitable for high-fat foods because
204 of the possibility of lipid oxidation (Liao *et al*., 2020). In addition, large-scale process needs to
205 be developed for commercial use.
206
207 **4. Ozone**
208 Ozone contains three oxygen molecules with high bactericidal activity, oxidation potential,
209 and viricidal properties. Ozone has two different mechanisms of bacterial destruction (Khan *et*
210 *al*., 2017). Ozone oxidizes sulfhydryl groups, enzymes, peptides, amino acids, and proteins in
211 the first mechanism. Ozone oxidizes polyunsaturated fatty acids (PUFAs) and converts them
212 into peroxides and acids in the second mechanism (Khan *et al*., 2017). Through these
213 mechanisms, vital components (e.g., proteins, RNA, DNA, and enzymes) are completely
214 oxidized when ozone enters microbial cells and causes cell death (Brodowska *et al*., 2018). The
215 effectiveness of ozone decontamination is affected by the treatment method, concentration,
216 exposure time, ozone yield, microbial sensitivity to ozone, and inlet gas composition (Rifna *et*
217 *al*., 2019, Bahrami *et al*., 2020).

Ozone treatment (1×10^{-2} kg/m^3 at 22℃) in turkey breast meat for 8 h reduced 2.9 Log CFU/g of total aerobic mesophilic bacteria, 2.3 Log CFU/g of Enterobacteriaceae, and 1.9 Log CFU/g of yeast and mold (Ayranci et al., 2020). In chicken drumsticks, ozonated water treatment (8 mg/L) with 10-time washes for 4 min reduced *S.* Typhimurium and *Salmonella* Choleraesuis counts below the detection limit (Megahed *et al*., 2020). Giménez *et al*. (2021) found that treatment with 280 mg O_3/m^3 ozone for 5–10 min every 30 min for 5 h reduced *L. monocytogenes* in beef by 2 Log CFU/g. However, increasing the treatment time results in a color change and oxidative damage to the lipids found in the meat (Giménez *et al*., 2021). Thus, combined treatment with ozone and other technologies has been studied to decontaminate meat products without changing their characteristics. Ozone (0.6 ppm for 10 min) and lyophilization (sequential drying of 20.5 h at 0℃, 12 h at 0℃, and 8.5 h at 10℃ at 30 Pa) combination treated in raw chicken fillets reduced lactic acid bacteria by 4.8 Log CFU/g and total aerobic mesophilic bacteria by 6.8 Log CFU/g (Cantalejo *et al*., 2016).

According to Dilmaçünal and Kuleaşan (2018), the major merit of ozone processing is that excess ozone quickly breaks down into oxygen without leaving any chemical residues in the food. However, the disadvantages of ozone processing are its low decontamination efficiency against spores and viruses, high cost, changes in food quality due to high-concentration treatments, and ozone instability when pH of the medium increases (Khan *et al*., 2017; Pandiselvam *et al*., 2017).

5. Pulsed light

Most of the energy used in pulsed light (PL) technology comes from the UV part of the spectrum (John and Ramaswamy, 2018). The wavelength range of PL is 200-1,100 nm, with UV wavelengths ranging from 200 to 400 nm, visible (VIS) wavelengths ranging from 400 to 700 nm, and near-infrared region (IR) wavelengths ranging from 700 to 1,100 nm (Elmnasser

et al., 2007; Palgan *et al*., 2011). This technology functions by mixing short-wavelength UV rays with high energy and inhibiting microbial growth through photochemical activity (Chatterjee and Abraham, 2018). Mechanisms caused by permanent changes in DNA molecules stop cellular growth and eventually result in cell inactivation (Kramer *et al*., 2016). In addition, the photophysical and photothermal effects of the PL process led to microbial decontamination. A stronger infrared light component produces a photothermal effect, which causes localized overheating, cell damage, and cell rupture (Wekhof *et al*., 2001; Elmnasser *et al*., 2007). Photophysical effects of the PL process identified changes in cell membranes and shapes, leakage of internal chemicals, and cytoplasmic damage (Takeshita *et al*., 2003). The PL decontamination process is affected by physical factors (e.g., fluence rate, pulse fluence or light intensity, number of flashes, pulse energy level, applied voltage, distance between the lamp and sample, and UV content), sample type, packaging, and microbial strain (John and Ramaswamy, 2018).

PL can potentially be applied in meat processing, where the sample surface is a risk factor for microbial contamination. of PL treatment (5.31 J/cm^2) in a sliced cured meat product reduced 1.6 Log CFU/g of *L. monocytogenes* (Borges et al., 2023). PL (2.82 to 9.67 J/cm^2) treated in poultry meat showed 1–1.3 Log CFU/g of Enterobacteriaceae reduction, while same treatment reduced less than 1 Log CFU/g of *C. jejuni* (Baptista et al., 2022). Paskeviciute et al. (2011) found that PL treatment inactivated *L. monocytogenes* and *S*. Typhimurium in chicken without affecting the organoleptic qualities. Also, a range of 3.38–62.24 J/cm^2 treated in various parts of the chicken decreased the counts of *C. jejuni* by 2.1 Log CFU/cm^2, *S.* Typhimurium by 2.4 Log CFU/cm^2, and *E. coli* by 2.9 Log CFU/cm^2 (Cassar *et al*., 2019). However, when fluence treatment time increased, the surface temperature of the chicken increased, potentially affecting sensory sensitivity (Cassar *et al*., 2019). PL treatment (1.25–18.0 J/cm^2) on the chicken fillet surface decreased the counts of *S.*

Enteritidis, enterohemorrhagic and extended-spectrum β-lactamase producing *E. coli*, *L. monocytogenes*, *Pseudomonas* spp., *Carnobacterium divergens*, *S. aureus*, and *B. thermospacta* by 0.9–3.0 Log CFU/cm^2 (McLeod *et al*., 2018). PL treatment (8.4 J/cm^2) reduced the count of *L. monocytogenes* by 1.8 Log CFU/cm^2 in ham and 1.1 Log CFU/cm^2 in Bologna slices (Hierro *et al*., 2011). In beef carpaccio, 4.2 J/cm^2 fluence of PL reduced the count of *E. coli*, *S.* Typhimurium, and *L. monocytogenes* by 0.6–1.0 Log CFU/cm^2 without changing the raw attributes (Hierro *et al*., 2012). PL treatment (0.52–19.11 J/cm^2) on pork skin reduced the counts of *Salmonella* by 1.7–3.2 Log CFU/cm^2 and the counts of *Yersinia* by 1.5–4.4 Log CFU/cm^2 (Koch *et al*., 2019).

One advantage of PL over static UV treatment is short time required for energy delivery to food (Chaine *et al.*, 2012). Also, this technology promotes few sensory and nutritional changes, making it suitable for processing into meat products containing high lipids and proteins. However, PL affects the composition and color of food during microbiological decontamination; when used at high concentrations, it overheats and changes its properties (Heinrich *et al*., 2016).

6. Pulsed electric field

A pulsed electric field (PEF) uses short pulses of high voltage (5–80 kV) to inactivate microorganisms. For PEF treatment, food is placed between two high-voltage electrodes for decontaminating vegetative cells of bacteria, yeasts, and molds (Ziuzina et al., 2018). Dielectric breakdown and electroporation are the main PEF mechanisms for microorganism decontamination (Bahrami *et al*., 2020). When multiple pulses of short high-voltage stimuli are delivered to the decontaminated sample, the cell membrane is disrupted by the formation of novel pores or the enlargement of previous pores, allowing intracellular macromolecular components to penetrate and rupture the cell membrane (Slavov *et al*., 2019). The PEF

293 decontamination process is influenced by the strength of the electric field and the exposure
294 time and quantity of pulses (Ramaswamy *et al*., 2019).

295 PEF can be regarded as an innovative method for meat decontamination. PEF (7 kV/cm)
296 efficiently reduced the cell counts of *E. coli* in meat injection solutions by 2 log CFU/mL (Rojas
297 *et al*., 2007). While, the use of PEF to suppress *E. coli* O157:H7 growth in beef was ineffective,
298 which could be due to the low voltage and high protein and fat concentrations in beef (Bolton
299 *et al*., 2002). Although PEF was insufficient to reduce *C. jejuni*, *E. coli*, and *S.* Enteritidis cell
300 concentrations in chicken, it was effective in treating poultry processing fluids and poultry
301 scalds (Haughton *et al*., 2012). According to a recent study, chicken products contaminated
302 with 4.4 Log CFU/g of *C. jejuni* were not significantly reduced by PEF treatment (0.25–1
303 kV/cm) alone. In contrast, the products had significant reduction when a combination of PEF
304 (1 kV/cm) with oregano essential oil was used for 20 min (Clemente *et al*., 2020).

305 PEF is effective in microbial reduction without compromising nutrition, flavor, or color.
306 Furthermore, PEF is a promising method because it may permeabilize cell membranes, which
307 can change the appearance and water-holding capacity of meat and improve the transfer of
308 weight during brining and curing (Bhat *et al*., 2019). However, the mild processing conditions
309 of PEF cannot inactivate the spores and gram-positive bacteria (Bermudez-Aguirre, 2018).
310 Because of the high percentage of cell survival during PEF treatments in the 10–19 kV/cm
311 range, treatments above 25 kV/cm are efficient in eliminating microorganisms, increasing the
312 PEF intensity reduces food sensory sensitivity (Bahrami *et al*., 2020).

313

314 **7. Irradiation**

315 Ionizing radiation is used as a decontaminant during irradiation to extend shelf life and
316 the safety of foods (Mik-Krajnik *et al*., 2017). Irradiation is used in the food industry to prevent
317 germination, delay the rate of ripening, destroy insects and parasites, and destroy non-spore-

318 forming pathogens (Bahrami *et al*., 2020). The process of food is subjected it to ionizing
319 radiation from one of three sources: electron beam for a electron accelerator, X-rays produced
320 when high energy electrons contact a metal plate, or γ-rays released by cesium-137 (^{137}Cs) and
321 cobalt-60 (^{60}Co) (Deng *et al*., 2020).

322 Radurization, radicidation, and radappertization are categorized according to the used
323 dose of γ-irradiation in food processing. Radurization (0.1-2.5 kGy) and radicidation (3.0-10.0
324 kGy) are two of them that have been proven to be efficient in decontaminating pathogenic
325 bacteria and spoilage without altering the properties of the food (Rosario *et al.,* 2021).
326 Microbial decontamination occurs during irradiation via radiolysis, which directly damages
327 DNA and makes reactive molecules such as hydrogen peroxide, hydroxyl radicals, and
328 hydrogen atoms that disrupt cellular metabolic pathways, leading to cell lysis and intracellular
329 oxidation (Ziuzina *et al*., 2018). The radiation dosage, rate of absorption, physiological state
330 of microbial strains, and environmental variables affect microbial inactivation by ionizing
331 radiation (Bahrami *et al*., 2020; Rosario *et al*., 2021).

332 The main use of irradiation technology is the microbiological decontamination of meat
333 products. (Rosario *et al*., 2021). γ-irradiation (2.5kGy) reduced 2.2 Log CFU/g of total viable
334 counts, 1.2 Log CFU/g of *S. aureus,* and 0.7 Log CFU/g of *E. coli* in smoked guinea fowl meat
335 (Otoo *et al.*, 2022). According to Xavier *et al*. (2014), 2.5 kGy of γ-irradiation reduced the
336 counts of *E. coli* O157:H7 and *L. monocytogenes* in bovine trimmings for production of patties
337 by 5 Log CFU/g and 2 Log CFU/g, respectively. Additionally, L*, a*, or b* values of beef
338 patties were unaffected by irradiation doses up to 5 kGy, and it indicated that irradiation may
339 be useful in improving the safety of bovine trimming (Xavier *et al.,* 2014). Over 90% of
340 bacteria can be inactivated by extending the shelf life of meat using low-dose irradiation
341 (Lacroix *et al*., 2000). Also, as the dose of γ-irradiation increased to dry fermented pork
342 sausages, the reduction of total plate counts increased (Kim *et al*., 2012). The γ-irradiation

treatment (0.5 kGy) reduced 0.9 Log CFU/g of total plate counts, and 4 kGy of γ-irradiation treatment reduced total plate counts in the dry fermented pork sausages by 3.9 Log CFU/g (Kim *et al*., 2012). Moreover, a combination of γ-irradiation (15 kGy) with NTP treated with the voltage amplitude of 6 kV and 20 kHz repetition frequency in raw beef reduced pathogenic *E. coli* levels by 0.9 Log CFU/cm^2 after 2 min treatment and 1.8 Log CFU/cm^2 after 5 min treatment (Stratakos and Grant, 2018).

According to Baptista *et al*. (2014), ionizing radiation can extend shelf life and improve food safety. Additionally, γ-irradiation may be performed on unpackaged matrices in previously packed or ready-to-eat goods to minimize the microbial growth and eliminate cross-contamination while food processing (Baptista *et al*. 2014). Thus, many large-scale industrial irradiation facilities are commercialized. However, concerns regarding the changes in nutrient loss, consumer acceptance, and organoleptic qualities remain (Lopez *et al*., 2018).

8. Ultraviolet light

In the electromagnetic spectrum, UV light has a wavelength range of 100-400 nm. Thus, it is a viable alternative to heat and chemical cleansing techniques (Deng *et al*., 2020). UV light is categorized into UV-A (315–400 nm), UV-B (280–315 nm), UV-C (200–280 nm), or vacuum UV (100–200 nm). UV-C is primarily employed to inactivate microorganisms because it can absorb light at a maximal level at 254 nm (Deng *et al*., 2020). Genetic damage is a key factor in UV light-induced inactivation of microorganisms. UV-C absorption causes photochemical changes in microbial DNA, creating thymine dimers and inhibiting transcription and replication activities, making microorganisms inactive (Deng *et al.*, 2020). The UV light decontamination efficiency is affected by elements such as reactor geometry, wavelength, O_2 level, radiated energy, microbiological load, treatment time, product composition, and thickness (Lopez *et al*., 2018, Rosario *et al*., 2021).

Several studies on the application of UV-C radiation to meat products were conducted, and UV-C radiation was found to be effective on lowering the microbial load and prolonging the product shelf life. UV-C dose of 1,000 ± 50 μW/cm^2 within 5 min to 10 min treated in for chicken skin reduced 1.0 Log CFU/g of *S.* Enteritidis (Byun et al., 2022). UV light treatment (3,600 mWs/cm^2) in chicken breast reduced the counts of both Hepatitis A virus and murine norovirus-1 by 1.2 PFU/mL (Park and Ha, 2015). Another study reported that UV light treatment at 1.95 mW/cm^2 for 120 s reduced the concentration of *Salmonella* spp. in chicken by 0.6 Log CFU/g (Lázaro *et al*., 2014). In addition, treatment of beef Bologna with 164 mJ/cm^2 of UV light resulted in a count reduction in *E. coli* by 4.6 Log CFU/mL (Tarek *et al*., 2015). UV-C irradiation has a dose-dependent bactericidal effect on reducing *L. monocytogenes*, *C. jejuni*, and *S.* Typhimurium counts by 1.3, 1.3, and 1.2 Log CFU/g, respectively in chicken breast with 5 kJ/m^2 UV-C treatment (Chun *et al*., 2010). A combination of 1% lemongrass oil with UV-C (200 mW/cm for 2 min) in goat meat resulted in a synergistic microbial reduction of *E. coli* count by 6.7 Log CFU/mL, which was substantially higher than that of individual and other hurdle treatments (Degala *et al*., 2018). However, goat meat no appreciable changes in texture, color changes, or oxidative stability were observed (Degala *et al*., 2018).

Because of its bactericidal effects, energy saving, low cost, ease of installation and maintenance, lack of toxicity and waste production, and low damage to nutritional and sensory qualities in food products, the use of continuous UV light is an attractive strategy in the food industry (Delorme *et al*., 2020; Rosario *et al*., 2021). However, the limitations of UV light are its poor penetration and the shade effect caused by the complex surface characteristics of some products. Thus, foods with irregular or highly porous surfaces are unsuitable for UV light treatment. In addition, UV radiation can alter various light-sensitive substances, including unsaturated fatty acids, vitamins, and folic acids (Deng *et al*., 2020).

9. Ultrasound

Ultrasound waves have a frequency higher than the human hearing threshold (20 kHz). Based on the frequency-power ultrasound, the ultrasound frequencies used in the food industry can be categorized as high-power range (20–100 kHz), large-amplitude waves, and low-frequency, with common uses including modification of the physicochemical qualities or structure of foods (Feng *et al*., 2011). Chemical processes are triggered by low-intensity ultrasound, and antibacterial free radicals (such as hydroxyl ions) can be developed in the process (Feng *et al*., 2011). High-intensity ultrasound (HIUS), which is extensively used in the food industry, operates at high frequencies (20–100 kHz), with strengths ranging from 100 to 500 W/cm^2 (Deng *et al*., 2020). The decontamination mechanism of ultrasound is principally related to cavitation, which is the regular and alternating expansion and compression of liquid-medium molecules when ultrasound passes through the medium (Chen *et al*., 2020). Acoustic cavitation from high-speed alternating pressure and temperature produces free radicals with high oxidation potential, which degrade DNA, inactivate enzymes, and damage bacterial cell membranes or cell walls in food without affecting the nutritional quality or textural properties (O'Donnell *et al*., 2010; Li *et al*., 2015; Rosario *et al*., 2017; Chen *et al*., 2020).

The lethal effect of ultrasound depends on factors such as applied power per volume, frequency, treatment time and temperature, reactor shape, and physical and biological properties of the bacteria (Bahrami *et al*., 2020). HIUS is typically used in the surface treatment of fresh produce to inactivate various microorganisms, such as *E. coli*, *L. innocua*, *S.* Enteritidis and *S. aureus*. According to Caraveo *et al*. (2015), ultrasound treatment (40 kHz, 11 W/cm^2, and 90 min) decreased the counts of total coliforms, mesophilic bacteria, and psychrophilic bacteria in beef extract by 2.2, 2.9, and 3.2 Log CFU/mL, respectively. In addition, the cell counts of *S. aureus* in chicken breast significantly decreased after 50 min of HIUS treatment

(40 kHz, 9.6 W/cm^2) compared to the non-treated sample. On the other hand, there were no significant differences in the counts of mesophiles, psychrophiles, lactic acid bacteria, *E. coli*, and *Salmonella* (Piñon *et al*., 2020). A combination of ultrasound (40 kHz, 2.5 W/cm^2) with lactic acid exhibited a bactericidal effect against gram-negative bacteria (e.g., *E. coli*, *Salmonella* Anatum, *Proteus* spp., and *Pseudomonas fluorescens*). Thus, it was considered appropriate for decontaminating the skin of poultry carcasses (Kordowska-Wiater and Stasiak, 2011). Combining HIUS with 0.3% oregano essential oil treatment resulted in the greatest reduction of mesophilic populations (3.4 Log CFU/mL), anaerobic bacteria (3.1 Log CFU/mL), and lactic acid bacteria (2.3 Log CFU/mL) in chicken breasts (Piñon *et al*., 2015). Furthermore, ultrasound treatment not only reduced growth of microorganisms but also increased the tenderness of meat products by accelerating the enzymatic reactions and destroying muscle cells (Turantaş *et al*., 2015). Another study found that a combination of ultrasound (230 W, 25 kHz for 10 min at 10℃) with electrolyzed water (pH 6.0, 5 ppm chlorine, and an oxidation-reduction potential of 800–850 mV) reduced the counts of lactic acid bacteria, psychrotrophic bacteria, and mesophilic bacteria in chicken breasts (Cichoski *et al*., 2019).

The United States has used large-scale ultrasound applications in the food industry, providing a strategic advantage at various stages of processing (Chen et al., 2020). Also, this technology is effective on inactivation of microorganisms in meat products. However, ultrasound treatment changes the physical and chemical factors of food caused by hydroxyl radicals. In particular, ultrasound-induced lipid degradation of high-fat foods reduces the nutritional quality and safety of the food due to unpleasant odors and secondary reaction products (Chen et al., 2020).

Conclusion

Ensuring the safety and quality of meat and meat products is a challenge for the meat industry because of growing concerns regarding foodborne pathogens. According to the reviewed research papers, non-thermal technology can be used to enhance the safety and quality of meat product processing. In addition, it has been confirmed that a combination of nonthermal technology with other hurdles might be an alternative to heat or conventional chemical strategies to decontaminate bacteria that can occur in various processing steps of meat. However, certain stress-resistant microorganisms and bacterial spores are still problematic in non-thermal decontamination technologies.

Conflicts of Interests

The authors declare no potential conflicts of interest.

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Author contributions

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Ethics Approval

This article does not require IRB/IACUC approval because there is no human or animal participants.

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Table 1. Efficiency of various non-thermal technologies in the reduction of spoilage and pathogenic microorganisms in meat

Method	Food produce	Target bacteria	Treatment condition	Reduction	Reference
HPP	Chicken meat	*Salmonella* spp.	400-500 Mpa, 1-5 min	Below the detection limit	Cap et al., 2020
	Pork burger	Lactic acid bacteria	600MPa, 5 min, 10℃	4.8 Log CFU/g	Amaro-Blanco et al., 2018
		Psychrotrophic bacteria		6.7 Log CFU/g	
		Mesophilic bacteria		7 Log CFU/g	
	Beef fillet	Total coliform	300 MPa, 5 min	2.2 Log CFU/g	Giménez et al., 2015
		Lactic acid bacteria		2.9 Log CFU/g	
		Mesophilic bacteria		1.5 Log CFU/g	
	Chicken breast fillet	*Escherichia coli*	300 MPa, 5 min	1.7 Log CFU/g	Kruk et al., 2011
		Salmonella Typhimurium		0.6 Log CFU/g	
		Listeria monocytogenes		3.2 Log CFU/g	
	Poultry	Mesophilic bacteria	300 MPa, 10 min	1.5 Log CFU/g	Canto et al., 2015
		Psychrotrophic bacteria		>2.4 Log CFU/g	
	Poultry sausage	*Brochothrix thermosphacta*	350 Mpa, 120 s	>6.0 Log CFU/g	Al-Nehlawi et al., 2014
		Leuconostoc carnosum		0.5 Log CFU/g	
		Listeria innocua		0.5 Log CFU/g	
		Salmonella Enteritidis		3.5 Log CFU/g	
		Campylobacter jejuni	200 MPa, 5 min	0.04 Log CFU/g	Jackowska-Tracz & Tracz, 2015
	Beef	*E. coli*	500 MPa, 2 min	1.3 Log CFU/g	Park et al., 2021
		Salmonella		6.5 Log CFU/g	
		L. monocytogenes		3.9 Log CFU/g	
		Staphylococcus aureus		0.9 Log CFU/g	

SC-CO_2	Chicken breast	*E. coli* *L. innocua*	14 MPa, 40ºC, 15 min	1.3 Log CFU/g 1.4 Log CFU/g	Santi et al., 2023
	Chicken breast	Mesophilic bacteria	100 bar,40ºC, 90 min	Below the detection limit	Morbiato et al., 2019
	Dry-cured ham	*L. monocytogenes*	12 MPa, 45℃, 5 min	3 Log CFU/g	Ferrentino et al., 2013
	Raw pork meat	Mesophilic bacteria	6 MPa, 25℃, 60 min	2 Log CFU/g	Cappelletti et al., 2015
	Ground pork	Mesophilic bacteria *Salmonella* spp.	140 bar, 45℃, 40 min	1.7 Log CFU/g 2.2 Log CFU/g	Bae et al., 2010
NTP	Ready-to-eat chicken products	*Salmonella* spp. Mesophilic bacteria	24 kV, 3 min	1.5 Log CFU/g 0.7 Log CFU/g	Lee et al., 2020
	Chicken	Natural microflora	100 kV, 5 min	2 Log CFU/g	Moutiq et al., 2020
	Chicken breast	*S.* Typhymurium *E. coli* O157:H7 *L. monocytogenes*	2-100 W, 10 min	2.7 Log CFU/g 2.7 Log CFU/g 2.1 Log CFU/g	Lee et al., 2016
	Pork	Total number of microorganisms Yeast and molds Psychrotrophic bacteria	20 kPa, 10 min	1.1 Log CFU/g 1.9 Log CFU/g 1.6 Log CFU/g	Ulbin-Figlewicz et al., 2015
	Beef	total number of microorganisms yeast and molds Psychrotrophic bacteria		2.1 Log CFU/g 1.0 Log CFU/g 1.5 Log CFU/g	
Irradiation	Bovine trimming	*L. monocytogenes* *E. coli*	2.5 kGy	2 Log CFU/g 5 Log CFU/g	Xavier et al., 2014
	Dry fermented sausage	Total plate counts	0.5 kGy 4 kGy	0.9 Log CFU/g 3.9 Log CFU/g	Kim et al., 2012

	Raw beef	Pathogenic *E. coli*	15 kGy + voltage amplitude of 6 kV and 20 kHz repetition, 2 min 15 kGy + voltage amplitude of 6 kV and 20 kHz repetition, 5 min	0.9 Log CFU/cm2 1.8 Log CFU/cm^2	Stratakos and Grant, 2018
Ozone	Turkey breast meat	Total aerobic mesophilic bacteria Enterobacteriaceae Yeast and molds	1×10^{-2} kg/m^3, 22ºC, 8 h	2.9 Log CFU/g 2.3 Log CFU/g 1.9 Log CFU/g	Ayranci et al., 2020
	Chicken drumsticks	*Salmonella* spp.	8 mg/L	Complete reduction	Megahed et al., 2020
	Turkey meat	*Salmonella* strians	0.3 ppm	Complete reduction	Tîrziu et al., 2017
	Beef	*L. monocytogenes*	280 mg O3/m^3, 5–10 min duration every 30 min for 5 h	2 Log CFU/g	Giménez et al., 2021
	Raw chicken fillets	Lactic acid bacteria Mesophilic bacteria	ozone (0.6 ppm and 10 min) + lyophilization (sequential drying of 20.5 h at 0ºC, 12 h at 0ºC, and 8.5 h at 10ºC at 30 Pa)	4.8 Log CFU/g 6.8 Log CFU/g	Cantalejo et al., 2016
PL	Sliced cured meat product	*L. monocytogenes*	5.31 J/cm^2	1.6 Log CFU/g	Borges et al., 2023
	Poultry meat	Enterobacteriaceae	2.82–9.67 J/cm^2	1–1.3 Log CFU/g	Baptista et al., 2022
	Dry-cured loin *Salchichon*	*L. monocytogenes* *S.* Thyphimurium *L. monocytogenes* *S.* Thyphimurium	0.7–11.9 J/cm^2	1.0–1.6 Log CFU/cm^2 0.5–1.7 Log CFU/cm^2 0.9–1.8 Log CFU/cm^2 0.3–1.5 Log CFU/cm^2	Ganan *et al.*, 2013
	Lean chicken thighs Skin surface chicken thigh Lean chicken thighs Skin surface chicken thigh	*C. jejuni* *E. coli* 	3.38–62.24 J/cm^2 53.38–62.24 J/cm^2 	1.5–2.1 Log CFU/cm^2 1.1–1.9 Log CFU/cm^2 1.2–2.0 Log CFU/cm^2 1.2–2.9 Log CFU/cm^2	Cassar et al., 2019
	Skinless chicken fillet	*E. coli (EHEC)*	1.25–18 J/cm^2	3.0 Log CFU/cm^2	McLeod et al., 2018

		E. coli (ESBL)	1.25–18 J/cm^2	2.8 Log CFU/cm^2	McLeod et al., 2019
	Lean chicken thighs	*S.* Typhimurium	3.38–62.24 J/cm^2	1.6–2.4 Log CFU/cm^2	Cassar et al., 2019
	Skin surface chicken thighs		53.38–62.24 J/cm^2	0.9–1.8 Log CFU/cm^2	Cassar et al., 2019
	Skinless chicken breast		0.78–5.4 J/cm^2	2.0 Log CFU/g	Paskeviciute et al., 2009
	Chicken breast		2.7–67 J/cm^2	2.4 Log CFU/cm^2	Keklik et al., 2010
	Skinless chicken fillet	*S.* Enteritidis	1.25–18 J/cm^2	2.4 Log CFU/cm^2	McLeod et al., 2018
	Chicken fillet	*L. monocytogenes*		2.0 Log CFU/cm^2	
	Skinless chicken breast		0.78–5.4 J/cm^2	2.4 Log CFU/g	Paskeviciute et al., 2011
	Skinless chicken fillet	*S. aureus*	1.25–18 J/cm^2	3.0 Log CFU/cm^2	McLeod et al., 2018
	Beef *carpaccio*	*L. monocytogenes*	0.7–11.9 J/cm^2	0.3–0.9 Log CFU/cm^2	Hierro et al., 2012
		E. coli		0.6–1.2 Log CFU/cm^2	
		S. Typhimurium		0.3–1.0 Log CFU/cm^2	
	Pork skin	*S.* Typhimurium	0.52–19.11 J/cm^2	3.2 Log CFU/cm^2	Koch et al., 2019
	Pork loin			1.7 Log CFU/cm^2	
	Pork skin	*Yersinia enterocolitica*		4.3 Log CFU/cm^2	
	Pork loin			1.7 Log CFU/cm^2	
	Meat injection solution	*E. coli*	7 kV/cm	2 Log CFU/mL	Rojas et al., 2007
	Chicken product	*C. jejuni*	1 kV/cm + oregano essential oil	Complete reduction	Clemente et al., 2020
UV light	Chicken breast	Murine norovirus-1	3600 mWs/cm^2	1.2 PFU/mL	Park and Ha, 2015
		Hepatitis A virus	3600 mWs/cm^2	1.2 PFU/mL	
	Chicken	*Salmonella* spp.	1.95 mW/cm^2, 120 s	0.6 Log CFU/g	Lázaro et al., 2014
	Beef Bologna	*E. coli*	164 mJ/cm^2	4.6 Log CFU/mL	Tarek et al., 2015

	Chicken breast	*L. monocytogenes*	5 kJ/m^2	1.3 Log CFU/g	Chun et al., 2010
		C. jejuni		1.3 Log CFU/g	
		S. Typhimurium		1.2 Log CFU/g	
	Goat mieat	*E. coli*	200 mW/cm^2 + 1% lemongrass oil, 2 min	6.7 Log CFU/mL	Degala et al., 2018
	RTE sliced ham	*L. monocytogenes*	8000J/m^2	2.7 Log CFU/g	Chun et al., 2009
		S. Typhimurium		2.0 Log CFU/g	
		C. jejuni		1.7 Log CFU/g	
Ultrasound	Sausage	psychrotrophic bacteria	25 kHz + slightly acidic electrolyzed water	0.8 Log CFU/g	Cichoski et al., 2015
		Lactic acid bacteria		0.8 Log CFU/g	
		Mesophilic bacteria		1.0 Log CFU/g	
	Beef extract	Coliform	40 kHz, 11 W/cm^2, 90 min	2.2 Log CFU/mL	Caraveo et al., 2015
		Mesophilic bacteria		2.9 Log CFU/mL	
		Psychrophilic bacteria		3.2 Log CFU/mL	
	Chicken breast	*S. aureus*	40 kHz, 9.6 W/cm^2, 50 min	significant reduction	Piñon et al., 2020
		Mesophilic bacteria	60 kHz, 40 W, 0.3% oregano oil	2.3 Log CFU/mL	Piñon et al., 2015

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