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REVIEW

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.

Keywords 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 (Turantaş et al., 2015). 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 (Jadhav et al., 2021; Wang et al., 2016). 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 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.

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 (Rosario et al., 2021). 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 (Campus, 2010; Hugas et al., 2002). Moreover, cellular processes (e.g., protein synthesis, enzyme activity, and cellular components such as ribosomes) are inhibited or altered (Rendueles et al., 2011).

HPP inactivates bacteria, yeast, and mold by blocking DNA synthesis, denaturing proteins, inactivating enzymes, and destroying cellular membranes and organelles (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 below the detection limit in chickens (Cap et al., 2020). Also, HPP treatment (600 MPa, 5 min) at 10°C 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

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	Population	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	600 MPa, 5 min, 10°C	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 and Tracz, 2015
	Beef	*E. coli*	500 MPa, 2 min	1.3 Log CFU/g	Park et al., 2022
		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*	14 MPa, 40°C, 15 min	1.3 Log CFU/g	Santi et al., 2023
		L. innocua		1.4 Log CFU/g	
	Chicken breast	Mesophilic bacteria	100 bar, 40°C, 90 min	Below the detection limit	Morbiato et al., 2019
	Dry-cured ham	*L. monocytogenes*	12 MPa, 45°C, 5 min	3 Log CFU/g	Ferrentino et al., 2013
	Raw pork meat	Mesophilic bacteria	6 MPa, 25°C, 60 min	2 Log CFU/g	Cappelletti et al., 2015
	Ground pork	Mesophilic bacteria	140 bar, 45°C, 40 min	1.7 Log CFU/g	Bae et al., 2010
		Salmonella spp.		2.2 Log CFU/g	
NTP	Ready-to-eat chicken products	*Salmonella* spp.	24 kV, 3 min	1.5 Log CFU/g	Lee et al., 2020
		Mesophilic bacteria		0.7 Log CFU/g	
	Chicken	Natural microflora	100 kV, 5 min	2 Log CFU/g	Moutiq et al., 2020
	Chicken breast	*S.* Typhymurium	2–100 W, 10 min	2.7 Log CFU/g	Lee et al., 2016
		E. coli O157:H7		2.7 Log CFU/g	
		L. monocytogenes		2.1 Log CFU/g	

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

Method	Food produce	Target bacteria	Treatment condition	Population	Reference
	Pork	Total number of microorganisms	20 kPa, 10 min	1.1 Log CFU/g	Ulbin-Figlewicz et al., 2015
		Yeast and molds		1.9 Log CFU/g	
		Psychrotrophic bacteria		1.6 Log CFU/g	
	Beef	Total number of microorganisms		2.1 Log CFU/g	
		Yeast and molds		1.0 Log CFU/g	
		Psychrotrophic bacteria		1.5 Log CFU/g	
Irradiation	Bovine trimming	*L. monocytogenes*	2.5 kGy	2 Log CFU/g	Xavier et al., 2014
		E. coli		5 Log CFU/g	
	Dry fermented sausage	Total plate counts	0.5 kGy	0.9 Log CFU/g	Kim et al., 2012
			4 kGy	3.9 Log CFU/g	
	Raw beef	Pathogenic *E. coli*	15 kGy+voltage amplitude of 6 kV and 20 kHz repetition, 2 min	0.9 Log CFU/cm^2	Stratakos and Grant, 2018
			15 kGy+voltage amplitude of 6 kV and 20 kHz repetition, 5 min	1.8 Log CFU/cm^2	
Ozone	Turkey breast meat	Total aerobic mesophilic bacteria	1×10^{-2} kg/m^3, 22°C, 8 h	2.9 Log CFU/g	Ayranci et al., 2020
		Enterobacteriaceae		2.3 Log CFU/g	
		Yeast and molds		1.9 Log CFU/g	
	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 O_3/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	Ozone (0.6 ppm and 10 min)+lyophilization (sequential drying of 20.5 h at 0°C, 12 h at 0°C, and 8.5 h at 10°C at 30 Pa)	4.8 Log CFU/g	Cantalejo et al., 2016
		Mesophilic bacteria		6.8 Log CFU/g	
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	*L. monocytogenes*	0.7–11.9 J/cm^2	1.0–1.6 Log CFU/cm^2	Ganan et al., 2013
		S. Thyphimurium		0.5–1.7 Log CFU/cm^2	
	Salchichon	*L. monocytogenes*		0.9–1.8 Log CFU/cm^2	
		S. Thyphimurium		0.3–1.5 Log CFU/cm^2	
	Lean chicken thighs	*C. jejuni*	3.38–62.24 J/cm^2	1.5–2.1 Log CFU/cm^2	Cassar et al., 2019

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

Method	Food produce	Target bacteria	Treatment condition	Population	Reference
	Skin surface chicken thigh			1.1–1.9 Log CFU/cm^2	
	Lean chicken thighs	*E. coli*		1.2–2.0 Log CFU/cm^2	
	Skin surface chicken thigh		53.38–62.24 J/cm^2	1.2–2.9 Log CFU/cm^2	
	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., 2018
	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., 2011
	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	3,600 mWs/cm^2	1.2 PFU/mL	Park and Ha, 2015
		Hepatitis A virus	3,600 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	

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

Method	Food produce	Target bacteria	Treatment condition	Population	Reference
	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*	8,000 J/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

HPP, high-pressure processing; SC-CO_2, supercritical carbon dioxide; NTP, non-thermal plasma; PL, pulsed light.

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, Salmonella* 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°C 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°C every 100 MPa (Morales-de la Peña 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°C–20°C); thus, they do not significantly disrupt the sensory sensitivity of food (Heinz and Buckow, 2010).

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 (Damar and Balaban, 2006; Dillow et al., 1999; Garcia-Gonzalez et al., 2007; Giulitti et al., 2011; Spilimbergo and Bertucco, 2003). 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., 2023). 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 *L. 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°C, 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 (HIUS) reduced the cell counts of *Salmonella enterica* in raw chicken breast and *L. monocytogenes* in cured ham (Morbiato et al., 2019; Sara et al., 2014). 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°C 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 inactivate 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).

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*; Lee et al., 2017; Nehra et al., 2008; 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 (Bahrami et al., 2020). 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 (Qiu et al., 2019; Ulbin-Figlewicz et al., 2015).

NTP decontamination is effective on meat products (Lee et al., 2020; Moutiq et al., 2020). 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 microorganisms, yeasts, molds, and psychrotrophic microorganisms was reduced by 1.1–1.5 Log CFU/cm^2 in pork and 1.0–2.1 Log CFU/cm^2 in beef after cold plasma treatment at 20 kPa for 10 min (Ulbin-Figlewicz et al., 2015). Several studies have reported the antimicrobial effects of combined treatment of cold plasma with natural compounds. Thyme oil/silk fibroin nanofibers treated with cold plasma exhibited antimicrobial effects against *S.* Typhimurium in chicken and duck meat (Lin et al., 2019). Breast chicken fillets inoculated with *S. aureus* and *E. coli* showed significant microbial reductions (3–4 Log CFU/g) after cold plasma treatment at 32 kHz for 10 min and essential oil (marinade solutions) treatment (Sahebkar et al., 2020).

The antimicrobial effectiveness of the NTP is affected by the electrode type, gas composition, applied voltage, relative humidity, treatment time and temperature, and bacterial strain (Bahrami et al., 2020). However, NTP treatment is not suitable for high-fat foods because of the possibility of lipid oxidation (Liao et al., 2020). In addition, large-scale process needs to be developed for commercial use.

Ozone

Ozone contains three oxygen molecules with high bactericidal activity, oxidation potential, and viricidal properties (Khan et al., 2017). Ozone has two different mechanisms of bacterial destruction (Khan et al., 2017). Ozone oxidizes sulfhydryl groups, enzymes, peptides, amino acids, and proteins in the first mechanism (Khan et al., 2017). Ozone oxidizes polyunsaturated fatty acids and converts them into peroxides and acids in the second mechanism (Khan et al., 2017). Through these mechanisms, vital components (e.g., proteins, RNA, DNA, and enzymes) are completely oxidized when ozone enters microbial cells and causes cell death (Brodowska et al., 2018). The effectiveness of ozone decontamination is affected by the treatment method, concentration, exposure time, ozone yield, microbial sensitivity to ozone, and inlet gas composition (Bahrami et al., 2020; Rifna et al., 2019).

Ozone treatment (1×10^{-2} kg/m^3 at 22°C) 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°C, 12 h at 0°C, and 8.5 h at 10°C 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).

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 from 200 to 400 nm, visible wavelengths from 400 to 700 nm, and near-infrared region (IR) wavelengths 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 (Elmnasser et al., 2007; Wekhof et al., 2001). 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. thermosphacta* 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).

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

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

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

Irradiation

Ionizing radiation is used as a decontaminant during irradiation to extend shelf life and the safety of foods (Mikš-Krajnik et al., 2017). Irradiation is used in the food industry to prevent germination, delay the rate of ripening, destroy insects and parasites, and destroy non-spore-forming pathogens (Bahrami et al., 2020). The process of food is subjected it to ionizing radiation from one of three sources: electron beam for a electron accelerator, X-rays produced when high energy electrons contact a metal plate, or γ-rays released by cesium-137 (^{137}Cs) and cobalt-60 (^{60}Co; Deng et al., 2020).

Radurization, radicidation, and radappertization are categorized according to the used dose of γ-irradiation in food processing. Radurization (0.1–2.5 kGy) and radicidation (3.0–10.0 kGy) are two of them that have been proven to be efficient in decontaminating pathogenic bacteria and spoilage without altering the properties of the food (Rosario et al., 2021).

Microbial decontamination occurs during irradiation via radiolysis, which directly damages DNA and makes reactive molecules such as hydrogen peroxide, hydroxyl radicals, and hydrogen atoms that disrupt cellular metabolic pathways, leading to cell lysis and intracellular oxidation (Ziuzina et al., 2018). The radiation dosage, rate of absorption, physiological state of microbial strains, and environmental variables affect microbial inactivation by ionizing radiation (Bahrami et al., 2020; Rosario et al., 2021).

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

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).

Ultrasound

Ultrasound waves have a frequency higher than the human hearing threshold (20 kHz; Feng et al., 2011). 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). 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 (Chen et al., 2020; Li et al., 2015; O'Donnell et al., 2010; Rosário et al., 2017).

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°C) 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 (Chen et al., 2020). 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. However, certain stress-resistant microorganisms and bacterial spores are still problematic in non-thermal decontamination technologies.

Conflicts of Interest

The authors declare no potential conflicts of interest.

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Author Contributions

Conceptualization: Lee Y, Yoon Y. Data curation: Lee Y. Writing - original draft: Lee Y. Writing - review & editing: Lee Y, Yoon Y.

Ethics Approval

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

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