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.

Key words: meat processing, emerging technologies, novel meat processing, meat safety

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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 non-intact 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 Candoan (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 Emir 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 (Hygeree 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 log10 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-inorporated 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., 2011). 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/cm² resulted in 1.78 and 1.11 log₁₀ CFU/cm² 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/cm² (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 log₁₀ 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 reduce bacterial loads of ≤3 log₁₀ 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 log10 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 log10 CFU/g were seen for *E. coli* O157:H7 on beef, whereas lower reductions, averaging 1 log10 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/cm², 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 Knöchel, 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/cm² 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 Knöchel, 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<sub>10</sub> 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 of 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<sub>10</sub> 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<sub>10</sub> 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<sub>10</sub> 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. Rodriguez-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<sub>10</sub> CFU/cm². 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 concentration and mixture of bioactive compounds as well as the species and strain of the target microorganism (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; Kska 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; Kska 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.

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