Meat and Muscle Biology™

Emerging Meat Processing Technologies for Microbiological Safety of Meat and Meat Products

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Abstract: A consumer trend toward convenient, minimally processed meat products has exerted tremendous pressure on meat processors to ensure the safety of meat and meat products without compromising product quality and the meeting of consumer demands. This has led to challenges in developing and implementing novel processing technologies as the use of newer technologies may affect consumer choices and opinions of meat and meat products. Novel technologies adopted by the meat industry for controlling foodborne pathogens of significant public health implications, gaps in the technologies, and the need for scaling up technologies that have been proven to be successful in research settings or at the pilot scale will be discussed. Novel processing technologies in the meat industry warrant microbiological validation prior to becoming commercially viable options and enacting infrastructural changes. This review presents the advantages and shortcomings of such technologies and provides an overview of technologies that can be successfully implemented and streamlined in existing processing environments.

Introduction

Over the past 2 decades, there has been an increased demand for convenient yet minimally processed meat and meat products. With this expectation from the consumers, there is an ever increasing responsibility for meat processors to manufacture safe meat and meat products without compromising quality. Ensuring microbial safety and quality of meat and meat products is an ongoing challenge as meat provides an ideal medium for the growth of microorganisms. Additionally, the highly perishable nature of meat requires new and innovative technologies to constantly be developed and applied to destroy and/or prevent growth of pathogenic and spoilage

microorganisms (Troy et al., 2016). According to Bruhn (2007), increasing awareness among consumers has shifted their focus toward convenience and safety without compromises in the health-enhancing properties of their desired foods. As a result of this, research over the past decade has focused on the invention and application of newer processing technologies (Raouche et al., 2011). In the current times, in which social media and access to science-based knowledge is readily available, enhancing consumer awareness about newer processing technologies, including benefits and drawbacks, is critical to assist in the decision-making process to purchase meat and meat products. Traditional thermal pasteurization technologies have been widely used in the meat industry; however, several reports suggest a negative

effect on sensory characteristics, flavor, and nutritional content of food. Therefore, nonthermal processing technologies have gained widespread attention (Farkas, 2016), and some of the new and widely used technologies include, but are not limited to, high pressure, pulsed electric field (PEF), pulsed light, electron beam, plasma, and intelligent and modified atmosphere packaging. Published literature on the previously mentioned technologies is extensive and is active worldwide, although factors such as cost, worker safety, floorspace and throughput challenges, public perception, etc. can limit their commercial applications. This review summarizes recent developments in technologies to enhance safety of meat and meat products with a focus on implementation of laboratory-scale technologies to commercial domains.

Microbiological Safety of Meat and Meat Products

Meat and meat products represent a steadily growing sector of the global food production (FAO, 2019). As meat is one of the food commodities most commonly implicated in foodborne outbreaks, the disease burden associated with consumption of contaminated meat and meat products remains substantial (CDC, 2019). The most prevalent causative agents of meat-related outbreaks are *Salmonella*, Shiga-toxigenic *Escherichia coli*, *Listeria monocytogenes*, and to a lesser extent *Staphylococcus aureus*, *Bacillus cereus*, *Clostridium perfringens*, *C. botulinum*, and *Trichinella spiralis* in pork (Omer et al., 2018; CDC, 2019). There are several regulations to prevent contamination of the meat supply with foodborne pathogens and subsequently minimize the risk to the consumers. For example, in 2011, the United States Department of Agriculture's (USDA) Food Safety and Inspection Service (FSIS), under the Federal Meat Inspection Act, declared that *E. coli* O157:H7 and serogroups O26, O45, O103, O111, O121, and O145 were considered adulterants in raw nonintact beef and intact beef products intended for nonintact use (76 FR 58157) (Federal Register, 2011). Similarly, in 2003, a zero-tolerance rule for *L. monocytogenes* in post-lethality exposed ready-to-eat (RTE) meat and poultry products was implemented (68 FR 34224) (Federal Register, 2003).

Meat animals naturally carry significant microbial load on their skin, hair, feet, and most importantly, in their gastrointestinal tract. Among them are foodborne pathogens that can be transferred to the meat processing facilities upon slaughter (Gill, 2005). Cattle and other ruminants are frequently colonized with *E. coli* O157:H7 and can shed high loads of the pathogen in their feces without exhibiting any signs of disease (Bell, 1997). Consequently, more than half of the reported *E. coli* O157:H7 outbreaks are linked to beef and beef products (Callaway et al., 2009) although, increasingly, contaminated fresh produce is being linked to this pathogen and consequently the outbreaks (CDC, 2019). In a recent survey, Omer et al. (2018) reported that from 1980 to 2015, the meat categories most frequently associated with outbreaks of *E. coli* O157:H7 and other non-O157 serotypes were fresh processed meats and raw-cured fermented sausages. The prevalence of *E. coli* in cattle may vary, and Elder et al. (2000) reported *E. coli* O157 incidence levels of 28% and 11% on feces and hides, respectively. Most importantly, this study showed a correlation in *E. coli* O157 prevalence between pre-slaughter and processing, with incidence levels of 43% at pre-evisceration and 2% at post-chill. In a recent study, the incidence of non-O157 enterohaemorrhagic *E. coli* on cattle hides was reported at 79% (630/800) of the hide samples contaminated with at least one serogroup of enterohaemorrhagic *E. coli* (Schneider et al., 2018).

Salmonella can also colonize the intestinal tract of cattle, swine, and poultry (Stevens et al., 2009). There are numerous disease-causing serovars of *Salmonella enterica*, but *Salmonella enterica* serovar Typhimurium is the most common serovar implicated in meat-related outbreaks, with raw-cured fermented sausages as a major food vehicle for infection (Omer et al., 2018). It is difficult to estimate average prevalence of *Salmonella* in meat products, as they vary greatly based on geographical regions and production practices (Carrasco et al., 2012). Fecal prevalence of *Salmonella* on beef cattle may range from 2% to 9% but can be isolated at higher rates, up to 97%, from the hide (Barkocy-Gallagher et al., 2003). Post processing and at retail, the prevalence is much lower, ranging from 2% to 7% for some products (Bosilevac et al., 2009). Similar trends are also reported for pork products, with reported *Salmonella* levels decreasing to 4% after chilling of pork carcasses (Schmidt et al., 2012) and to undetectable levels at retail (Sanchez-Maldonado et al., 2017).

Among the confirmed outbreaks related to consumption of meat products caused by etiologic agents other than *Salmonella* and *E. coli*, outbreaks caused by *L. monocytogenes* are of significant importance. *L. monocytogenes* is a pathogen of concern in RTE meat products due to its ubiquitous and persistent nature in meat processing facilities (Glass and Doyle, 1989). Additionally, outbreaks caused by

L. monocytogenes result in higher mortality rates compared with other bacterial pathogens (CDC, 2019). Recent estimates from the European Food Safety Authority on the levels of *L. monocytogenes* contamination of RTE meat products report a 0.43% prevalence based on the microbiological limit of 100 colony forming units (CFU) per gram (EFSA BIOHAZ Panel, 2018). Given the presence of foodborne pathogens in highly perishable foods such as meat and meat products, it is critical to develop and implement processing technologies to effectively mitigate the risk and enhance public health.

Packaging Technologies

Packaging is an essential operation for marketing meat and meat products. The primary function of packaging is to provide a protective barrier against environmental and physical damage, enzymatic oxidation, and microbial deterioration, as well as to prevent contamination (Han, 2003). Vacuum and modified atmosphere packaging are widely used technologies designed to improve the microbiological safety and extend shelf life of meat and meat products during storage (Narasimha Rao and Sachindra, 2002). However, newer and innovative packaging technologies (active and intelligent packaging) have emerged in recent years in an effort to meet the increased regulatory scrutiny regarding the safety and quality of meat and meat products.

Active packaging

Active packaging relies on the interaction between packaging materials, the product, and the environment for shelf life extension and food safety assurance (Quintavalla and Vicini, 2002). The internal environment can be controlled by substances acting as scavengers or emitters of specific gases, such as oxygen, ethylene, or carbon dioxide (Janjarasskul and Suppakul, 2018). Active food packaging systems are classified based on their bioactive ingredients and methods of application. For example, oxygen scavengers and carbon dioxide emitters are commonly incorporated into sachets or pads placed inside the package (Otoni et al., 2016). These sachets can also be used to deliver antimicrobial compounds such as chlorine dioxide (Park and Kang, 2015). However, another more frequently used technology is one in which the antimicrobial substances are dispersed, immobilized, or coated onto the packaging film (Muriel-Galet et al., 2013; Han et al., 2014;

Woraprayote et al., 2018). Antimicrobial packaging has shown great potential as an effective application of active packaging technology, particularly for meat and meat products (Quintavalla and Vicini, 2002). Microbial contaminants of meats are primarily concentrated on the surface, and microbial growth can therefore be inhibited as the food surface comes in contact with the antimicrobial substances in the packaging (Han, 2003). Antimicrobial packaging systems can be classified based on the delivery method of the active agent:

1. Incorporating antimicrobials into sachets and absorbent pads. Often, sachets carry volatile antimicrobials that diffuse into the package headspace (Otoni et al., 2016), whereas absorbent pads are designed to retain excess moisture from meat products but can also carry antimicrobial agents and act through direct surface contact (Agrimonti et al., 2019);
2. Incorporating or coating antimicrobial substances into packaging polymers, where preservative effects are achieved via controlled migration of the active substance onto the foods. A slow release of the biocidal agent provides extended exposure to the antimicrobial without posing toxicological risk to consumers (Han, 2003). To prevent extensive migration, antimicrobial agents can be chemically immobilized to the surface of the packaging material; however, direct contact with the food is still required (Muriel-Galet et al., 2013); and
3. Use of edible coatings consisting of biopolymers with innate antimicrobial properties or antimicrobial agents (Arkoun et al., 2018). A number of substances have been researched for their antimicrobial properties once incorporated into packaging systems. These systems commonly rely on natural, food-grade antimicrobials such as essential oils, bacteriocins, and antimicrobial polysaccharides (Marcos et al., 2013; Han et al., 2014).

Essential oils are effective for use in the meat industry and have extensive applications in packaging (Mousavi Khaneghah et al., 2018). In particular, oregano, thyme, and clove essential oils have received attention for their antimicrobial activity when incorporated into synthetic and edible films. Yemi and Cando an (2017) demonstrated antimicrobial activity of soy edible films incorporated with oregano and thyme essential oils at concentrations of 1%, 2%, and 3% against *E. coli* O157:H7, *L. monocytogenes*, and *S. aureus* in a concentration-dependent manner

during refrigerated storage of beef cuts. The antimicrobial effects of edible soy films with added oregano essential oils were also examined by Emiro lu et al. (2010) on fresh ground beef patties. Films with 5% oregano essential oil reduced *Pseudomonas* spp. and coliforms by 0.74 and 1.6 $\log_{10}$ CFU/g, respectively, yet no reduction was seen for total viable counts, lactic acid bacteria, or *Staphylococcus* spp. during 12 d of storage at 4°C. Synthetic films with incorporated essential oils, particularly low-density polyethylene, have shown promise as antimicrobial packaging systems against pathogens in meats, both in vitro (Shemesh et al., 2015) and on fresh beef (Han et al., 2014).

Bacteriocins from lactic acid bacteria have been reported to have applicability in antimicrobial packaging of meat and meat products with nisin-based films being used as popular alternatives due to their potential to inhibit pathogenic bacteria, particularly in RTE products (Nguyen et al., 2008; Marcos et al., 2013). Nguyen et al. (2008) showed that bacterial cellulose films with nisin incorporated at 2,500 IU/mL reduced populations of *L. monocytogenes* on the surface of frankfurters by 2 $\log_{10}$ CFU/g during 14 d of refrigerated storage. In a different study, nisin-containing polyvinyl alcohol films demonstrated reductions of 1.4 $\log_{10}$ CFU/g on *L. monocytogenes* at the end of the 90-d refrigerated storage period (Marcos et al., 2013). Novel bacteriocins have been investigated over the years, for their potential use in antimicrobial packaging of foods (Woraprayote et al., 2018). For instance, a study by Barbiroli et al. (2017) showed that incorporation of the peptide Sakacin A—recovered from a strain of *Lactobacillus sakei*—onto polyethylene-coated paper sheets reduced *Listeria innocua* populations by 1.5 $\log_{10}$ CFU/g in thin-cut veal meat slices.

Oxygen scavengers and carbon dioxide generators are among the most commercially available active packaging technologies, along with absorbent pads, and have been widely used in the food industry due to their antimicrobial and antioxidant properties (Otoni et al., 2016). Carbon dioxide emitters are commonly used in combination with oxygen scavengers to inhibit the growth of spoilage organisms, thus extending the shelf life of many meat and poultry products (Fang et al., 2017). These systems have also been investigated for food safety applications (Holck et al., 2014), and Chen and Brody (2013) showed that oxygen scavengers and carbon dioxide emitters control the growth of *L. monocytogenes* on cooked ham when incorporated into antimicrobial films. Furthermore, emitting sachets of chlorine dioxide have been evaluated for their antimicrobial activity against major foodborne pathogens (Ellis et al., 2006; Park and Kang, 2015). Shin et al. (2011) reported reductions of *S.* Typhimurium and *L. monocytogenes* on raw chicken breasts when sachets of chlorine dioxide were used in combination with modified atmosphere packaging. Similar results were reported by Ellis et al. (2006), with reductions of about 1 $\log_{10}$ CFU/g on chicken breasts under refrigerated storage.

In recent years, nanotechnology has been regarded as a promising tool to improve antimicrobial packaging of foods (Duncan, 2011). Applications in meat packaging include the use of metal nanoparticles as antimicrobial agents incorporated into packaging systems, as well as the development of biopolymer nanocomposite films and coatings (Singh et al., 2016). A study by Mahdi et al. (2012) showed nanosilver polyvinyl chloride packaging tray inhibited the growth of *E. coli* on minced beef during 7 d of refrigerated storage. Cellulose pads incorporated with silver nanoparticles exhibited average reductions of 1 $\log_{10}$ CFU/g for *Pseudomonas* spp., *Enterobacteriaceae*, and total aerobic bacteria on beef stored under modified atmosphere packaging (Fernandez et al., 2010). Chitosan has also been extensively studied in antimicrobial packaging of meats (Dehnad et al., 2014), and chitosan-based nanocomposite films have exhibited antimicrobial activity against *E. coli* in inoculated veal meat during a 7-d storage at 4°C, with reported reductions of > 1-log CFU/g (Arkoun et al., 2018).

Intelligent packaging

Intelligent packaging is a novel packaging technology that goes beyond providing a physical protective barrier between the product and packaging environment (Fang et al., 2017). Intelligent packaging systems are designed to monitor this interaction through indicators and sensors and have been commercially used as indicators of freshness, atmosphere integrity, time and temperature, and radio frequency identification (Fuertes et al., 2016). When combined with nanotechnology, intelligent packaging can be applied as a rapid monitoring intervention for food safety. Nanosensors can be used to detect changes in oxygen levels (Borisov and Klimant, 2009), temperature fluctuations during storage (Nopwinyuwong et al., 2014), and formation of toxic compounds as indicators of microbial growth (Wang et al., 2011). Some examples include the development of an oxygen gas indicator from nano TiO_2 powder that can be incorporated in the packaging film (Liu et al., 2013) or the coupling of gold nanoprobes with superparamagnetic beads for the detection of

aflatoxin M1 in milk (Zhang et al., 2013). Future applications of this technology in food safety include incorporation of fluorescent nanoparticles to detect pathogens and their toxins in food samples (Stanisavljevic et al., 2015). Quantum dots have been successfully used, for example, in the development of Förster resonance energy transfer nanosensors for detection of botulinum neurotoxin A (Sapsford et al., 2011) and staphylococcal enterotoxin B (Vinayaka and Thakur, 2013).

Nonthermal Technologies

Consumer trends favor the production of minimally processed foods that retain "fresh" organoleptic characteristics without compromising microbiological safety and extended shelf life. Traditional thermal processing technologies of foods are considered reliable interventions but can induce undesirable effects on the sensorial and nutritional value of certain food products. In recent years, researchers have focused efforts toward the development of nonthermal technologies characterized by low treatment intensity and high efficiency that are able to provide a comparable level of protection against microbial and enzymatic activity while maintaining food quality (Bhavya and Umesh Hebbar, 2017; Barbosa-Cánovas and Zhang, 2019; Pérez-Baltar et al., 2020).

High-pressure processing

High-pressure processing (HPP), a nonthermal food preservation technology, relies on the application of high pressure (100–1,000 MPa) for the inactivation of spoilage organisms and foodborne pathogens (Torres and Velazquez, 2005). Industrial applications of HPP for food safety has been growing rapidly in recent years, especially with RTE meats and seafood (Huang et al., 2017).

Implementation of HPP in meat processing has been approved by the USDA-FSIS as it has shown remarkable capability of inhibiting the growth of *L. monocytogenes* in post-lethality–exposed RTE meats (USDA-FSIS, 2012, 2014). Its applicability as an effective antimicrobial intervention has been demonstrated in other meat products such as dry-cured ham (Hereu et al., 2012; Bover-Cid et al., 2017), cooked ham (Jofré et al., 2008; Han et al., 2011), and ground beef (Black et al., 2010; Hsu et al., 2015). Pérez-Baltar et al. (2020) showed that HPP treatment at 600 MPa for 5 min reduced *L. monocytogenes* by 2 and 3 log units on the surface and interior of deboned dry-cured hams,

respectively. Novel approaches in meat processing rely on the combination of HPP with other antimicrobial interventions as a multi-hurdle strategy to increase the lethality of HPP and decrease production costs (Hygreeva and Pandey, 2016). Combinations of HPP with extracts of *Melissa officinalis* (commonly known as lemon balm) leaves was reported to reduce *E. coli*, which included major serotypes of Shiga toxin–producing *E. coli*, by 3 to 6 $\log_{10}$ CFU/g in ground beef after 24 h of refrigerated storage (Chien et al., 2019). Pérez-Baltar et al. (2019) showed that a combination of enterocins and HPP treatment at 450 MPa for 10 min reduced *L. monocytogenes* on dry-cured ham slices for up to 30 d of storage at 4°C and 12°C. Synergistic effects of HPP and active packaging on meat products have been reported, including antimicrobial packaging incorporated with natural oils (Ahmed et al., 2017; Amaro-Blanco et al., 2018), edible films supplemented with probiotics (Pavli et al., 2018), and nisin-incorporated polyvinyl alcohol films (Marcos et al., 2013).

HPP can be combined with heat to improve inactivation of pathogenic spores in meat products (Zhu et al., 2008; Silva, 2016), a process known as pressure-assisted thermal processing (PATP; Valdez-Fragoso et al., 2011). The PATP can quickly increase the temperature of food as a result of compression heating due to high pressure, thus minimizing the defects caused by high temperatures, as sterilization is attained in a shorter time with lower temperature (Barbosa-Cánovas et al., 2014). Shorter processing times might not inactivate *C. botulinum*, which would be a limiting factor for adopting this technology (Raso and Barbosa-Cánovas, 2003). With the application of PATP technology, promising results in terms of quality in foods such as chicken breast fillets and fish products have been observed. However, its potential to improve food safety in meat products needs to be further evaluated (Lau and Turek, 2007; Sevenich, 2016).

Pulsed Electrical Field (PEF)

PEF is another emerging antimicrobial technology with varied applications in the food industry (Wan et al., 2009; Buckow et al., 2013; Barbosa-Cánovas and Zhang, 2019). Analogous to other nonthermal preservation technologies, PEF can kill microorganisms without undesirable changes to the organoleptic characteristics in foods (Buckow et al., 2013). The technology consists of application of short, high-voltage electric field pulses to food that is placed between 2 electrodes. For food safety applications, electric field

strengths of 20 to 50 kV/cm for 1–10 μs are necessary (Buckow et al., 2013). PEF has been proven to be a successful decontamination technology in many liquid foods, such as milk (Pina-Pérez et al., 2012), juices (Buckow et al., 2013; Jin et al., 2014), and liquid eggs (Monfort et al., 2010; Espina et al., 2014). However, its preservative efficacy in meat products seems limited, due to the poor conductivity associated with high protein and fat levels (Bhat et al., 2019). Bolton et al. (2002) reported that PEF treatment of beef burgers and trimmings was unsuccessful at reducing *E. coli* O157:H7, which was further supported by Stachelska et al. (2012). The authors showed that a PEF treatment of 300 V/m at a frequency of 28 MHz did not inactivate *Yersinia enterocolitica* in minced beef; however, reductions were observed when a frequency of 2,800 MHz was used. Enhanced antimicrobial efficacy of PEF has been reported in meat solutions (Rojas et al., 2007) and meat products immersed in brine (Saif et al., 2006). However, this technology continues to have limited applicability in enhancing the microbiological safety of meat and meat products.

Pulsed light

Pulsed light technology is another form of nonthermal technology that has been gaining popularity in recent years for its food safety applications (Heinrich et al., 2015; Bhavya and Umesh Hebbar, 2017). Pulsed light uses high-frequency light pulses of varied wavelengths (200–1,100 nm) for short time periods to achieve microbial inactivation in foods (Dunn et al., 1995; Bhavya and Umesh Hebbar, 2017). Similar to PEF, its efficacy as a preservation technology has been extensively reviewed in liquid foods (Palgan et al., 2011; Pataro et al., 2011), while studies evaluating its antimicrobial effects on meat and meat products are limited. Pulsed light has the potential to enhance microbiological safety and shelf life of RTE meat products at post-packaging (Hierro et al., 2011, 2012). In a study by Hierro et al. (2011), the surface application of PL at 8.4 J/cm^2 resulted in 1.78 and 1.11 log$_{10}$ CFU/cm^2 reductions of *L. monocytogenes* in vacuum-packaged cooked ham and bologna slices, respectively. Similar reductions were achieved for *L. monocytogenes* and *S.* Typhimurium on the surface of dry-cured meat products when pulsed light was applied at 11.9 J/cm^2 (Ganan et al., 2013).

Cold plasma technology

Cold plasma technology is a novel nonthermal treatment exhibiting a wide range of activity against major foodborne pathogens of concern to the meat industry (Yun et al., 2010; Ziuzina et al., 2013; Han et al., 2016; Yong et al., 2017). Cold plasma technology generates reactive oxygen species, reactive nitrogen species, and ultraviolet (UV) radiation that can induce lesions on cell membranes and DNA damage (Laroussi et al., 2003). Hence, this technology can inactivate bacteria, fungi, and even viruses of food safety importance (Lacombe et al., 2017; Yong et al., 2017; Sen et al., 2019). Various methods of plasma technology have been investigated for meat decontamination. Exposure to dielectric barrier discharge plasma, for example, can achieve reductions of ≤0.5 log$_{10}$ CFU/g for *E. coli* and *L. monocytogenes* in pork loins with minimum impact on food quality (Kim et al., 2013). Radio-frequency atmospheric pressure plasma has been shown to inactivate *S. aureus* inoculated onto the surface of beef jerky; however, inactivation was associated with longer treatment times (8 min) that increase the temperature of the food product (Kim et al., 2014). Yong et al. (2017) also investigated the antimicrobial effects of cold plasma technology on beef jerky, reporting that application of a flexible thin-layer plasma treatment for 10 min could induce reductions of 2 to 3 log$_{10}$ CFU/g on microbial populations of *E. coli* O157:H7, *L. monocytogenes*, *S.* Typhimurium, and *Aspergillus flavus*. Furthermore, atmospheric pressure plasma has also shown efficacy against pathogenic bacteria on the surface of meat packaging films without compromising physicochemical and sensorial properties (Bauer et al., 2017). This technology therefore serves as a desirable candidate in multi-hurdle approaches with extensive applications in food packaging surface decontamination (Pankaj et al., 2014).

Irradiation

Irradiation is an established and effective decontamination technology for the production of safe foods; however, consumer perceptions have limited the acceptability of irradiated meat products. The technology was authorized for use in red meats by the USDA in 1997 (62 FR 64107) (Federal Register, 1997), and it has proven successful at controlling *L. monocytogenes* in RTE meat products upon refrigerated storage (Sommers et al., 2004). Nonthermal applications of irradiation for food safety purposes consist of low doses of ionizing radiation, usually gamma, ranging from 1 to 10 kGy. Doses as low as 3 kGy can reduce bacterial loads of *E. coli* O157:H7 and *L. monocytogenes* in raw beef sausage by more than 3 log units and maintain undetectable levels of the pathogens

during refrigerated storage for 12 d (Badr, 2005). Furthermore, Jo et al. (2004) showed that irradiation doses of 4 kGy applied to marinated beef ribs were able to inactivate all 6 $\log_{10}$ CFU/g of *S. aureus*, *B. cereus*, *S.* Typhimurium, and *E. coli* during storage at 4°C.

Electron beam irradiation has emerged in recent years as a food decontamination technology with comparable efficacy to the more traditional gamma rays (Jo et al., 2004). This technology has a high-energy beam of pulsed electrons as the source of ionizing radiation that can disrupt microbial cells (Lung et al., 2015). As reported by Kundu et al. (2014), doses of electron beam treatment as low as 1 kGy can reduce bacterial populations of *E. coli* on beef surfaces. Average log reductions of 4 $\log_{10}$ CFU/g were seen for *E. coli* O157:H7 on beef, whereas lower reductions, averaging 1 $\log_{10}$ CFU/g, were exhibited for *Salmonella* serotypes. The potential of electron beam irradiation technology was also highlighted by Cabeza et al. (2009), who reported inactivation of *L. innocua* and serovars of *S. enterica* on dry fermented meat products when a dose of 1.3 kGy of electron beam irradiation was applied.

Ultrasound

Ultrasound technology for food preservation relies on the application of sound pressure waves with a frequency greater than 20 kHz. Commonly known as high-power ultrasound, the antimicrobial effects of this technology are due to inducing chemical alterations on microbial cell membranes and generation of free radicals (Chemat et al., 2011). Ultrasound treatments at high intensity, above 1 W/cm^2, with frequencies ranging between 20 and 500 kHz have been successfully used for decontamination of juices (Ferrario et al., 2015) and fresh produce (São José et al., 2012). The potential of high-power ultrasound as a decontamination technology for application in meat and poultry products has also been investigated, yet data are still limited (Haughton et al., 2012). Researchers report inconsistent antimicrobial effects of ultrasound technology when the technology is used as a single hurdle (Birk and Knøchel, 2009; Morild et al., 2011; Kordowska-Wiater and Stasiak, 2011). In a recent study, Kang et al. (2017) showed that ultrasound treatment of 20.96 W/cm^2 for 120 min effectively inhibited *E. coli* O157:H7 in brine for curing but could not reduce pathogen populations on beef. However, improved antimicrobial efficacy of ultrasound has been reported by other authors when used in combination with steam (Morild et al., 2011), marination (Birk and Knøchel, 2009), or lactic acid solutions (Kordowska-Wiater and Stasiak, 2011).

Thermal Technologies

Thermal processing to inactivate pathogens in meat products typically employ steam or hot water during meat processing. These conventional methods slowly conduct heat from the source to the thermal center of the meat, which requires longer cooking times and causes nonuniform heating of the product (Wang et al., 2009). Prolonged cooking leads to deterioration in the product quality, e.g., off-flavors and loss of nutrients (Mckenna et al., 2006). To overcome the drawbacks of conventional methods, there have been recent advancements in novel thermal processing technologies, such as ohmic heating, high-frequency heating (which involves long-time heat treatment of meat products), and radiofrequency and microwave heating (which involve generation of heat directly inside the food, thereby inactivating pathogens) (Kumar, 2018).

Ohmic heating

Ohmic heating, also referred to as electrical resistance heating, involves the passage of alternating electric current through the food to produce heat. Heat in the food is produced by electrical resistance offered by the food, which converts electrical energy to heat energy (Stratakos and Koidis, 2015). Ohmic heating leads to microbial inactivation by its thermal effects which destroy the bacterial cell membrane and enzymes in the food products (Sun et al., 2011). In addition to thermal inactivation, ohmic heating results in the phenomenon of electroporation, i.e., the formation of pores in the microbial cell membrane. This phenomenon leads to leakage of cellular contents such as amino acids, nucleic acids, and proteins, eventually causing cell death (Knirsch et al., 2010). Moreover, ohmic heating facilitates the formation of free radicals and metal ions which cause the chemical inactivation of bacterial cells (Guillou and El Murr, 2002). Several studies have been conducted to verify the efficacy of ohmic heating against pathogenic microorganisms in meat and meat products. Sengun et al. (2014) studied the effect of ohmic heating (50 Hz, 15.26 V/cm, 75°C, 0-s holding time) against *Salmonella* spp., *S. aureus*, and *L. monocytogenes* on meatballs and reported complete elimination of *Salmonella* spp., a reduction of *S. aureus* to an undetectable level from meatballs, but a lack of effect against *L. monocytogenes*. Mitelut et al. (2011) reported that ohmic heating (50 Hz, 81°C, 10 min) resulted in complete inactivation of *S. aureus* and *P. aeruginosa* in minced pork meat and meatball samples. Another study comparing the effect of

conventional steam heating (71°C, 105 min) and ohmic heating (50 Hz, 8.33 V/cm, 72°C, 15 min) against *L. innocua* in meat reported that similar inactivation of *L. innocua* by 7 $\log_{10}$ CFU/g was observed for both the treatments (Zell et al., 2010). However, inactivation by ohmic heating was achieved with a shorter heating time of 15 min compared with the conventional steam heating (105 min). Sengun et al. (2015) studied the effect ohmic heating in combination with infrared heating against *S. aureus*, *Salmonella* spp., *C. perfringens*, *L. monocytogenes*, and *E. coli* O157:H7 in meatballs and reported complete elimination of all pathogenic microorganisms tested. These results suggest that ohmic heating is an effective technology to eradicate pathogens from meat and meat products; however, its efficacy depends on processing parameters used during ohmic heating (Knirsch et al., 2010).

High-frequency heating

Radiofrequency heating. Radiofrequency heating is a volumetric method that imparts direct heat to the food by converting electrical energy into heat energy in the food itself (Guo et al., 2006). A radiofrequency heating system comprises a radiofrequency generator that produces an alternating electric field between the 2 electrodes where the food material is placed. Oscillating molecules and ions in the food material undergo a rotational movement of positive ions toward negative regions of the electric field and vice versa at a high frequency of 27 MHz (Awuah et al., 2005). This leads to molecular friction which facilitates dissipation of heat energy throughout the food material, thereby inactivating pathogens (Orsat and Raghavan, 2014). Radiofrequency heating has the ability to penetrate up to 20 cm into the food, ensuring uniform heating inside the food matrix (Altemimi et al., 2019). In recent years, the potential of radiofrequency heating has been investigated against pathogenic microorganisms in meat and meat products. Rincon and Singh (2016) reported that radiofrequency cooking (27.12 MHz and 6 kW radiofrequency oven power) of nonintact beefsteaks to 65°C resulted in a 5-log reduction of *E. coli* O157:H7, O26:H11, and O111. Another study reported that radiofrequency heating of ground beef inoculated with *E. coli* K-12 resulted in pathogen reduction to undetectable levels (Guo et al., 2006). Byrne et al. (2010) investigated the efficacy of radiofrequency heating (500 W, 80°C, 33 min) and reported 5.3 and 6.9 $\log_{10}$ CFU/g reductions in *B. cereus* and *C. perfringens*, respectively, in pork luncheon rolls. Schlisselberg et al. (2013) studied the effect of radiofrequency heating (7.5 min) on

S. Typhimurium, *E. coli*, and *L. monocytogenes* inoculated on meatballs and reported that radiofrequency treatment resulted in reduction of *Salmonella* by 5.5 $\log_{10}$ CFU/g and *E. coli* populations below the limit of detection, while *L. monocytogenes* inoculated on meatballs were resistant to radiofrequency cooking (reduction < 0.5 $\log_{10}$ CFU/g). Limited documentation is available to justify the resistant nature of *L. monocytogenes* to heat generated by radiofrequency. While the efficiency of radiofrequency heating against pathogenic bacteria in meat has been evaluated, more research is required to explore its potential in improving the safety of RTE meat products.

Microwave heating. Microwave heating technology is widely used in households; however, it has a limited industrial acceptance for improving the safety of meat products (Stratakos and Koidis, 2015). Similar to radiofrequency heating, microwave heating results in volumetric heating in which heat is generated inside the food matrix from the conversion of electromagnetic radiations (915–2,450 MHz) into thermal energy, increasing the temperature of food at a faster rate (Hebbar and Rastogi, 2012). In a study conducted to explore the antimicrobial efficacy of microwave heating against *E. coli* O157:H7 inoculated on mechanically tenderized beef, it was found that microwave heating at 80°C for 1 min eliminated *E. coli* O157:H7 (Huang and Sites, 2010). The authors further suggested that a 2-step microwave heating, i.e., initial heating (65°C for 1 min) followed by secondary heating (65°C for 3 min or 70°C for >1 min) eliminated *E. coli* O157:H7 from the samples resulting in uniform heating while preventing overcooking or internal explosions in the meat product. Rodríguez-Marval et al. (2009) showed that microwave heating (1,100 W at 2,450 MHz) of frankfurters for 75 s can reduce *L. monocytogenes* by up to 3.7 $\log_{10}$ CFU/cm^2. It has also been reported that the electromagnetic energy in microwave heating leads to the thermal irreversible denaturation of proteins, nucleic acids, and enzymes in the microorganisms, eventually leading to cell death (Dev et al., 2012). However, microwave heating is often associated with the problem of nonuniform heating in the product, which can possibly lead to the survival of pathogens in the cold spots within the food (Ahmed and Ramaswamy, 2004). Therefore, to improve the efficiency of microwave heating for microbial safety of meat products, it is recommended to use this technique in combination with traditional heating such as in microwave assisted pasteurization system or microwave assisted thermal sterilization (MATS) (Neetoo

et al., 2012). MATS is the combination of microwave heating with thermal sterilization and utilizes water as a heating medium (initial heating step) followed by microwave heating of food (Khan et al., 2017). MATS has been suggested as an emerging technology that permits effective sterilization while preserving the nutritional, sensory, and quality attributes of food, thereby overcoming the limitations of microwave heating (Barbosa-Cánovas et al., 2014; Soni et al., 2020). Limited documentation suggesting the efficacy of MATS in improving the microbial safety of meat and meat products is available, thus warranting future research.

Other Emerging Technologies

A review of the literature suggests that other technologies such as chemical and biological interventions are widely and successfully used for reduction of pathogens in meat and meat products. Chemical interventions including organic acids, oxidizing antimicrobials, and ozone have been widely implemented for meat safety; however, negative consumer perceptions about chemical antimicrobials have prompted the need to investigate and adopt alternative interventions such as essential oils, bacteriocins, and bacteriophages. These pathogen control strategies are further discussed below.

Organic acids

Organic acids such as lactic and acetic acids are commonly used for reducing the prevalence and number of pathogens during meat processing. Organic acids can be applied pre evisceration (after hide removal) or post evisceration before chilling, during chilling, or after chilling. The most common route of application is spraying in a spray cabinet, but immersion may also be used (Loretz et al., 2011; King et al., 2012; EFSA CEP Panel, 2018). The efficacy of antimicrobial activity depends on the type of meat product, initial microbial load, type of bacterial contaminants, and ability to form biofilms (Lianou et al., 2012; Koutsoumanis and Skandamis, 2013); however, operational parameters such as temperature and duration of application as well as coverage and contact time (Lianou et al., 2012; DeGreer et al., 2016) are critical for efficacy against pathogens. Concerns about the use of organic acids that can limit their use during meat processing include quality retention, acid adaptation, and hazards for operators (Koutsoumanis and Skandamis, 2013).

Peroxyacetic acid

Peroxyacetic acid (PAA) belongs to a class of man-made chemicals known as organic peroxides (Lianou et al., 2012). The high oxidizing potential and low pH of PAA ensures it functions well as an antimicrobial; however, PAA can also be used over a wide range of temperatures and pH, is not affected by organic material, and does not have adverse effects on meat quality (Lianou et al., 2012; Kocharunchitt et al., 2020). It is primarily used as a carcass rinse in beef processing plants but may also be applied during spray chilling of carcasses (Cap et al., 2019). However, some research has shown that it may be more effective when sprayed on hot carcasses (Han et al., 2020), but findings on the effectiveness of PAA are conflicting and depend on concentration, carcass part, application method, contact time, and stage of processing (Thomas et al., 2020).

Electrolyzed oxidizing water

Electrolyzed oxidizing water (EOW) is produced by electrolyzing water and salt in an electrolysis chamber. When electric current passes through the chamber, the saline solution dissociates into alkaline and acidic EOW. Alkaline EOW has strong reducing capacity and can be used in place of a detergent (Cheng et al., 2012), while acidic EOW has strong oxidation reduction potential, making it a good antimicrobial against microorganisms (Al-Holy and Rasco, 2015). EOW is generated on-site, which eliminates problems with transport, storage, and handling of dangerous chlorine. However, it loses antimicrobial activity quickly if not continuously generated due to evaporation of chlorine (Cheng et al., 2012).

Ozonation

Ozone is an allotrope of oxygen with strong oxidative properties against both gram-positive and gram-negative bacteria (Cardenas et al., 2011; Kalchayanand et al., 2019). The two main methods to generate ozone are photochemical (UV) and corona discharge, with UV being the most applicable in the food industry (Brodowska et al., 2018). Use of ozone is promising since it does not leave chemical residues, can be applied to many different types of foods, and is relatively eco-friendly (Tapp and Rice, 2012; Brodowska et al., 2018; Pandiselvam et al., 2019). However, some disadvantages include that ozone cannot be stored and must be generated on-site for application, since it has a relatively short half-life.

Additionally, the effectiveness of ozone relies on factors such as type of meat product, target microorganism, and initial level of contamination (Chawla et al., 2012; Miller et al., 2013; Brodowska et al., 2018).

Essential oils

Essential oils are plant-based products that have shown a wide range of antimicrobial activity against spoilage and pathogenic microorganisms (Dussault et al., 2014; Liu et al., 2017). The antimicrobial effects of essential oils come from their major bioactive compounds (e.g., terpenes such as thymol and carvacrol or phenylpropanoids such as cinnamaldehyde and eugenol) with antimicrobial efficacy dependent on the composition and concentration of mixtures of bioactive compounds as well as the species and strain of the target microorganisms (Efenberger-Szmechtyk et al., 2020). Essential oils are limited in use because of their sensory changes to meat products, unknown toxicity, and marked decrease in activity in food systems versus in vitro (Hygreeva et al., 2014). They may be better suited for use in a hurdle system in which lower concentrations can be combined with other antimicrobial technologies (Jayasena and Jo, 2013).

Bacteriocins

Bacteriocins are natural antimicrobials that are extracellularly released bioactive peptides synthesized by the ribosome of bacteria and have been reported to have bactericidal or bacteriostatic activity against closely related microbial species by destroying the cytoplasmic membrane (Castellano et al., 2017; K ska et al., 2017; da Costa et al., 2019). Bacteriocins generally show a wide spectrum of activity against gram-positive bacteria but may require impairment of the outer membrane by other methods before they can be effective against gram-negative bacteria (Castellano et al., 2017). While many bacteria are capable of producing bacteriocins, lactic acid bacteria are the most commonly studied because of their application in the food industry (Kareem and Razavi, 2020). There are 2 methods to incorporate bacteriocins into meat products: (1) addition of purified or semi-purified bacteriocins into products or (2) use of bacteriocin-producing bacterial strains for in situ production (Castellano et al., 2017; K ska et al., 2017; da Costa et al., 2019). Bacteriocins are limited in use because their effectiveness depends on interaction with the food matrix, target bacteria, or meat microbiota (Todorov et al., 2010; Campos et al., 2013). Furthermore, there is limited information about their toxicity and presence of virulence factors (Carneiro et al., 2014; Favaro and Todorov, 2017), making it challenging to incorporate as an intervention for safety of meat and meat products.

Bacteriophages

Bacteriophages are viruses that infect and kill bacterial cells. There are numerous post-harvest applications for bacteriophages given their activity against a broad spectrum of foodborne pathogenic bacteria (Yeh et al., 2018). Phages are highly specific to one bacterial species or even one strain of a species, which means they have limited application and bacterial targets may rapidly develop resistance (Zhang et al., 2015). Therefore, developing bacteriophage cocktails containing multiple, diverse phages that use different bacterial surface receptors could counter this limitation (Moye et al., 2018). There are multiple limiting factors for the use of bacteriophages in meat production, including decrease in bacteriophage titers when applied to meat products, reduction (but not elimination) of bacterial targets, and inhibition of efficacy when used with chemical sanitizers, food additives, or antibiotics (Cooper, 2016).

Conclusions

New technologies play an important role and have shown potential benefits for meat processors and consumers. However, these technologies should be a part of a multi-hurdle approach to food safety as there is limited information about the success of any single technology individually controlling and/or eliminating the hazards. Additionally, success of application of technologies to enhance meat safety relies on research demonstrating enhancement of safety of meat and meat products without compromising quality, responding to consumer concerns, and offering tangible benefits of meat processing technologies.

Literature Cited

Agrimonti, C., J. C. White, S. Tonetti, and N. Marmiroli. 2019. Antimicrobial activity of cellulosic pads amended with emulsions of essential oils of oregano, thyme and cinnamon against microorganisms in minced beef meat. Int. J. Food Microbiol. 305:108246. https://doi.org/10.1016/j.ijfoodmicro.2019.108246.

Ahmed, J., and H. S. Ramaswamy. 2004. Microwave pasteurization and sterilization of foods. Food Sci Tech. Marcel Dekker, New York. 167:691.

Ahmed, J., M. Mulla, and Y. A. Arfat. 2017. Application of high-pressure processing and polylactide/cinnamon oil packaging on chicken sample for inactivation and inhibition of *Listeria monocytogenes* and *Salmonella* Typhimurium, and post-processing film properties. Food Control. 78:160–168. https://doi.org/10.1016/j.foodcont.2017.02.023.

Al-Holy, M. A., and B. A. Rasco. 2015. The bactericidal activity of acidic electrolyzed oxidizing water against *Escherichia* coli O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes* on raw fish, chicken, and beef surfaces. Food Control. 54:317–21. https://doi.org/10.1016/j.foodcont.2015.02.017.

Altemimi, A., S. N. Aziz, A. R. Al-HiIphy, N. Lakhssassi, D. G. Watson, and S. A. Ibrahim. 2019. Critical review of radio-frequency (RF) heating applications in food processing. Food Quality and Safety. 3:81–91. https://doi.org/10.1093/fqsafe/fyz002.

Amaro-Blanco, G., J. Delgado-Adámez, M. J. Martín, and R. Ramírez. 2018. Active packaging using an olive leaf extract and high pressure processing for preservation of sliced dry-cured shoulders from Iberian pigs. Innov. Food Sci. Emerg. 45:1–9. https://doi.org/10.1016/j.ifset.2017.09.017.

Arkoun, M., F. Daigle, R. A. Holley, M. C. Heuzey, and A. Ajji. 2018. Chitosan-based nanofibers as bioactive meat packaging materials. Packag. Technol. Sci. 31:185–195. https://doi.org/10.1002/pts.2366.

Awuah, G. B., H. S. Ramaswamy, A. Economides, and K. Mallikarjunan. 2005. Inactivation of *Escherichia coli* K-12 and *Listeria innocua* in milk using radio frequency (RF) heating. Innov. Food Sci. Emerg. 6:396–402. https://doi.org/10.1016/j.ifset.2005.06.002.

Badr, H. M. 2005. Elimination of *Escherichia coli* O 157: H7 and *Listeria monocytogenes* from raw beef sausage by γ-irradiation. Mol. Nutr. Food Res. 49:343–349. https://doi.org/10.1002/mnfr.200400095.

Barbiroli, A., A. Musatti, G. Capretti, S. Iametti, and M. Rollini. 2017. Sakacin-A antimicrobial packaging for decreasing *Listeria* contamination in thin-cut meat: preliminary assessment. J. Sci. Food Agr. 97:1042–1047. https://doi.org/10.1002/jsfa.8120.

Barbosa-Cánovas, G. V., and Q. H. Zhang. (Eds.). 2019. Pulsed electric fields in food processing: Fundamental aspects and applications. CRC Press, Boca Raton, FL.

Barbosa-Cánovas, G. V., I. Medina-Meza, K. Cando an, and D. Bermúdez-Aguirre. 2014. Advanced retorting, microwave assisted thermal sterilization (MATS), and pressure assisted thermal sterilization (PATS) to process meat products. Meat Sci. 98:420–434. https://doi.org/10.1016/j.meatsci.2014.06.027.

Barkocy-Gallagher, G. A., T. M. Arthur, M. Rivera-Betancourt, X. Nou, S. D. Shackelford, T. L. Wheeler, and M. Koohmaraie. 2003. Seasonal prevalence of Shiga toxin–producing *Escherichia coli*, including O157: H7 and non-O157 serotypes, and Salmonella in commercial beef processing plants. J. Food Protect. 66:1978–1986. https://doi.org/10.4315/0362-028x-66.11.1978.

Bauer, A., Y. Ni, S. Bauer, P. Paulsen, M. Modic, J. L. Walsh, and F. J. M. Smulders. 2017. The effects of atmospheric pressure cold plasma treatment on microbiological, physical-chemical and sensory characteristics of vacuum packaged beef loin. Meat Sci. 128:77–87. https://doi.org/10.1016/j.meatsci.2017.02.003.

Bell, R. G. 1997. Distribution and sources of microbial contamination on beef carcasses. J. Appl. Microbiol. 82:292–300. https://doi.org/10.1046/j.1365-2672.1997.00356.x.

Bhat, Z. F., J. D. Morton, S. L. Mason, and A. E. D. A. Bekhit. 2019. Current and future prospects for the use of pulsed electric field in the meat industry. Crit. Rev. Food Sci. 59:1660–1674. https://doi.org/10.1080/10408398.2018.1425825.

Bhavya, M. L., and H. Umesh Hebbar. 2017. Pulsed light processing of foods for microbial safety. Food Quality and Safety. 1:187–202. https://doi.org/10.1093/fqsafe/fyx017.

Birk, T., and S. Knøchel. 2009. Fate of food-associated bacteria in pork as affected by marinade, temperature, and ultrasound. J. Food Protect. 72:549–555. https://doi.org/10.4315/0362-028x-72.3.549.

Black, E. P., K. A. Hirneisen, D. G. Hoover, and K. E. Kniel. 2010. Fate of *Escherichia coli* O157: H7 in ground beef following high-pressure processing and freezing. J. Appl. Microbiol. 108:1352–1360. https://doi.org/10.1111/j.1365-2672.2009.04532.x.

Bolton, D. J., T. Catarame, C. Byrne, J. J. Sheridan, D. A. McDowell, and I. S. Blair. 2002. The ineffectiveness of organic acids, freezing and pulsed electric fields to control *Escherichia coli* O157: H7 in beef burgers. Lett. Appl. Microbiol. 34:139–143. https://doi.org/10.1046/j.1472-765x.2002.01063.x.

Borisov, S. M., and I. Klimant. 2009. Luminescent nanobeads for optical sensing and imaging of dissolved oxygen. Microchim. Acta. 164:7. https://doi.org/10.1007/s00604-008-0047-9.

Bosilevac, J. M., M. N. Guerini, N. Kalchayanand, and M. Koohmaraie. 2009. Prevalence and characterization of salmonellae in commercial ground beef in the United States. Appl. Environ. Microb. 75:1892–1900. https://doi.org/10.1128/AEM.02530-08.

Bover-Cid, S., N. Belletti, T. Aymerich, and M. Garriga. 2017. Modelling the impact of water activity and fat content of dry-cured ham on the reduction of *Salmonella enterica* by high pressure processing. Meat Sci. 123:120–125. https://doi.org/10.1016/j.meatsci.2016.09.014.

Brodowska, A. J., A. Nowak, and K. migielski. 2018. Ozone in the food industry: Principles of ozone treatment, mechanisms of action, and applications: An overview. Crit. Rev. Food Sci. 58:2176–2201. https://doi.org/10.1080/10408398.2017.1308313.

Bruhn, C. M. 2007. Enhancing consumer acceptance of new processing technologies. Innov. Food Sci. Emerg. 8:555–558. https://doi.org/10.1016/j.ifset.2007.04.006.

Buckow, R., S. Ng, and S. Toepfl. 2013. Pulsed electric field processing of orange juice: a review on microbial, enzymatic, nutritional, and sensory quality and stability. Compr. Rev. Food Sci. F. 12:455–467. https://doi.org/10.1111/1541-4337.12026.

Byrne, B., J. G. Lyng, G. Dunne, and D. J. Bolton. 2010. Radio frequency heating of comminuted meats-considerations in

relation to microbial challenge studies. Food Control. 21:125–131. https://doi.org/10.1016/j.foodcont.2009.03.003.

Cabeza, M. C., L. De La Hoz, R. Velasco, M. I. Cambero, and J. A. Ordóñez. 2009. Safety and quality of ready-to-eat dry fermented sausages subjected to E-beam radiation. Meat Sci. 83:320–327. https://doi.org/10.1016/j.meatsci.2009.05.019.

Callaway, T. R., M. A. Carr, T. S. Edrington, R. C. Anderson, and D. J. Nisbet. 2009. Diet, *Escherichia coli* O157: H7, and cattle: a review after 10 years. Curr. Issues Mol. Biol. 11:67–79.

Campos, C., M. Castro, F. Rivas, and L. Schelegueda. 2013. Bacteriocins in food: Evaluation of the factors affecting their effectiveness. In: A. Méndez-Vilas, editor, Microbial pathogens and strategies for combating them: Sciences, technology and education. Formatex, Badajoz, Spain. p. 994–1004.

Cap, M., S. Vaudagna, M. Mozgovoj, T. Soteras, A. Sucari, M. Signorini, and G. Leotta. 2019. Inactivation of Shiga toxin-producing *Escherichia coli* in fresh beef by electrolytically-generated hypochlorous acid, peroxyacetic acid, lactic acid and caprylic acid. Meat Sci. 157:107886. https://doi.org/10.1016/j.meatsci.2019.107886.

Cardenas, F. C., S. Andres, L. Giannuzzi, and N. Zaritzky. 2011. Antimicrobial action and effects on beef quality attributes of a gaseous ozone treatment at refrigeration temperatures. Food Control. 22:1442–1447. https://doi.org/10.1016/j.foodcont.2011.03.006.

Carneiro, B., A. Braga, M. Batista, P. Rahal, L. Favaro, A. Penna, and S. Todorov. 2014. *Lactobacillus plantarum* ST202Ch and *Lactobacillus plantarum* ST216Ch – What are the limitations for application? Journal of Nutritional Health & Food Engineering. 1:61–63. https://doi.org/10.15406/jnhfe.2014.01.00010.

Carrasco, E., A. Morales-Rueda, and R. M. García-Gimeno. 2012. Cross-contamination and recontamination by Salmonella in foods: A review. Food Res. Int. 45:545–556. https://doi.org/10.1016/j.foodres.2011.11.004.

Castellano, P., M. Pérez Ibarreche, M. Blanco Massani, C. Fontana, and G. M. Vignolo. 2017. Strategies for pathogen biocontrol using lactic acid bacteria and their metabolites: A focus on meat ecosystems and industrial environments. Microorganisms. 5:1–25. https://doi.org/10.3390/microorganisms5030038.

CDC. 2019. Surveillance for foodborne disease outbreaks, United States, 2017, Annual Report. Atlanta, GA, U.S. Department of Health and Human Services, Centers for Disease Control and Prevention.

Chawla, A. S., D. R. Kasler, S. K. Sastry, and A. E. Yousef. 2012. Microbial decontamination of food using ozone. In: A. Demirci, and M. O. Ngadi, editors, Microbial decontamination in the food industry: Novel methods and applications. Woodhead Publishing, Cambridge, UK. p. 495–532.

Chemat, F., Zill-e-Huma, M. K. Khan. 2011. Applications of ultrasound in food technology: Processing, preservation and extraction. Ultrason. Sonochem. 2011;18:813–835. https://doi.org/10.1016/j.ultsonch.2010.11.023.

Chen, J., and A. L. Brody. 2013. Use of active packaging structures to control the microbial quality of a ready-to-eat meat product. Food Control. 30:306–310. https://doi.org/10.1016/j.foodcont.2012.07.002.

Cheng, K.-C., S. R. S. Dev, K. L. Bialka, and A. Demirci. 2012. Electrolyzed oxidizing water for microbial decontamination of food. In: A. Demirci, and M. O. Ngadi, editors, Microbial decontamination in the food industry: Novel methods and applications. Woodhead Publishing, Cambridge, UK. p. 563–591.

Chien, S. Y., S. Sheen, C. Sommers, and L. Y. Sheen. 2019. Combination effect of high-pressure processing and essential oil (*Melissa officinalis* extracts) or their constituents for the inactivation of *Escherichia coli* in ground beef. Food Bioprocess Tech. 12:359–370.

Cooper, I. R. 2016. A review of current methods using bacteriophages in live animals, food and animal products intended for human consumption. J. Microbiol Meth. 130:38–47. https://doi.org/10.1016/j.mimet.2016.07.027.

da Costa, R. J., F. L. S. Voloski, R. G. Mondadori, E. H. Duval, and A. M. Fiorentini. 2019. Preservation of meat products with bacteriocins produced by lactic acid bacteria isolated from meat. J. Food Quality. 1:1–12. https://doi.org/10.1155/2019/4726510.

DeGreer, S. L., L. Wang, G. N. Hill, M. Singh, S. F. Bilgili, and C. L. Bratcher. 2016. Optimizing application parameters for lactic acid and sodium metasilicate against pathogens on fresh beef, pork and deli meats. Meat Sci. 118:28–33. https://doi.org/10.1016/j.meatsci.2016.03.008.

Dehnad, D., H. Mirzaei, Z. Emam-Djomeh, S. M. Jafari, and S. Dadashi. 2014. Thermal and antimicrobial properties of chitosan–nanocellulose films for extending shelf life of ground meat. Carbohyd. Polym. 109:148–154. https://doi.org/10.1016/j.carbpol.2014.03.063.

Dev, S. R. S., S. L. Birla, G. S. V. Raghavan, and J. Subbiah. 2012. Microbial decontamination of food by microwave (MW) and radio frequency (RF). In: Microbial decontamination in the food industry. Woodhead Publishing, Cambridge, UK. p. 274–299.

Duncan, T. V. 2011. Applications of nanotechnology in food packaging and food safety: barrier materials, antimicrobials and sensors. J. Colloid Interf. Sci. 363:1–24. https://doi.org/10.1016/j.jcis.2011.07.017.

Dunn, J., T. Ott, and W. Clark. 1995. Pulsed-light treatment of food and packaging. Food Technol-Chicago. 49:95–98.

Dussault, D., K. D. Vu, and M. Lacroix. 2014. In vitro evaluation of antimicrobial activities of various commercial essential oils, oleoresin and pure compounds against food pathogens and application in ham. Meat Sci. 96:514–520. https://doi.org/10.1016/j.meatsci.2013.08.015.

Efenberger-Szmechtyk, M., A. Nowak, and A. Czyzowska. 2020. Plant extracts rich in polyphenols: Antibacterial agents and natural preservatives for meat and meat products. Crit. Rev. Food Sci. 1–30. https://doi.org/10.1080/10408398.2020.1722060.

EFSA BIOHAZ Panel. 2018. Scientific opinion on the *Listeria monocytogenes* contamination of ready-to-eat foods and the risk for human health in the EU. European Food Safety Authority (EFSA) Panel on Biological Hazards (BIOAZ). 16:5134–5173.

EFSA CEP Panel. 2018. Evaluation of the safety and efficacy of lactic and acetic acids to reduce microbiological surface contamination on pork carcasses and pork cuts. European Food

Safety Authority (EFSA) Panel on Food Contact Materials, Enzymes and Processing Aids (CEP). 16:5482–5558.

Elder, R. O., J. E. Keen, G. R. Siragusa, G. A. Barkocy-Gallagher, M. Koohmaraie, and W. W. Laegreid. 2000. Correlation of enterohemorrhagic *Escherichia coli* O157 prevalence in feces, hides, and carcasses of beef cattle during processing. P. Natl. Acad. Sci. USA. 97:2999–3003. https://doi.org/10.1073/pnas.060024897.

Ellis, M., K. Cooksey, P. Dawson, I. Han, and P. Vergano. 2006. Quality of fresh chicken breasts using a combination of modified atmosphere packaging and chlorine dioxide sachets. J. Food Protect. 69:1991–1996. https://doi.org/10.4315/0362-028x-69.8.1991.

Emiro lu, Z. K., G. P. Yemi , B. K. Co kun, and K. Cando an. 2010. Antimicrobial activity of soy edible films incorporated with thyme and oregano essential oils on fresh ground beef patties. Meat Sci. 86:283–288. https://doi.org/10.1016/j.meatsci.2010.04.016.

Espina, L., S. Monfort, I. Álvarez, D. García-Gonzalo, and R. Pagán. 2014. Combination of pulsed electric fields, mild heat and essential oils as an alternative to the ultrapasteurization of liquid whole egg. Int. J. Food Microbiol. 189:119–125. https://doi.org/10.1016/j.ijfoodmicro.2014.08.002.

Fang, Z., Y. Zhao, R. D. Warner, and S. K. Johnson. 2017. Active and intelligent packaging in meat industry. Trends Food Sci Tech. 61:60–71. https://doi.org/10.1016/j.tifs.2017.01.002.

FAO. 2019. Food outlook. Biannual report on global food markets. Rome, Food and Agriculture Organization of the United Nations. June 2019. http://www.fao.org/3/ca4526en/ca4526en.pdf. (Accessed 27 April 2020).

Farkas, D. F. 2016. A short history of research and development efforts leading to the commercialization of high-pressure processing of food. In: High pressure processing of food. Springer, New York, NY. p. 19–36.

Favaro, L., and S. D. Todorov. 2017. Bacteriocinogenic LAB strains for fermented meat preservation: perspectives, challenges, and limitations. Probiotics Antimicro. 9:444–458. https://doi.org/10.1007/s12602-017-9330-6.

Federal Register. 1997. Irradiation in the production, processing and handling of food. 62 FR 64107.

Federal Register. 2003. Control of *Listeria monocytogenes* in ready-to-eat meat and poultry products; Final Rule. 68 FR 34224.

Federal Register. 2011. Shiga toxin-producing *Escherichia coli*. 76 FR 58157.

Fernandez, A., P. Picouet, and E. Lloret. 2010. Reduction of the spoilage-related microflora in absorbent pads by silver nano-technology during modified atmosphere packaging of beef meat. J. Food Protect. 73:2263–2269. https://doi.org/10.4315/0362-028x-73.12.2263.

Ferrario, M., S. M. Alzamora, and S. Guerrero. 2015. Study of the inactivation of spoilage microorganisms in apple juice by pulsed light and ultrasound. Food Microbiol. 46:635–642. https://doi.org/10.1016/j.fm.2014.06.017.

Fuertes, G., I. Soto, R. Carrasco, M. Vargas, J. Sabattin, and C. Lagos. 2016. Intelligent packaging systems: Sensors and nanosensors to monitor food quality and safety. J. Sensors. 2016. https://doi.org/10.1155/2016/4046061.

Ganan, M., E. Hierro, X. F. Hospital, E. Barroso, and M. Fernández. 2013. Use of pulsed light to increase the safety of ready-to-eat cured meat products. Food Control. 32:512–517. https://doi.org/10.1016/j.foodcont.2013.01.022.

Gill, C. O. 2005. Sources of microbial contamination at slaughtering plants. In: Improving the safety of fresh meat. Woodhead Publishing, Sawston, UK. p. 231–243.

Glass, K. A., and M. P. Doyle. 1989. Fate of *Listeria monocytogenes* in processed meat products during refrigerated storage. Appl. Environ. Microb. 55:1565–1569.

Guillou, S., and N. El Murr. 2002. Inactivation of *Saccharomyces cerevisiae* in solution by low-amperage electric treatment. J. Appl. Microbiol. 92:860–865. https://doi.org/10.1046/j.1365-2672.2002.01593.x.

Guo, Q., P. Piyasena, G. S. Mittal, W. Si, and J. Gong. 2006. Efficacy of radio frequency cooking in the reduction of *Escherichia coli* and shelf stability of ground beef. Food Microbiol. 23:112–118. https://doi.org/10.1016/j.fm.2005.02.004.

Han, J. H. 2003. Antimicrobial food packaging. In: R. Ahvenainen, editor, Novel food packaging techniques. 1st edition. Woodhead Publishing, Sawston, UK. p. 50–70.

Han, Y., Y. Jiang, X. Xu, X. Sun, B. Xu, and G. Zhou. 2011. Effect of high pressure treatment on microbial populations of sliced vacuum-packed cooked ham. Meat Sci. 88:682–688. https://doi.org/10.1016/j.meatsci.2011.02.029.

Han, J., X. Luo, Y. Zhang, L. Zhu, Y. Mao, P. Dong, X. Yang, R. Liang, D. L. Hopkins, and Y. Zhang. 2020. Effects of spraying lactic acid and peroxyacetic acid on the bacterial decontamination and bacterial composition of beef carcasses. Meat Sci. 164:108104. https://doi.org/10.1016/j.meatsci.2020.108104.

Han, C., J. Wang, Y. Li, F. Lu, and Y. Cui. 2014. Antimicrobial-coated polypropylene films with polyvinyl alcohol in packaging of fresh beef. Meat Sci. 96:901–907. https://doi.org/10.1016/j.meatsci.2013.09.003.

Han, L., D. Ziuzina, C. Heslin, D. Boehm, A. Patange, D. M. Sango, V. P. Valdramidis, P. J. Cullen, and P. Bourke. 2016. Controlling microbial safety challenges of meat using high voltage atmospheric cold plasma. Front. Microbiol. 7:977. https://doi.org/10.3389/fmicb.2016.00977.

Haughton, P. N., J. G. Lyng, D. J. Morgan, D. A. Cronin, F. Noci, S. Fanning, and P. Whyte. 2012. An evaluation of the potential of high-intensity ultrasound for improving the microbial safety of poultry. Food Bioprocess Tech. 5:992–998. https://doi.org/10.1007/s11947-010-0372-y.

Hebbar, H. U., and N. K. Rastogi. 2012. Microwave heating of fluid foods. In: Novel thermal and non-thermal technologies for fluid foods. Academic Press. p. 369–409.

Heinrich, V., M. Zunabovic, J. Bergmair, W. Kneifel, and H. Jäger. 2015. Post-packaging application of pulsed light for microbial decontamination of solid foods: A review. Innov. Food Sci. Emerg. 30:145–156. https://doi.org/10.1016/j.ifset.2015.06.005.

Hereu, A., S. Bover-Cid, M. Garriga, and T. Aymerich. 2012. High hydrostatic pressure and biopreservation of dry-cured ham to meet the Food Safety Objectives for *Listeria monocytogenes*. Int. J. Food Microbiol. 154:107–112. https://doi.org/10.1016/j.ijfoodmicro.2011.02.027.

Hierro, E., E. Barroso, L. De la Hoz, J. A. Ordóñez, S. Manzano, and M. Fernández, M. 2011. Efficacy of pulsed light for shelf-life extension and inactivation of *Listeria monocytogenes* on ready-to-eat cooked meat products. Innov. Food Sci. Emerg. 12:275–281. https://doi.org/10.1016/j.ifset.2011.04.006.

Hierro, E., M. Ganan, E. Barroso, and M. Fernández, M. 2012. Pulsed light treatment for the inactivation of selected pathogens and the shelf-life extension of beef and tuna carpaccio. Int. J. Food Microbiol. 158:42–48. https://doi.org/10.1016/j.ijfoodmicro.2012.06.018.

Holck, A. L., M. K. Pettersen, M. H. Moen, and O. Sørheim. 2014. Prolonged shelf life and reduced drip loss of chicken filets by the use of carbon dioxide emitters and modified atmosphere packaging. J. Food Protect. 77:1133–1141. https://doi.org/10.4315/0362-028X.JFP-13-428.

Hsu, H., S. Sheen, J. Sites, J. Cassidy, B. Scullen, and C. Sommers. 2015. Effect of high-pressure processing on the survival of shiga toxin-producing *Escherichia coli* (Big Six vs. O157:H7) in ground beef. Food Microbiol. 48:1–7. https://doi.org/10.1016/j.fm.2014.12.002.

Huang, L., and J. Sites. 2010. New automated microwave heating process for cooking and pasteurization of microwaveable foods containing raw meats. J. Food Sci. 75:E110–E115. https://doi.org/10.1111/j.1750-3841.2009.01482.x.

Huang, H. W., S. J. Wu, J. K. Lu, Y. T. Shyu, and C. Y. Wang. 2017. Current status and future trends of high-pressure processing in food industry. Food Control. 72:1–8. https://doi.org/10.1016/j.foodcont.2016.07.019.

Hygreeva, D., and M. C. Pandey. 2016. Novel approaches in improving the quality and safety aspects of processed meat products through high pressure processing technology-A review. Trends Food Sci Tech. 54:175–185. https://doi.org/10.1016/j.tifs.2016.06.002.

Hygreeva, D., M. C. Pandey, and K. Radhakrishna. 2014. Potential applications of plant based derivatives as fat replacers, antioxidants and antimicrobials in fresh and processed meat products. Meat Sci. 98:47–57. https://doi.org/10.1016/j.meatsci.2014.04.006.

Janjarasskul, T., and S. Panuwat. 2018. Active and intelligent packaging: The indication of quality and safety. Crit. Rev. Food Sci. 58:808–831. https://doi.org/10.1080/10408398.2016.1225278.

Jayasena, D. D., and C. Jo. 2013. Essential oils as potential antimicrobial agents in meat and meat products: A review. Trends Food Sci Tech. 34:96–108.

Jin, T. Z., M. Guo, and R. Yang. 2014. Combination of pulsed electric field processing and antimicrobial bottle for extending microbiological shelf-life of pomegranate juice. Innov. Food Sci. Emerg. 26:153–158. https://doi.org/10.1016/j.ifset.2014.07.011.

Jo, C., N. Y. Lee, H. J. Kang, D. H. Shin, and M. W. Byun. 2004. Inactivation of foodborne pathogens in marinated beef rib by ionizing radiation. Food Microbiol. 21:543–548. https://doi.org/10.1016/j.fm.2003.11.005.

Jofré, A., M. Garriga, and T. Aymerich. 2008. Inhibition of *Salmonella* sp. *Listeria monocytogenes* and *Staphylococcus aureus* in cooked ham by combining antimicrobials, high hydrostatic pressure and refrigeration. Meat Sci. 78:53–59. https://doi.org/10.1016/j.meatsci.2007.06.015.

Kalchayanand, N., D. Worlie, and T. Wheeler. 2019. A novel aqueous ozone treatment as a spray chill intervention against *Escherichia coli* O157:H7 on surfaces of fresh beef. J. Food Protect. 82:1874–1878. https://doi.org/10.4315/0362-028X.JFP-19-093.

Kang, D., Y. Jiang, L. Xing, G. Zhou, and W. Zhang. 2017. Inactivation of *Escherichia coli* O157: H7 and *Bacillus cereus* by power ultrasound during the curing processing in brining liquid and beef. Food Res. Int. 102:717–727. https://doi.org/10.1016/j.foodres.2017.09.062.

Kareem, R. A., and S. H. Razavi. 2020. Plantaricin bacteriocins: As safe alternative antimicrobial peptides in food preservation–A review. J. Food Safety. 40:e12735. https://doi.org/10.1111/jfs.12735.

K ska, P., J. Stadnik, D. Zieli ska, and D. Koło yn-Krajewska. 2017. Potential of bacteriocins from lab to improve microbial quality of dry-cured and fermented meat products. Acta Scientiarum Polonorum Technologia Alimentaria. 16:119–126. https://doi.org/10.17306/J.AFS.0466.

Khan, I., C. N. Tango, S. Miskeen, B. H. Lee, and D. H. Oh. 2017. Hurdle technology: A novel approach for enhanced food quality and safety–A review. Food Control. 73:1426–1444. https://doi.org/10.1016/j.foodcont.2016.11.010.

Kim, J. S., E. J. Lee, E. H. Choi, and Y. J. Kim. 2014. Inactivation of *Staphylococcus aureus* on the beef jerky by radio-frequency atmospheric pressure plasma discharge treatment. Innov. Food Sci. Emerg. 22:124–130. https://doi.org/10.1016/j.ifset.2013.12.012.

Kim, H. J., H. I. Yong, S. Park, W. Choe, and C. Jo. 2013. Effects of dielectric barrier discharge plasma on pathogen inactivation and the physicochemical and sensory characteristics of pork loin. Curr. Appl. Phys. 13:1420–1425. https://doi.org/10.1016/j.cap.2013.04.021.

King, A. M., R. K. Miller, A. Castillo, D. B. Griffin, and M. D. Hardin. 2012. Effects of lactic acid and commercial chilling processes on survival of *Salmonella, Yersinia enterocolitica*, and *Campylobacter coli* in pork variety meats. J. Food Protect. 75:1589–1594. https://doi.org/10.4315/0362-028X.JFP-12-004.

Knirsch, M. C., C. A. Dos Santos, A. A. M. De Oliveira Soares Viciente, and T. C. Vessoni Penna. 2010. Ohmic heating – a review. Trends Food Sci Tech. 21:436–441. https://doi.org/10.1016/j.tifs.2010.06.003.

Kocharunchitt, C., L. Mellefont, J. P. Bowman, and T. Ross. 2020. Application of chlorine dioxide and peroxyacetic acid during spray chilling as a potential antimicrobial intervention for beef carcasses. Food Microbiol. 87:103355. https://doi.org/10.1016/j.fm.2019.103355.

Kordowska-Wiater, M., and D. M. Stasiak. 2011. Effect of ultrasound on survival of gram-negative bacteria on chicken skin surface. B. Vet. I. Pulawy. 55:207–210.

Koutsoumanis, K., and P. Skandamis. 2013. New research on organic acids and pathogen behavior. In: J. Sofos, editor, Advances in microbial food safety. Woodhead Publishing, Cambridge, UK. p. 355–384.

Kumar, T. 2018. A review on ohmic heating technology: Principle, applications and scope. International Journal of Agriculture, Environment and Biotechnology. 11:679–687.

Kundu, D., A. Gill, C. Lui, N. Goswami, and R. Holley. 2014. Use of low dose e-beam irradiation to reduce *E. coli* O157: H7, non-O157 (VTEC) *E. coli* and *Salmonella* viability on meat surfaces. Meat Sci. 96:413–418. https://doi.org/10.1016/j.meatsci.2013.07.034.

Lacombe, A., B. A. Niemira, J. B. Gurtler, J. Sites, G. Boyd, D. H. Kingsley, X. Li, and H. Chen. 2017. Nonthermal inactivation of norovirus surrogates on blueberries using atmospheric cold plasma. Food Microbiol. 63:1–5. https://doi.org/10.1016/j.fm.2016.10.030.

Laroussi, M., D. A. Mendis, and M. Rosenberg. 2003. Plasma interaction with microbes. New J. Phys. 5:41. https://doi.org/10.1088/1367-2630/5/1/341.

Lau, M. H., and E. J. Turek. 2007. Determination of quality differences in low-acid foods sterilized by high pressure versus retorting. In: High pressure processing of foods. p. 195–217.

Lianou, A., K. P. Koutsoumanis, and J. N. Sofos. 2012. Organic acids and other chemical treatments for microbial decontamination of food. In: A. Demirci, and M. O. Ngadi, editors, Microbial decontamination in the food industry: Novel methods and applications. Woodhead Publishing, Cambridge, UK. p. 592–664.

Liu, Y., L. C. McKeever, and N. S. Malik. 2017. Assessment of the antimicrobial activity of olive leaf extract against foodborne bacterial pathogens. Front. Microbiol. 8:1–8. https://doi.org/10.3389/fmicb.2017.00113.

Liu, X. H., S. Y. Xie, L. B. Zhou, Y. Yang, and H. B. Li. 2013. Preparation method of nano TiO2 powder and method for preparing oxygen gas indicator from nano TiO2 powder (Chinese patent). Patent CN103641163A, 28.

Loretz, M., R. Stephan, and C. Zweifel. 2011. Antibacterial activity of decontamination treatments for cattle hides and beef carcasses. Food Control. 22:347–359. https://doi.org/10.1016/j.foodcont.2010.09.004.

Lung, H. M., Y. C. Cheng, Y. H. Chang, H. W. Huang, B. B. Yang, and C. Y. Wang. 2015. Microbial decontamination of food by electron beam irradiation. Trends Food Sci Tech. 44:66–78. https://doi.org/10.1016/j.tifs.2015.03.005.

Mahdi, S. S., R. Vadood, and R. Nourdahr. 2012. Study on the antimicrobial effect of nanosilver tray packaging of minced beef at refrigerator temperature. Global Veterinaria. 9:284–289. https://doi.org/10.5829/idosi.gv.2012.9.3.1827.

Marcos, B., T. Aymerich, M. Garriga, and J. Arnau. 2013. Active packaging containing nisin and high-pressure processing as post-processing listericidal treatments for convenience fermented sausages. Food Control. 30:325–330. https://doi.org/10.1016/j.foodcont.2012.07.019.

McKenna, B. M., J. Lyng, N. Brunton, and N. Shirsat. 2006. Advances in radiofrequency and ohmic heating of meats. J. Food Eng. 77:215–29. https://doi.org/10.1016/j.jfoodeng.2005.06.052.

Miller, F. A., C. L. M. Silva, and T. R. S. Brandao. 2013. A review on ozone-based treatments for fruit and vegetables preservation. Food Eng. Rev. 5:77–106. https://doi.org/10.1007/s12393-013-9064-5.

Mitelut, A., M. Popa, M. Geicu, P. E. T. R. U. Niculita, D. Vatuiu, I. Vatuiu, I., B. Gilea, R. Balint, and R. Cramariuc. 2011. Ohmic

treatment for microbial inhibition in meat and meat products. Rom. Biotech. Lett. 16:149–152.

Monfort, S., E. Gayán, G. Saldaña, E. Puértolas, S. Condón, J. Raso, and I. Álvarez. 2010. Inactivation of *Salmonella* Typhimurium and *Staphylococcus aureus* by pulsed electric fields in liquid whole egg. Innov. Food Sci. Emerg. 11:306–313. https://doi.org/10.1016/j.ifset.2009.11.007.

Morild, R. K., P. Christiansen, A. H. Sørensen, U. Nonboe, and S. Aabo. 2011. Inactivation of pathogens on pork by steam-ultrasound treatment. J. Food Protect. 74:769–775. https://doi.org/10.4315/0362-028X.JFP-10-338.

Mousavi Khaneghah, A. M. I. N., S M. B. Hashemi, I. E , D. Fracassetti, and S. Limbo. 2018. Efficacy of antimicrobial agents for food contact applications: biological activity, incorporation into packaging, and assessment methods: a review. J. Food Protect. 81:1142–1156. https://doi.org/10.4315/0362-028X.JFP-17-509.

Moye, Z. D., J. Woolston, and A. Sulakvelidze. 2018. Bacteriophage applications for food production and processing. Viruses. 10:205. https://doi.org/10.3390/v10040205.

Muriel-Galet, V., J. N. Talbert, P. Hernandez-Munoz, R. Gavara, and J. M. Goddard. 2013. Covalent immobilization of lysozyme on ethylene vinyl alcohol films for nonmigrating antimicrobial packaging applications. J. Agr. Food Chem. 61:6720–6727. https://doi.org/10.1021/jf401818u.

Narasimha Rao, D., and N. M. Sachindra. 2002. Modified atmosphere and vacuum packaging of meat and poultry products. Food Rev. Int. 18:263–293.

Neetoo, H., H. Chen, and D. G. Hoover. 2012. Emerging methods for post-packaging microbial decontamination of food. In: Microbial decontamination in the food industry. Woodhead Publishing, Cambridge, UK. p. 746–787.

Nguyen, V. T., M. J. Gidley, and G. A. Dykes. 2008. Potential of a nisin-containing bacterial cellulose film to inhibit *Listeria monocytogenes* on processed meats. Food Microbiol. 25:471–478. https://doi.org/10.1016/j.fm.2008.01.004.

Nopwinyuwong, A., T. Kaisone, P. Hanthanon, C. Nandhivajrin, W. Boonsupthip, C. Pechyen, and P. Suppakul. 2014. Effects of nanoparticle concentration and plasticizer type on colorimetric behavior of polydiacetylene/silica nanocomposite as time-temperature indicator. Enrgy Proced. 56:423–430. https://doi.org/10.1016/j.egypro.2014.07.175.

Omer, M. K., A. Alvarez-Ordonez, M. Prieto, E. Skjerve, T. Asehun, and O. A. Alvseike. 2018. A systematic review of bacterial foodborne outbreaks related to red meat and meat products. Foodborne Pathog. Dis. 15:598–611. https://doi.org/10.1089/fpd.2017.2393.

Orsat, V., and G. V. Raghavan. 2014. Radio-frequency processing. In: Emerging technologies for food processing. Academic Press. p. 385–398.

Otoni, C. G., P. J. Espitia, R. J. Avena-Bustillos, and T. H. McHugh. 2016. Trends in antimicrobial food packaging systems: Emitting sachets and absorbent pads. Food Res. Int. 83:60–73. https://doi.org/10.1016/j.foodres.2016.02.018.

Palgan, I., I. M. Caminiti, A. Muñoz, F. Noci, P. Whyte, D. J. Morgan, D. A. Cronin, and J. G. Lyng. 2011. Effectiveness of high intensity light pulses (HILP) treatments for the control of *Escherichia coli* and *Listeria innocua* in apple juice, orange

juice and milk. Food Microbiol. 28:14–20. https://doi.org/10.1016/j.fm.2010.07.023.

Pandiselvam, R., S. Subhashini, E. P. Banuu Priya, A. Kothakota, S. V. Ramesh, and S. Shahir. 2019. Ozone based food preservation: A promising green technology for enhanced food safety. Ozone-Sci. Eng. 41:17–34. https://doi.org/10.1080/01919512.2018.1490636.

Pankaj, S. K., C. Bueno-Ferrer, N. N. Misra, V. Milosavljević, C. P. O'donnell, P. Bourke, K. M. Keener, and P. J. Cullen. 2014. Applications of cold plasma technology in food packaging. Trends Food Sci Tech. 35:5–17. https://doi.org/10.1016/j.tifs.2013.10.009.

Park, S. H., and D. H. Kang. 2015. Antimicrobial effect of chlorine dioxide gas against foodborne pathogens under differing conditions of relative humidity. Lebensm.-Wiss. Technol. 60:186–191. https://doi.org/10.1016/j.lwt.2014.09.031.

Pataro, G., A. Muñoz, I. Palgan, F. Noci, G. Ferrari, and J. G. Lyng. 2011. Bacterial inactivation in fruit juices using a continuous flow pulsed light (PL) system. Food Res. Int. 44:1642–1648. https://doi.org/10.1016/j.foodres.2011.04.048.

Pavli, F., A. A. Argyri, G. J. Nychas, C. Tassou, and N. Chorianopoulos. 2018. Use of Fourier transform infrared spectroscopy for monitoring the shelf life of ham slices packed with probiotic supplemented edible films after treatment with high pressure processing. Food Res. Int. 106:1061–1068. https://doi.org/10.1016/j.foodres.2017.12.064.

Pérez-Baltar, A., A. Serrano, D. Bravo, R. Montiel, and M. Medina. 2019. Combined effect of high pressure processing with enterocins or thymol on the inactivation of *Listeria monocytogenes* and the characteristics of sliced dry-cured ham. Food Bioprocess Tech. 12:288–297. https://doi.org/10.1007/s11947-018-2212-4.

Pérez-Baltar, A., A. Serrano, R. Montiel, and M. Medina. 2020. *Listeria monocytogenes* inactivation in deboned dry-cured hams by high pressure processing. Meat Sci. 160:107960. https://doi.org/10.1016/j.meatsci.2019.107960.

Pina-Pérez, M. C., A. Martinez-López, and D. Rodrigo. 2012. Cinnamon antimicrobial effect against *Salmonella* typhimurium cells treated by pulsed electric fields (PEF) in pasteurized skim milk beverage. Food Res. Int. 48:777–783. https://doi.org/10.1016/j.foodres.2012.06.027.

Quintavalla, S., and L. Vicini. 2002. Antimicrobial food packaging in meat industry. Meat Sci. 62:373–380. https://doi.org/10.1016/s0309-1740(02)00121-3.

Raouche, S., M. Mauricio-Iglesias, S. Peyron, V. Guillard, and N. Gontard. 2011. Combined effect of high pressure treatment and anti-microbial bio-sourced materials on microorganisms' growth in model food during storage. Innov. Food Sci. Emerg. 12:426–434. https://doi.org/10.1016/j.ifset.2011.06.012.

Raso, J., and G. V. Barbosa-Cánovas. 2003. Nonthermal preservation of foods using combined processing techniques. Crit. Rev. Food Sci. 43:265–285. https://doi.org/10.1080/10408690390826527.

Rincon, A. M., and R. K. Singh. 2016. Inactivation of Shiga toxin-producing and nonpathogenic *Escherichia coli* in non-intact steaks cooked in a radio frequency oven. Food Control. 62:390–396. https://doi.org/10.1016/j.foodcont.2015.11.021.

Rodríguez-Marval, M., I. Geornaras, P. A. Kendall, J. A. Scanga, K. E. Belk, and J. N. Sofos. 2009. Microwave oven heating for inactivation of *Listeria monocytogenes* on frankfurters before consumption. J. Food Sci. 74:M453–M460. https://doi.org/10.1111/j.1750-3841.2009.01325.x.

Rojas, M. C., S. E. Martin, R. A. Wicklund, D. D. Paulson, F. A. Desantos, and M. S. Brewer. 2007. Effect of high-intensity pulsed electric fields on survival of *Escherichia coli* K-12 suspended in meat injection solutions. J. Food Safety. 27:411–425. https://doi.org/10.1111/j.1745-4565.2007.00086.x.

Saif, S. M. H., Y. Lan, L. L. Williams, L. Joshee, and S. Wang. 2006. Reduction of *Escherichia coli* O157: H7 on goat meat surface with pulsed dc square wave signal. J. Food Eng. 77:281–288. https://doi.org/10.1016/j.jfoodeng.2005.06.031.

Sanchez-Maldonado, A. F., M. Aslam, C. Service, C. Narváez-Bravo, B. P. Avery, R. Johnson, and T. H. Jones. 2017. Prevalence and antimicrobial resistance of *Salmonella* isolated from two pork processing plants in Alberta, Canada. Int. J. Food. Microbiol. 241:49–59. https://doi.org/10.1016/j.ijfoodmicro.2016.10.004.

São José, J. F. B., and M. C. D. Vanetti. 2012. Effect of ultrasound and commercial sanitizers in removing natural contaminants and *Salmonella enterica* Typhimurium on cherry tomatoes. Food Control. 24:95–99. https://doi.org/10.1016/j.foodcont.2011.09.008.

Sapsford, K. E., J. Granek, J. R. Deschamps, K. Boeneman, J. B. Blanco-Canosa, P. E. Dawson, K. Sumusu, M. H. Stewart, and I. L. Medintz. 2011. Monitoring botulinum neurotoxin activity with peptide-functionalized quantum dot resonance energy transfer sensors. ACS Nano. 5:2687–2699. https://doi.org/10.1021/nn102997b.

Schlisselberg, D. B., E. Kler, E. Kalily, G. Kisluk, O. Karniel, and S. Yaron. 2013. Inactivation of foodborne pathogens in ground beef by cooking with highly controlled radio frequency energy. Int. J. Food Microbiol. 160:219–226. https://doi.org/10.1016/j.ijfoodmicro.2012.10.017.

Schmidt, J. W., D. M. Brichta-Harhay, N. Kalchayanand, J. M. Bosilevac, S. D. Shackelford, T. L. Wheeler, and M. Koohmaraie. 2012. Prevalence, enumeration, serotypes, and antimicrobial resistance phenotypes of *Salmonella enterica* isolates from carcasses at two large United States pork processing plants. Appl. Environ. Microb. 78:2716–2726. https://doi.org/10.1128/AEM.07015-11.

Schneider, L. G., Z. R. Stromberg, G. L. Lewis, R. A. Moxley, and D. R. Smith. 2018. Cross-sectional study to estimate the prevalence of enterohaemorrhagic *Escherichia coli* on hides of market beef cows at harvest. Zoonoses Public Hlth. 65:625–636. https://doi.org/10.1111/zph.12468.

Sen, Y., B. Onal-Ulusoy, and M. Mutlu. 2019. *Aspergillus* decontamination in hazelnuts: Evaluation of atmospheric and low-pressure plasma technology. Innov. Food Sci. Emerg. 54:235–242. https://doi.org/10.1016/j.ifset.2019.04.014.

Sengun, I. Y., F. Icier, and G. Kor. 2015. Effects of combined ohmic–infrared cooking treatment on microbiological inactivation of meatballs. J. Food Process Eng. 40:e12309. https://doi.org/10.1111/jfpe.12309.

Sengun, I. Y., G. Y. Yildiz Turp, F. Icier, P. Kendirci, and G. Gamze Ko. 2014. Effects of ohmic heating for pre-cooking of meatballs on some quality and safety attributes.

Lebensm-Wiss. Technol. 55:232–239. https://doi.org/10.1016/j.lwt.2013.08.005.

Sevenich, R. 2016. High pressure processing at ambient and high temperatures and its influence on food processing contaminants, food borne diseases and bacterial spores in model- and real-food systems. https://www.depositonce.tu-berlin.de/bitstream/11303/5426/4/sevenich_robert.pdf. (Accessed 27 April 2020).

Shemesh, R., D. Goldman, M. Krepker, Y. Danin-Poleg, Y. Kashi, A. Vaxman, and E. Segal. 2015. LDPE/clay/carvacrol nanocomposites with prolonged antimicrobial activity. J. Appl. Polym. Sci. 132:41261.

Shin, J., B. Harte, S. Selke, and Y. Lee. 2011. Use of a controlled chlorine dioxide (ClO2) release system in combination with modified atmosphere packaging (MAP) to control the growth of pathogens. J. Food Quality. 34:220–228. https://doi.org/10.1111/j.1745-4557.2011.00381.x

Silva, F. V. 2016. High pressure thermal processing for the inactivation of *Clostridium perfringens* spores in beef slurry. Innov. Food Sci. Emerg. 33:26–31. https://doi.org/10.1016/j.ifset.2015.12.021.

Singh, P. K., G. Jairath, and S. Ahlawat. 2016. Nanotechnology: a future tool to improve quality and safety in meat industry. J. Food Sci. Tech. Mys. 53:1739–1749. https://doi.org/10.1007/s13197-015-2090-y.

Sommers, C., X. Fan, B. Niemira, and K. Rajkowski. 2004. Irradiation of ready-to-eat foods at USDA's Eastern Regional Research Center-2003 update. Radiat. Phys. Chem. 71:511–514. https://doi.org/10.1016/j.radphyschem.2004.03.070.

Soni, A., J. Smith, A. Thompson, and G. Brightwell. 2020. Microwave-assisted thermal sterilization-A review on history, technical progress, advantages and challenges as compared to conventional methods. Trends Food Sci Tech. 97:433–442. https://doi.org/10.1016/j.tifs.2020.01.030.

Stachelska, M. A., W. Stankiewicz-Szymczak, A. Jakubczak, R. wisłocka, and W. Lewandowski. 2012. Influence of pulsed electric field on the survival of *Yersinia enterocolitica* in minced beef meat: assessment of microbiological activity of selected cell lines of bacteria under influence of physical-chemical factors. Aparatura Badawcza i Dydaktyczna. 17:13–17.

Stanisavljevic, M., S. Krizkova, M. Vaculovicova, R. Kizek, and V. Adam. 2015. Quantum dots-fluorescence resonance energy transfer-based nanosensors and their application. Biosens. Bioelectron. 74:562–574. https://doi.org/10.1016/j.bios.2015.06.076.

Stevens, M. P., T. J. Humphrey, and D. J. Maskell. 2009. Molecular insights into farm animal and zoonotic Salmonella infections. Philos. T. Roy. Soc. B. 364:2709–2723. https://doi.org/10.1098/rstb.2009.0094.

Stratakos, A. C., and A. Koidis. 2015. Suitability, efficiency and microbiological safety of novel physical technologies for the processing of ready-to-eat meals, meats and pumpable products. Int. J. Food Sci. Tech. 50:1283–1302. https://doi.org/10.1111/ijfs.12781.

Sun, H., F. Masuda, S. Kawamura, J. I. Himoto, K. Asano, and T. Kimura. 2011. Effect of electric current of ohmic heating on nonthermal injury to *Streptococcus thermophilus* in milk. J.

Food Process Eng. 34:878–892. https://doi.org/10.1111/j.1745-4530.2009.00515.x.

Tapp, C., and R. G. Rice. 2012. Generation and control of ozone. In C. O'Donnell, B. K. Tiwari, P. J. Cullen, and R. G. Rice, Editors, Ozone in food processing. 1st ed. Blackwell Publishing Ltd., Chichester. p. 33–46.

Thomas, C., H. Thippareddi, M. Rigdon, S. Kumar, R. W. McKee, M. W. Sims, and A. M. Stelzleni. 2020. The efficacy of antimicrobial interventions on Shiga toxin producing *Escherichia coli* (STEC) surrogate populations inoculated on beef striploins prior to blade tenderization. Lebensm-Wiss. Technol. 117:108689.

Todorov, S. D., M. Wachsman, E. Tomé, X. Dousset, M. T. Destro, L. M. T. Dicks, B. D. G. M. Franco, M. Vaz-Velho, and D. Drider. 2010. Characterisation of an antiviral pediocin-like bacteriocin produced by *Enterococcus faecium*. Food Microbiol. 27:869–879. https://doi.org/10.1016/j.fm.2010.05.001.

Torres, J. A., and G. Velazquez. 2005. Commercial opportunities and research challenges in the high pressure processing of foods. J. Food Eng. 67:95–112. https://doi.org/10.1016/j.jfoodeng.2004.05.066.

Troy, D. J., Ojha, K. S., Kerry, J. P., and Tiwari, B. K. 2016. Sustainable and consumer-friendly emerging technologies for application within the meat industry: An overview. Meat Sci. 120:2–9. https://doi.org/10.1016/j.meatsci.2016.04.002

USDA-FSIS. 2012. High pressure processing (HPP) and inspection program personnel (IPP) verification responsibilities. Directive 6120.2. United States Department of Agriculture-Food Safety and Inspection Service. https://www.fsis.usda.gov/wps/wcm/connect/a64961fa-ed6f-44d1-b637-62232a18f998/6120.2.pdf?MOD=AJPERES. (Accessed 27 April 2020).

USDA-FSIS. 2014. FSIS compliance guideline: Controlling *Listeria monocytogenes* in post-lethality exposed ready-to-eat meat and poultry products. United States Department of Agriculture-Food Safety and Inspection Service. http://www.fsis.usda.gov/wps/portal/fsis/topics/regulatory-compliance/compliance-guidesindex#Listeria. (Accessed 27 April 2020).

Valdez-Fragoso, A., H. Mújica-Paz, J. Welti-Chanes, and J. A. Torres. 2011. Reaction kinetics at high pressure and temperature: effects on milk flavor volatiles and on chemical compounds with nutritional and safety importance in several foods. Food Bioprocess Tech. 4:986–995. https://doi.org/10.1007/s11947-010-0489-z.

Vinayaka, A. C., and M. S. Thakur. 2013. Facile synthesis and photophysical characterization of luminescent CdTe quantum dots for Forster resonance energy transfer based immunosensing of staphylococcal enterotoxin B. Luminescence. 28:827–835. https://doi.org/10.1002/bio.2440.

Wan, J., J. Coventry, P. Swiergon, P. Sanguansri, and C. Versteeg. 2009. Advances in innovative processing technologies for microbial inactivation and enhancement of food safety–pulsed electric field and low-temperature plasma. Trends Food Sci Tech. 20:414–424. https://doi.org/10.1016/j.tifs.2009.01.050.

Wang, J. J., B. H. Liu, Y. T. Hsu, and F. Y. Yu. 2011. Sensitive competitive direct enzyme-linked immunosorbent assay and gold nanoparticle immunochromatographic strip for detecting aflatoxin M1 in milk. Food Control. 22:964–969. https://doi.org/10.1016/j.foodcont.2010.12.003.

Wang, Y., J. M. Tang, B. Rasco, S. J. Wang, A. A. Alshami, and F. B. Kong. 2009. Using whey protein gel as a model food to study dielectric heating properties of salmon (*Oncorhynchus gorbuscha*) fillets. Lebensm-Wiss. Technol. 42:1174–1178. https://doi.org/10.1016/j.lwt.2009.01.005.

Woraprayote, W., L. Pumpuang, A. Tosukhowong, T. Zendo, K. Sonomoto, S. Benjakul, and W. Visessanguan. 2018. Antimicrobial biodegradable food packaging impregnated with Bacteriocin 7293 for control of pathogenic bacteria in pangasius fish fillets. Lebensm.-Wiss. Technol. 89:427–433. https://doi.org/10.1016/j.lwt.2017.10.026.

Yeh, Y., F. H. de Moura, K. Van Den Broek, and A. S. de Mello. 2018. Effect of ultraviolet light, organic acids, and bacteriophage on *Salmonella* populations in ground beef. Meat Sci. 139:44–48. https://doi.org/10.1016/j.meatsci.2018.01.007.

Yemi , G. P., and K. Cando an. 2017. Antibacterial activity of soy edible coatings incorporated with thyme and oregano essential oils on beef against pathogenic bacteria. Food Sci. Biotechnol. 26:1113–1121. https://doi.org/10.1007/s10068-017-0136-9.

Yong, H. I., H. Lee, S. Park, J. Park, W. Choe, S. Jung, and C. Jo. 2017. Flexible thin-layer plasma inactivation of bacteria and mold survival in beef jerky packaging and its effects on the meat's physicochemical properties. Meat Sci. 123:151–156. https://doi.org/10.1016/j.meatsci.2016.09.016.

Yun, H., B. Kim, S. Jung, Z. A. Kruk, D. B. Kim, W. Choe, C. Jo. 2010. Inactivation of *Listeria monocytogenes* inoculated on disposable plastic tray, aluminum foil, and paper cup by atmospheric pressure plasma. Food Control. 21:1182–1186. https://doi.org/10.1016/j.foodcont.2010.02.002.

Zell, M., J. G. Lyng, D. A. Cronin, and D. J. Morgan. 2010. Ohmic cooking of whole beef muscle—Evaluation of the impact of a novel rapid ohmic cooking method on product quality. Meat Sci. 86:258–263. https://doi.org/10.1016/j.meatsci.2010.04.007.

Zhang, J., Z. Li, Z. Cao, L. Wang, X. Li, S. Li, and Y. Xu. 2015. Bacteriophages as antimicrobial agents against major pathogens in swine: A review. J. Anim. Sci. Biotechno. 6:39. https://doi.org/10.1186/s40104-015-0039-7.

Zhang, Z., M. Lin, S. Zhang, and B. Vardhanabhuti. 2013. Detection of aflatoxin M1 in milk by dynamic light scattering coupled with superparamagnetic beads and gold nanoprobes. J. Agr. Food Chem. 61:4520–4525. https://doi.org/10.1021/jf400043z.

Zhu, S., F. Naim, M. Marcotte, H. Ramaswamy, and Y. Shao. 2008. High-pressure destruction kinetics of *Clostridium sporogenes* spores in ground beef at elevated temperatures. Int. J. Food Microbiol. 126:86–92. https://doi.org/10.1016/j.ijfoodmicro.2008.05.009.

Ziuzina, D., S. Patil, P. J. Cullen, K. M. Keener, and P. Bourke. 2013. Atmospheric cold plasma inactivation of *Escherichia coli* in liquid media inside a sealed package. J. Appl. Microbiol. 114:778–787. https://doi.org/10.1111/jam.12087.